Enhancing Cultural Heritage with Tangible Mixed Reality

Supporting Designers Through a Toolkit

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- HANNE

Executive Summary

Extended Reality (XR) technologies offer exciting opportunities for cultural heritage, allowing stories and artifacts to come to life in immersive, interactive ways. However, designing meaningful XR experiences—especially those that combine physical and digital interaction—is not straightforward, especially for designers with limited technical expertise. This thesis addresses that challenge by developing a toolkit that supports designers in creating tangible Mixed Reality experiences for cultural heritage contexts.

The goal of this project was to explore how tangible interaction and XR can be combined in a way that feels natural and intuitive, particularly in museum settings where visitors may not be familiar with XR technologies. Through research and design experimentation, the project led to the creation of the HIT-KIT: a design toolkit intended to lower the threshold for designing meaningful XR heritage experiences using tangible interaction. The toolkit includes beginner-friendly tutorials, a digital workbook to guide the user through the design process, a card deck to offer inspiration and support, and digital building blocks that allow for quick prototyping

The HIT-KIT was developed alongside a case study: the design of The Calculator's Desk, an interactive museum experience that uses tangible Mixed Reality to explore the story behind analog calculators. The design process of this experience offered valuable insights into the challenges of designing for XR and heritage, and helped shape the toolkit's structure and content.

While the current version of the toolkit is still conceptual, it lays the foundation for further development into a practical and accessible design method. This project shows that such a toolkit can make working with XR more approachable, especially for those who are new to this field.

Looking ahead, the toolkit could be further developed and tested with a wider range of users, including museum professionals and exhibition designers. This would help tailor the content to different contexts and skill levels, and expand its relevance beyond TU Delft. Additionally, the approach could be applied to other heritage narratives to test how well it works across different themes and artifacts.

In summary, this thesis contributes to the field of design for cultural heritage by offering a practical toolkit for combining tangible interaction with XR. This way, designers can be empowered to create more engaging and meaningful heritage experiences.

Glossary

AR – Augmented Reality

A technology that overlays digital content onto the physical world in real time, enhancing the user's perception of their environment.

CH – Cultural Heritage

The legacy of physical artifacts and intangible attributes of a group or society, inherited from past generations and preserved for future generations.

HCI – Human-Computer Interaction

The study and practice of designing user interfaces and interactions between people and computers, focusing on usability, user experience, and accessibility.

HMD – Head-Mounted Display

A wearable device that places a screen or displays in front of the user's eyes, commonly used in immersive virtual and augmented reality applications.

MR – Mixed Reality

A hybrid environment where digital and physical elements coexist and interact in real time, blending aspects of both virtual and augmented reality.

TUI – Tangible User Interface

A type of user interface that allows users to interact with digital information through the physical manipulation of objects.

VR – Virtual Reality

An immersive digital environment that fully replaces the user's real-world surroundings, typically experienced through a headset or HMD.

XR – Extended Reality

An umbrella term encompassing all immersive technologies, including virtual reality (VR), augmented reality (AR), and mixed reality (MR).

Content

1. Introduction

Museums and cultural institutions are always looking for new ways to engage visitors and bring their collections to life. In recent years, digital technologies have played a growing role in how heritage is shared and experienced. Among these technologies, Extended Reality (XR) and Tangible User Interfaces (TUIs) offer exciting possibilities for making exhibitions more immersive, interactive, and educational. Despite growing interest in these tools, many museum visits still involve relatively passive forms of interaction—looking at objects behind glass or reading informational panels. This highlights an opportunity to rethink how visitors connect with cultural heritage.

Extended Reality is an umbrella term that includes Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR). These technologies can create immersive environments that let users explore digital representations of artifacts, historical places, or events—often in ways that aren't possible in the physical world (Figure 1). TUIs, on the other hand, involve using physical objects or surfaces to control digital information. This allows users to interact with technology through touch, making the experience feel more natural and intuitive (Figure 2).

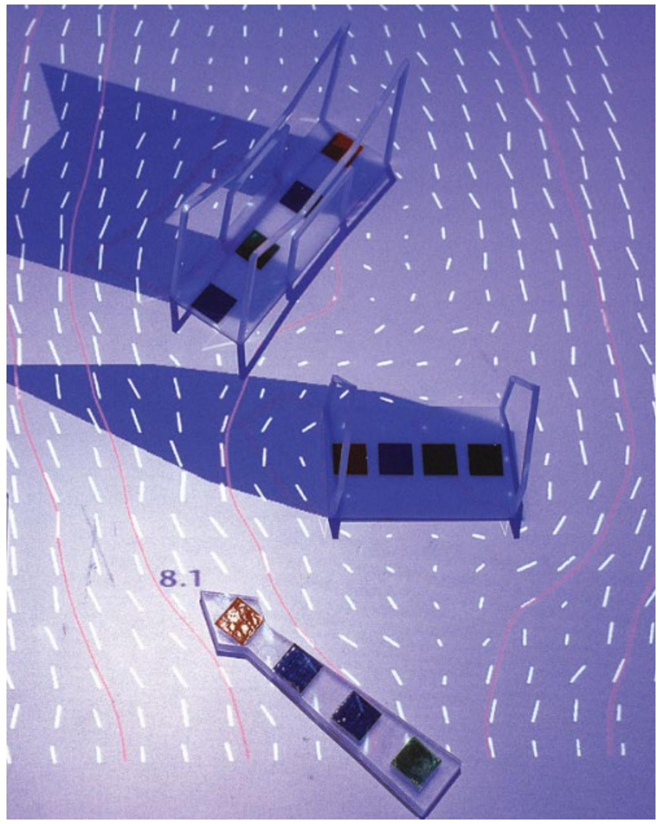


Figure 2. Urp is a TUI that uses physical scale models of architectural buildings to simulate and control elements like shadows, light reflection, wind flow, and other environmental factors, all projected onto a physical workbench (Ishii et al., 2012).

Figure 1. An XR exhibition at the Petersen Automotive Museum in Los Angeles. Head-Mounted Displays were used to showcase the evolution of the Ford GT, blending holograms and spatial audio to highlight its design and racing legacy (Microsoft News, 2017).

Figure 3. In the virtual reality experience DelightfulGardenVR, visitors wearing a VR headset can explore a virtual world based on Hieronymus Bosch's painting 'Garden of Earthly Delights' (Museum für Kommunikation Frankfurt, n.d.).

Together, XR and TUIs can support new ways of storytelling and embodied exploration in museum settings. Research has shown that XR can increase engagement by turning passive observation into active participation, allowing visitors to experience artifacts in their historical contexts and from new perspectives (Bekele et al., 2018; Giariskanis et al., 2022; Innocente et al., 2023). However, there are still challenges when it comes to making these technologies work well for all users. Many visitors aren't familiar with XR and might be hesitant to use it or find it awkward—especially when interacting with standard VR controllers (Figure 3) that don't match the way we naturally use our hands to interact with objects (Bekele et al., 2018; Kim et al., 2023; Moran-Ledesma et al., 2021; Neamu et al., 2024).

This is where tangible interaction can help. Tangible User Interfaces allow people to control digital systems using physical props, which can match the look, feel, and weight of real-world objects. This kind of interaction can be more intuitive and engaging, especially for first-time users. Tactile feedback also strengthens the connection between what visitors see and what they feel. Combining this with XR supports learning and helps make experiences more memorable, personal and meaningful (Cannavò et al., 2024; Cardoso, 2021; Petrelli & Roberts, 2023). Mixed Reality (MR), in particular, blends digital and physical environments in real time, allowing users to interact with virtual content through tangible, real-world objects. This reduces the need for traditional XR controllers and opens up more natural, hands-on ways of engaging with cultural content.

On the museum side, there's another challenge: designing and building XR and TUI experiences often requires specialized technical skills. Curators, educators, and exhibition designers may have strong creative, interpretive and storytelling expertise but often lack the tools or training to implement them in interactive, digital formats. To make these technologies more widely usable, we need methods and tools that lower the barrier to entry—making it easier for non-technical professionals to create their own immersive experiences.

This thesis explores how MR and TUIs can work together to create engaging, embodied interactions with heritage artifacts. It focuses not only on the visitor experience, but also on how designers can be supported in creating these kinds of interactive exhibitions. By exploring practical tools and methods that lower the technical and creative barriers, this work aims to make immersive technologies more accessible to a broader range of museum professionals, helping cultural institutions make better use of digital interaction in their exhibitions.

1.1 Goal & scope

Despite the growing interest in Mixed Reality and Tangible User Interfaces within cultural heritage, there is still limited research on how to combine these technologies in ways that are both meaningful for visitors and accessible for designers without technical backgrounds. This thesis explores how MR and TUIs can support meaningful visitor engagement with heritage artifacts, while also envisioning how designers—especially those with limited technical expertise—can be supported in creating such experiences.

The research is guided by two main questions:

1. *How can Mixed Reality combined with Tangible User Interfaces enhance visitor engagement with heritage artifacts?*
2. *What design tools can support professionals with limited technical expertise in creating these experiences?*

To answer these questions, the thesis investigates the design process of an MR+TUI-based interactive exhibition. This design process acts as a case study, identifying key challenges and opportunities when working with MR and TUIs. Insights from this case study form the basis for a conceptual toolkit aimed at making immersive heritage design more approachable for non-expert users.

Given the wide scope of cultural heritage, this thesis focuses specifically on scientific heritage—artifacts such as historical instruments that were originally designed for practical and scientific use. These objects often gain meaning through their function, but in a museum setting, their hands-on use is usually not possible due to preservation concerns. This makes it difficult for visitors to understand how they worked, especially when internal mechanisms are hidden from view.

Scientific heritage therefore offers a compelling case study for MR and TUIs, as these technologies can recreate embodied interactions and reveal abstract or hidden components. In this project, analog calculators and their histories are used as a representative artifacts to explore this approach (Figure 4).

Figure 4. Katherine Johnson at work in 1962. Johnson was a American mathematician whose calculations were critical to NASA's early space missions. On her desk is a Monroe mechanical calculator (NASA, n.d.).

Therefore, this thesis is structured around two interconnected design goals:

Design an MR+TUI-based interactive heritage experience that allows visitors to meaningfully engage with analog calculators as scientific heritage artifacts.

The aim is to recreate the embodied interaction these instruments originally required, using a combination of physical and digital elements to communicate their function and historical context in a museum setting.

Design a conceptual toolkit that supports designers with limited technical expertise in creating immersive heritage experiences using Mixed Reality and Tangible User Interfaces.

The toolkit should offer accessible guidance through the design process, enabling creative exploration of MR+TUI integration without requiring advanced programming skills.

1.2 Approach

This project follows a Research through Design approach: by designing my own immersive heritage experience that combines Mixed Reality and Tangible User Interfaces, I aim to explore the key insights to designing a MR+TUI Heritage Toolkit. The toolkit is intended for designers with limited coding experience who want to create immersive heritage experiences using MR and TUIs. I also fall within this target group, as I had no prior experience with XR before starting this project. While my personal engagement in the design process will play a formative role in generating knowledge for the final toolkit design, I acknowledge that my perspective is just one of many. To broaden the scope of insights, I will involve other design students in brainstorming and evaluation sessions throughout the project.

The final outcomes of this thesis are the following:

- A prototype of an **immersive heritage experience** that combines Mixed Reality with tangible interactions.
- A prototype for a **toolkit** to support the MR+TUI heritage design process.

To come to these end products, I will go through the following steps:

- **Contextual Analysis:** I will begin by deepening my understanding of the project's key themes. I will use several methods for this analysis to gain insights from different perspectives – a literature review, interviews with experts and auto-ethnographic observations. The insights from this analysis will be translated into design directions that will form the basis for the design of my immersive heritage experience. The contextual analysis will be discussed in chapter 2.
- **Case Study:** Based on the contextual analysis, I will design an immersive experience focused on the history of analog calculators. This design process will be discussed in chapter 3.
- **Final Design:** Throughout the design process I will learn many lessons about designing with MR and TUIs. These insights will be used to develop the MR+TUI Heritage Toolkit. Chapter 4 discusses the process of designing this toolkit and presents the final outcome.
- **Conclusion & Reflection:** Finally, Chapter 5 will reflect on the project's contributions, acknowledge its limitations, and propose directions for future research.

2. Contextual Analysis

Before starting the design of a heritage experience, it's important to first understand the context in which it will take shape. In this chapter, I will examine the role of HCI in museums, with a particular focus on its application in scientific heritage. I will then explore the key technologies that will form the basis of the immersive heritage experience and its supporting toolkit: Extended Reality and tangible interactions. What do these technologies involve, how have they been used in cultural heritage so far, and what can we learn from those examples? Lastly, I'll look into the design of interactive exhibitions more generally.

2.1 Human-Computer Interaction in Cultural Heritage

Human-Computer Interaction is a field of research and practice that explores how people interact with digital technology. Emerging in the early 1980s, it initially focused on making personal computing more usable and accessible. Over time, HCI expanded beyond desktop interfaces to include mobile devices, the internet, and the incorporation of computing into everyday objects and environments, such as cars, home appliances and clothing (Carroll, 2014).

At its core, HCI seeks to design technology that enhances human activities and experiences. It studies how users interact with digital systems, how these interactions evolve, and how technology can be designed to better support human needs (Carroll, 2014). With the growing implementation of digital systems in museums and the broader cultural heritage sector, these spaces have become valuable testing grounds for HCI research and technological innovation (Hornecker & Ciolfi, 2019).

While museums originated from private collections or "cabinets of curiosities," they have evolved into institutions aimed at public education, cultural preservation, and research. Over time, their roles have expanded to include community development and contributions to the cultural and tourism sectors (Hornecker & Ciolfi, 2019). For example, the "New Museology" movement of the late 1980s and 1990s challenged the elitism and traditional curatorial authority of museums, placing greater emphasis on visitor engagement and sensory experiences. This movement argued that sensory engagement enhances learning and creates a deeper connection with the history of artifacts (Hornecker & Ciolfi, 2019; Spence et al., 2020). Digital technologies support this 'Rehabilitation of Touch' by enabling interactions with artifacts without risking damage (Bekele et al., 2018). These evolving trends in museum contexts have driven advancements in research and practice related to digital technologies in museums. Museums continue to be spaces for exploring ideas and creatively presenting artifacts and information. By experimenting with innovative presentation techniques, they aim to attract more visitors, which in turn make them ideal environments for testing new interactive technologies (Hornecker & Ciolfi, 2019).

HCI can play a key role in how museums connect with audiences and present exhibitions by incorporating digital technologies into cultural experiences, using interactive system design to enhance accessibility, engagement, and educational value. These interactive and immersive experiences can captivate visitors and create more dynamic and memorable experiences, allowing museums to present complex historical or scientific topics in a more engaging and personalized way. Additionally, digital technologies can provide assistance to visitors to make museums more inclusive and accessible to a diverse audience (Hornecker & Ciolfi, 2019).

2.2 Interactions through Extended Reality

I began by examining the concept of Extended Reality, its past applications in the cultural heritage sector, and the key insights drawn from existing research. This literature review aimed to address the following questions:

- *What are XR technologies?*
- *How have XR technologies been used to experience tangible heritage artifacts?*
- *What insights can be gained from previous applications that are relevant to designing XR heritage exhibitions?*

2.2.1 Defining Extended Reality

Extended Reality can be described as technologies on the reality-virtuality continuum, a framework originally introduced by Milgram & Kishino (1994). These technologies vary from fully digital worlds in Virtual Reality to the combination of real and virtual content in Augmented Reality (Figure 5). Three main types of XR can be recognized on this continuum: Augmented Reality (AR), Mixed Reality (MR) and Virtual Reality (VR). AR overlays digital content onto the real world, enhancing the physical environment without replacing it. MR merges real and virtual elements, allowing interaction between both in real time. VR replaces the physical world entirely, fully immersing the user in a computer-generated environment (Bekele et al., 2018; Meta, 2024).

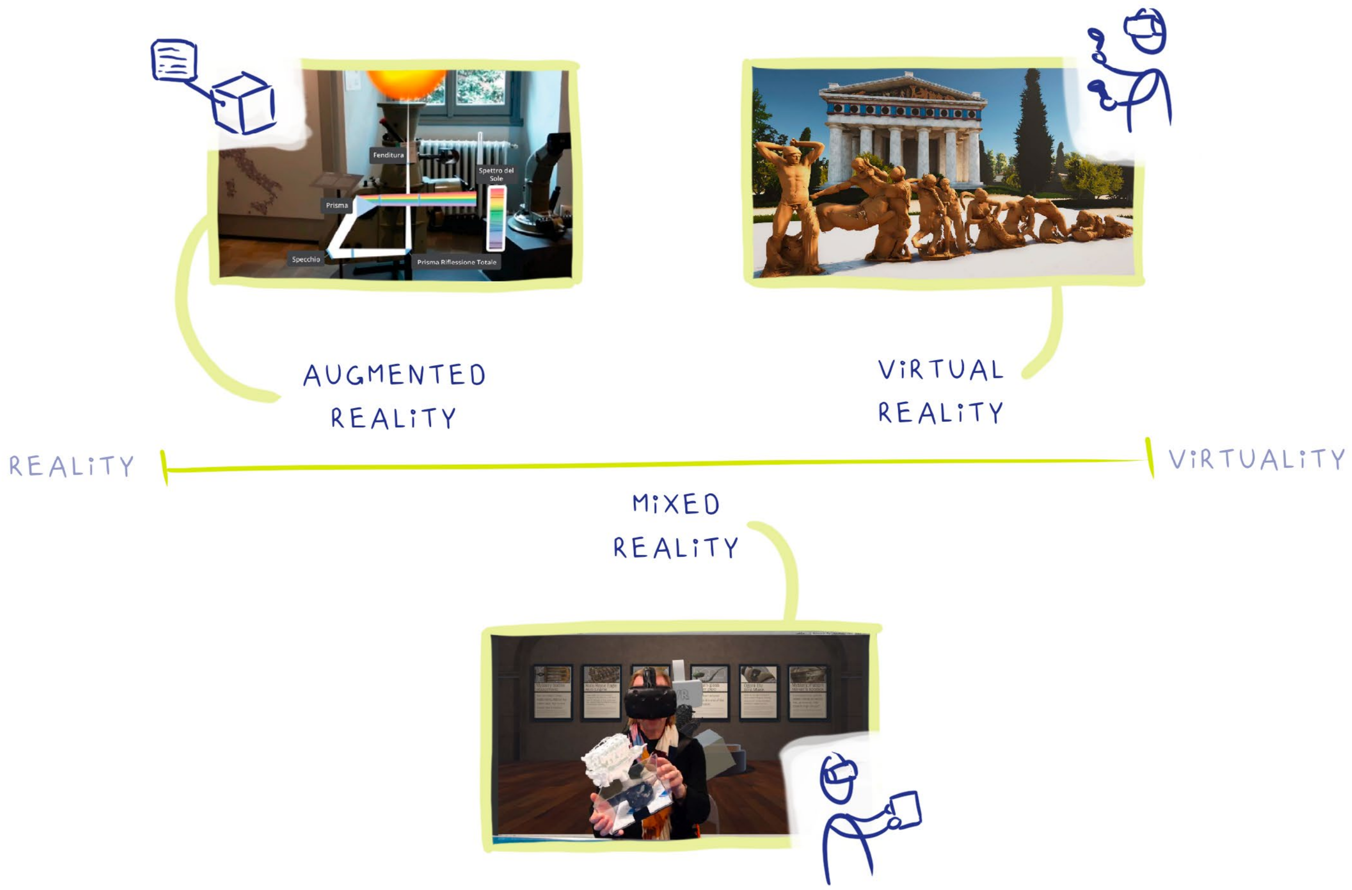


Figure 5. The Reality-Virtuality Continuum and the definitions of Extended Reality categories. Examples by Spadoni et al. (2022), Spence et al. (2020), and Plecher et al. (2019).

There are several ways to display virtual content in XR experiences. The most commonly used display is the Head-Mounted Display (HMD): a wearable device, typically worn on the head, that presents visual information directly in front of the user's eyes (Bekele et al., 2018).

2.2.2 XR applied in cultural heritage contexts

In recent years, XR technologies have been increasingly applied in the field of cultural heritage. They are often seen as useful tools for increasing visitor engagement in museums and allowing both experts and the public to explore artifacts in a safe and interactive way. At the same time, there are challenges to adopting XR in this context. More advanced XR applications often need powerful hardware and skilled developers, which can be a barrier for museums that have limited budgets or lack technical expertise (Plecher et al., 2019).

Bekele et al. (2018) categorized the main purposes of XR within cultural heritage as exploration, reconstruction, exhibition enhancement, education, and virtual museums. While many XR heritage projects combine multiple purposes, each category will be discussed separately in the next section with recent examples.

Exploration

XR allows users to visualize and explore historical and contemporary perspectives of cultural heritage, and acquire new insights and knowledge by doing so. Digital models can be explored without risking damage to the original artifact. For example, the ArcheoBox let users handle digitized artifacts naturally by interacting with AR cards (Figure 6). The digital model appeared on a screen on top of the box, allowing users to examine the artifact while moving the card (Kobeisse, 2021, 2023).

Manipulating digital replicas enables visitors to feel connected to otherwise inaccessible artifacts and supports engagement through detailed examination (Kobeisse, 2023). Additionally, digital reconstructions of larger artifacts convey a sense of scale and proportion, allowing users to experience artifacts in their original grandeur and as they were intended to be seen (Petrelli & Roberts, 2023).

Reconstruction

XR enables users to interact with and visualize restored historical representations of cultural heritage, for example by restoring missing components of artifacts. Haindl & Sedlacek (2016) applied shape prediction algorithms to reconstruct missing parts of an Iron Age Celtic druid head, which could then be examined in a virtual environment. Plecher et al. (2019), on the other hand, used AR to indicate which parts of ancient Greek statues were non-original and reconstructed in the physical statue (Figure 7).

Figure 6. This tangible AR interface lets users pick up, handle, and explore digitized historical artifacts naturally and interactively (Kobeisse, 2021).

Figure 7. This AR application shows how ancient Greek statues originally looked, before parts were reconstructed (Plecher et al., 2019).

Exhibition enhancement

XR technologies enable users to engage more deeply with exhibitions by interacting with them, creating more immersive and interactive experiences compared to traditional displays. For instance, after creating digital models of small cultural artifacts, Lee et al. (2015) developed an installation where visitors could explore these models using their phone flashlights. A fish-eye camera captured the flashlight's direction, dynamically adjusting the digital model's lighting accordingly (Figure 8). In another example, Van Der Vaart & Damala (2015) developed an interactive AR magnifying lens that used image recognition technology to display relevant digital content when visitors looked at the museum's artifacts (Figure 9).

VR using HMDs can fully immerse users in reconstructed environments, creating a strong sense of presence by eliminating distractions from the real world. This heightened immersion can also enhance cultural presence, allowing visitors to experience not only the architecture but also elements of daily life. This adds context to the lives and practices of historical inhabitants within the virtual environment. Research has demonstrated that VR environments effectively induce a strong sense of "being there," both physically and socially (Petrelli & Roberts, 2023).

Virtual Humans can further enhance storytelling by serving as engaging narrators in VR environments. Combining these with Speech User Interfaces (SUIs) can enable intuitive and personalized communication. Cannavò et al. (2024) demonstrated this by designing an immersive exploration of Egyptian artifacts in which users could ask questions to a virtual guide (Figure 10). In this application, the combined use of SUIs and TUIs was preferred by the users over conventional controllers and interfaces.

XR also facilitates visitor contributions to exhibitions. Zhang & Lopez Silva (2020) combined VR with tangible elements to create a virtual environment where visitors could learn about Monarch butterflies and grow their own virtual butterfly by collecting materials in VR. The butterfly was placed in a physical jar, and the next visitor could release it before repeating the growing process.

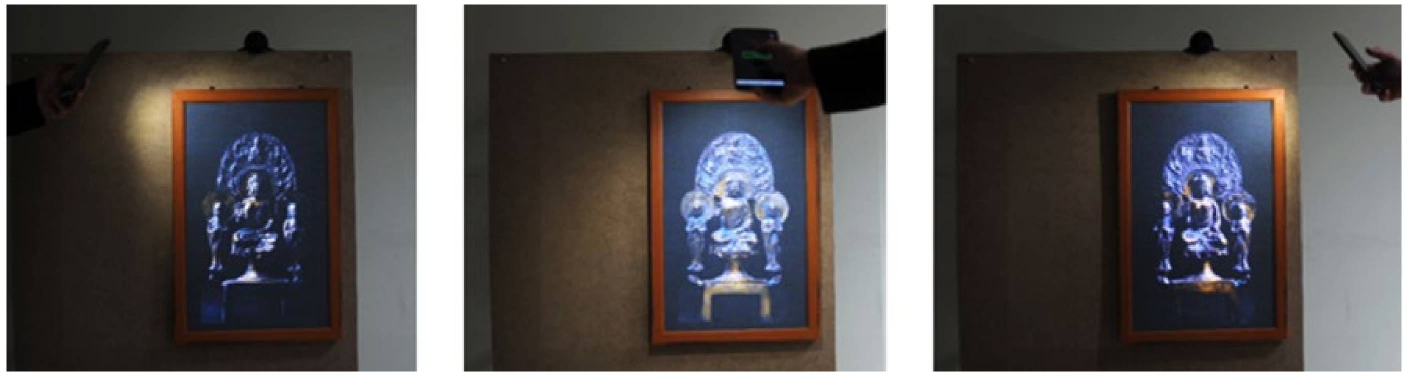


Figure 8. Visitors interact using their smartphone flashlights to explore lighting effects. A 2D image of cultural artifacts responds dynamically to the light direction (Lee et al., 2015).

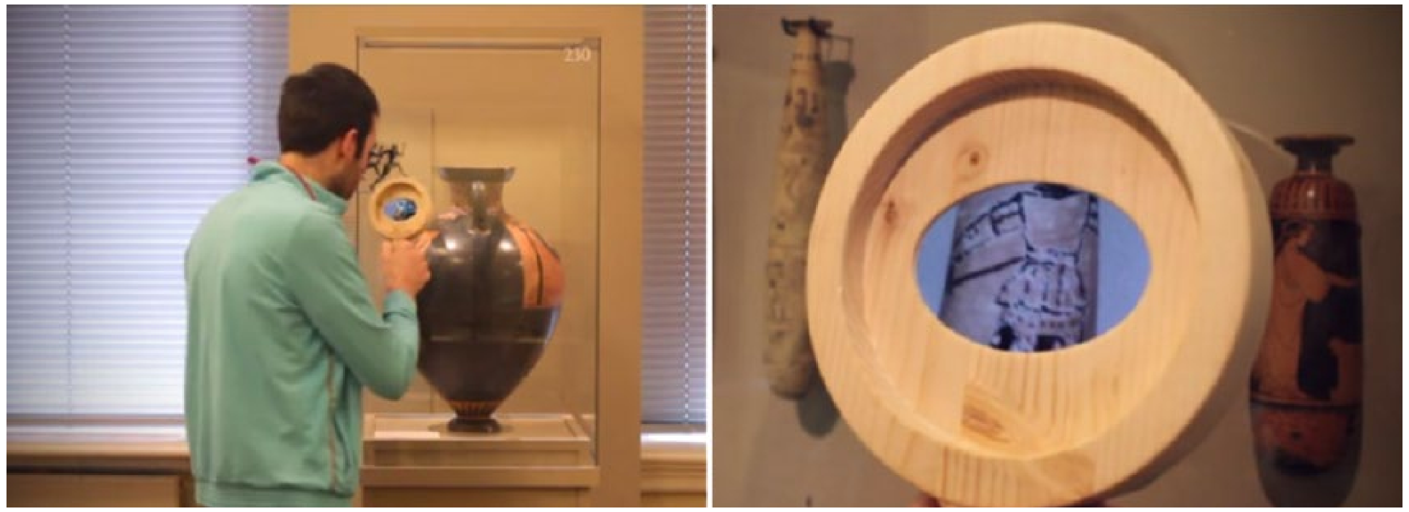


Figure 9. The Loupe is an AR wooden magnifying lens embedded with an iPhone. It enables visitors to examine objects up close and access extra digital content (Van Der Vaart & Damala, 2015; Zancanaro et al., 2015).

Figure 10. An immersive experience for exploring ancient Egyptian artifacts. Users interact with 3D-printed replicas for tactile feedback and engage in conversational dialogue with a virtual curator (Cannavò et al., 2024).

Education

XR can help users learn about the historical aspects of cultural heritage. Studies show that users engaging with XR are more likely to retain knowledge (Ribeiro et al., 2024). Using XR to fill in the missing pieces can enhance storytelling, making exhibitions more relatable and engaging by providing context to fragmented artifacts. Petrelli & Roberts (2023) designed a VR experience using environmental narrative principles to add context to exhibits from the Forum of Augustus. Visitors explored fragments of stories scattered across the VR world, reconstructing life in ancient Rome through visual and auditory cues (Figure 11). Similarly, Plecher et al. (2019) developed a gamified museum experience where AR-enabled statues of Greek gods guided visitors through riddles and puzzles, unlocking historical information by solving these tasks.

Virtual museums

XR technologies have been used to promote virtual tourism, enabling access to cultural artifacts and historical sites from anywhere in the world. VR experiences serve as virtual museums, presenting historical artifacts in immersive environments. Sooai et al. (2017) made digital replicas of Indonesian artifacts accessible worldwide, through a publicly accessible virtual environment.

Furthermore, virtual museums can provide culturally rich and immersive heritage experiences to people who might otherwise lack access to such heritage. For example, Vishwanath (2023) developed a portable VR museum for retirement homes, enabling senior citizens to engage with heritage artifacts and experience the personal stories associated with them.

In addition to enabling "travel" to distant locations, VR allows users to explore historical time periods. For instance, a completely virtual reconstruction of the Temple of Zeus featured 3D scans of statues placed according to historical research (Figure 12), offering visitors an opportunity to explore the past from any location with an HMD (Plecher et al., 2019).

Figure 11. This VR experience brings the Forum of Augustus to life through interactive storytelling. Using a VR device, visitors trigger VR scenes as they move through Trajan's Market, where artifacts from the Forum are displayed (Petrelli & Roberts, 2023).

Figure 12. This VR experience allows users to visit a digital reconstruction of the Temple of Zeus and its statues (Plecher et al., 2019).

2.2.3 Design implications

These examples provide useful lessons for designing immersive XR heritage experiences. In this section, I have turned these insights into practical design implications to guide the development of my own XR experience. These implications are shown below.

Embed artifacts in historical contexts

Place artifacts within the environments they were originally used to illustrate how these tools were integrated into daily life. XR can add extra layers of context to the artifacts, helping users to grasp not just what the artifact is, but *why* it mattered.

Use interactive digital reconstructions

Provide users with hands-on interaction with functioning digital replicas. This interaction deepens engagement and understanding, especially for complex artifacts that are usually behind glass or too fragile to handle.

Add realism through sensory cues

To counteract the artificial feel of virtual experiences, incorporate audio and visual feedback that mimics the real-world use of the original artifacts.

Consider the accessibility and scalability of the experience

Advanced XR applications often require high-performance computers and experienced developers, which can make implementation challenging for museums with limited budgets and technical expertise. A balance needs to be found between the functionality of the XR experience and the level of capabilities needed to develop this.

2.2.4 Discussion

IIn reviewing the literature on the use of XR in cultural heritage, several observations arise. First, a significant part of the existing research is based on scientific experiments or pilot projects, which, while informative, often lack insights into how XR truly functions when applied in everyday museum settings. There is a gap in understanding how these technologies work on a large scale, particularly in terms of sustainability, user experience, and integration with traditional exhibition practices. Additionally, many studies focus on what XR could do in theory, rather than its current challenges – such as technical limitations or audience engagement barriers – that still need to be overcome for effective integration in real-world heritage institutions.

Scientific heritage remains underrepresented in current research, which tends to focus more on artistic or archaeological applications. Although many of the reviewed studies explore interaction within XR environments, few address the challenge of replicating an artifact's original function, which is a key challenge when designing for scientific heritage. Nevertheless, these examples still offer valuable insights into how interactive elements can enhance XR experiences more broadly.

Finally, not all lessons from the literature are directly applicable to my own project. Many of the studies are conducted by teams with far more resources, expertise, and technological capabilities than I have within this thesis. As a result, while the findings are valuable, they may not always be fully relevant to the scope and constraints of my own work. This supports the need for further research tailored to smaller-scale, resource-limited XR projects in cultural heritage.

2.3 Tangible & embodied interactions

As discussed before, tangible interactions, facilitated through tangible user interfaces (TUIs) or physical props, could offer more natural and intuitive experiences within XR experiences. However, including this kind of interactivity within heritage experiences comes with its own set of challenges. The next section aims to answer the following questions through a literature review:

- *What are Tangible User Interfaces?*
- *How have tangible interactions been used in heritage experiences?*
- *What insights can be gained from previous applications that are relevant to designing heritage exhibitions with tangible interactions?*

2.3.1 Tangible User Interfaces

The concept of Tangible User Interfaces (TUIs) was first introduced by Ishii & Ullmer in 1997 as a response to the growing disconnect between digital and physical experiences caused by the rise of personal computers and their Graphical User Interfaces (GUIs). To address this divide, they proposed "Tangible Bits," a concept that allows users to interact with digital information (bits) by coupling it with physical objects and surfaces.

The goal of TUIs was to bridge the gap between cyberspace and the physical world, making computing ubiquitous and seamlessly integrated into everyday environments. Instead of confining digital interaction to a single GUI, such as the desktop PCs of their time, Ishii and Ullmer envisioned a world where the entire environment could serve as an interactive interface. Unlike GUIs, TUIs leverage the full range of human sensory and motor skills, creating a more immersive, intuitive, and engaging way to interact with digital information (Ishii & Ullmer, 1997).

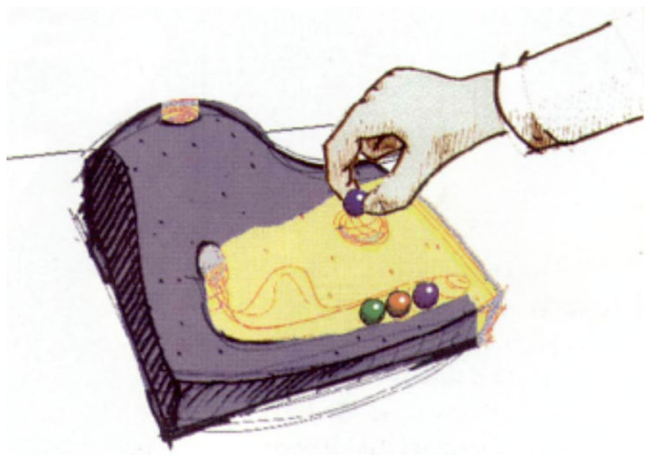


Figure 13. The Marble Answering Machine connects the digital information of a voice message to the physical embodiment of a marble (Ishii & Ullmer, 1997).

One of the most well-known examples of TUIs is the Marble Answering Machine (Figure 13) described by Ishii & Ullmer (1997). This concept reimagines a traditional telephone answering machine by physically embodying voice messages as marbles. Each marble represents a recorded message, allowing users to interact with their messages in a tangible way. To play a message, a user simply picks up a marble, and to return a call, they place the marble on an augmented telephone. This design connects digital information (the voice messages) to physical objects (the marbles).

Working with TUIs comes with its own set of challenges, such as their limited adaptability compared to the dynamic nature of pixels on a GUI. While tangible interfaces enable direct manipulation of digital data, they struggle to display real-time changes due to the constraints of physical materials. Mapping every virtual object to a physical counterpart is impractical, time-consuming, and environmentally wasteful. To address this, multi-purpose or reconfigurable TUIs can reduce the need for numerous physical objects, or digital overlays (Figure 14) can be used to display dynamic updates on tangible components (Holmquist, 2023; Ishii & Ullmer, 1997; Moran-Ledesma et al., 2021).

Another key factor in the effectiveness of TUIs is perceptual coupling – the seamless synchronization between tangible objects and their digital counterparts. When this connection is not intuitive, TUIs can become confusing or ineffective. Users must easily understand how physical interactions correspond to digital changes for the system to be successful (Ishii et al., 2012).

Ishii and Ullmer's concept of Tangible Bits has been highly influential in the field of Human-Computer Interaction, making TUIs a significant area of research since their introduction. However, despite their potential and continued academic interest, TUIs have not had the widespread impact on everyday products that was initially anticipated (Holmquist, 2023). Nearly three decades later, most digital interactions still rely on GUIs. That said, GUIs have evolved significantly since the introduction of TUIs. Devices like smartphones, tablets, and smartwatches have become deeply embedded in our daily lives, making GUIs more pervasive and context-aware. While these interfaces may not be tangible in the sense Ishii and Ullmer imagined, they still contribute to the original goal of bridging the gap between the digital and physical worlds – by making computing ubiquitous and seamlessly integrated into everyday environments.

One of the primary barriers to the broader adoption of TUIs is the high cost of creating and distributing physical interactive artifacts. Unlike GUIs, which are relatively inexpensive to develop, replicate, and scale, TUIs require physical components that add complexity and expense. While TUIs can offer richer user experiences, GUIs are often preferred when their lower cost and greater flexibility outweigh the benefits of tangible interaction (Holmquist, 2023).

Sustainability is another challenge. Many TUI systems depend on electronic components that are difficult to recycle, contributing to the growing problem of e-waste (Holmquist, 2023). While the same can be said for GUIs, digital screens can display many different representations within a single device, whereas TUIs often require multiple physical components for different interactions. This means that, in some cases, TUIs generate more electronic waste than their GUI counterparts.

Despite these challenges and their limited adoption in consumer products, TUIs have played a significant role in interactive museum exhibitions. The flexibility limitations of TUIs are less of an issue in museum settings, where applications are often designed for specific exhibitions rather than for everyday and diverse use. Additionally, these installations are typically custom-built rather than mass-produced, making TUIs more viable. The following section will therefore explore the application of TUIs within museums.

Figure 14. PICO is a tabletop interaction surface that uses electromagnets to track and move small objects, allowing users to physically interact with computational optimization processes, such as cellphone tower placement (Ishii et al., 2012).

2.3.2 Tangible interactions in cultural heritage contexts

Traditionally, digital interactive museum exhibits depended on separate GUI devices such as mobile guides or interactive desktop stations. However, research on tangible user interfaces has driven a shift toward embedding technology directly within exhibitions (Marshall et al., 2016). Tangible interactions engage visitors in meaning-making rather than passive observation, aiming to create deeper emotional connections with heritage artifacts. Additionally, sensory stimulation through TUIs stimulates curiosity and encourages learning. This leads to improved understanding of artifacts and better knowledge retention (Cannavò et al., 2024; Kim et al., 2023; Petrelli & Roberts, 2023; Spence et al., 2020).

TUIs within exhibitions

TUIs can give visitors a more active role in exhibitions enabling them to contribute directly to the experience. For example, Weaving Time is an interactive installation that immerses visitors in the craft of Incan weaving. It allows them to create and extend a digital tapestry by selecting and arranging pattern tiles on a table (Figure 13). Through this TUI, visitors contribute to produce a dynamic, evolving, collaborative artwork that brings Incan heritage to life (Gagarín, n.d.).

TUIs can enhance visitor engagement by guiding them through exhibitions and creating a more immersive experience. Studies have shown that visitors are more likely to engage with the stories and information linked to artifacts when interacting through TUIs, compared to traditional text labels. TUIs can also encourage social interaction, as people often use them together—sharing the interface, starting conversations, and exploring exhibits collaboratively (Damala et al., 2019).

For example, Petrelli & Roberts (2023) developed an exhibition where an interactive ritual lamp led visitors through a personalized ritual (Figure 16). As they selected deities and performed symbolic acts of worship, the lamp responded by lighting up or extinguishing, allowing visitors to connect with the intentionality and cultural significance of Roman religious traditions.

Similarly, in an exhibition about life in The Hague during the Second World War, TUIs served as interactive keys that unlocked additional narrative layers at different points in the exhibition (Figure 17). This allowed visitors to explore the content from a personalized perspective, deepening their engagement with the historical material (Marshall et al., 2016).

Figure 15. Weaving Time allows visitors to add their own design to a digital tapestry (Gagarín, n.d.).

Figure 16. My Roman Pantheon is a tangible interactive installation that immerses visitors in Roman religious culture through hands-on rituals (Petrelli & Roberts, 2023).

Figure 17. Visitors can use interactive replicas to unlock additional narrative layers. (A) A visitor chooses a smart replica and (B) activates the narratives (Damala et al., 2016).

Combining XR and TUIs

TUIs can be used in combination with XR, which allows users to engage with XR experiences through tangible artifacts (Cardoso, 2021). For example, Kim et al. (2023) enabled users to explore artifacts by handling 3D-printed replicas equipped with sensors. Movements of these replicas were mapped in real-time to a high-precision 3D-scanned model in VR, and the sensors replicated the texture and shape of real artifacts for a realistic multisensory experience (Figure 18).

This approach is an example of passive TUIs—physical props that mimic the form and tactile qualities of virtual objects. Rather than relying on simulated haptic feedback, passive TUIs create interaction through actual touch and handling, closely resembling how people engage with real-world objects. This method enhances immersion while avoiding the technical complexity of computational simulations (Cannavò et al., 2024; Moran-Ledesma et al., 2021).

In contrast to passive TUIs, active TUIs use actuation to simulate a wider range of physical sensations, often through vibrotactile, thermal, or force-feedback mechanisms. These effects are commonly delivered via haptic devices such as handheld controllers or gloves, which can simulate sensations like vibration, pressure, texture, or even temperature. Haptic gloves, in particular, are capable of more advanced feedback, including resistance or the sensation of grasping objects with varying rigidity.

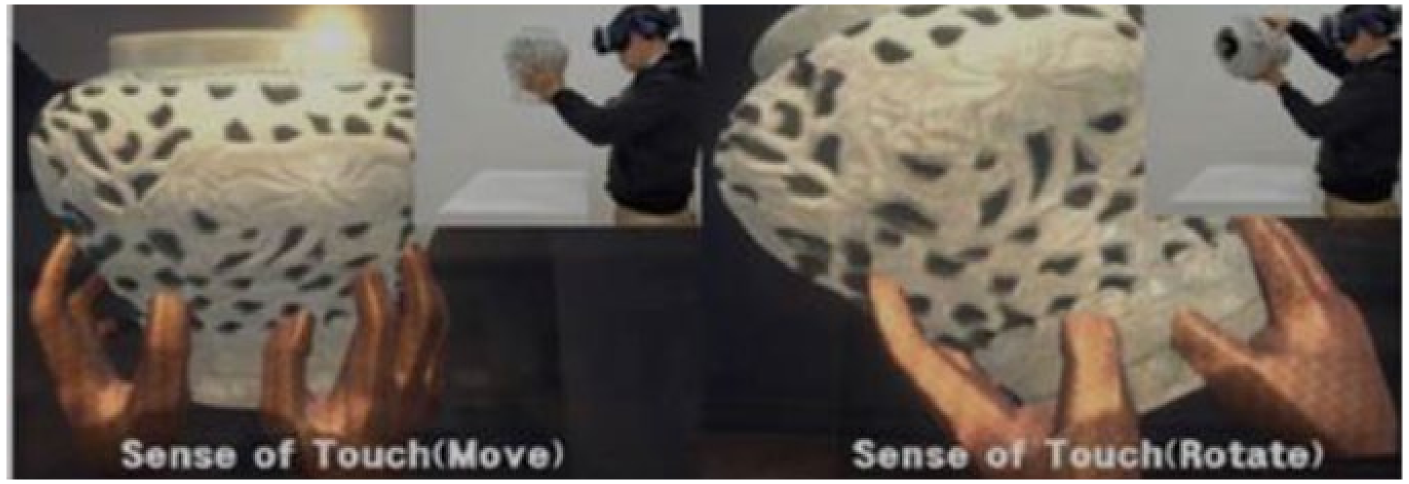


Figure 18. This system allows users to naturally manipulate virtual objects using 3D-printed replicas (Kim et al., 2023).

Figure 19. This experience allows users to operate a virtual reconstruction of a traditional Chinese wheelbarrow, by connecting handheld controller to a physical wheelbarrow (Guojun et al., 2023).

Handheld controllers remain the most accessible form of active TUIs, as they are widely supported in standard XR development platforms. However, they can be complex to use, particularly for novices, and they often offer a limited range of feedback (Cannavò et al., 2024; Moran-Ledesma et al., 2021). To make these interactions feel more intuitive, active TUIs can also be embedded in real-world props. For example, Guojun et al. (2023) developed a VR game in which users controlled a virtual reconstruction of a traditional Chinese wheelbarrow by physically moving a real wheelbarrow equipped with XR controllers (Figure 19). This combination of tangible props and active feedback mechanisms allows for more realistic and embodied interactions that better reflect real-world handling.

TUIs and scientific heritage

Tangible User Interfaces (TUIs) offer valuable opportunities for presenting scientific heritage, particularly when the goal is to let visitors interact with artifacts in meaningful, embodied ways. Since direct interaction with original objects is often restricted due to their fragility or conservation requirements, replicas can serve as a practical alternative. In particular, "smart replicas" – physical models enhanced with sensors, actuators, or other digital technologies – can bridge the gap between heritage and interactivity. By enabling multisensory engagement, they allow visitors to explore how historical artifacts functioned, without risking damage to the originals (Marshall et al., 2016; Spence et al., 2020).

However, replicas are not the same as authentic artifacts. Does this affect how visitors experience exhibitions that use replicas? Hampp & Schwan (2015) suggest that visitors perceive authenticity through four key dimensions:

1. **Historical significance:** The object's connection to past events.
2. **Charisma:** The perceived "aura" or uniqueness of the original.
3. **Rarity:** The object's exclusivity, often reinforced by media coverage.
4. **Functionality:** The object's ability to demonstrate how something works.

Their study found that, in the context of scientific and technical artifacts, functionality often outweighed the other factors. Visitors appreciated objects that could clearly show how scientific principles or technologies worked, even when those objects were replicas or models. In some cases, these functional stand-ins were preferred over original artifacts because they offered a more understandable or engaging experience.

This suggests that smart replicas, combined with TUIs, can play a key role in communicating the significance of scientific heritage. By prioritizing interactivity and clarity, museums can create compelling, educational experiences while also protecting their authentic collections.

2.3.3 Design implications

The following implications translates the insights from the literature on tangible interactions into design guidelines to support the development of my own tangible heritage experience.

Design for natural and intuitive interaction

Avoid reliance on traditional VR controllers, especially for general audiences who may find them unintuitive. Instead, integrate TUIs that replicate the physical properties and mechanisms of heritage artifacts, enabling users to engage with the experience using natural, real-world gestures. Ensure that these interactions are easy to learn and self-explanatory, with a clear connection between physical actions and digital outcomes.

Balance tangibility with flexibility and scalability

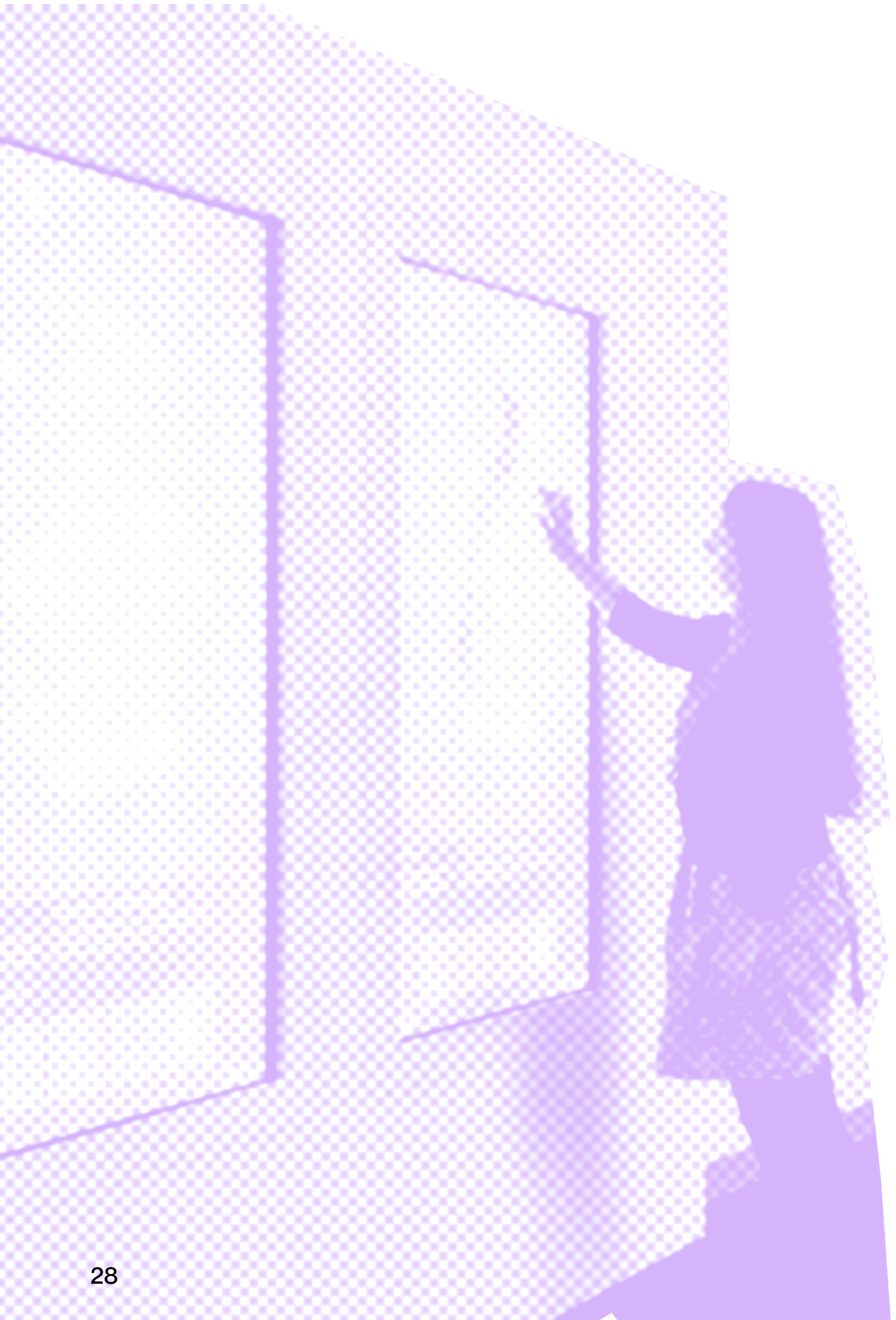
Consider how the broadest range of tangible interactions can be achieved with the fewest amount of components. For example, use multi-purpose or modular TUIs to represent different artifacts or functions without the need for multiple distinct physical replicas. Or add XR overlays to dynamically update visuals on static physical props, allowing real-time data changes without requiring fully dynamic physical interfaces.

Prioritize functionality over material authenticity

Focus on functional representations that clearly demonstrate how the artifacts work, rather than exact historical and material authenticity. Use smart replicas that blend tactile interaction with XR visualization to convey complex scientific principles, allowing users to learn through hands-on experience.

2.3.4 Discussion

This review of TUIs and tangible interactions in heritage settings was not a full or systematic study, but based mostly on examples found during the earlier XR literature review and key papers suggested by my supervisors. Because of this, it gives a general overview rather than a complete picture of how tangible interactions have been used in cultural heritage. Also, the research into the combination of TUIs with XR could have been more extensive. Right now, it mostly highlights examples of this combined use, but it doesn't delve deeper into its design process. Still, it's useful to understand how TUIs have previously been used in similar contexts and what we can learn from this.



2.4 Designing interactive exhibitions

Designing interactive exhibitions comes with its own set of challenges and requires a thoughtful design process. In this section, I look at tangible interactions and immersive technologies from a design perspective. I focused on two main questions:

- *How are interactive technologies currently used in museums, and how do visitors experience them?*
- *What design factors are important when creating heritage exhibitions that use tangible interactions and XR technologies?*

To explore these questions, I interviewed two heritage professionals to learn more about how interactive exhibitions are designed – both from the point of view of visitors and the people creating the exhibitions. I also visited three different museums, each time with a different companion who could offer their own perspective. This auto-ethnographic approach helped me gather first-hand insights into how interactive technologies influence the experience of scientific heritage and science museums.

2.4.1 Design lessons from experts

I interviewed two heritage experts who work at the TU Delft: Cormac Duggan and Alice Bodanzky. Cormac (Figure 20) is the project lead for the Tailor-made Approach to Faculty Collections project. Since TU Delft's beginnings, departments and faculties have collected a wide variety of objects for teaching and research. This project focuses on supporting faculties in inventorying, evaluating and (re)using these scientific heritage artifacts.

Alice Bodanzky (Figure 21) is the project manager at the TU Delft Library Learning Centre and focuses on helping to shape the Library's digital transformation and engagement strategy. She has lead the Collection Wall project, a project focused on turning the library's iconic book wall into an interactive experience designed to inspire exploration, discovery, and serendipity – the Collection Wall.

Figure 20. Cormac Duggan, project lead Tailor-made Approach to Faculty Collections, TU Delft.

Figure 21. Alice Bodanzky, project manager TU Delft Library Learning Centre.

The aim of the interviews was to explore two main questions:

- *How do heritage experts approach the design of exhibitions?*
- *What are their experiences with exhibiting scientific heritage, and what opportunities and challenges do they encounter?*

While these questions provided a general structure, the interviews remained flexible, allowing space for the experts to delve into related and relevant topics. The conversation with Cormac mainly focused on the visitor's perspectives on interactive exhibitions, whereas Alice centered more on the design process and strategic considerations behind such exhibitions.

In addition to the interview questions, both experts were presented with "opportunity" and "obstacle" cards from the first iteration of the Immersive Heritage Design Deck – a card deck I developed based on insights from the literature studies on XR and TUIs. These cards served as prompts to guide the conversation toward key challenges and opportunities in creating interactive heritage experiences. The design and development of the deck are discussed in more detail in Chapter 4.3.1.

Tangible interactions and visitor engagement

Both Cormac and Alice emphasized the importance of sparking and sustaining curiosity. According to Alice, physical heritage objects often trigger excitement among students, wbut this initial spark of interest is crucial.

The object itself plays a big role in attracting attention, but so does the way it is presented. Cormac stressed that exhibition design must account for how visitors are led to the tangible elements. For example, placing an item under a bell jar or on a pedestal naturally draws attention – visitors are often curious about what they're not supposed to touch. Simply putting up a sign saying "Do not touch" often backfires. A better approach, he suggested, is to provide a designated object that can be touched – a 'sacrificial' artifact. These items have some heritage values, but are not part of the protected collection.

Once you have the visitor's attention, it's important to keep it. Gamification and collaborative experiences, especially in XR, are promising strategies for engaging younger audiences, according to Alice.

Cormac emphasized that interaction should not be a gimmick; it needs to meaningfully contribute to the exhibition's narrative. He pointed out that while some museum staff see technology as a cure-all solution, others are hesitant or resistant. The reality lies somewhere in between. While newer generations are more comfortable with technology, it's still important to consider visitors' varying levels of digital literacy. Museums often prefer using stable, proven technologies rather than experimenting with less predictable innovations. Alice also added to this that immersive technologies like XR headsets can be a barrier to visitor's curiosity if they are difficult or embarrassing to use. She proposed using fixed headsets as viewing boxes, allowing users to look inside without needing to put anything on – lowering the threshold for engagement.

Figure 22. In the Collection Wall project, heritage artifacts are connected to the first thesis of each faculty and a physical token.

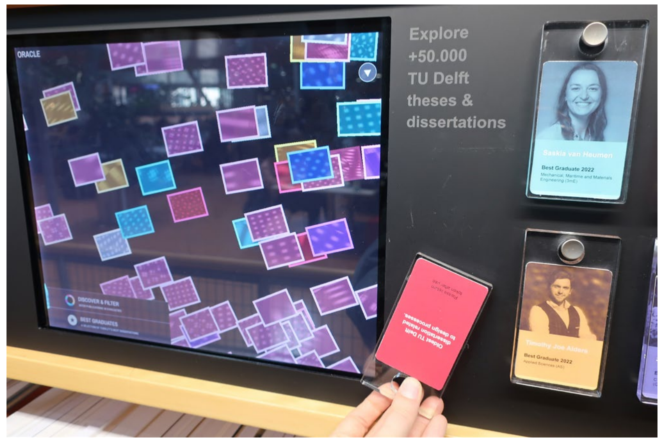


Figure 23. Physical tokens can be scanned to find relevant info.

Scientific heritage and storytelling

In the context of scientific heritage, Cormac highlighted the need to clearly define the story being told and to talk to the right experts. A key challenge is determining what makes a scientific artifact significant – what made it technically disruptive? He suggested that while certain items may stand out due to unique stories, there are often similar, less unique items that can be safely used for interaction. Again, these 'sacrificial' items can help bridge the gap between preservation and hands-on learning.

Cormac also emphasized that exhibitions should encourage exploration without overwhelming visitors. QR codes, for instance, can offer optional deeper content, but shouldn't be required to understand the main story. Visitors want to uncover patterns, connect dots, and solve small mysteries embedded in the exhibition. Alice expanded on this with specific examples from student interactions. She noticed that students are particularly drawn to experiences that show connections between past and present, reveal inner workings, or offer the ability to zoom in and view things at different scales.

Design process

Alice emphasized the value of involving stakeholders early through co-creation and prototyping. In the Collection Wall project, her team began by defining which artifacts to include and which stories to tell. These ideas were then turned into cards – representing concepts, objects, or themes – that could be used as conceptual building blocks in their design process. These cards served as tools to spark discussions, provide inspiration, and keep the process accessible to a wide group of stakeholders.

One of the key challenges Alice encountered was designing tangible experiences without allowing visitors to directly handle fragile heritage objects. Their solution was to connect each artifact to a physical token, which visitors could scan to access digital information. For example, they linked an original printed thesis (one per faculty) to a related heritage object and a modern digital thesis on a similar topic, providing a layered narrative across time (Figure 22-23).

2.4.2 Observations in museum

I visited three museums, each with a different companion. The companions were informed beforehand about the research goal: to explore how they experience interactive exhibitions. During the visits, they were asked to think aloud and share their thoughts as they moved through the exhibitions. The museums were chosen for the following reasons:

- **Teylers Museum:** Established in 1784, Teylers Museum is the oldest museum in the Netherlands. It exhibits a diverse array of artifacts, including historical scientific instruments, fossils, and paintings. I chose this museum to explore a more traditional "look-but-don't-touch" approach to exhibiting scientific instruments. The display methods here have remained largely unchanged since the museum's founding, offering a historical perspective on exhibition practices.
- **National Maritime Museum:** This museum is dedicated to the Netherlands' maritime history and features a rich collection of artifacts related to shipping and sailing. I visited to examine how scientific instruments – specifically naval navigation tools – are presented in a modern museum setting. Following a major renovation between 2007 and 2011, the museum integrated more interactive elements while maintaining a relatively traditional exhibition style.
- **Artis Micropia:** This interactive science museum focuses on microbes, featuring over 40 species of living microorganisms that visitors can observe under microscopes connected to an on-site laboratory. While the museum includes scientific instruments – such as real microscopes that visitors can control – it does not display heritage artifacts. However, its strong emphasis on interactivity makes abstract and invisible microbes feel more tangible. This approach offers valuable insights into how hands-on experiences can enhance understanding of complex scientific topics.

The first impression upon stepping into Teylers Museum is pure awe. It's a stunning historical building filled with countless artifacts (Figure 24). However, this initial excitement fades quickly, and it becomes difficult to stay engaged. The large number of scientific instruments, all locked away in glass cabinets (Figure 25), feels overwhelming. The labels provide only minimal information, usually just the name and purpose of each item, without any deeper context (Figure 26). While it's clear that these artifacts are old and significant, why they matter remains unclear. There's no real understanding of how these machines work or what role they played in scientific history. As a result, boredom sets in quickly, and the visit doesn't leave many lasting insights.

Figure 25. Scientific instruments displayed at Teylers Museum.

Figure 26. Scientific instruments and their descriptions.

In contrast, the National Maritime Museum takes a slightly different approach to exhibiting historical instruments. At first, it seems similar to Teylers – glass cabinets filled with navigation tools – but next to them are interactive screens (Figure 27). These screens provide additional explanations about how the instruments worked, allowing visitors to engage with 2D simulations to explore their functions (Figure 28). By interacting with these representations, visitors can get a better sense of how sailors once determined their coordinates at sea.

At first, my companion was excited about these interactive screens, exclaiming that they finally understood how the instruments worked. However, they later admitted that the 2D representation wasn't entirely clear because it was shown from an unfamiliar angle, different from how the original

Figure 24. The scientific instruments exhibition at Teylers Museum.

Figure 27. The naval navigation instruments exhibitions at the National Maritime Museum.

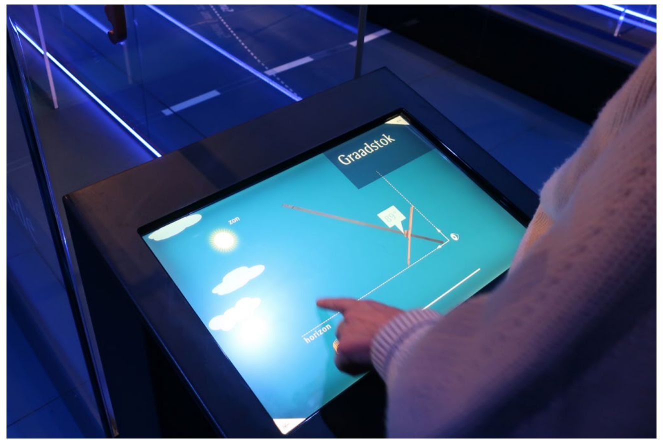


Figure 28. Interacting with a digital representation of the navigation instruments.

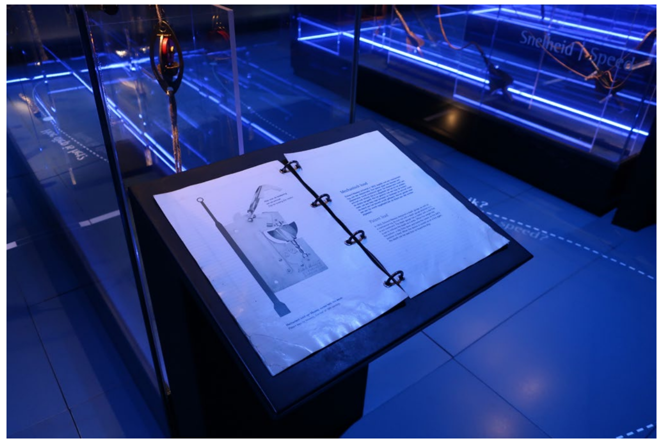


Figure 29. Written explanation of a navigation instrument.

instruments would have been used. This is why they expressed their wish to try out a physical replica to gain a better understanding. They also emphasized the importance of experiencing the cultural context of these artifacts: “You need to feel what it was like for the original user. I want to experience the magic from that time.”

Another interesting observation was the presence of booklets offering additional explanations for some instruments (Figure 29). Unlike the digital screens, these booklets didn’t seem as effective. My companion attempted to read through one but quickly gave up, saying that the explanations were too difficult to follow.

Out of the three museums, Micropia sparked the most enthusiasm. Although it’s relatively small, it’s packed with interactive elements that immediately grab attention. Visitors are naturally drawn in by curiosity – spotting an interesting button and wondering, “What happens if I press this?” This kind of engagement keeps visitors exploring.

The highlight for my companion were the microscope stations (Figure 30). These featured real, working scientific microscopes connected to a user-friendly interface, allowing visitors to observe living microbes. The interactive setup

Figure 30. Examining microbes under a microscope.

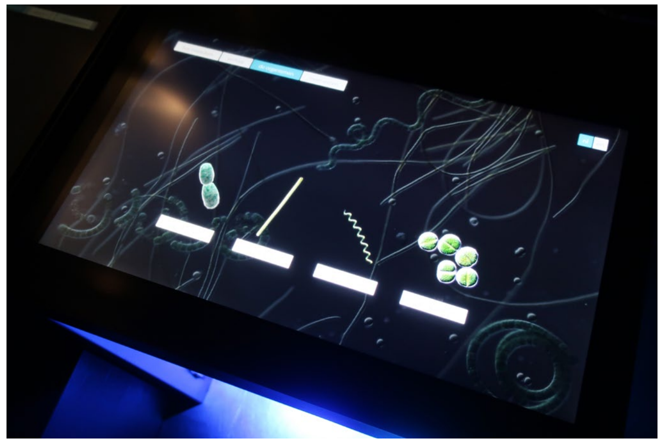


Figure 31. Interactive screen displaying a live feed from the microscope and which microbes can be found in the sample.

Figure 32. Examining the microbes that were collected on the stamp card.

made it easy to adjust the lenses, change focus, and explore samples in real time. What made the experience even more enjoyable was the ability to collaborate. Next to each microscope was a screen displaying a live feed, where a second person could follow along, read additional information, and help identify microbes (Figure 31). This created a fun teamwork dynamic, where one person guided the search while the other controlled the microscope. My companion particularly loved this aspect, saying their favorite part was “working together and actually seeing my actions have an effect on something living.” Interestingly, each microbe station also included an explanatory video, but my companion never watched them. They mentioned that they didn’t have the patience for videos and preferred skimming through text instead.

Another engaging feature was the microbe stamp system. Each microbe station had a stamp, which visitors could use to mark a card as they “discovered” different microbes. At the end of the exhibition, scanning this card revealed a personal collection of microbes found during the visit (Figure 32). Visitors could even select microbes to display on a large central screen for everyone to see. This made the discoveries feel tangible, as visitors could directly connect their findings to the real-life samples they had observed. It also offered a playful way for visitors to actively contribute to the exhibition content, making their experience part of a shared, visible display.

2.4.3 Design implications

The insights from the museum observations and expert interviews were combined into the following design implications:

Show relevance through storytelling

Select artifacts with compelling stories to ground the experience in local and scientific relevance and show why these artifacts mattered. Go beyond technical functionalities to highlight how these instruments changed the world and still impact us today.

Support layered curiosity

Spark an initial curiosity with visually striking models or environments, then sustain interest through interactive simulations, guided exploration, or playful mechanics. Offer just enough information at first, then let users "dig deeper" at their own pace. Let casual users enjoy short, intuitive interactions, while more dedicated visitors can explore full technical breakdowns or historical paths.

Create intentional interactions at tangible touchpoints

Use physical cues like bell jars and pedestals to invite interaction where it's intended. Allow visitors to interact with replicas or "sacrificial" objects at these places, satisfying their curiosity without damaging delicate heritage artifacts.

Stimulate engagement through gamification

Introduce game-like elements to guide visitors through the exhibition and to stimulate further exploration.

Support social and collaborative interaction

Allow users to collaborate by designing interfaces that support multi-user or shared usage, encouraging social learning and conversation.

Lowering digital barriers for casual visitors

Ensure that digital content is instantly available, intuitive, and doesn't require prior knowledge to explore. For example, by designing fixed installations like XR viewing boxes, touch tables, or AR looking glasses.

2.4.4 Discussion

The expert interviews and museum visits offered valuable insights into the design of interactive heritage experiences, though both methods came with certain limitations that are important to acknowledge.

The expert interviews with Cormac Duggan and Alice Bodanzky offered useful insights into how scientific heritage exhibitions are developed. Although they weren't specialists in XR or tangible interfaces, their perspectives helped clarify how visitors engage with heritage and how interactive elements are typically approached in practice. They also pointed to some of the real-world challenges that come with designing for museum spaces. While the focus of the interviews was mainly on exhibition design and visitor experience, it might have been helpful to further explore what kinds of design tools professionals like them would find useful – especially when working with unfamiliar technologies like XR. That could have added more direction to the development of the toolkit.

There was some convenience sampling present in the museum observations – museums were chosen primarily based on proximity and scheduling, rather than strict relevance or variation. While all three museums had some link to scientific heritage, the level of focus on heritage varied. For instance, Micropia is more of a science museum than a heritage institution. Furthermore, the visits were auto-ethnographic in nature, meaning I reflected on my own experience and that of my companion to generate insights. This approach can be very valuable in understanding how people interact with exhibitions in real life, but it also introduces a certain level of subjectivity. The insights gathered were shaped by my perspective and those of my companions, and therefore can't be considered as definitive evaluations. Still, they offer useful inspiration and direction for design.

3. Case Study:

Designing an Immersive Heritage Experience

After exploring the context of immersive heritage experiences and how they're designed, the next step was to apply what I learned in my own heritage project. The goal of this case study was to design an immersive heritage experience that combines Mixed Reality with tangible interactions to engage users with the history of analog calculators. The insights I gained during this design process would then help shape the MR+TUI Heritage Toolkit.

This chapter walks through the steps I took during the design process. Figure 63 gives an overview of these steps and how they are structured in the following sections. I began by turning the earlier research insights into concrete design criteria and defining the scope of the project. Then, I explored the possibilities from three key perspectives: narratives, technologies, and interactions. These explorations helped me better understand what kind of experience I could create.

From these insights, I defined a set of key design elements that formed the foundation of the concept. I then brought these elements together during the ideation phase and selected a concept to develop further. Using what I had learned, I shaped and prototyped this concept into a working experience. This prototype was then tested with users, which provided valuable feedback and recommendations for the future development of the toolkit.

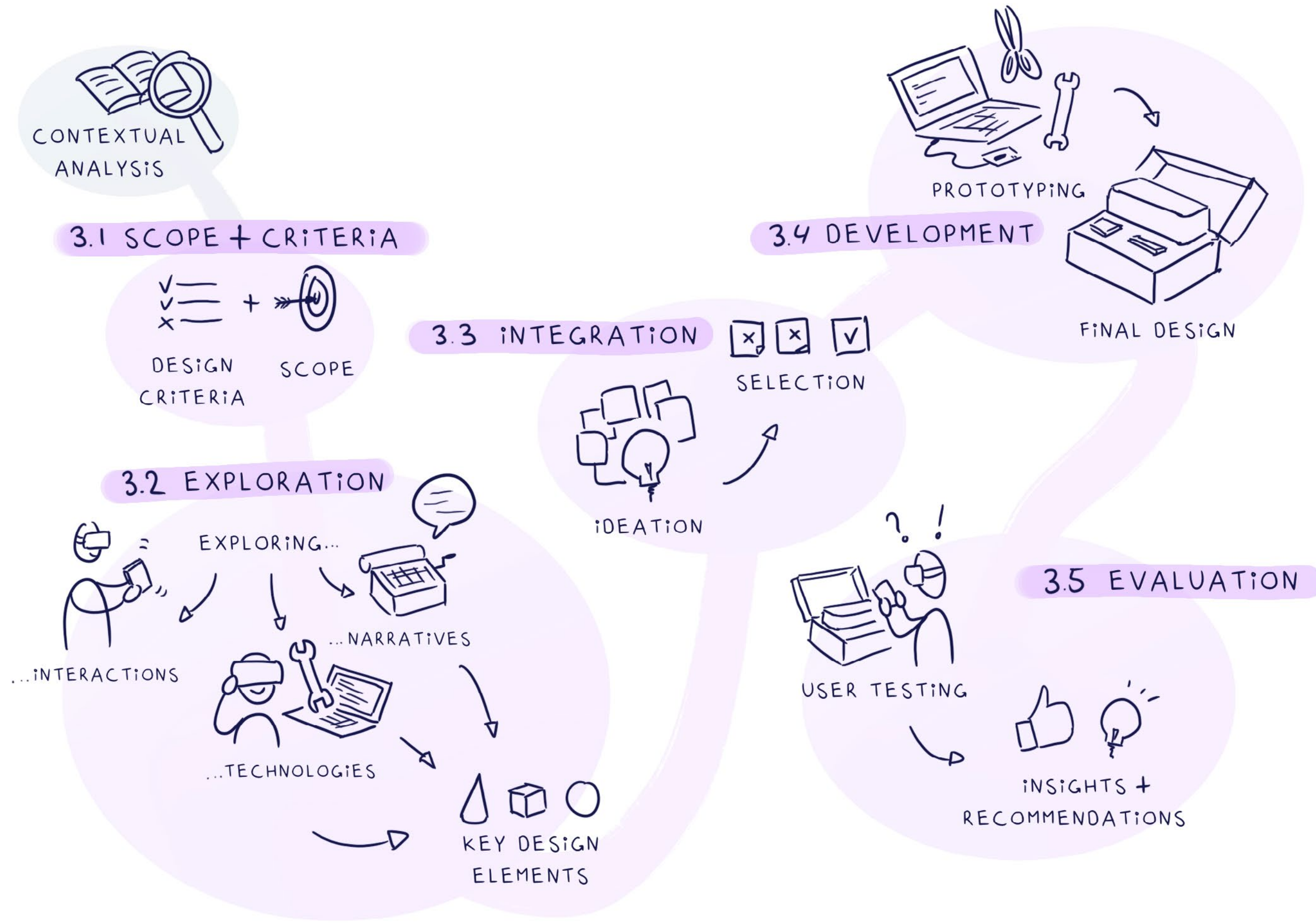


Figure 33. Overview of the case study design process and structure of this chapter.

3.1 Scope & criteria

My immersive heritage experience focuses on telling the story of analog calculators. These artifacts were chosen because they are rich examples of scientific heritage: their function is tied closely to physical interaction, and understanding how they work often requires hands-on engagement. This makes them especially suitable for an MR+TUI approach, where embodied interaction can help convey abstract or hidden mechanisms.

To better define the scope of the project, I chose a specific location and target audience. I picked the TU Delft Library (Figure 34) as the setting for the exhibition. This choice was mainly based on practical reasons – I had easy access to the space, which made it easier to imagine and design for that context. But it also made sense content-wise: the TU Delft Library has a scientific heritage collection of its own, which includes various historical scientific instruments. In fact, a mechanical calculator was already featured in Alice Bodanzky's Collection Wall project (Figure 30), making the topic a logical fit for this location.

With the location set, the target audience also became clear: engineering students. This group connects well with the topic. Calculators, though digital today, are still important tools in their daily studies and future professions. Both experts I interviewed mentioned how visitors tend to connect more with exhibitions when they can relate the topic to their own lives – something this project can easily tap into.

Figure 34. The main hall of the TU Delft Library (Mecanoo, n.d.).

The goal of this design process isn't to build a fully working, final exhibition ready to be installed in a museum. Instead, the aim is to go through the design process and learn from it. These insights will then inform the development of the MR+TUI Heritage Toolkit. That's why I focus more on the steps of the design process, from early ideas to a prototype. This final prototype may not be fully functional yet, but it will be developed to a degree in which the experience can be tested and evaluated with users.

The insights from the earlier contextual analysis were restructured into design criteria, which guide the rest of the design. These criteria are divided into three priority levels:

1. **Crucial:** Core to the success of the experience or toolkit. Without these, the design fails to meet its goals.
2. **Important:** Strongly recommended to create a high-quality and effective result. These significantly enhance the experience but aren't absolutely foundational.
3. **Enhancing:** Valuable additions that enrich the experience, but can be deprioritized or postponed if resources are limited.

The design criteria are shown on the following page.

Physical interaction without controllers

The system must support direct interaction with tangible interfaces, eliminating the need for VR controllers.

Interactive artifacts

The experience must provide users with embodied interaction with functioning artifacts, either originals that will be 'sacrificed' for the experience or replicas.

Historical context of artifacts

The experience must connect artifacts to their historical context and show the relevance to us today.

Multiple levels of engagement

The experience must include both brief, intuitive interactions and optional deeper content layers to support different user interests.

Sensory feedback

Audio and visual cues could be integrated to simulate authentic user interaction with the original devices.

Gamified elements

Gamification mechanics could be used to spark curiosity.

Multi-user and social functionality

The spatial setup and interface design could accommodate multiple users interacting simultaneously, encouraging discussion and collaborative learning.

3.2 Exploration

I began the design process with an exploration aimed at discovering the possibilities and opportunities within the project. This helped me better understand what was technically and conceptually feasible, and how I could create something meaningful within those boundaries. I approached this exploration from three perspectives:

- The **narrative** perspective focuses on the story being told: what makes the artifact meaningful, what historical context is important, and how the story can resonate with users.
- The **technology** perspective addresses how the experience can be built: what technical components are needed, what types of interactions are possible, and what constraints must be considered.
- The **interaction** perspective considers how users physically and emotionally engage with the design: how they interact with the artifacts, what makes these interactions intuitive or memorable, and how the tangible aspects support this.

3.2.1 Exploring narratives

This section explores the narrative perspective of the case study. It examines the role of scientific heritage in museums and the history of analog calculators. Based on these insights, I identify key narrative elements that should be reflected in the design.

The challenge of exhibiting scientific heritage

The adoption of HCI in museums is particularly valuable for scientific heritage, which is a diverse and dynamic field, including but not limited to human-made artifacts, instruments, specimens, laboratories, and research practices (Lourenço & Wilson, 2013). A challenge in exhibiting scientific heritage is the dynamic nature of scientific instruments. Unlike objects created purely for aesthetic appreciation, these instruments were designed as functional tools, and their original use often played a central role in understanding their purpose and significance. However, using them today is rarely feasible, as using these artifacts accelerates their deterioration, which is in direct conflict with the goal of preserving scientific heritage. At the same time, without embodied use, it can be difficult to grasp how these instruments functioned and the technological and scientific principles behind them. Additionally, some of the most intriguing aspects are found within their internal mechanisms, which might not be easily visible without disassembling the artifacts. Interactive exhibitions offer a potential solution to this challenge, as they have increasingly proven effective in conveying abstract concepts that are otherwise difficult for visitors to visualize (Spadoni et al., 2022).

Throughout history, scientific heritage artifacts have been exhibited in various ways. Similar to broader cultural heritage, the first generation of science museums originated as curiosity cabinets, where private collections of natural artifacts were displayed (Figure 35). These later evolved into natural history museums, which prioritized collections, object-rich displays, and an educational approach based on "look-but-don't-touch" principles (Pedretti & Iannini, 2020).

By the twentieth century, the second generation of science museums shifted focus toward technological progress, moving away from static collections to highlight advancements in science and industry. In an era of technological optimism, these museums celebrated human achievements in industrialization (Pedretti & Iannini, 2020).

In the latter half of the twentieth century, the third generation of science museums moved beyond object-based exhibitions, embracing interactive and hands-on experiences (Figure 36). These museums prioritized emotion, wonder, and immersion to make science more engaging and accessible (Pedretti & Iannini, 2020). It was during this period that HCI became a fundamental part of museum exhibitions. While the third generation of science museums has successfully engaged visitors with the world of science and engineering, scholars have criticized their tendency to focus solely on hands-on displays while overlooking the broader social and ethical contexts of science. Critics argue that science museums must move beyond self-referential, interactive exhibits and actively address societal issues (Pedretti & Iannini, 2020).

Even though third-generation science museums prioritize scientific concepts over artifacts, these objects remain crucial for understanding scientific practices and ensuring that future generations comprehend how we have come to understand nature, the universe, and ourselves (Lourenço & Wilson, 2013). However, identifying which artifacts belong to scientific history can be challenging. Because scientific research is an ongoing process, the distinction between historical artifacts and active scientific tools is often blurry. Instruments gradually evolve into new applications, making it difficult to determine where history ends and everyday technology begins. Additionally, mass-produced, everyday objects are often overlooked in favor of visually aesthetic or historically significant artifacts. This bias towards aesthetics and uniqueness risks erasing an important part of the history of science (Lourenço & Wilson, 2013).

This raises the question how we can elevate the role of scientific artifacts in modern science museums while preserving the interactive, hands-on experiences that made third-generation museums so engaging and inspiring. Could HCI support new forms of interaction that help visitors better understand scientific artifacts and their significance in our shared history?

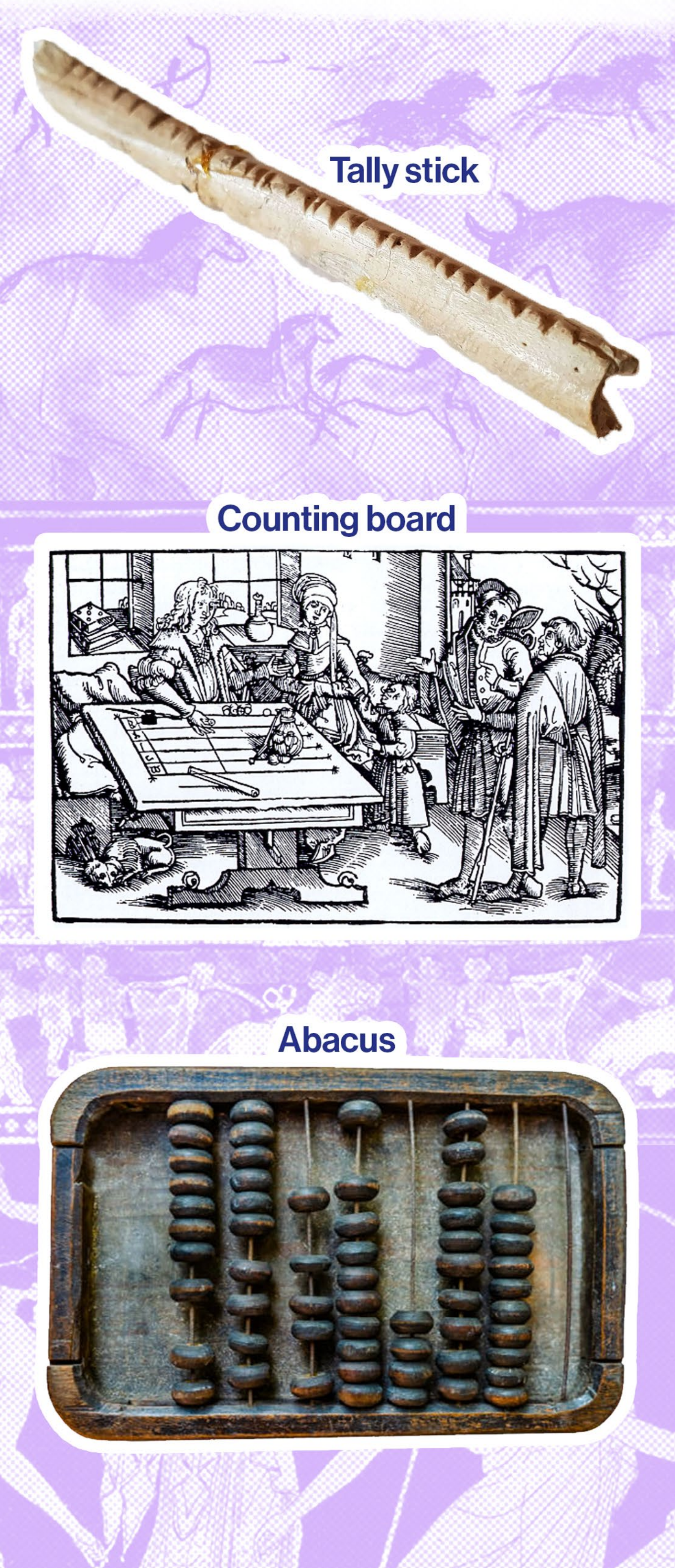
Figure 35. An example of a first generation science museum: Teylers Museum in Haarlem, founded in 1784, is the oldest museum in the Netherlands. Initially established around the personal collection of Pieter Teyler, it now exhibits a diverse range of artifacts, including historical wscientific instruments, fossils, and paintings.

Figure 36. An example of a third generation science museum: NEMO Science Museum in Amsterdam focuses on teaching children the fundamental principles of science and technology. Children are encouraged to "learn by doing, experiencing, observing, feeling, and listening," (NEMO, n.d.).

The history of the calculator

As Lourenço & Wilson (2013) put it, “If an object is meaningful as heritage, then its meaning comes from the life it has lived.” In other words, scientific instruments become heritage not just because of what they are, but because of the stories we uncover through research and documentation. This is exactly what I set out to do. In this section, I will explore the history of analog calculators.

The timeline below traces the history of calculation tools, highlighting how humans have performed arithmetic – basic mathematical operations like addition, subtraction, multiplication, and division – throughout history. It focuses specifically on analog methods, from early tools like the abacus to the development and eventual decline of mechanical calculators with the rise of digital technology. An extended timeline which explores these calculators in more detail can be found in appendix B.



Prehistoric & ancient times: Counting without machines

We learned to count with our 10 fingers. This is why we still use a decimal or base-10 system today that counts in tens (10, 100, 1000, etc.). The earliest tools used for arithmetic were tally sticks – simple wooden rods with notches carved into them. People used these notches to keep track of things like days passing or goods received (Houston, 2023).

The next innovation were counting boards, which also allowed subtraction by placing pebbles on marked surfaces. This method eventually gave rise to the abacus, used across cultures for centuries. Today, abacuses are still used in countries such as Japan and China, both as a tool for teaching basic math concepts and as an aid to enhance mental calculation speed. In fact, in 1946, a contest was held between a Japanese abacus and an American electromechanical calculator, where the abacus outperformed the calculator in addition, subtraction, and division (Houston, 2023).

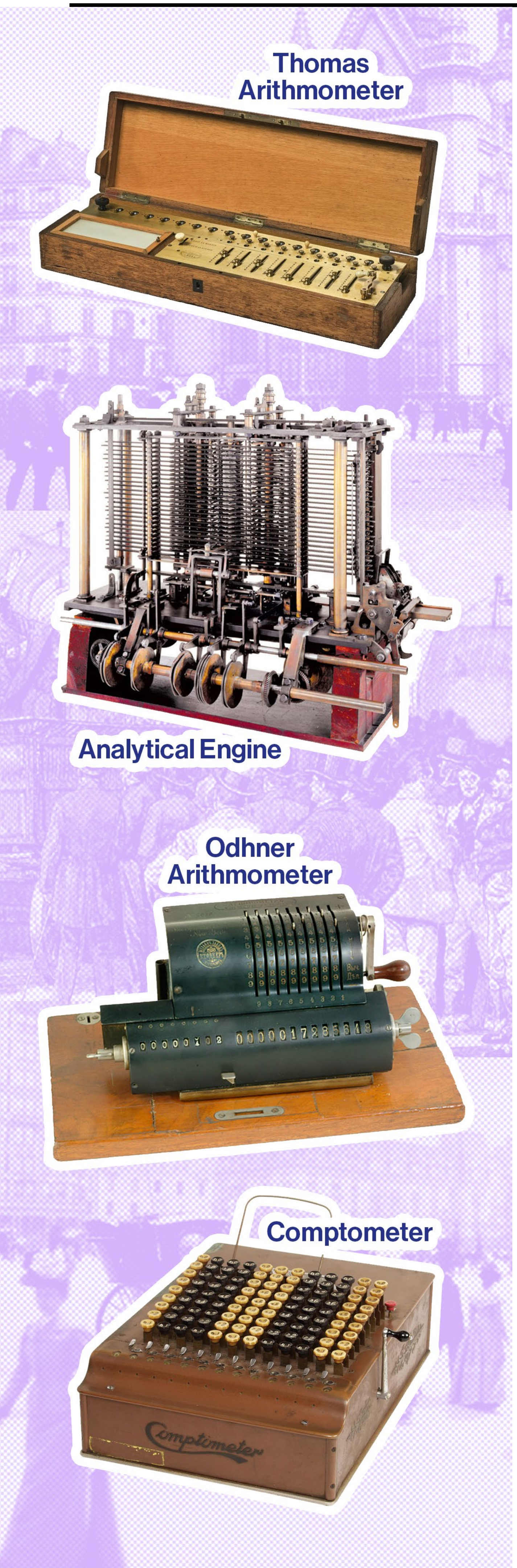
1600

1650

17th century: The clockwork age

The 1600s introduced more advanced calculation tools. John Napier’s invention of the logarithm in 1614 inspired Edmund Gunter, who developed the Gunter’s Scale – a ruler with a logarithmic scale that could be used for multiplications and divisions. In 1622, William Oughtred took this concept further with the slide rule, combining two logarithmic scales make these calculations easier and faster. The slide rule would become the engineer’s standard calculator for the next 350 years (Houston, 2023).

At the same time, inventors began creating the first mechanical calculators. In 1623, Wilhelm Schickard designed the Rechenuhr, considered the first mechanical calculator in theory, using gears to perform arithmetic. However, it remained only a concept on paper and was never built. Thus, the title of first mechanical calculator goes to Blaise Pascal’s Pascaline, invented in 1642 to help his father with tax calculations. Later, in 1673, Gottfried Leibniz introduced the Stepped Reckoner, which could perform all four basic arithmetic operations using his innovative stepped drum mechanism. Despite these breakthroughs, mechanical calculators did not become widely adopted at the time due to high production costs and reliability issues. Nevertheless, the inventions by Pascal and Leibniz laid important foundations for future, more successful mechanical calculators (Houston, 2023).



1800

1850

19th century: The industrial age

After a gap of over a decade in calculator innovations, the 1800s brought mechanical calculation into widespread use. The Thomas Arithmometer, introduced in 1820, was the first commercially successful calculator, using Leibniz's stepped drum mechanism to perform all four basic arithmetic operations (Houston, 2023).

Although never fully realized, Charles Babbage's Analytical Engine from the 1830s introduced groundbreaking concepts such as memory, punch cards, and general-purpose computation, earning it recognition as the first computer design. Ada Lovelace wrote the first algorithm intended for this machine, making her the world's first computer programmer (Swaine & Freiberger, 2024).

Later improvements made mechanical calculators more practical and affordable. The Odhner Arithmometer (1873) featured a more compact pinwheel mechanism, reducing size and cost (Leipälä, 2003). The Comptometer (1887) further improved calculation speed with its large keyboard, becoming a popular tool business and accounting (Norman, 2025).

1900

Early to Mid-20th Century: Combining mechanics and electricity

In the first half of the 20th century, calculators evolved with electricity. Electromechanical calculators combined traditional mechanical components with electric motors to automate arithmetic operations such as addition, subtraction, multiplication, and division. These machines offered greater speed, accuracy, and ease of use compared to fully manual calculators. Widely used in offices, engineering, and scientific work, these machines played a vital role before the rise of electronic calculators – often operated by women whose behind-the-scenes calculations supported major achievements, including America's first crewed orbital spaceflight (Houston, 2023).

As electromechanical devices advanced, simple and affordable tools like adders – small stylus-operated slide calculators – were developed for everyday use through the mid-century (Smithsonian, n.d.).

1950

1950s–1980s: Going fully electronic

The transition from mechanical to fully electronic calculators began with the Casio 14-A (1957), the first all-electric, relay-based calculator. About the size of a desk, it used 342 electromechanical relays to perform basic arithmetic, replacing traditional mechanical parts (Houston, 2023).

Subsequent innovations significantly reduced the size and increased the accessibility of electronic calculators. The ANITA Mark VII and VIII (1961) were the first commercially available all-electronic desktop calculators, while the Sharp QT-8B (1970) became the first mass-produced battery-powered model, enabling portable use. The HP-35 (1972) marked a turning point by offering advanced scientific functions in handheld form – effectively replacing the slide rule and ending the era of the analog calculator (Houston, 2023; Tout, 2004).

2000

1980s-Today: Modern calculators

In 1985, the Casio fx-7000G became the world's first graphing calculator available to the public. It featured a LCD capable of plotting mathematical functions, along with programmability and a wide range of scientific functions (National Museum of American History, n.d.).

In the 21st century, calculators have become seamlessly woven into the fabric of everyday digital life. Rather than existing as separate devices, they are now built into the tools we use daily – whether it's a simple calculator app on a smartphone or advanced computational software like Excel, MATLAB, or WolframAlpha. While physical calculators still hold a place in education, particularly in math classrooms and exams, they too have been fully digital for decades. The age of analog calculators has long passed, closing a remarkable chapter in the history of human computation.

Designing with the narrative

After developing the historical timeline and – based on insights from the experiential research – deciding to focus on showcasing analog methods of calculation, I revisited the timeline to identify three potential narratives that could shape my immersive heritage experience:

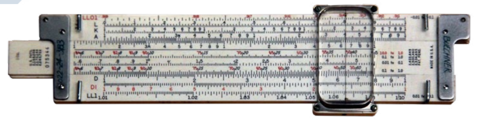
- **Connecting with engineering students:** This narrative would build a bridge between the target audience – engineering students – and the world of historical calculators. It would focus on the tools used throughout history to perform the kinds of calculations engineers still engage with today.
- **Uncovering hidden stories:** One aspect that especially intrigued me was the overlooked role of women in the history of calculators. There's a common assumption – also repeated in one of my user tests – that calculators were "male" tools. In reality, many types of calculators were used primarily by women, especially in administrative and computational roles. This narrative would focus on those contributions.
- **Calculators shaped by their users:** This narrative explores how many historical calculators were born not from scientific interest, but from real, practical needs. Inventors often designed tools to suit their specific tasks, which led to a wide variety of calculator types, each optimized for a different context or user.

Ultimately, I chose to continue with the third narrative: calculators shaped by their users. I felt this narrative best aligned with my goal of revealing the mechanics and logic of analog computation. It allows for hands-on, interaction-driven exploration while still embedding the artifacts in a meaningful historical context – a design element that also resulted from my experiential analysis.

Based on this narrative direction, as well as the artifacts I already had or could realistically replicate within my timeframe, I selected three distinct calculators to focus on. Each represented a different type of user, offering a diverse view into how needs shaped design:

Slide rule

The slide rule was invented to simplify multiplication through the use of logarithmic principles. It quickly became a vital tool for scientists and engineers, who relied on it for complex calculations. Its inherent limitations in precision significantly influenced the development of engineering standards at the time, particularly those related to safety, where estimation and tolerance were key. Despite these limitations, the slide rule remained widely used until the 1970s, when affordable digital pocket calculators made it largely obsolete. Over time, a range of specialized slide rules were developed, each featuring custom scales tailored to the needs of different professions.

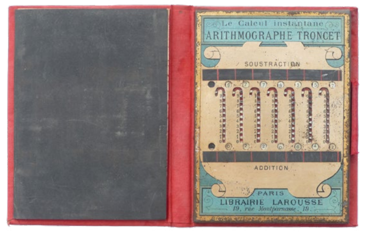


Arithmometer

The Thomas Arithmometer, the first mass-produced mechanical calculator, was designed to simplify administrative tasks such as bookkeeping and tax calculations. Its most significant innovation was the effective implementation of the stepped drum mechanism, which laid the foundation for many following mechanical calculators. As the technology evolved, later iterations of the arithmometer were optimized for speed and efficiency, making them more useful in office environments. Eventually, electromechanical descendants of the arithmometer were used by human "computers," many of whom were women, to perform large-scale scientific calculations, especially before the rise of digital computation.

Adders

Adders were small, inexpensive, and intended for everyday use by the general public. Their simplicity made them accessible tools for performing basic arithmetic operations in daily life. Although limited in their capabilities, when used in combination with a slide rule, users could perform all four basic arithmetic operations. Over time, manufacturers created specialized versions of adders tailored to specific professional or personal use cases.



Discussion

This section provided an overview of the historical development of calculators, but it's important to note that I'm not a trained historian, and a deep historical analysis was beyond the scope of this project. The timeline I presented is largely based on existing timelines and sources created by others, rather than offering a completely new historical perspective. While the timeline may not be fully complete, it does clearly highlight which calculators played a significant role in history—these are consistently mentioned across different sources.

Not all information could be verified through academic literature. The story I outlined is mainly based on Houston (2023) and an interview with Paul Breedveld, a collector and restorer of mechanical calculators, which served as the starting point for further research. However, many of the details about mechanical calculators come from private collectors and enthusiasts, that were found through Wikipedia and Google. This means that while their knowledge is often rich and detailed, it isn't always fully supported by scientific or peer-reviewed sources.

There's also some bias in the timeline, as my exploration began with the calculators introduced to me by Paul Breedveld. As a result, certain unusual or niche devices may have received more attention than they would in a more traditional historical account. For example, the adder ended up playing a central role in the narrative, largely because I had direct access to one. From a broader or more neutral historical perspective, it might not have been as prominent. That said, the aim of this case study is not to provide a perfectly complete history, but to offer an engaging and educational experience. The stories and machines that stood out to me are likely to be just as compelling to visitors.

3.2.2 Exploring technology

This phase of the design process was all about exploring ideas and possibilities. I began with an initial round of ideation based on insights from the contextual analysis, then moved on to technical exploration—considering what I could realistically prototype using the tools and materials I had. The goal was to explore a wide range of directions before narrowing things down into a final concept.

Throughout this phase, I worked with two vintage adders that I purchased secondhand (Figure 37). I decided to focus on these specific devices after the conversation with mechanical calculator expert Paul Breedveld, who suggested focusing on adders and stepped drum mechanisms. His advice helped me stay within the limits of what I could realistically prototype, while still engaging with meaningful and historically rich artifacts.

Ideation

I began the design process with an ideation phase, which gave shape to the next steps in the technological exploration. I aimed to keep the ideation as open as possible. I used the Immersive Heritage Design Deck (further discussed in chapter 4.3.1) to spark new ideas and explore different directions.

Figure 37. The two adders used in this project: an Addiator Universal (left) and a X-ACTA Pocket Calculating Machine (right), both ca. 1960.

After brainstorming, I grouped my ideas into the following clusters:

- **Zooming in & out:** These ideas used XR to expand or deepen the experience by adding layers of context. For example, by showing cultural background information around an artifact or visualizing its internal mechanisms.
- **Tangible storylines:** These concepts focused on letting users interact with the narrative itself. By manipulating physical elements, visitors could explore how calculators developed over time in different ways.
- **Changing perspectives:** These ideas allowed users to explore artifacts from different perspectives. For instance, one lens could highlight technical details, while another would focus on the social context or the people who used the artifact.
- **Gamification:** These ideas introduced game-like elements to make the experience more playful and engaging.
- **Tangible exploration:** This broader category included ideas that used physical interaction as a way of exploring artifacts. These elements could often be combined with other concepts from the other clusters.

At this point, I didn't yet choose one specific design direction. Instead, I treated these ideas as inspiration to guide the technological exploration.

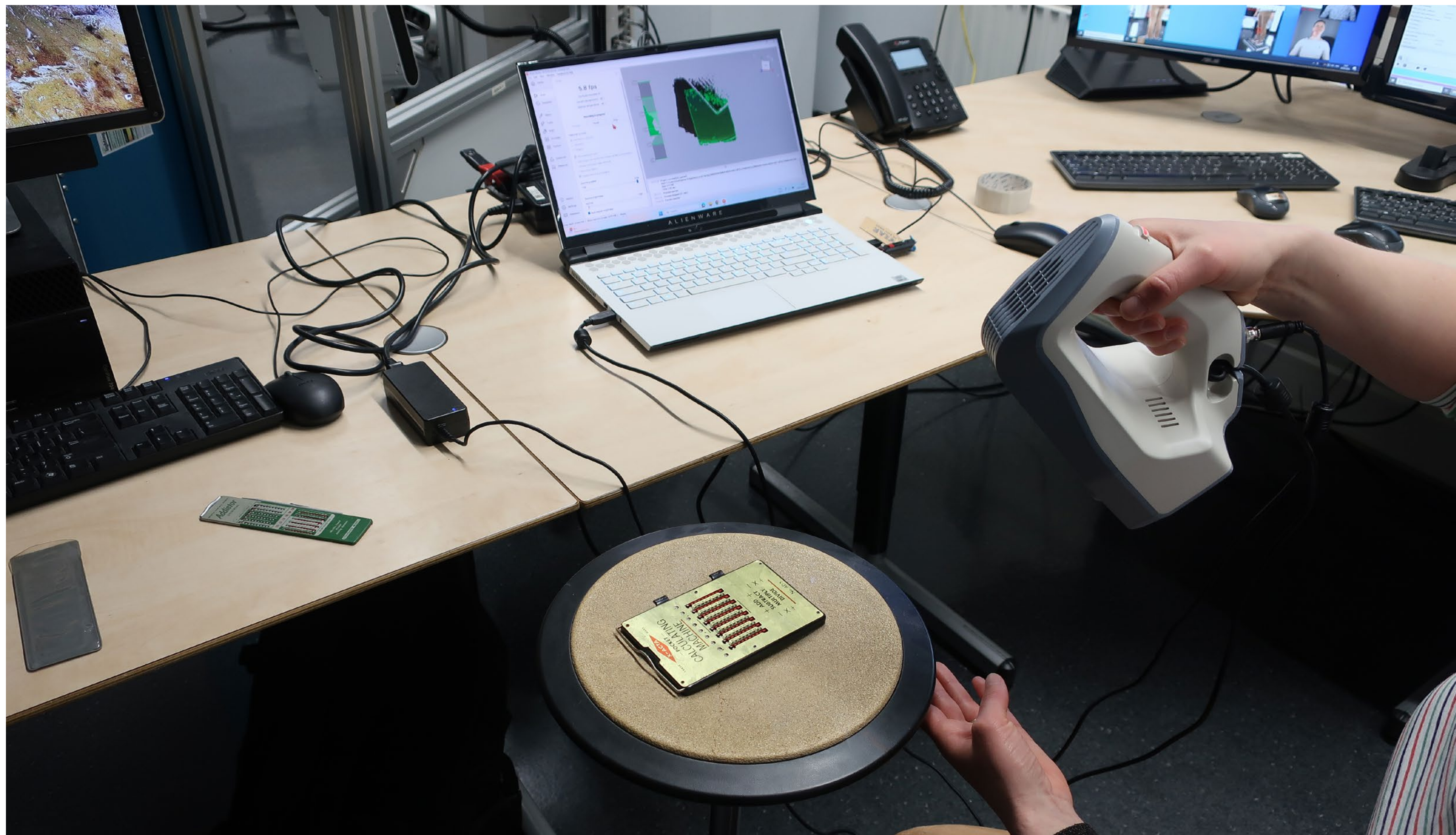
3D scanning artifacts

Full 3D scans of the two original adders were made using the Artec Spider, a structured light scanner (Figure 38). These scans allowed me to recreate their the artifacts with 3D printing, placing detailed digital replicas in virtual environments, and linking these to visual markers.

The scanning process, however, came with several challenges. Some parts of the adders were dark and reflective, which made it difficult for the scanner to accurately capture their shape. Applying dry shampoo helped reduce reflections, but that workaround would only work for objects that aren't too delicate or valuable, since the spray can leave visible residue.

Other scanning methods—such as photogrammetry or laser scanning—could have been used, but they also tend to struggle with fine details, shiny materials, and dark surfaces. Since I had access to a structured light scanner, I chose that method. Despite some limitations, it proved to be a promising approach. Most of the inaccuracies were in the textures rather than the shape, and some of these could be corrected later by editing the UV map (Figure 39) in tools like Photoshop.

Figure 38. 3D scanning the adder using the Artec Spider, a structured light scanner.



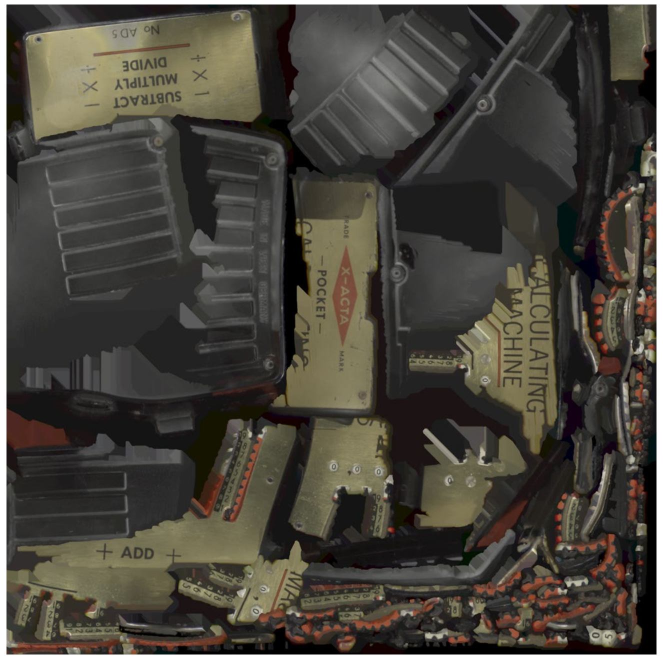


Figure 39. UV map of the X-ACTA adder.

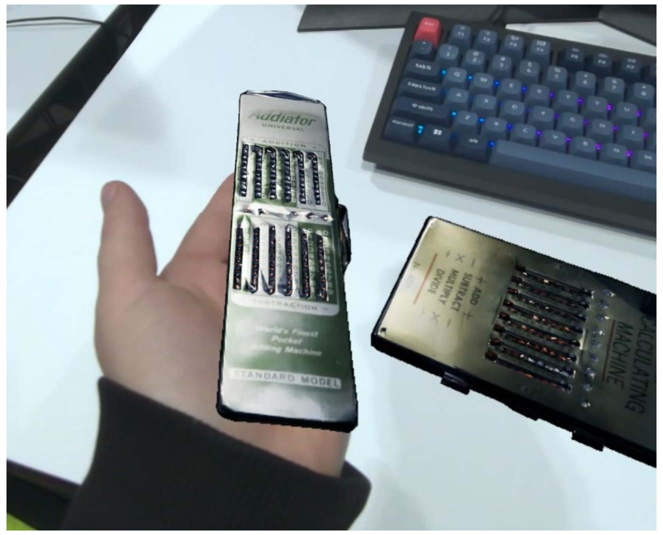


Figure 40. The 3D scans attached to paper visual markers.

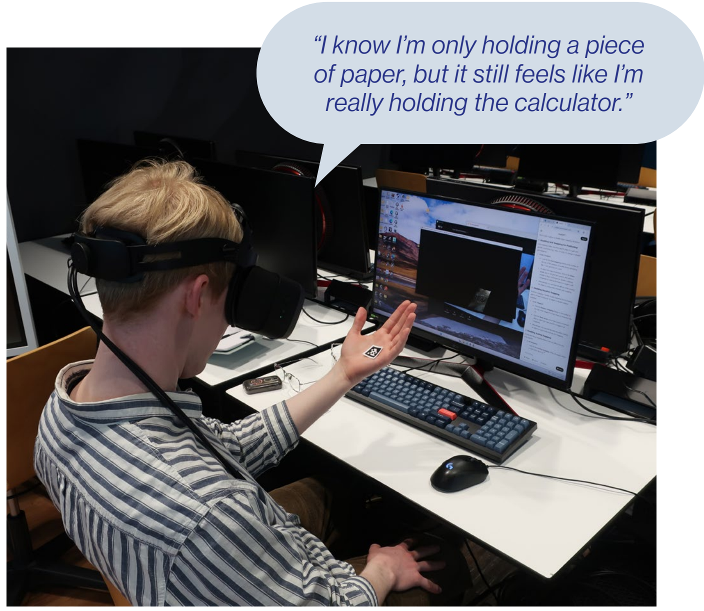


Figure 41. A user exploring the 3D scans through the paper visual markers.

Once the 3D scans were added to an XR environment and linked to visual markers (Figure 40), users could interact with them – rotating them, examining details, and observing how light reflects off their surfaces. These visual markers will be discussed further in the following sections. Interestingly, many of the small inaccuracies were not visible or noticeable in the XR setting, either because they were too subtle or because users were focused on the interaction itself. Even in the first test, where the model was linked to a simple paper marker (Figure 41), a user commented: "I know I'm only holding a piece of paper, but it still feels like I'm really holding the calculator." This shows the potential of using 3D scans and visual markers to create convincing interactive experiences.

3D printed replicas

3D printing helped bring the scanned artifacts into the physical world, which was key for making them tangible and interactive.

I explored two types of replicas:

- **Visual replicas** aimed to match the look and feel of the original replicas.
- **Functional replicas** aimed to recreate the functionality of the original artifacts.

3D printing offers a promising way to produce these replicas – it allows for flexible shapes, fast prototyping, and is supported by a large online community that shares open-source 3D models. It's also relatively affordable, especially when working with small artifacts and low production volumes, since there's no need for expensive tools like molds.

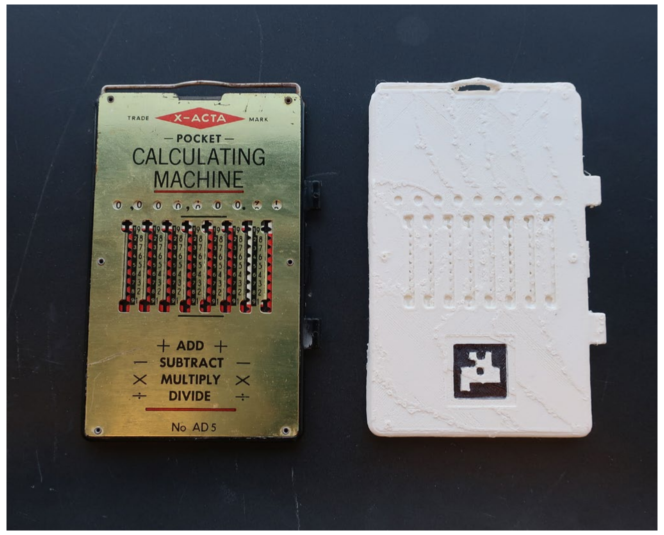


Figure 42. The original artifact (left) and its 3D printed replica with integrated visual marker (right).

Figure 43. A 3D scan attached to a physical replica with an integrated visual marker (left) and the original artifact (right).

To create the visual replicas, I used 3D scans of the original artifacts and printed them using Fused Deposition Modeling (FDM). This resulted in replicas that closely matched the original in shape and size (Figure 42), but didn't capture surface details or materials. The FDM printer created solid white prints that lacked color, and some uneven surfaces added texture. Despite these visual and tactile differences, the similarity in shape and scale meant the interaction remained quite similar – you naturally picked up and held the replica just as you would with the original artifact (Figure 43).

Functional replicas were created by adjusting open-source models of adders and stepped drums (Figures 44-45). While not always exact copies, they reproduced the essential mechanical principles.

Visual markers

A key element in making visual replicas interactive is the use of visual markers. These markers let me link digital content to physical objects so that when a user moves the object in real life, the digital version moves in the same way in XR. Visual markers can also be used to display extra information, like explanatory text, next to physical artifacts. I used Varjo markers, which are recognized by the Varjo XR headset that I used throughout this project.

After some initial experiments with paper markers, I also tested 3D-printed markers, to see if I could embed them directly into replicas (Figure 46). I printed several variants, differing in size, depth of the indents and color. Testing showed that the paper markers still worked the best, likely because of their matte surface. The

Figure 44. A 3D printed adder (left) and the original artifact (right).

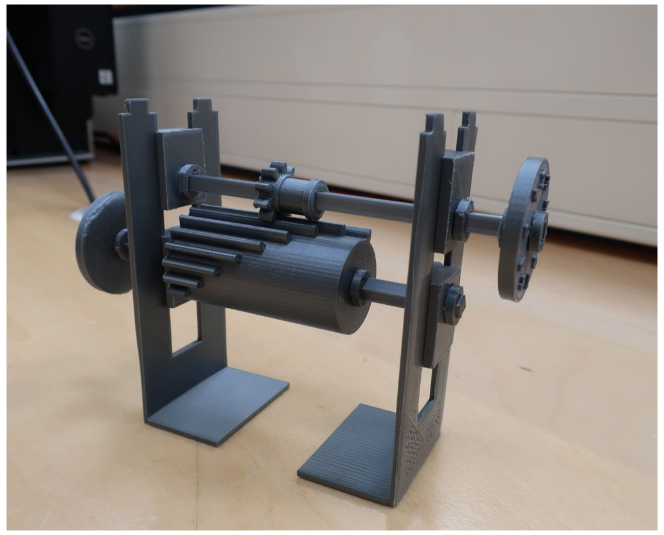


Figure 45. Stepped drum prototype.

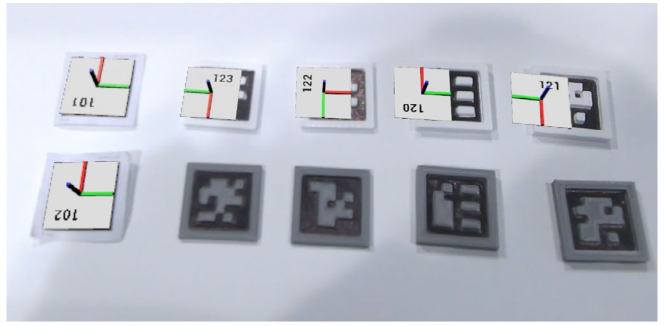


Figure 46. Testing the markers. From left to right: paper markers, 2x 2 mm markers, 2x 3 mm markers.

3D-printed white markers worked okay, as long as the indents were shallow and contrast was high. Grey markers didn't work at all.

The final experiment with visual markers involved integrating 3D printed markers directly into the 3D models of scanned artifacts (Figure 43). This allowed you to see the digital version of the artifact in XR while holding a physical object with

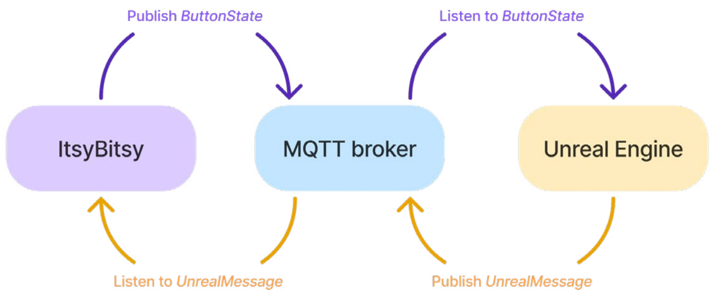


Figure 47. Simplified overview of the MQTT connection between the ItsyBitsy and Unreal Engine.

Figure 48. ToF/light sensor prototype: The calculators are recognized and lights will turn on if they're placed in the correct slots.

the same shape and size. Although the tracking was still a bit buggy—likely due to the marker's reflectiveness—and aligning the digital model with the physical object required precision, the test was successful. The interaction felt more natural than with paper markers alone, as the physical form now matched what you saw in XR.

Connecting electronics & XR

The final part of my technology exploration focused on connecting my tangible electronics prototypes to the XR environment. Specifically, I wanted to find a way to send signals from my ItsyBitsy microcontroller to Unreal Engine, so that an action performed on a physical prototype would trigger a response in XR. This is an important part of combining XR and TUIs, as the goal is to allow interaction without relying on standard XR controllers.

For this, I used MQTT, a lightweight communication protocol often used in IoT. I had worked with it before, and with major support from my supervisor and the TU Delft XR Zone, we built an MQTT plugin for Unreal Engine. It worked smoothly in both directions—physical input changed things in XR, and XR events sent signals back to the microcontroller (Figure 47). The messages moved in both directions with very little delay—quick enough that it wouldn't negatively affect the type of interactions I wanted to create. This showed that smooth, low-latency communication between a microcontroller and Unreal Engine is possible using MQTT.

Next, I wanted to use the MQTT connection to create meaningful interactions that fit the theme of an immersive heritage experience focused on analog calculators. After some ideation and testing a few electronics-only prototypes, I built one that I connected to MQTT. This prototype used a Time-of-Flight (ToF) sensor and a light sensor to detect when an artifact was placed in a specific location (Figure 48)—a concept that had come up several times during my earlier design sketches.

I considered using RFID or NFC to identify different objects, but decided against it. Both would've added extra hardware and more complex coding, which didn't fit my goal of keeping the setup simple and easy to prototype.

Once connected to Unreal via MQTT, the prototype worked as intended: when an object was placed correctly, the XR display updated in real-time to show which object had been detected (Figures 49-50). The interaction was smooth and worked in real-time.

Figure 49. A connection between the ItsyBitsy: When a certain artifact is detected, the text fields in Unreal Engine will update correspondingly.

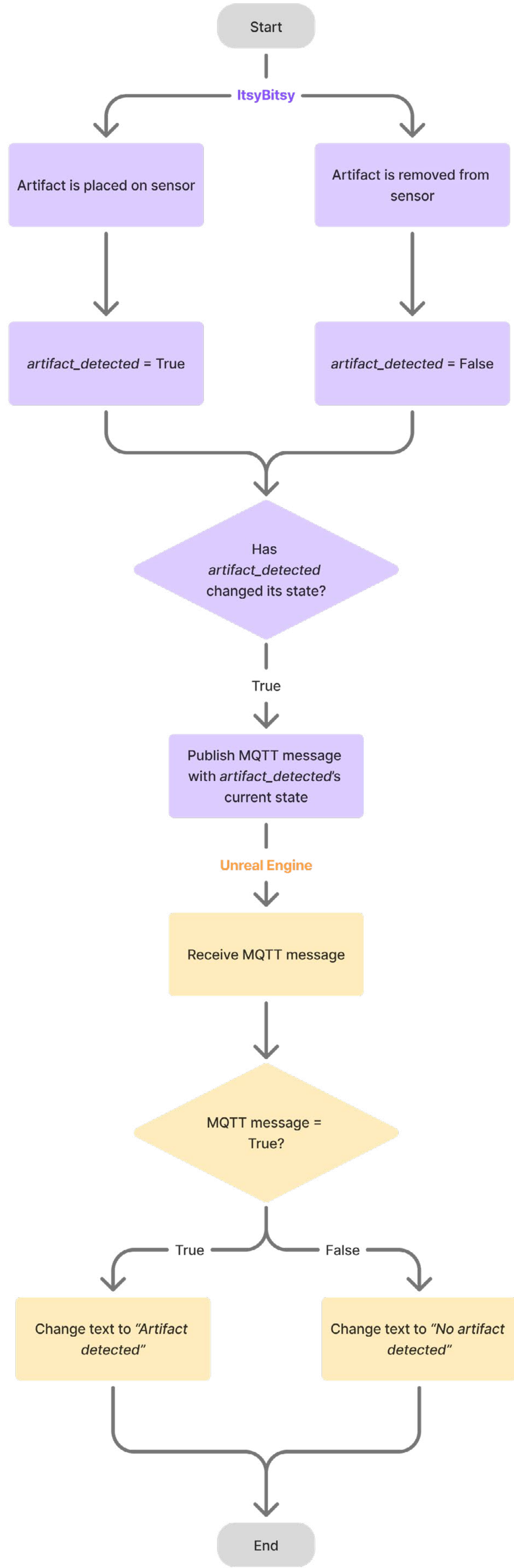


Figure 50. Simplified flowchart describing the communication process between the ItsyBitsy and Unreal Engine.

Designing with the technology

Reflecting on my technological exploration led me to a key decision: I would not aim to create a prototype that was both fully functional and visually accurate in one single object. During this exploration, it became clear that both the functional and visual prototypes still had some bugs and limitations. While combining them into a single, seamless prototype would likely result in the most meaningful and immersive outcome, it simply wasn't feasible within the available timeframe and technical constraints of this project.

Instead, I focused on finding a way to capture the strengths of both approaches while maintaining meaningful interaction. This led me to define two technological approaches for enabling interaction with artifact:

Visual replicas

For the visual replicas, I decided to map 3D scans of the original artifacts onto 3D-printed models that match the shape and size of the originals. This approach allows users to physically manipulate a tangible object while experiencing the visual design through XR.

Functional replicas

For the functional replicas, I focused on recreating (some of) the key operations of the original artifacts. These replicas would exist in the real world and be visible through a mixed reality headset, where they could be enhanced by virtual elements – such as contextual information or visual links to the original artifact – without attempting to replicate their full appearance and functionality in XR.

Discussion

This technological exploration was heavily shaped by the tools and resources I had access to – like the structured light scanner and the Varjo XR headset. These high-end tools opened up certain possibilities but might not be possible to use in all design contexts. Designers working with museums that are new to these technologies, for example, may not have access to these kinds of resources. It's important to acknowledge that this kind of equipment can be expensive and not always easily available, especially in early-stage or low-budget projects.

Another important factor was being realistic about my own time and skill level. I had to make practical choices about which technologies to continue exploring in my final design. This meant not always choosing the most advanced or polished outcome, but rather focusing on what was achievable within the scope of the project. While this sometimes limited the potential impact, it actually aligns well with my intended target audience – people with a similar level of technical experience. In that sense, the exploration stayed grounded and relevant: the tools and techniques I used could realistically be replicated by other designers.

When it comes to the electronics and XR integration, I focused mainly on establishing a stable connection between the physical and digital components – getting the data to move back and forth via MQTT. That said, it would have been useful to explore how different kinds of inputs or sensor configurations could shape different types of interactions. For instance, how do different forms of physical-digital interaction change the way people understand or engage with the content? This would be meaningful to explore in future iterations.

3.2.3 Exploring interactions

In this phase, I explored how users interact with both original artifacts and replicas. The look and feel of an artifact not only influence its function but also shape the user's overall experience – engaging the senses, sparking associations, and evoking emotions or actions. This phase aimed to answer the following questions:

1. *Which aspects of interacting with heritage artifacts significantly influence the user's experience?*
2. *How does the user's experience differ when engaging with original heritage artifacts versus their replicas?*

Experiential Characterization

Method

To explore these questions, I used the Experiential Characterization Method, which looks at the user experience across four different layers:

1. **Performative:** How the artifact shapes physical interactions and use patterns
2. **Sensorial:** How the artifact is perceived through the senses (sight, touch, sound, etc.)
3. **Interpretive:** The meanings users attribute to the artifact
4. **Affective:** The emotions and feelings it elicits

Participants were first given time to freely explore and interact with the artifacts. Afterwards, they completed a worksheet that helped them reflect on their experience across the four levels (Figure 51). I selected this method because it provides a structured vocabulary that supports deeper and more focused conversations around the users' experiences.

I conducted sessions with four participants, each of whom interacted with both an original vintage adder and a 3D-printed functional replica (Figures 52-53). Two participants began with the original artifact and two with the replica, to investigate what kind of role order bias plays in the experience.

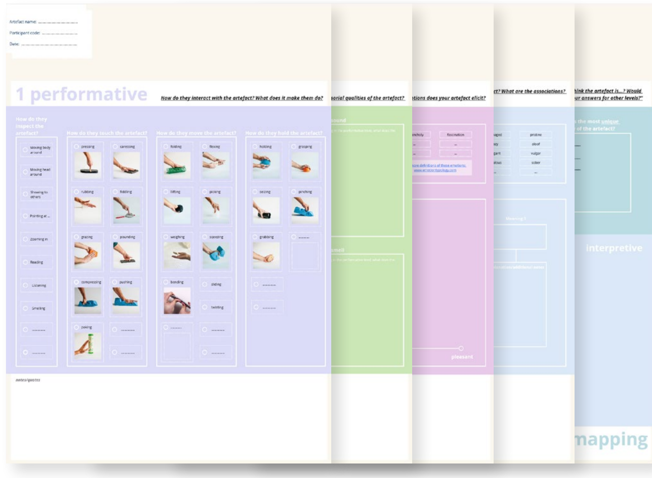


Figure 51. The experiential characterization worksheet.

Figure 52. A participant interacting with a functional replica.

Figure 53. A participant filling in the worksheet.

Analysis

The sessions were audio-recorded and later transcribed. I then coded the transcripts, identifying recurring themes and meaningful observations. These were synthesized into 17 statement cards, which captured key insights and user reflections (Figure 54). I grouped the statement cards into thematic clusters and analyzed relationships between them to better understand patterns in user experience.

A qualitative approach was chosen over a quantitative one for two main reasons:

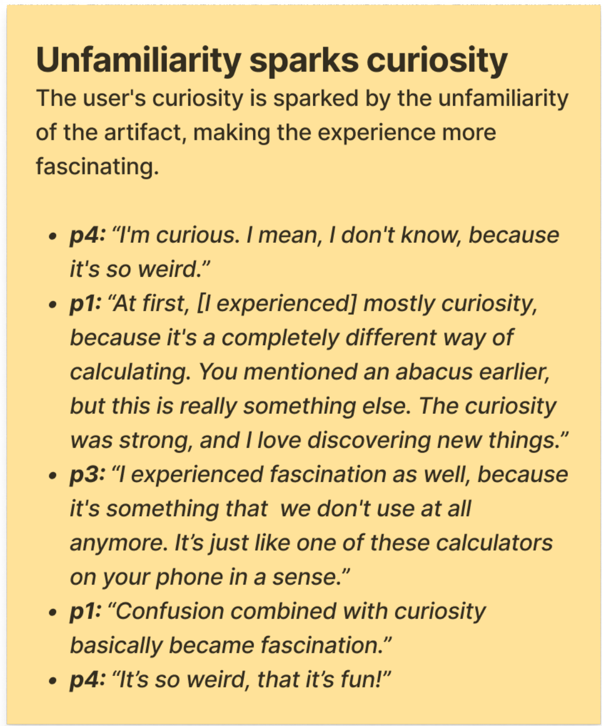
- With only four participants, statistical data would not yield reliable or meaningful conclusions.
- I aimed to extract broader insights about interaction with analog calculators and their replicas, not just the specific artifacts used in the tests. The open-ended nature of qualitative analysis allowed for greater reflection on the users' experiences.

Results

The user testing revealed a range of experiential responses to both original heritage artifacts and their replicas. These responses were influenced by the artifacts' physical characteristics, how they functioned, and how authentic they were perceived to be. A complete overview of the statement cards can be found in Appendix C. Figure 55 presents the thematic clusters and the relationships between them.

<u>Emotional shifts and the role of familiarity</u>

Participants often experienced a noticeable emotional shift over time. Initial engagement—especially with the original artifact—was marked by curiosity, excitement, and playfulness. As users became more familiar with how the artifact worked, this shifted toward confidence and comfort. However, replicas occasionally introduced feelings of disappointment or frustration, especially when users noticed visual or functional inconsistencies, or when the replica didn't respond as smoothly as the original.


Unfamiliarity sparks curiosity

The user's curiosity is sparked by the unfamiliarity of the artifact, making the experience more fascinating.

- ***p4:*** *"I'm curious. I mean, I don't know, because it's so weird."*
- ***p1:*** *"At first, [I experienced] mostly curiosity, because it's a completely different way of calculating. You mentioned an abacus earlier, but this is really something else. The curiosity was strong, and I love discovering new things."*
- ***p3:*** *"I experienced fascination as well, because it's something that we don't use at all anymore. It's just like one of these calculators on your phone in a sense."*
- ***p1:*** *"Confusion combined with curiosity basically became fascination."*
- ***p4:*** *"It's so weird, that it's fun!"*

Figure 54. One of the statement cards from the experiential characterization.

<u>Interpretation and perception of authenticity</u>

The perceived authenticity and visual presentation of the artifact strongly influenced user interpretation. Original artifacts were generally regarded as professional and elegant tools. In contrast, replicas were sometimes described as toy-like or overly simplified. These perceptions affected the seriousness with which users approached the artifact. For example, a visually refined object invited more deliberate, respectful interaction, while more playful or crude aesthetics encouraged experimentation or even skepticism.

<u>Unfamiliarity as a double-edged sword</u>

Unfamiliarity emerged as a key factor in engagement. The analog calculators—unlike modern digital tools—felt strange and unknown to most users, which sparked intrigue and made the interaction more memorable. This novelty often led to a sense of discovery. However, unfamiliarity also caused friction: when users couldn't immediately grasp how the artifact worked, some expressed frustration or confusion. This dynamic created a tension between fascination and usability, which must be carefully balanced.

<u>The effect of tangibility</u>

Physical interaction played an important role in engagement. Participants expressed that the most compelling part of the experience was not necessarily the output or function of the device, but the process of exploring and manipulating it. The material aspect of doing analog calculations—as opposed to digital calculations—made the interaction more meaningful and intriguing.

<u>Originals vs. Replicas</u>

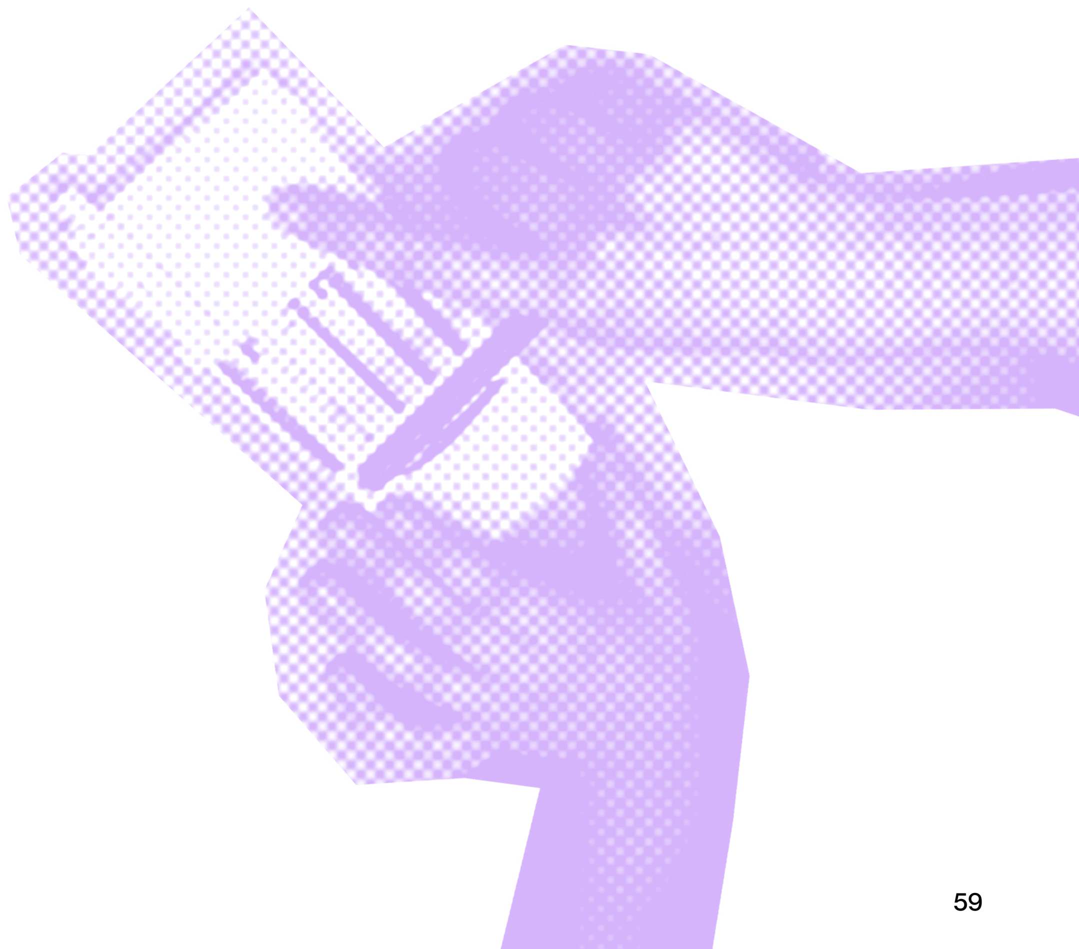
The presence of both original and replica versions of the artifact lead to direct comparisons. This often placed the replica at a disadvantage, particularly when it failed to replicate the refined appearance, weight, or precision of the original. Users expressed that while replicas do not need to be perfect imitations, they should preserve the meaningful aspects of the original, such as its interaction style or material feel. Interestingly, the act of comparison itself could shift the user's focus from exploration to critique, sometimes lowering the overall enjoyment of the interaction.

<u>Artifact-specific observations</u>

Some observations from the test were very specific to the particular artifacts used and might not apply as directly to other cases involving different objects. A key example was the interaction with the stylus and eraser— both elements that allowed users to interact with the artifacts directly and were often mentioned by the participants.

The stylus, in particular, played an important role in how participants engaged with the artifacts. It was frequently associated with a sense of playfulness and mentioned as a key part of the experience. It also became a point of comparison: while the original artifact had a sturdy metal stylus, the replica's 3D-printed version was often described as a "cheap knock-off."

Similar reactions came up around the eraser, which was included in the original calculator but missing from the replica. Participants noticed this absence, highlighting how even small elements can influence the authenticity and quality of the interaction.



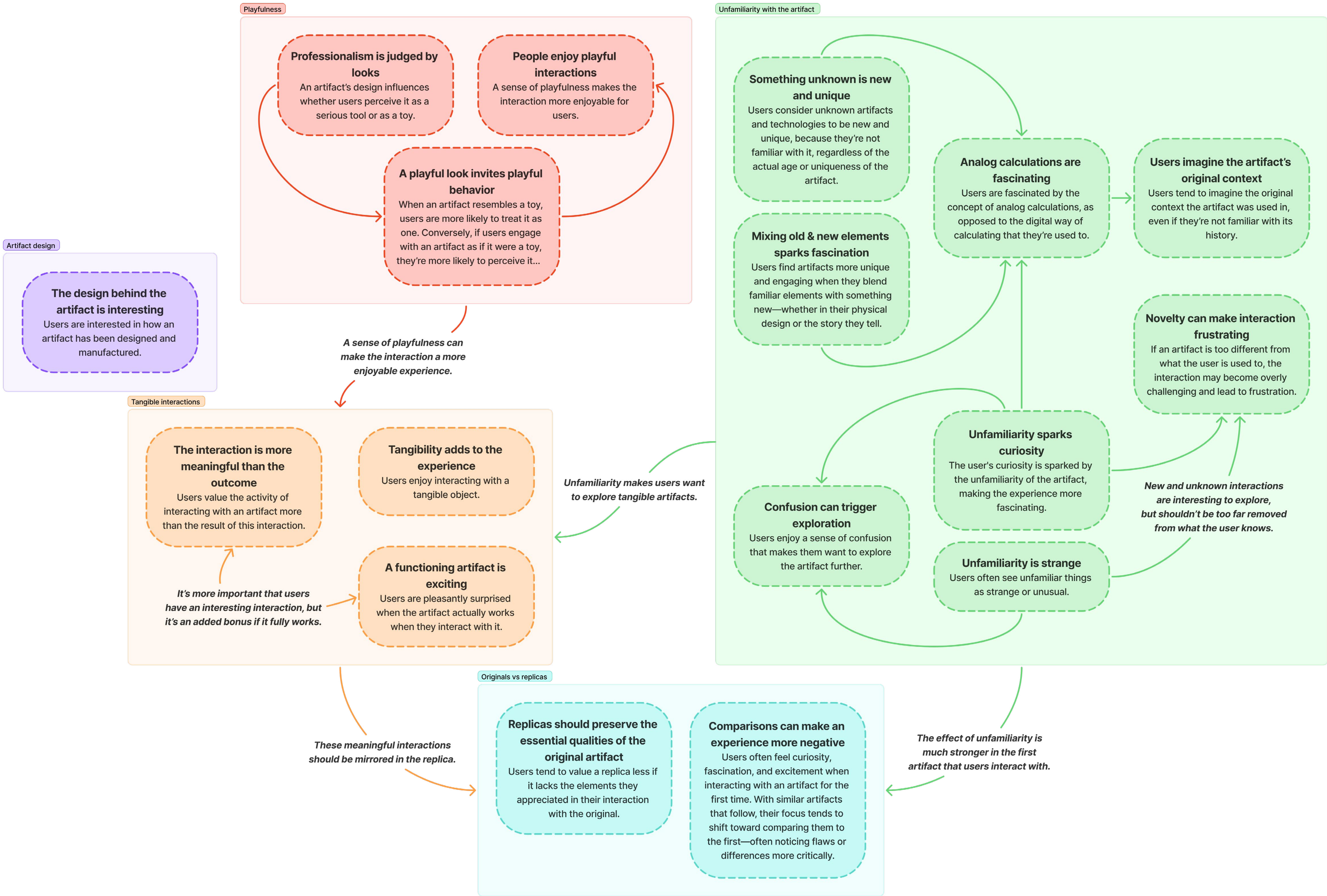


Figure 55. Overview of the clustered statement cards and their relationships to each other.

Designing with the interaction qualities

Reflecting on the outcomes of the experiential characterization generated a range of valuable insights that helped further define and narrow down my solution space. To make these insights actionable, I translated them into an additional set of design criteria, which are presented below.

Tactile responsiveness

Tangible components must provide physical feedback and feel rewarding to manipulate, even if they do not perfectly reproduce the original artifact's mechanical behavior.

Emotional resonance

Replicas must be designed to trigger similar emotional responses even if they cannot fully match the aesthetic or material qualities of the original artifact.

Balancing unfamiliarity and usability

The interaction design must include some unfamiliar or surprising elements to stimulate interest, but must also remain easy to understand without prior instruction.

Contextualizing replicas

The replica must clearly be presented as an interpretive tool, not a one-to-one reproduction.

Crucial

Important

Following that, I shifted my focus to the core objective of my immersive heritage experience: telling an interactive, engaging story about analog calculators. This reflection helped me identify a set of key interaction qualities that I wanted to incorporate into the final concept:

Analog technology

Participants were all intrigued by the analog nature of the calculators. I want the experience to center on this fascination – highlighting how calculations can be performed without digital tools, how analog methods work, and how they've evolved and been applied over centuries.

Playful exploration

Users appreciated the freedom to explore and discover through playful interaction. I aim to encourage this kind of open-ended, hands-on learning, allowing users to uncover more about the artifact by physically engaging with it.

Symbolic over functional interactions

Many users found the act of interacting more meaningful than achieving a specific outcome. Therefore, I will prioritize symbolic interactions over replicating the full functionality of the object in XR.

Historic context

The artifacts sparked conversations about history and seemed to tap into their imagination. I want to build on this by enabling users to explore the surrounding historical narratives alongside the artifacts themselves.

3.3.4 Discussion

The experiential characterization tests were a valuable and insightful tool to gain a deeper understanding of what makes an interaction with heritage artifacts meaningful and memorable for users. However, a limitation of the tests was that I only compared original artifacts with functional replicas. At that point in the process, the visual replicas were not yet ready, so they couldn't be included. Even if they had been finished, adding a third category would have made the sessions too long, as each artifact already required around 30 minutes. Still, including visual replicas in future tests could offer additional insights into how different kinds of replication – functional, visual, or a combination – shape user experience.

3.3 Integration

With the key design elements from the narrative, technological, and interaction explorations in place, I set out to bring everything together into one cohesive concept. This section outlines that process – from early ideation to shaping the final concept for the immersive heritage experience. The development of this concept is discussed in the following section.

3.3.1 Ideation

First, I returned to the ideation phase. The insights I had gathered in each phase helped spark new ideas and refine existing ones. I revisited the early concepts I had come up with to see how their core ideas could be adapted or reimagined within the now clearer boundaries of my solution space. Additionally, I used the Immersive Heritage Deck again – this time as a tool to generate fresh perspectives and to enhance the concepts I had already started shaping. This process eventually led to the development of four distinct concept directions.

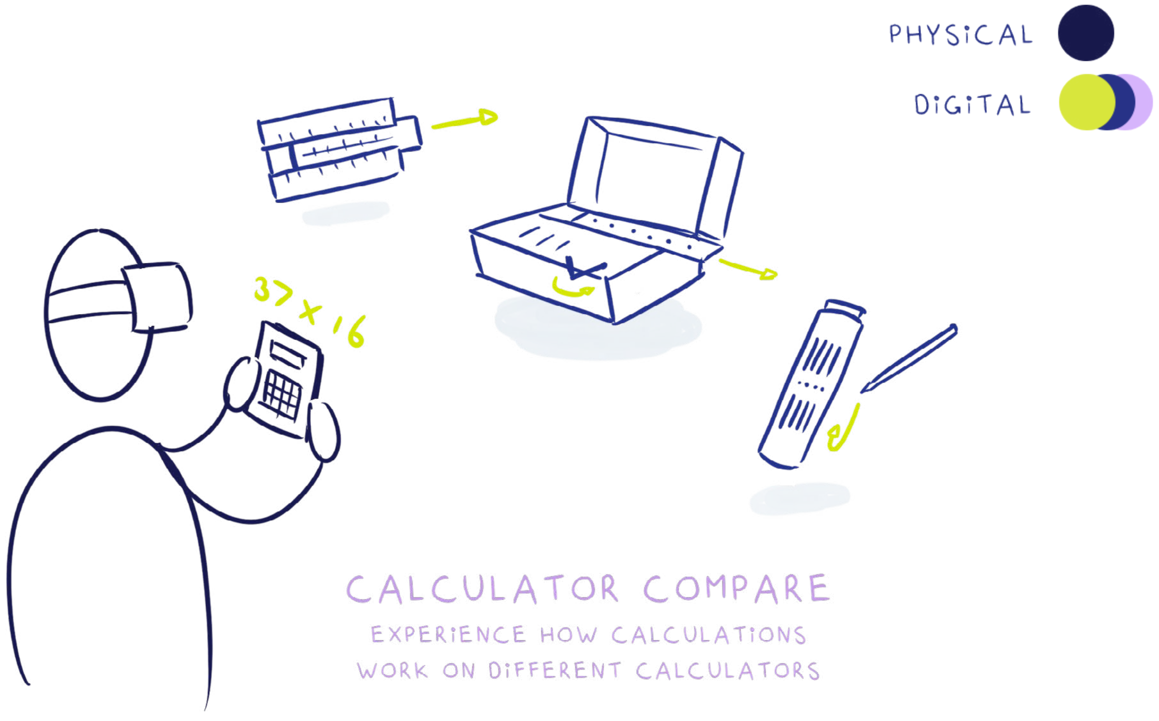


Figure 56. Sketch of the Calculator Compare concept.

Calculator Compare

Calculator Compare (Figure 56) focuses on highlighting the diversity of analog calculators and how their mechanisms differ not only from one another but also from the digital calculators we use today. In this experience, users interact with a physical digital calculator while viewing various analog calculator models in XR. By entering a calculation, the system shows whether and how that same operation could be performed with the different analog tools. The interaction design builds on users' familiarity with digital calculators, keeping the experience accessible.

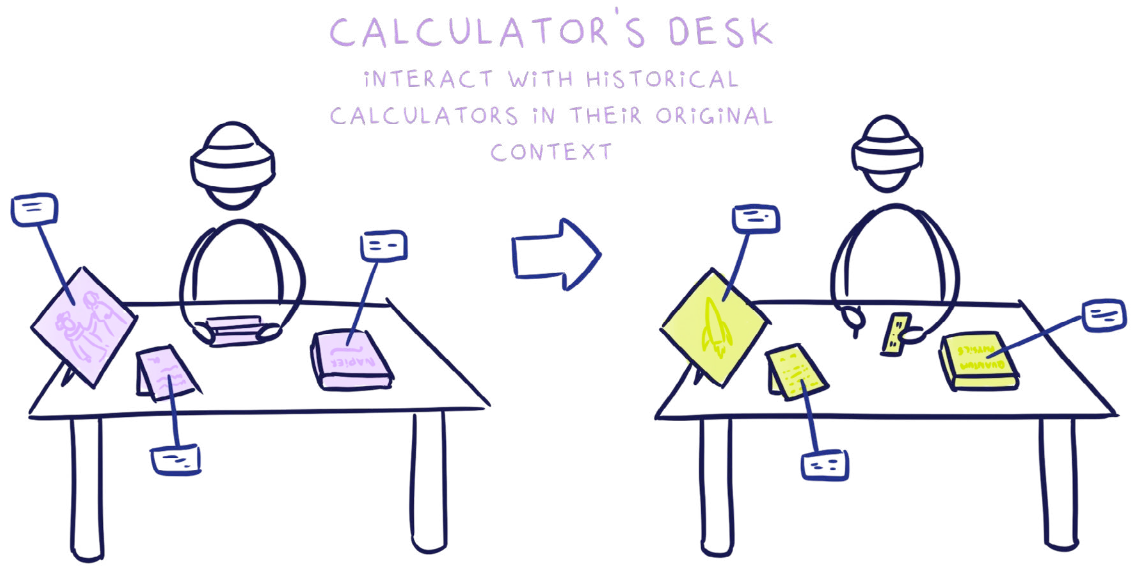


Figure 57. Sketch of the Calculator's Desk concept.

Calculator's Desk

The Calculator's Desk (Figure 57) aims to place calculators within their historical context in a more tangible way. This concept uses a physical desk setup with tangible props that look like abstract shapes without a headset. Users can open a box of physical calculator replicas, and when they put on the XR headset and pick one up, the surrounding environment transforms to reflect the time period that the calculator belongs to. Objects on the desk are visually overlayed with details from that era, and users can explore both the artifact and its historical setting. When a different calculator is selected, the scene transforms again. This idea combines tangible manipulation, immersive storytelling, and historical framing.

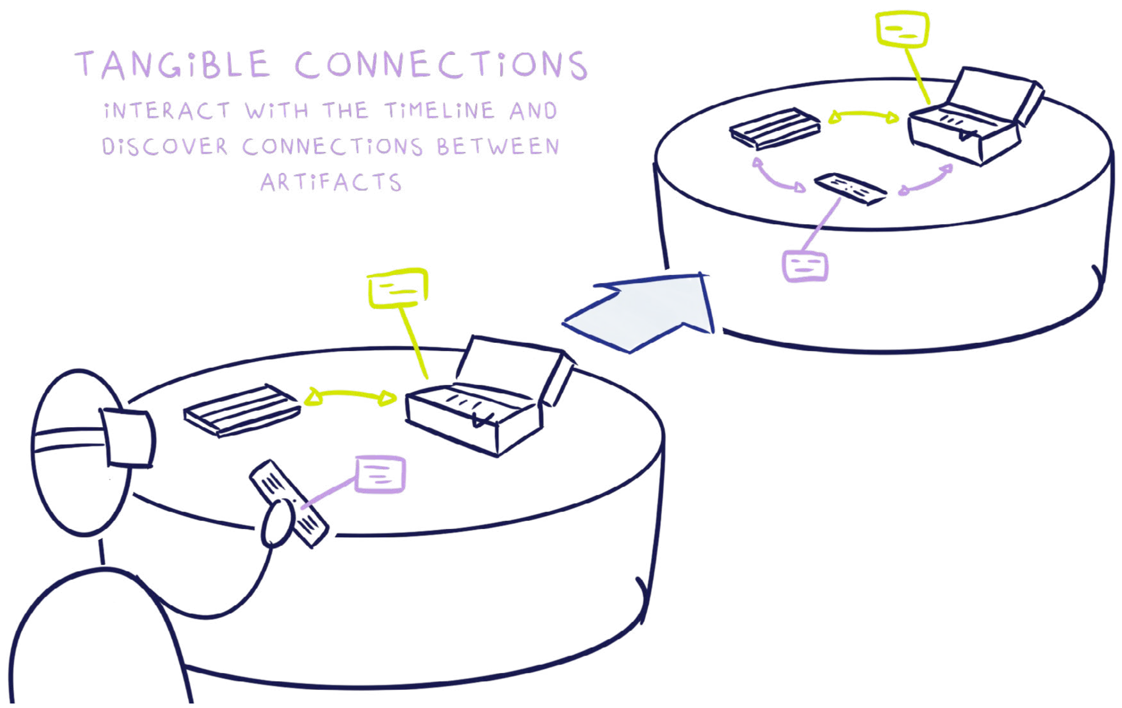


Figure 58. Sketch of the Tangible Connections concept.

Tangible Connections

Tangible Connections (Figure 58) focuses on helping users understand the relationships between historical artifacts. Here, users physically manipulate replicas of calculators and place them on a special table. The table uses XR overlays to provide information about the individual artifact and display connections between multiple objects – such as similarities, technological influences, or historical overlap. This encourages users to actively construct a narrative through physical exploration.

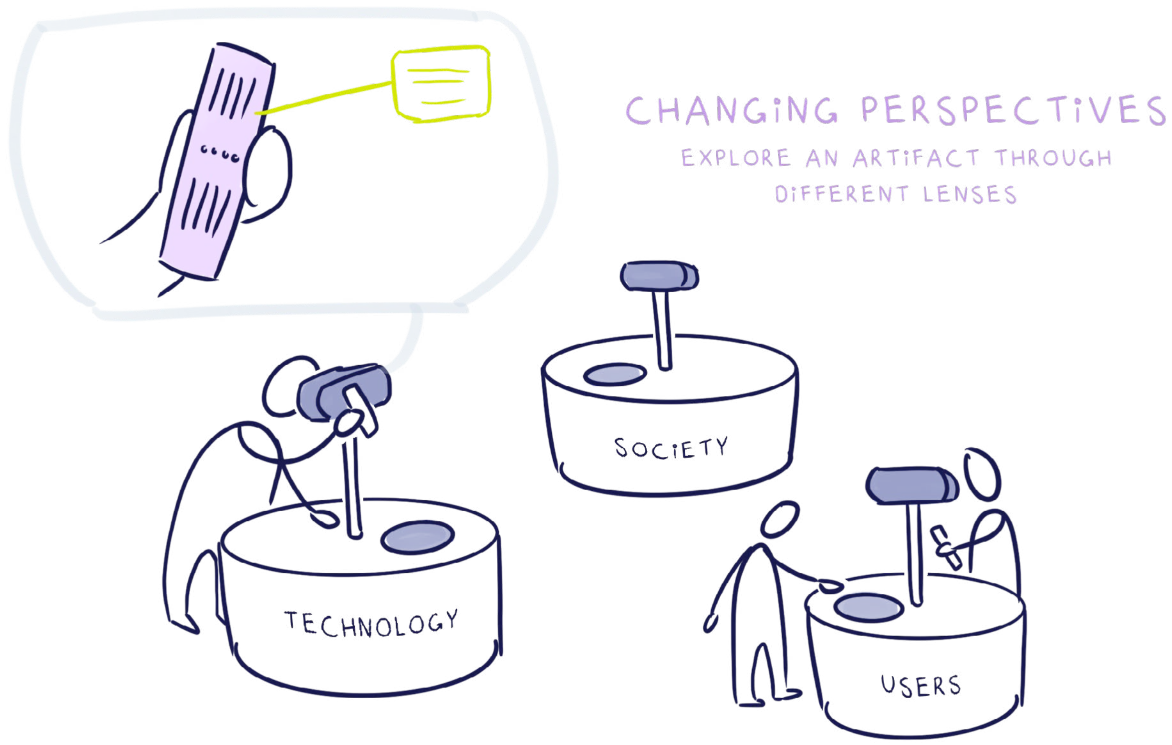


Figure 59. Sketch of the Changing Perspectives concept.

Changing Perspectives

Changing Perspectives (Figure 59) invites users to engage with artifacts through different thematic lenses, such as technological innovation or social impact. Users can carry a replica artifact through a physical exhibition space, where fixed XR stations offer mixed-reality views into specific perspectives. Looking through a headset at each station, users would see additional overlays and contextual information applied to the object. A screen next to the headset would mirror what's being viewed, allowing groups to experience it together.

Selection

To choose a final direction, I compared the concepts using my design criteria, including those derived from the experiential analysis. A Harris profile helped visualize how each idea performed across the criteria (Figure 60). Calculator Compare clearly underperformed in comparison to the others, mainly due to its lack of meaningful tangible interaction with the heritage artifacts. The remaining three—The Calculator's Desk, Tangible Connections, and Changing Perspectives—were more closely matched. I then considered which of these concepts truly used the potential of XR in a way that couldn't be replicated through other means. At that point, Tangible Connections dropped out, as a similar interaction could be achieved through projection-based and purely physical installations.

The decision then came down to Changing Perspectives and The Calculator's Desk. While Changing Perspectives is rich in layered storytelling and ideal for a museum setting—especially since it allows for shared experiences without needing users to sit down or be stationary—its technical and logistical requirements made it unfeasible to prototype meaningfully within the scope of this project. To prototype it now would mean significantly reducing its richness and interactivity, ultimately stripping away what made the concept compelling in the first place.

That's why I chose to move forward with The Calculator's Desk. It's a concept in which XR and tangible interaction both play a meaningful role. It aligns well with the insights from the experiential and technological exploration phases and is achievable within the available resources. Most importantly, I believe I can prototype it to a level that effectively communicates the experience and design intent to others.

	Calculator Compare				Calculator's Desk				Tangible Connections				Changing Perspectives			
Criteria	--	-	+	++	--	-	+	++	--	-	+	++	--	-	+	++
Physical interaction without controllers: The system must support direct interaction with tangible interfaces that mimic the function of original artifacts, eliminating the need for VR controllers.			■	■			■	■			■	■			■	■
Interactive artifacts: The experience must provide users with hands-on interaction with functioning artifacts, either originals that will be 'sacrificed' for the experience or replicas.	■	■					■				■				■	
Tactile responsiveness: Tangible components must provide physical feedback and feel rewarding to manipulate, even if they do not perfectly reproduce the original artifact's mechanical behavior.		■					■				■				■	
Historical context of artifacts: The experience must connect artifacts to their historical context and show the relevance to us today.		■					■	■			■	■			■	■
Multiple levels of engagement: The experience must include both brief, intuitive interactions and optional deeper content layers to support different user interests.		■				■				■					■	
Emotional resonance: Replicas must be designed to trigger similar emotional responses even if they cannot fully match the aesthetic or material qualities of the original artifact.		■					■				■				■	
Balancing unfamiliarity and usability: The interaction design must include some unfamiliar or surprising elements to stimulate interest, but must also remain easy to understand without prior instruction.		■					■	■			■				■	■
Contextualizing replicas: The replica must clearly be presented as an interpretive tool, not a one-to-one reproduction.			■	■			■				■				■	
Sensory feedback: Audio and visual cues could be integrated to simulate authentic user interaction with the original devices.		■					■				■		■	■		
Gamified elements: Gamification mechanics could be used to spark curiosity.			■				■	■			■				■	
Multi-user and social functionality: The spatial setup and interface design could accommodate multiple users interacting simultaneously, encouraging discussion and collaborative learning.	■	■				■	■		■	■					■	

Figure 60. Harris profile comparing the four concepts.

Crucial

Important

Enhanching

3.3.2 Connecting artifacts to narratives

After having selected the Calculator's Desk as the concept to continue with, it was time to select which artifacts would play a central role in this experience and to identify the narratives associated with each of them.

Table 1 shows the final combination of artifacts, narratives and replicas. This combination allowed me to work with a diverse set of narratives as well as a variety of replica types. From a narrative perspective, the chosen artifacts span multiple time periods. While the adder and the slide rule originate from roughly the same era, their distinct use cases ensure that they each bring a unique story to the experience. Initially, I intended to place the adder in the 1920s, but the actual artifacts I had access to were clearly from the 1960s – as indicated, for instance, by the "Imported from West Germany" marking. Similarly, the slide rule I had obtained at this point also dated from somewhere between the 1950s and 1970s. Despite their proximity in time, the adder's association with everyday personal use and the slide rule's use in scientific and engineering contexts provided two very different narrative angles.

In terms of replicas, the selection allowed for various explorations. I didn't have access to an original arithmometer to scan, but I was able to work with an open-source 3D model. For the adder, I could build on the 3D scans I had previously created. I also made a new scan of the slide rule, this time separating the inner and outer parts. This gave me the possibility to make the visual replica in XR partially functional by allowing these parts to move independently.

For the functional replicas, the adder and slide rule were well-suited for building fully operational versions. The arithmometer, however, was more complex. I initially planned to focus on just one key component – the stepped drum – as I had done during the technological exploration (Figure 45), but this time linking it to a digital model of the arithmometer in XR. After testing a few early prototypes, where a visual marker was attached to the mechanical model, I decided to leave this replica out. Developing it into something stable and interactive enough for repeated use proved too challenging within the project's scope.

Next, I developed three personas, each based on the narrative I wanted to tell with the corresponding calculators (Figure 61). The portraits used in these personas were created using Sora, a generative AI image generator.

Table 1. Selected calculators and their respective narratives and replicas.

Calculator	Narrative	Visual replica	Functional replica
Arithmometer	An accountant in the 1870s, United Kingdom	Open source 3D model of arithmometer	-
Adder	A shopkeeper in the early 1960s, The Netherlands	3D scans of adders	3D printed functional adder
Slide rule	An engineering student in the late 1960s, United States	3D scan of slide rule	3D printed functional slide rule

Figure 61. Personas connected to the three calculators.

3.3.3 Bodystorming

XR isn't the easiest technology to quickly prototype with. Since building even a basic experience takes a fair amount of time and effort, I wanted to make sure I had a clearer idea of what exactly my prototype should include before jumping into development. To do that, I decided to run a bodystorming session – a hands-on method where you physically act out an idea or scenario to explore how it might work in real life. Unlike regular brainstorming, bodystorming helps you get a feel for the experience by actually moving through it, which makes it easier to spot what's missing or what could be improved.

There were two goals in this session: first, to figure out what elements would help create a convincing sense of different historical time periods within the XR experience, and second, to explore how people might actually move through and interact with the experience.

Method

I did the bodystorming session with two other students from Industrial Design Engineering. I started by explaining the overall concept of the Calculator's Desk and what kind of experience I hoped to create. I then asked the participants to come up with physical items they thought should be on each persona's desk to immersive them in the historical context (Figure 62). We then discussed the different ideas and looked for items that popped up across multiple narratives or could be easily adapted. These were interesting as potential reconfigurable props – objects that could take on different meanings depending on which story they were used in. The full list of props we came up with is included in Appendix D.

Figure 62. Result of the brainstorm on props for historical context. Items are placed next to the corresponding persona.

Next, we quickly built mock-ups of the selected props using whatever materials we had on hand – paper, cardboard, and random objects lying around. I had set up a table to act as the Calculator's Desk, and the participants arranged the props on it in the way they imagined they would appear in the XR experience (Figure 63). Once everything was in place, we acted out the experience: picking up artifacts, exploring the desk, and imagining how users would learn about the calculators and their context (Figure 64).

We wrapped up with a discussion using two card decks: my Immersive Heritage Design Deck and the Tangible Interaction Cards by Hornecker (2010). We took turns drawing cards and used them as conversation starters (Figure 65). Each card prompted us to reflect on the setup – what worked, what didn't, and what we might want to adjust before going into actual development. This helped us refine the ideas and interactions, and gave me a much clearer picture of what elements were most important to develop in the actual prototype.

Results

The bodystorming session provided a lot of useful insights into how users might interact with the Calculator's Desk XR experience and what elements are needed to make it engaging and understandable. One of the first things that came up was how people behave as soon as they put on a VR headset – they immediately want to look around and take everything in. This underlined the importance of making the initial environment visually interesting and intuitive to explore, so users feel invited to start interacting right away.

Another key takeaway was the role of physical props. Participants appreciated that the props didn't reveal exactly what they were at first glance. Their abstract, non-descript shapes triggered curiosity and made the participants want to pick them up and figure out what they were. This "mystery element" added a layer of playful discovery that worked really well. The participants also imagined that watching someone else explore the strange props would be very intriguing and would make them want to try it themselves as well.

For navigation and explanation, participants stressed the importance of giving clear, simple cues. Some kind of visible onboarding or instruction layer is needed to help users understand what they can do and how to move through the XR world without getting lost or overwhelmed. To support interaction, participants suggested adding subtle indicators to show where props can be picked up – ideally in a way that doesn't interfere with the visual markers used in XR. This would help reduce confusion without breaking the illusion or flow of the experience.

Figure 63. Participants placing props on the desk.

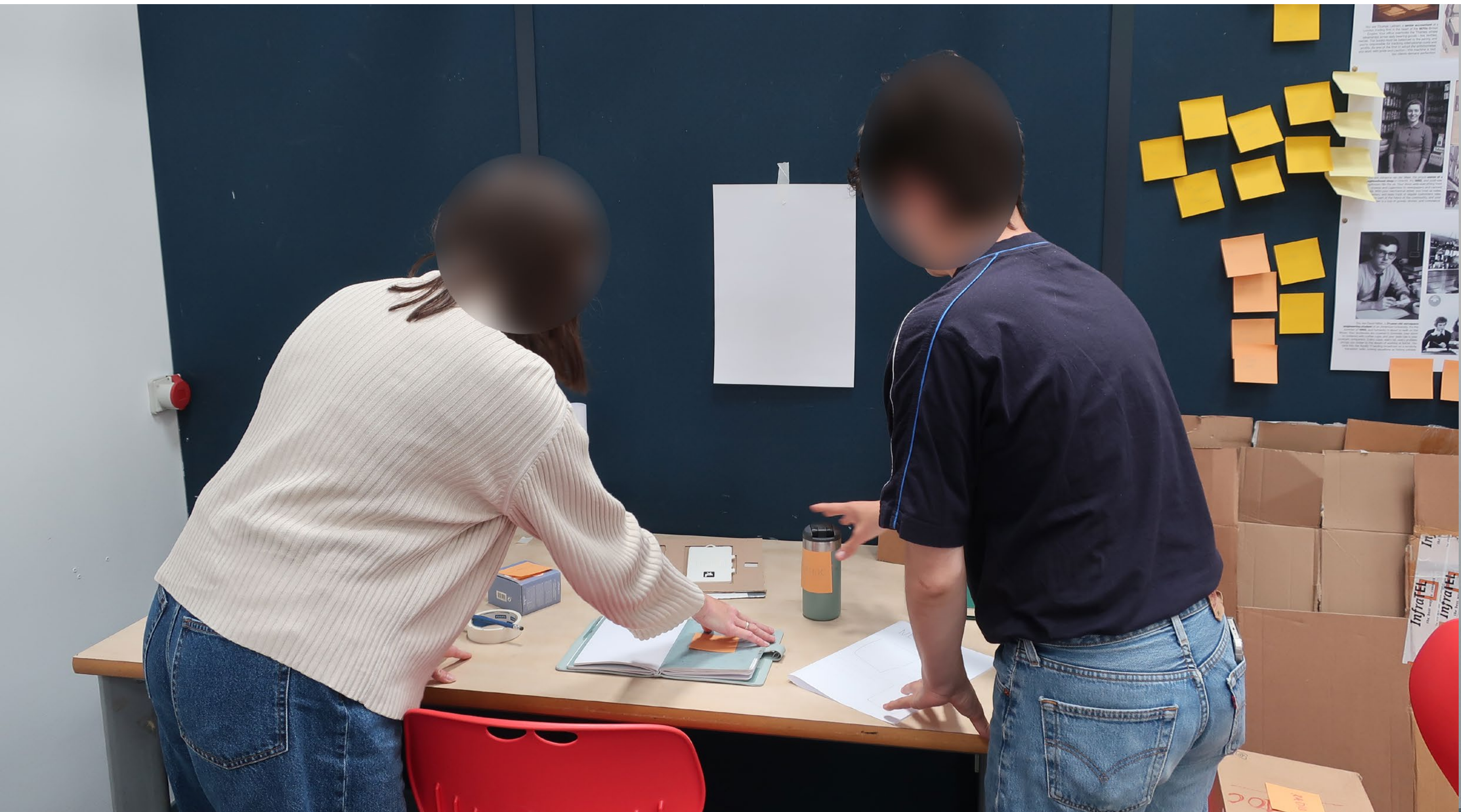
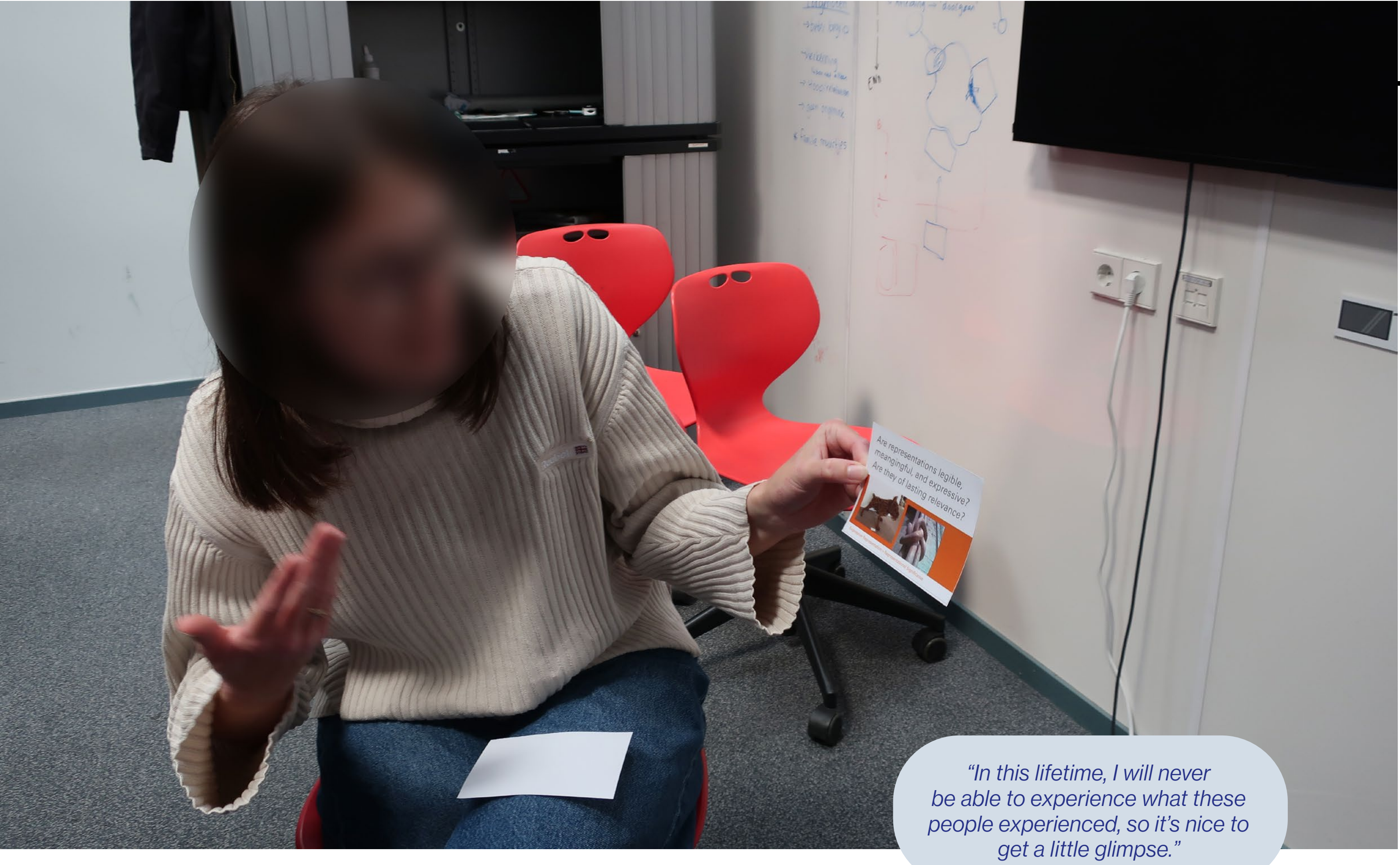


Figure 64. Participant roleplaying the XR experience.



"In this lifetime, I will never be able to experience what these people experienced, so it's nice to get a little glimpse."

Figure 65. Participant using the Tangible Interaction Cards.

Participants mentioned that while audio could help set the atmosphere, it shouldn't carry important information or instructions. Background audio was seen as a nice way to create a certain mood or sense of time, but too much audio-based interaction would pull focus away from the physical and visual experience.

In terms of which elements should be real vs. virtual, there was agreement that the desk, the chair, and a part of the wall should exist physically in the space. These tactile, physical elements help ground the experience and give users a reliable frame of reference in both the real and virtual layers. At the same time, the experience doesn't need to be hyper-realistic – the participants felt it was more important that it's fun and engaging than historically and technically perfect. A stylized or playful visual style could even help highlight the interactive elements more clearly.

The participants also discussed pacing and structure. They want to be able to explore at their own pace, but adding some sort of gamification could make the experience even more engaging. One suggestion was to build a scavenger hunt-style interaction, where users search the XR environment for clues or pieces of a story. This could help guide them through the narrative while keeping the experience exploratory and interactive.

Lastly, one participant said something particularly interesting: "In this lifetime, I will never be able to experience what these people experienced, so it's nice to get a little glimpse." This highlighted the emotional value of the experience – users aren't just learning; they're getting a chance to momentarily connect with a different time.

3.3.4 Interacting with props

The goal of this immersive heritage experience wasn't to design a finished product ready for museum implementation, but rather to explore the design process itself and the opportunities that emerge from combining MR and TUIs in cultural heritage settings. With this in mind, I used the prototype not only to create an engaging immersive experience, but also as a way to experiment with different types of tangible interactions that let users explore digital environments through physical objects. I was particularly interested in how combining TUIs and MR affects the user's experience of both the artifacts and the stories surrounding them.

The visual and functional replicas already introduced two distinct types of interaction. The visual replicas allowed users to physically hold and feel props that matched the size and shape of the original artifacts, while seeing their authentic appearance in XR (Figure 66-A). The functional replicas, on the other hand, invited users to interact with props in ways that mimicked the original mechanisms of the artifacts (Figure 66-B).

To push this exploration further, I also used the reconfigurable props determined during the bodystorming exercise. These props were especially valuable for testing how different levels of abstraction in physical form and interaction could affect user experience. The final set of reconfigurable props was designed to represent four distinct types, arranged from most abstract to most realistic:

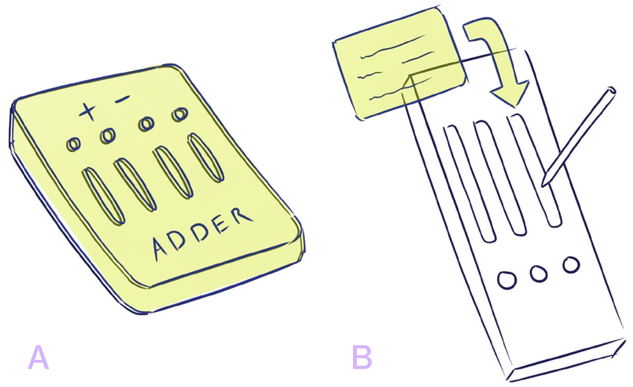


Figure 66. Physical and digital elements of replicas: A) Visual replica and B) Functional replica.

- **Marker only:** A simple marker that triggers a 3D object in XR. Users can move and rotate the digital object but cannot physically interact with it (Figure 67-A).
- **Abstract shape:** A generic physical shape that mirrors the basic geometry of the XR object. Users can hold the prop, but it lacks the exact shape and surface detail (Figure 67-B).
- **Realistic shape:** A prop that closely matches the physical shape and size of the XR object, allowing users to feel its details (Figure 67-C).
- **Realistic shape + interaction:** A detailed physical replica that not only resembles the XR object in form but also supports basic interactions similar to those of the original artifact (Figure 67-D).

These varying levels allowed me to explore how different forms of physicality and interactivity could shape the way users engage with digital content and what that means for designing future experiences around cultural heritage artifacts.

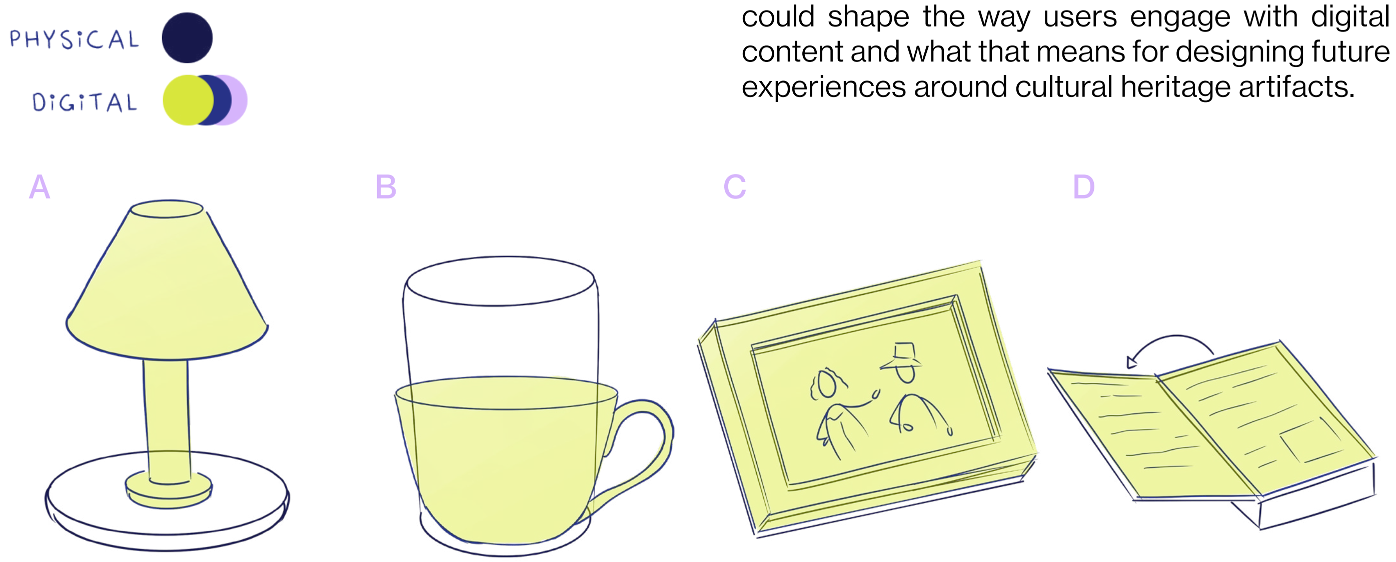


Figure 67. Physical and digital elements of reconfigurable props: A) Marker only, B) Abstract shape, C) Realistic shape, D) Realistic shape + interaction.

3.3.5 Discussion

This section described how the insights from the earlier exploration phases were synthesized into a single concept. While the final concept aligned well with the established design criteria, the decision to develop it was also strongly influenced by practical constraints such as time, project scope, and technical skills. Although other concepts, like Changing Perspectives, may have offered even more meaningful experiences, they simply weren't feasible within the boundaries of this project.

The bodystorming session proved to be a useful activity for generating ideas around the spatial setup and tangible elements of the XR environment. It helped surface design opportunities that might not have emerged through individual ideation alone. However, in retrospect, it could have been even more insightful if conducted at a later stage – once the XR environment was more fully developed. That way, the focus could have shifted from conceptual exploration to understanding how users actually move through and experience the environment, allowing for more targeted iteration on interaction and flow.

3.4 Development

In this section I will discuss the development of the Calculator's Desk. I will explore the most important aspects of the prototyping process and the final prototype that was created.

3.4.1 Prototyping

Once I had a clear idea of which elements the immersive experience needed to include, it was time to start building the prototype. This section discusses the highlights of the prototyping process.

MQTT communication

The first step involved establishing the MQTT connection to enable tangible interactions with the digital environment. In the final prototype, users could influence the digital content by picking up a calculator from the artifact box (Figure 68). Sensors attached to an ItsyBitsy microcontroller (two light sensors and one time-of-flight sensor) detected whether a calculator was present. These states were translated into MQTT messages, which were read by Unreal Engine and used to trigger corresponding digital responses.

Figure 68. A test participant picking up a calculator from the artifact box.

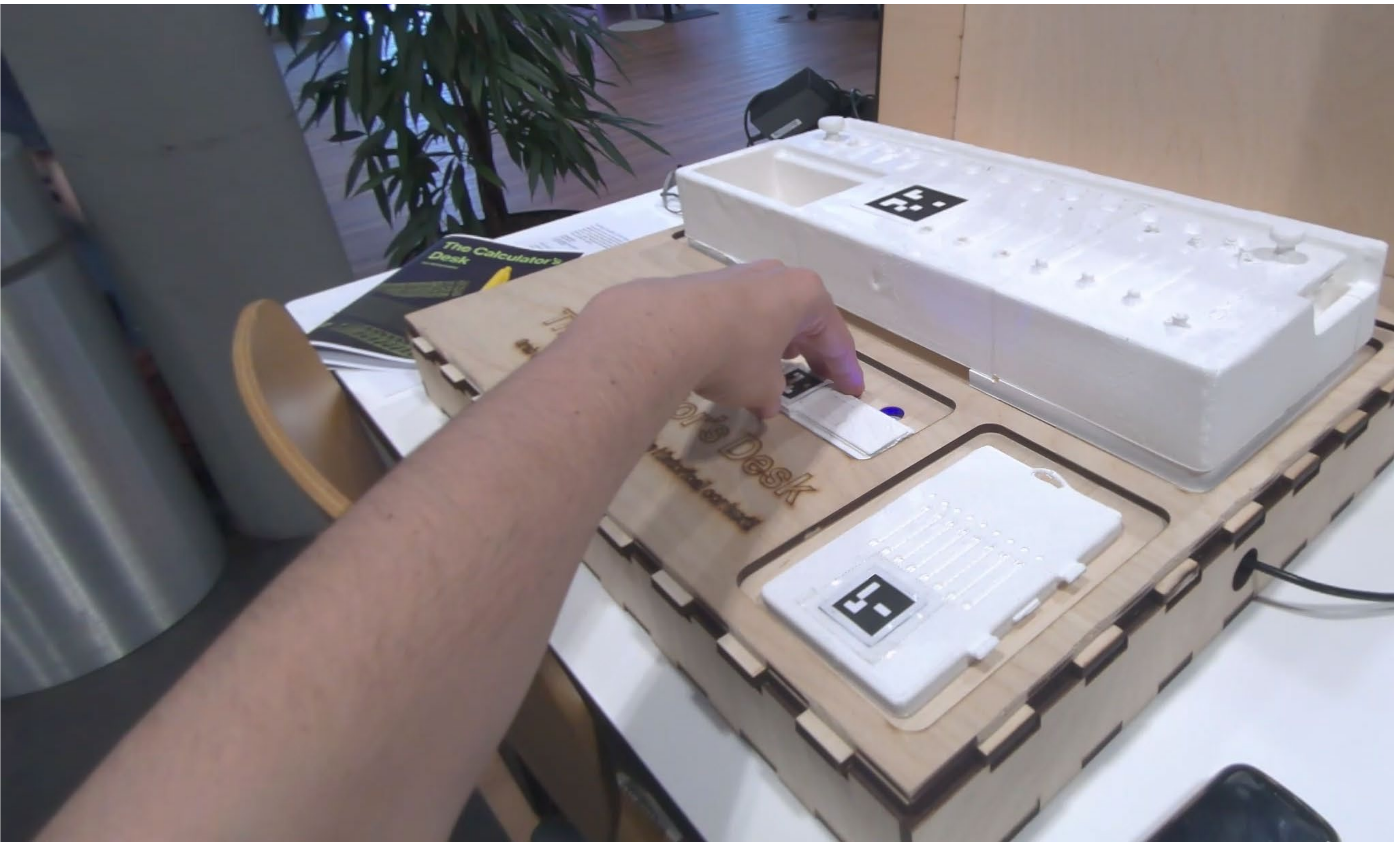


Figure 69. An error message is shown when two artifacts are taken at the same time.

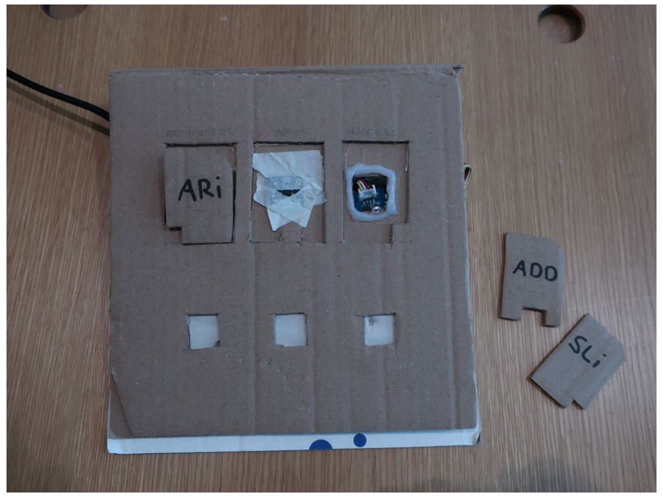


Figure 70. Cardboard prototype of the artifact box that was used during prototyping.

A LED would turn on once a calculator was picked up, to show the user that their action was registered correctly. To address potential misuse, such as removing multiple artifacts simultaneously, the system also checked whether more than one sensor was active. If so, an error message would be sent and displayed across all markers, overriding any spawned objects (Figure 69).

The logic of the code worked the same as was shown in the flowchart in Figure 50. While the final artifact box was 3D printed, most testing was done with a cardboard prototype that used the same code structure (Figure 70).

Reconfigurable props

The next stage involved designing reconfigurable props that connected physical interaction with digital content. The insights from the bodystorming session were combined with the envisioned interactions and objects were selected to reflect the historical context of each calculator. Digital 3D models were sourced from Sketchfab or created using UV maps generated with Sora AI – based on the three personas – and refined in Photoshop. These models were then imported into Unreal Engine.

Figure 71. Different content spawned on a single prop, depending on MQTT input.

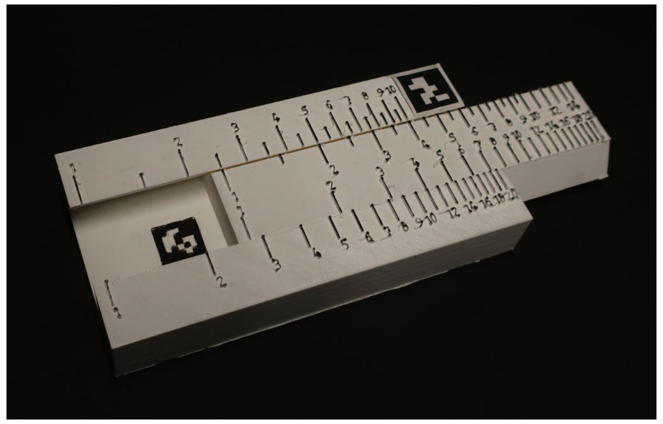


Figure 72. The functional slide rule with a 3D printed marker (left) and a paper marker (right).

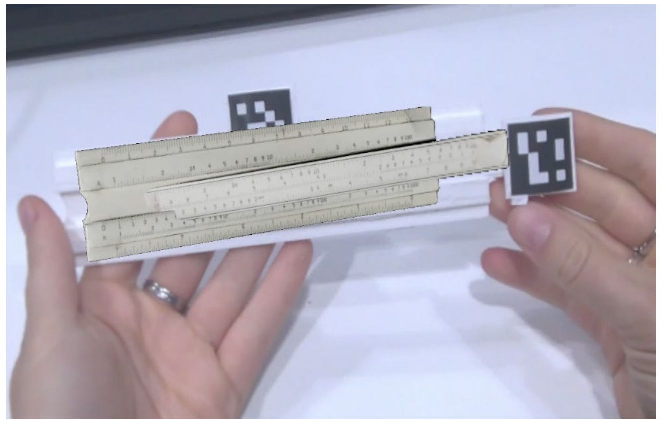


Figure 73. Experimenting with adding functionality to visual replicas.

To spawn the correct digital model on each Varjo marker, several Unreal Engine elements were developed:

- **BP_MQTT_Connector:** A blueprint that connects Unreal Engine to the MQTT broker and reads incoming messages from the artifact box. It forwards these messages to BP_Spawned.
- **BP_Marker_Controls:** A blueprint that detects Varjo markers and their IDs and spawns BP_Spawned when a marker is recognized.
- **ST_Objects:** A struct that links each marker ID to specific 3D models, based on which calculator is currently active.
- **BP_Spawned:** A blueprint that controls what digital object is placed on the marker, using both the marker ID and MQTT input to show the correct 3D model and behavior.

Figure 71 shows one of these reconfigurable props: a picture frame that shows a different portrait, depending on which calculator is recognized.

Varjo markers

Marker performance was critical to a stable XR experience. During the initial exploration, small 3D printed markers were used, but in this larger application they caused noticeable flickering and loss of tracking due to reflective surfaces and 3D printing inaccuracies. Medium-sized markers proved more reliable but were too large for some props. To improve tracking while maintaining scale, paper-printed markers were applied on top of the 3D prints (Figure 72). This slightly affected the visual cohesion but significantly improved user experience.

Combining visual and functional replicas

An attempt was made to create a replica of the slide rule that was both visually accurate and functional. The model was split into two movable parts, each with its own marker. While this allowed the user to slide the parts, inconsistent tracking caused visual glitches, with the two models misaligning in Unreal Engine (Figure 73). As a result, the prototype did not succeed as both a visual and functional replica and was excluded from the final design. Instead, an immovable visual replica was used, similar to the other visual replicas.

3.4.2 Final prototype

Figure 74 shows the final prototype of The Calculator's Desk that was tested with users. This section outlines the key elements that made up the final setup.

Visual replicas

Three visual replicas – one for each calculator (arithmometer, adder, and slide rule) – were created to match the shape and size of the original artifacts (Figure 75). These replicas acted as physical controllers for the MR experience. When a user picked up one of these artifacts from the artifact box, the digital environment responded by updating all visible props to match the corresponding historical context.

The arithmometer was too large for the 3D printer and had to be printed in multiple parts, with some sections removed. In MR, digital overlays of the calculators were displayed on top of these physical objects (Figure 76). The adder and slide rule were modeled using 3D scans, while the arithmometer model was sourced from Sketchfab.

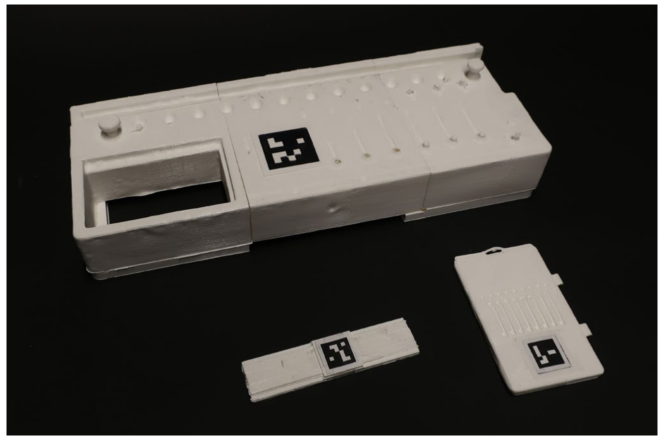


Figure 75. The visual replicas.

Figure 76. Digital overlay of the visual arithmometer replica.

Figure 74. A participant using the Calculator's Desk.

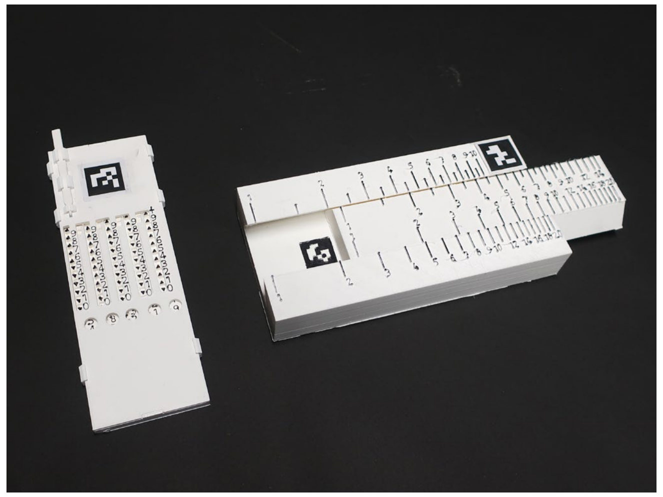


Figure 77. The functional replicas.

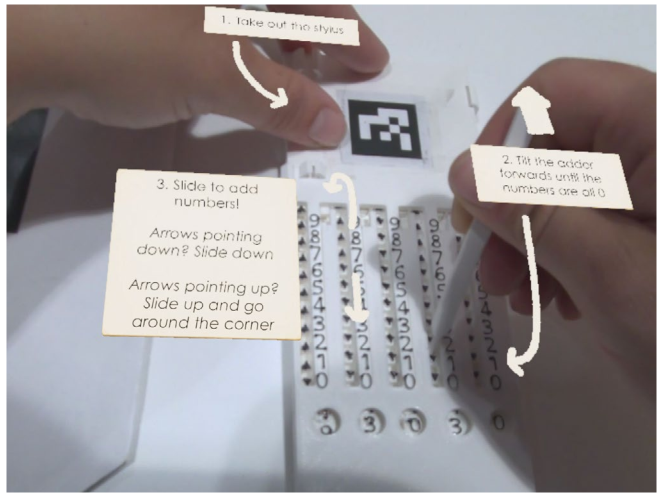


Figure 78. Instructions overlayed on the functional adder.

Functional replicas

Two functional replicas – the adder and slide rule – were created to allow users to perform basic calculations (Figure 77). When detected, these replicas triggered instructional overlays in XR to guide the user through their operation (Figure 78).

Reconfigurable props

The experience included a range of reconfigurable props, each offering a different level of abstraction:

- **Marker only:** A flat disc with a marker, projecting a lamp in XR (Figure 79).
- **Abstract shape:** A cylinder with markers on each side, which allowed the user to view the object from both sides, used to display a cup (Figure 80).
- **Realistic shape:** Picture frames and sheet of paper that mirrored their digital counterparts in shape and size (Figure 81).
- **Realistic + interactive:** A physical book that users could open, with markers on the cover and first page, triggering the corresponding digital visuals (Figure 82).

Setup & interaction

Figure 74 shows the setup of the experience. Users could freely move props on the table. When a calculator was removed from the artifact box, sensors detected the action and updated the XR environment accordingly.

Due to the large number of markers, the headset occasionally failed to recognize all at once. Fortunately, a temporary fix was found by briefly re-triggering the sensor, which most test participants didn't find disruptive to their experience – in fact, one participant said it added an extra layer of exploration.

Information & text

Information in the experience was presented through floating text labels attached to digital props. Each object explored a specific theme across all three calculator variants – for instance, the picture frames consistently provided context about the user of each calculator.

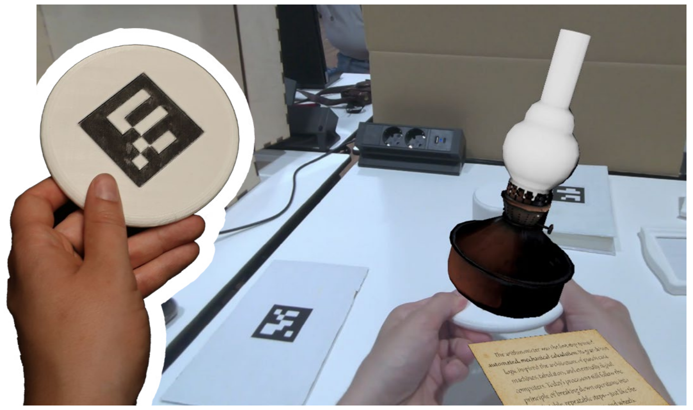


Figure 79. Marker only prop: A flat disc projecting a lamp in XR.

Figure 80. Abstract prop: A cylinder projecting a cup in XR.

Figure 81. Realistic prop: Picture frames and a piece of paper.

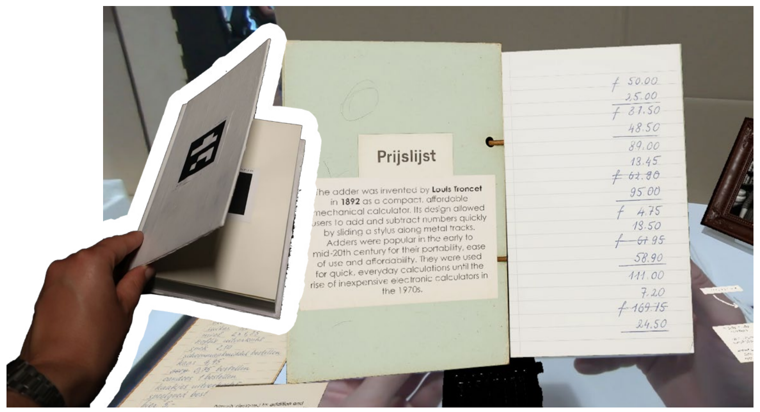


Figure 82. Realistic and interactive prop: A book that can be opened and viewed from the inside.

3.4.3 Discussion

The prototype remained clearly at a prototype level and, in its current form, is not yet ready for testing in a real museum setting. The XR experience is still too unstable: digital elements flicker due to imperfect marker tracking, and the overall interaction lacks the smoothness and polish expected in public-facing installations. Visually and technically, the setup would require further refinement to meet museum standards. However, creating a museum-ready product was never the goal. The main objective was to go through the design process of developing an immersive heritage experience, and in that regard, the prototype served its purpose.

If the concept were to be implemented in an actual museum, several additional questions would need to be addressed. One key concern is how the system holds up with frequent, unsupervised use. The prototype currently relies on manual intervention when issues arise. In museums, the setup would need to be far more robust and resistant to incorrect usage. Clearer feedback systems, durable hardware, and more stable software would be essential.

Another question is how the experience would be integrated within the broader visitor journey. The current setup assumes the presence of a guide to explain and troubleshoot, but in a real exhibition context, the interaction would need to be intuitive enough to stand on its own or come with a support system. It's also not yet defined whether the experience is meant to be fully self-guided or facilitated.

Finally, what could also be explored is how the experience would connect to the surrounding exhibition and its narrative. These are important considerations for future development if the concept is to be taken beyond the prototyping stage.

3.5 Evaluation

Once the prototype of the Calculator's Desk was completed, I conducted user testing to evaluate it both as an immersive heritage experience and as input for developing the MR+TUI Heritage Toolkit. The evaluation focused on the following research questions:

1. *How do users with limited XR experience engage with digital MR environments through tangible interactions?*
2. *How do different levels of abstraction or realism in props affect user experience in MR settings?*
3. *In what contexts would users engage with XR heritage experiences in museums?*
4. *How would designers with little or no prior XR experience approach designing such experiences, and what kind of support would they need?*

3.5.1 Method

The evaluation involved 10 participants, all Master's students in Industrial Design Engineering—representative of the toolkit's target audience. The session was structured into four parts:

1. **Introduction:** The setup and activities were explained to the participants. The participants also shared their background and previous experience with XR, both as users and designers.
2. **Using the prototype:** Participants freely explored the Calculator's Desk prototype and were encouraged to think aloud, sharing their thoughts and impressions during the interaction (Figure 83).
3. **Reflecting on the prototype:** Participants reflected on their experience. What did they enjoy? What felt confusing or frustrating? What changes would they suggest? They were also asked what would motivate or prevent them from engaging with this kind of installation in a museum setting.
4. **Designing with XR:** Shifting focus from the prototype, participants were asked to imagine designing an XR-based museum experience themselves. They described how they would approach the process, what challenges they anticipated, and where they'd need support. This activity was placed last to make sure that participants had some familiarity with XR before reflecting on its design process.

Participants filled in a workbook during activities 1, 3, and 4 (Figure 84), which, along with transcripts of recorded sessions, was analyzed to answer the research questions.

3.5.2 Analysis & results

The user tests were analyzed by coding both the transcripts of the recordings and the completed workbooks from the participants. This section presents the key findings from that analysis. It begins with a general evaluation of the Calculator's Desk as an immersive heritage experience, followed by a discussion of the four research questions.

General evaluation of the Calculator's Desk

The user testing provided valuable insights into how participants experienced the Calculator's Desk as an immersive heritage installation. The feedback addressed both the strengths and areas for improvement in the design, as well as its potential educational and experiential value.

Overall impressions

When asked to describe their experience with the Calculator's Desk the word educational was used the most often, followed by explorative, immersive, and interesting. The emotions amazed and curious were most often used to describe what participants enjoyed most, while astonished, playful, and surprised were associated with the more unique elements. These terms reflect the prototype's ability to convey historical content in an engaging way. The full list of associations mentioned can be found in appendix E.

Despite the positive feedback, several technical limitations affected the experience. The most frequently mentioned negative emotions were dizzy, nauseated, and out of control. These were typically linked to issues such as unstable tracking and poor alignment between physical and digital elements. Flickering visuals and misaligned props broke immersion and caused discomfort for some users.

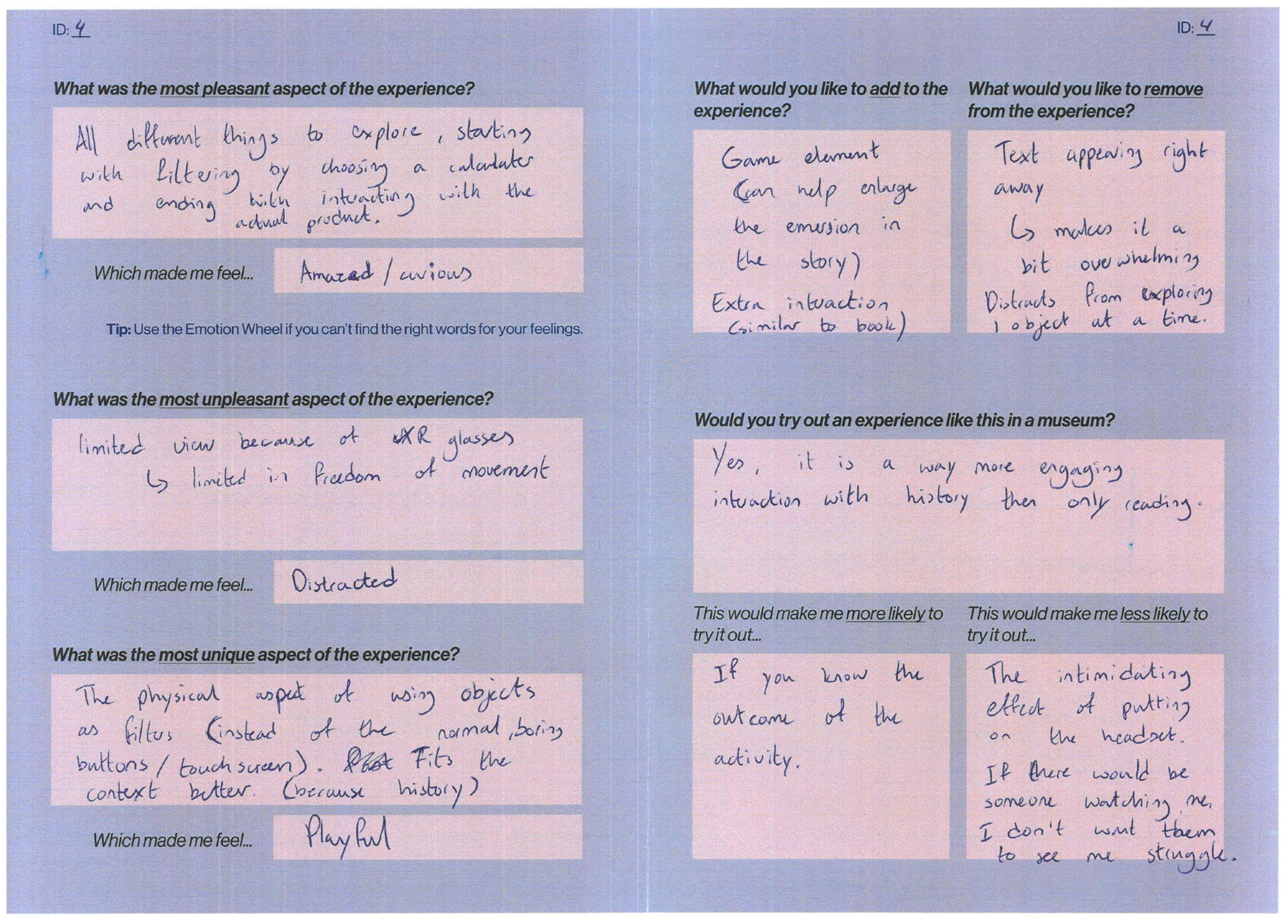
Historical context through immersion

A recurring theme in the feedback was the immersive quality of the scenery. Participants frequently mentioned that the changing environments helped them better understand the context in which the calculators were originally used. Rather than simply reading about history, they felt transported into it. This immersion helped participants visualize the daily lives of historical calculator users, making the subject matter more relatable and engaging.

"It really felt like you were sitting at their desk... It was very fun to imagine how Thomas was sitting at his table using his little calculator."

Figure 83. A participant interacting with the visual replica of the arithmometer.

Figure 84. A filled in workbook.



ID: 4

What was the most pleasant aspect of the experience?

All different things to explore, starting with filtering by choosing a calculater and ending with interacting with the actual product.

Which made me feel... Amazed / curious

Tip: Use the Emotion Wheel if you can't find the right words for your feelings.

What was the most unpleasant aspect of the experience?

limited view because of XR glasses
↳ limited in freedom of movement

Which made me feel... Distracted

What was the most unique aspect of the experience?

The physical aspect of using objects as filtus (instead of the normal, boring buttons / touch screen). ~~Bet~~ Fits the context better. (because history)

Which made me feel... Playful

ID: 4

What would you like to add to the experience?

Game element (can help enlarge the emersion in the story)
Extra intuaction (similar to book)

What would you like to remove from the experience?

Text appearing right away
↳ makes it a bit overwhelming
Distracts from exploring 1 object at a time.

Would you try out an experience like this in a museum?

Yes, it is a way more engaging intuaction with history then only reading.

This would make me more likely to try it out...

If you know the outcome of the activity.

This would make me less likely to try it out...

The intimidating effect of putting on the headset.
If there would be someone watching me, I don't want them to see me struggle.

Educational value

Many participants highlighted the educational potential of the experience. They appreciated learning about the artifacts while interacting with them, often expressing surprise at how much they had learned during the short session. The experience effectively combined historical storytelling with interactivity to support deeper understanding.

Suggestions for improvement

There are several recommendations that participants made for further development:

- **Improve stability:** The most common recommendation was to reduce bugs and visual instability in the XR setup to avoid nausea and improve immersion.
- **Guide users through the experience:** Many participants requested clearer guidance throughout the experience – either through video or audio introductions, challenges, or gamification – to help them navigate the content and maintain engagement.
- **Offer alternatives to text:** While some participants appreciated the amount of text, others preferred alternative formats like audio or video. Still, some mentioned that the immersive context made them more willing to engage with reading than they usually would in a museum.
- **Better alignment between objects and information:** Participants noted some inconsistencies between physical props and their accompanying information. While decorative elements (like lamps or mugs) helped set the mood, mismatches between the object and the historical content were sometimes confusing.

"But in a museum, if there isn't a challenge or something next to it, then I might think, 'Okay, I don't really get it, I'll just put it back'."

"I really like the installation because it's interactive. It makes you want to read and explore more than you usually want to."

Interacting with tangible Mixed Reality

This section addresses Research Question 1: *How do users with limited XR experience engage with digital MR environments through tangible interactions?*

All ten participants had limited experience with XR. Nine had interacted with XR once or twice as users, and one had no prior experience at all. As designers, none had worked extensively with XR. Six had designed – but not developed – XR concepts or tested other designers' prototypes, but this remained at a very basic level. This made the group representative of the intended audience for the toolkit: designers exploring XR and tangible interactions from a beginner-level.

Engagement through tangible interaction

Participants responded positively to the tangible aspect of the MR setup. Several identified it as the most pleasant and unique part of the experience. The opportunity to touch and manipulate objects – something typically prohibited in museums – stood out as a key feature. One participant also mentioned that using the objects as controllers for the virtual environment – instead of more traditional controllers or buttons – fit the context better, since the users depicted in the experience also wouldn't have had any screens or digital buttons.

Curiosity as a driver of exploration

Similar to the findings from the experiential characterization, curiosity can trigger users to explore. Before even starting the experience, many participants were intrigued by the physical props laid out on the table and expressed excitement about interacting with them. Uncovering hidden or unexpected information – such as new content revealed by opening a book – further encouraged exploration.

Preference for familiar interactions

Despite being encouraged to explore freely, many participants were hesitant to touch unfamiliar props. Objects with ambiguous forms – such as the marker discs – made them unsure if interaction was allowed. In contrast, familiar items like books were approached more confidently and naturally.

Participants enjoyed interactions that mimicked real-world behavior the most, such as opening the book. These actions felt intuitive and reinforced immersion. Familiarity made interactions feel more natural, which is important when working with users with limited XR experience.

Shifts in interaction behavior in XR

Interestingly, while participants understood how to interact with the objects, they often adapted their behavior in unexpected ways due to the XR environment. For instance, when labels appeared tilted, participants turned their heads awkwardly rather than simply rotating the object in their hands. This suggests that in XR, even simple real-world actions may require additional cues or support to feel intuitive.

The role of scale and detail

Larger, more detailed props – such as the arithmometer – were particularly engaging. Participants were surprised and delighted to discover that they could pick it up and interact with it, often spending extra time exploring it, both by touching and feeling the texture of the 3D print and by exploring the highly detailed digital model that was attached to it (Figure 85).

Enjoying digital exploration

While physical interaction was generally preferred, some participants also enjoyed exploring the digital models, especially those associated with the marker discs (Figure 86). These props were light, easy to manipulate, and offered stable digital overlays, which improved usability.

"I feel the urge to touch everything. I think it's because of the size of the holes and buttons. It just stands out and catches your eye."

Figure 85. A participant interacting with the visual replica of the arithmometer.

"The book is different because you can really open it. You can pick it up, which is already fun. But you can also do something with it – it has an extra function. That makes it more real. It's a real book with things inside."

"It would be cool if I could see my hand on top of it. Then I can really interact with it. It gives you more to experience."

Lack of hand tracking affects immersion

One commonly mentioned limitation was the invisibility of users' hands while touching props. This was particularly noticeable when interacting with larger props, where tactile feedback plays an important role. Participants expressed a desire for hand-tracking to improve realism and their sense of control.

Embodied interaction supports understanding

Physically interacting with functional replicas helped users understand how the historical calculators worked. The hands-on experience translated into a better understanding of their mechanical logic and historical use.

"I think [the marker disc] is maybe even the most fun... You can twist it all the way. It's very light to pick up."

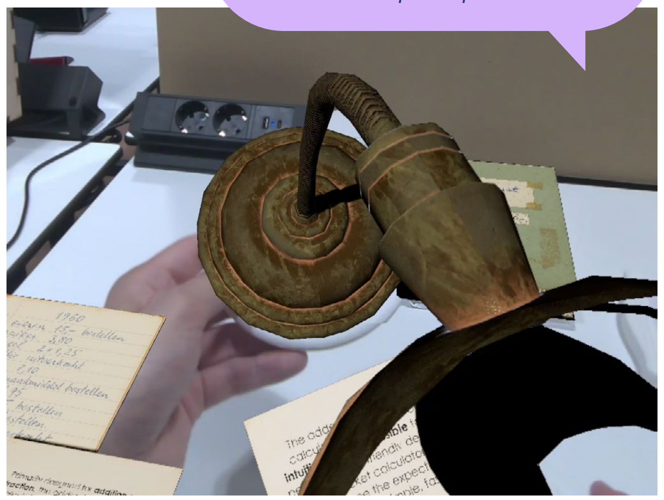


Figure 86. A participant inspecting the digital model attached to the marker disc.

XR bugs hinder engagement

Lastly, technical instability—such as latency, flickering, or misalignment—was a major issue for participants with little XR experience. These bugs sometimes became the focus of their experience, drawing attention away from the content and the interaction design. Since mixed reality blends digital and physical elements, instability is especially distracting when digital overlays don't align properly with the real world.

> *"It's kind of overwhelming. I'm not really a digital person."*

Levels of abstraction

This section addresses Research Question 2: *How do different levels of abstraction or realism in props affect user experience in MR settings?*

Matching physical and digital shapes

Participants interacted with a range of physical props—some designed to closely resemble their historical counterparts, others abstracted into simplified geometric forms. While individual preferences varied, one theme emerged clearly: digital and physical representations should either match very closely or be intentionally abstract. Partial realism created confusion and broke immersion.

For example, props like the cup had a physical base that resembled a cup in shape, but lacked familiar details like the handle. This mismatch led participants to expect interactions (e.g. grabbing the handle) that weren't possible.

By contrast, fully abstract props, like the marker discs, worked well when the digital overlay made their function clear. And highly realistic replicas, like the picture frames, were appreciated for how closely their physical shape and interaction matched the virtual counterpart.

Functionality enhances enjoyment and interpretation

Participants were enthusiastic about props that allowed for functioning interactions, such as the functional replicas (Figure 87) or the book. However, when artifacts appeared realistic but were non-functional, some participants expressed disappointment.

> *"So either you want it to match super well to the real thing—like the picture frame—or don't try at all—like the marker disc. Anything in the middle is kind of weird."*

> *"Very cool how the shininess is created—you can really see what's wood and what's painted."*

Figure 87. A participant interacting with the functional adder.

Realistic replicas trigger imagination

More realistic replicas—either in terms physical form or functionality—evoked stronger engagement with the historical context of the artifacts. These props prompted participants to ask more questions about the original users, materials, and functionalities.

Consistency in abstraction

The prototype intentionally presented props at different abstraction levels, but this inconsistency led to uncertainty. Participants had to relearn how to interact with each object individually, and the rules of interaction varied unpredictably between props.

Participants often made assumptions about the functionality or affordances of props based on previous interactions, and inconsistent abstraction levels disrupted these expectations, making the interaction feel less coherent.

Tangible Mixed Reality in museums

This section addresses Research Question 3: *In what contexts would users engage with XR heritage experiences in museums?*

All participants indicated they would try out a similar XR experience in a museum setting. For many, this was driven by an inherent curiosity and attraction to interactive exhibits. Participants expressed interest in XR because it provides a more unique, immersive, and engaging experience than traditional museum displays.

The role of the unknown

For some, it wasn't just the idea of interactivity, but the mystery of what the XR headset would reveal that sparked their interest. They felt that not knowing exactly what would happen inside the headset added to the excitement and motivated them to try it out. The physical props on display also functioned as attention-grabbers, prompting participants to want to explore what lies beneath the surface once the headset is put on.

However, some participants expressed the opposite. They described the intimidating nature of XR, particularly in public settings, and said they would prefer to know in advance what to expect.

This duality reveals the importance of designing for different types of museum visitors. Some are driven by curiosity and a sense of discovery, while others need reassurance and predictability.

> *"I would be curious to find out what can be seen with the glasses on."*

> *"[I'd be more likely to try it] if it was clear what I will see and learn."*

Successful XR setups may need to provide a balance between sparking intrigue and giving visitors enough context to feel comfortable participating.

Privacy

Many participants felt self-conscious about using XR in public, especially if they felt exposed or worried about being watched while using the headset. A semi-private, quieter area, perhaps near a wall or enclosed space, would be more inviting.

Easy to try out

A low barrier to entry was emphasized. Users were more likely to try XR if it was clearly presented, easy to approach, and possible to try out without needing assistance or prior instruction. A short waiting time is also part of this low barrier, as many participants said they would not wait in line, especially if others were already using the experience.

> *"[I'd be less likely to try it] If there would be someone watching me, I don't want them to see me struggle."*

> *"[I'd be more likely to try it] if it is presented as something simple and you can try it out by yourself."*

> *"If there is someone using it, I will not wait for it."*

Designing with Extended Reality

This section addresses Research Question 4: *How would designers with little or no prior XR experience approach designing such experiences, and what kind of support would they need?*

Participants were asked to describe how they would approach designing a tangible mixed reality experience for heritage settings. Their described processes closely resembled the design methodology commonly taught at the faculty. However, there were several elements that were emphasized more explicitly due to the unique challenges of working with XR and heritage content.

The individual approaches were synthesized into one average approach (Figure 88). This synthesized approach shows a design process with a greater emphasis on heritage research, technical exploration, and meaningful interaction design compared to more traditional design projects.

Researching XR and heritage content

Participants emphasized the need to research both the technical aspects of XR and the cultural context of the heritage content. Understanding what XR technologies could do and how to do this was seen as a necessary foundation for the rest of the process. At the same time, participants acknowledged that they weren't heritage experts themselves and would require support in this area.

Support needed:

- Guidance from heritage experts to select relevant artifacts and historical narratives.
- Introduction to the possibilities and constraints of XR to support experimentation.

Experimentation

Participants thought that experimentation was an important part of this design process. With limited prior XR experience, they relied on tinkering, prototyping, and testing to learn what was possible and discover creative directions.

Support needed:

- Access to tools and materials for fast, low-fidelity XR prototyping.
- Time to explore XR without pressure to perform or deliver results immediately.

Creating meaningful interactions

A recurring theme across participants was the desire to avoid creating XR experiences that felt superficial or gimmicky. They wanted their designs to be intentional, purpose-driven, and capable of offering users something that only XR could provide.

Support needed:

- Help during ideation to identify the unique affordances of XR.
- Case studies or inspirational examples showing meaningful uses of the technology.

Connecting the physical and digital

Some participants considered designing digital content as one challenge, and designing physical components as another – but merging the two effectively was considered especially complex.

Support needed:

- Support in prototyping methods that include both tangible and digital elements.
- Case studies or inspirational examples showing seamless physical-digital experiences in XR.

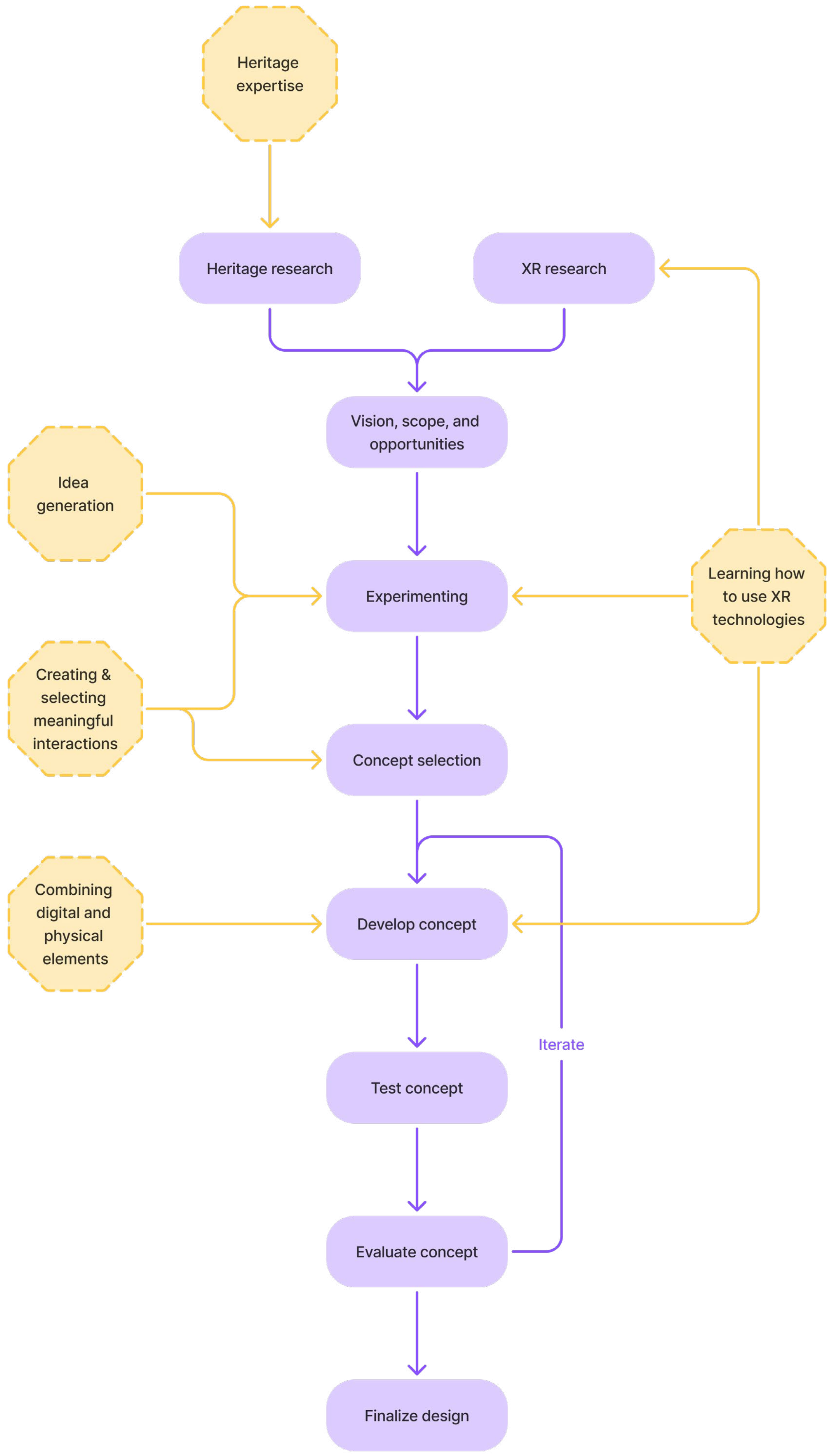


Figure 88. Synthesized design approach, based on input from participants. Yellow blocks indicate moments where participants would like extra support.

3.5.3 Criteria

To assess the effectiveness of the final prototype, the Calculator's Desk was evaluated against the design criteria established earlier in the project. A complete overview of this evaluation is included in Appendix F.

Overall, the prototype successfully met all crucial and important criteria for an immersive heritage experience. However, a few criteria were only partially fulfilled:

- **Tactile responsiveness:** The tangible components provided a degree of physical feedback and were engaging to manipulate. However, not all props' feedback mimic that of their original counterparts. More types of physical feedback could be included
- **Balancing unfamiliarity and usability:** The interactions included elements of surprise and discovery, which helped stimulate user interest. However, ease of use varied between participants – some found the interface intuitive, while others needed additional guidance.
- **Sensory feedback:** Visual cues were effectively used to support user interaction and engagement. However, audio feedback was not yet implemented.

The only criteria that were not met were the enhancing criteria, which included the integration of gamified elements and social functionality. These aspects were identified by users as valuable additions during the user tests, confirming their relevance. Although not included in this prototype, they could be addressed in future iterations to broaden the experience's appeal and interactivity.

3.5.4 Discussion

While the user tests provided valuable insights, it's important to acknowledge some limitations. The experience was only tested with design students, as one of the aims was to explore how designers approach the XR design process in a heritage context. However, this narrow user group likely influenced the evaluation of the prototype itself. Designers are typically more familiar with prototype testing and may be more forgiving of technical bugs or imperfections. They also tend to have greater affinity with new technologies than the average museum visitor. Testing the experience with a broader audience could have revealed different usability issues, emotional responses, or barriers to engagement.

Another point of consideration is the timing of certain questions. The reflections on the design process were gathered after participants had interacted with the Calculator's Desk. Their hands-on experience may have influenced how they imagined or described the design process, possibly skewing their answers toward what they had just encountered.

Finally, it's worth noting that all participants shared a common educational background in industrial design. This shaped their proposed approach to the MR+TUI design. A designer with a different background might approach this design process very differently, highlighting other aspects or challenges.

3.5.5 Conclusion

The user testing of the Calculator's Desk offered valuable insights into the potential and challenges of designing immersive, tangible mixed reality experiences for heritage contexts. Participants described the experience as educational, immersive, and explorative, highlighting its effectiveness in conveying historical content through hands-on interaction. The combination of physical props and digital overlays successfully sparked curiosity, supported understanding, and made the past feel more tangible and relatable. However, several technical issues – such as visual instability, lack of hand tracking, and misalignment between digital and physical elements – interfered with immersion for some users.

The results confirmed that even users with little prior XR experience could engage meaningfully with the experience, especially when guided by curiosity and supported by intuitive, tactile interactions. This prototype shows how tangible Mixed Reality can make historical narratives more accessible, engaging, and memorable.

4. Final Design: Supporting the Mixed Reality Design Process

After designing the immersive heritage experience, the insights gained throughout that process laid the groundwork for the development of the conceptual MR+TUI Heritage Toolkit. This chapter introduces the toolkit and walks through how it came together. I'll start by outlining the scope and design criteria, followed by my vision for the toolkit and the different components it includes. Then, I'll go into how each part was designed. Finally, I will present the final design and reflect on how the overall concept measures up against the criteria I set.

4.1 Scope & criteria

The toolkit developed in this thesis is intended as a proof of concept rather than a finished, market-ready product. Its purpose is to demonstrate how a toolkit can support the MR+TUI design process for designers with limited technical expertise. This early concept serves as a foundation for future iterations and further development.

To keep the project manageable and focused, the initial target group for this toolkit consists of users with some technical familiarity—such as industrial design students—but limited experience with MR or programming. This group is well-positioned to test early ideas while still representing the broader audience of creative professionals. In future research, the toolkit could be expanded and adapted to support users with no technical background at all, by simplifying the tools and including additional guidance on basic coding and interaction design.

The contextual analysis and the case study helped shape the direction of the toolkit and was translated into a set of design criteria. The contextual analysis and the case study helped shape the direction of the toolkit and was translated into a set of design criteria. These criteria guided the development process and are shown on the next page.

Supported coding

The toolkit must support designers with limited coding expertise in coding in Unreal Engine and CircuitPython by offering templates and instructions.

XR and TUI integration

The toolkit must provide modules that allow designers to connect CircuitPython interactions to responses in Unreal Engine with minimal configuration.

Built-in learning resources

The toolkit must include instructional guides, templates, and examples to support onboarding and inspire use.

Optimized for available technical setups

Experiences must run on hardware currently available for students at the TU Delft.

Narrative construction

The toolkit should support users in selecting relevant heritage artifacts and narratives.

Lofi prototyping tools

The toolkit should include quick, low-tech prototyping methods that allow users to experiment in early design phases.

Inspiration from examples

The toolkit should provide examples and case studies of succesful tangible Mixed Reality experiences to inspire throughout the design process.

Modular, reusable components

Designers could be able to construct experiences using pre-built components (digital and physical) that can be reused and adapted for different artifact scenarios.

Crucial

Important

Enhanching

4.2 Toolkit vision

Before developing the components of the toolkit, I took a step back to reflect on the design process and the findings from the user testing in the case study. These insights helped shape my vision for the toolkit and its key elements, which are outlined in the following section.

4.2.1 Design process

I started by imagining how a designer might actually use the toolkit – what they'd need, where they might get stuck, and how the toolkit could help along the way. To do this, I looked at the design process that came out of the user testing and focused on the parts where participants said they needed support. I also thought back to my own experience during the case study – specifically the moments where I felt stuck or lacked structure.

Using both the participants' process and my own as a starting point, I adapted the design process that resulted from the user tests (Figure 88) to better reflect what that journey looked like in practice. The result is a version of the process that combines insights from my target group with my own experience, thus reflecting both the needs from users at the start of a project and the experience of a designer who went through this. Figure 89 shows the updated design process and where the toolkit will provide support.

In this vision, the toolkit helps the designer from the very beginning – exploring their topic, learning what XR can do, and getting hands-on with quick experiments. It offers a mix of activities, templates, and prototyping tools to support both creative thinking and technical development. The goal isn't to tell the designer exactly what to do, but to provide just enough structure to help them move forward confidently. As the project evolves, the toolkit stays flexible, adapting to the designer's needs as they move from early ideas to a working prototype.

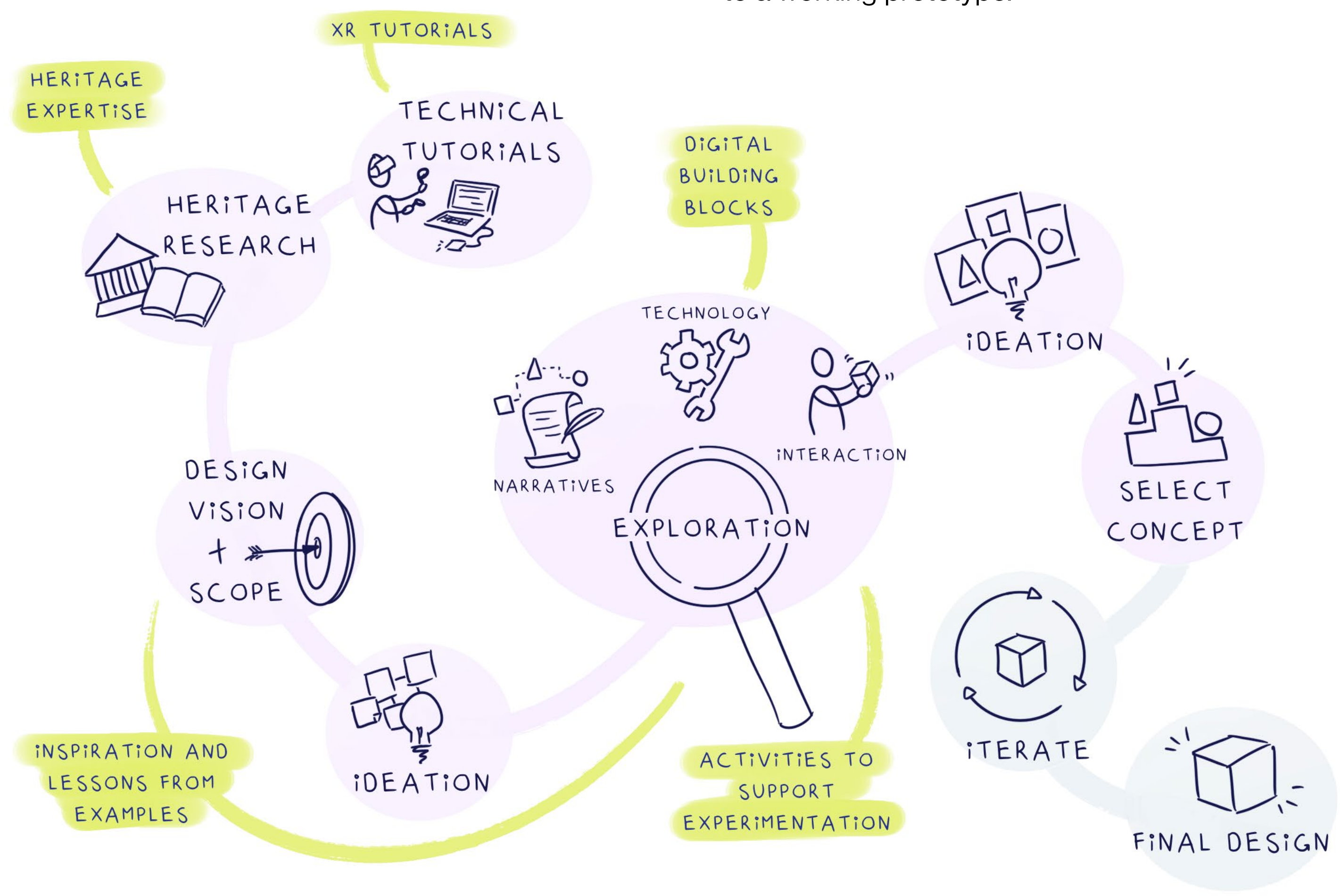


Figure 89. Design process when using the toolkit. The toolkit will provide support (green) throughout the first part of the process (purple).

4.2.2 Toolkit components

Based on this envisioned user journey, I identified several core components that will make up the toolkit.

- A **start guide** to help users quickly understand how to use the kit.
- A **digital workbook** filled with exercises that lead users through the design process offering guidance and structure at each step.
- An **inspirational card deck**, which provides lessons and inspiration from case studies throughout the process.
- **Digital building blocks** that simplify technical prototyping, such as pre-written code for visual markers or MQTT communication.
- A **physical box** to bring all the components together in a cohesive, tangible format.

I also see this initial version of the toolkit functioning as an add-on to existing educational resources, like the IDE's Connected Interaction Kit or the Unreal Engine tutorials from the Advanced Prototyping minor (Figure 90). This approach allows the toolkit to build on established learning materials, which fits with the current target audience of Industrial Design students.

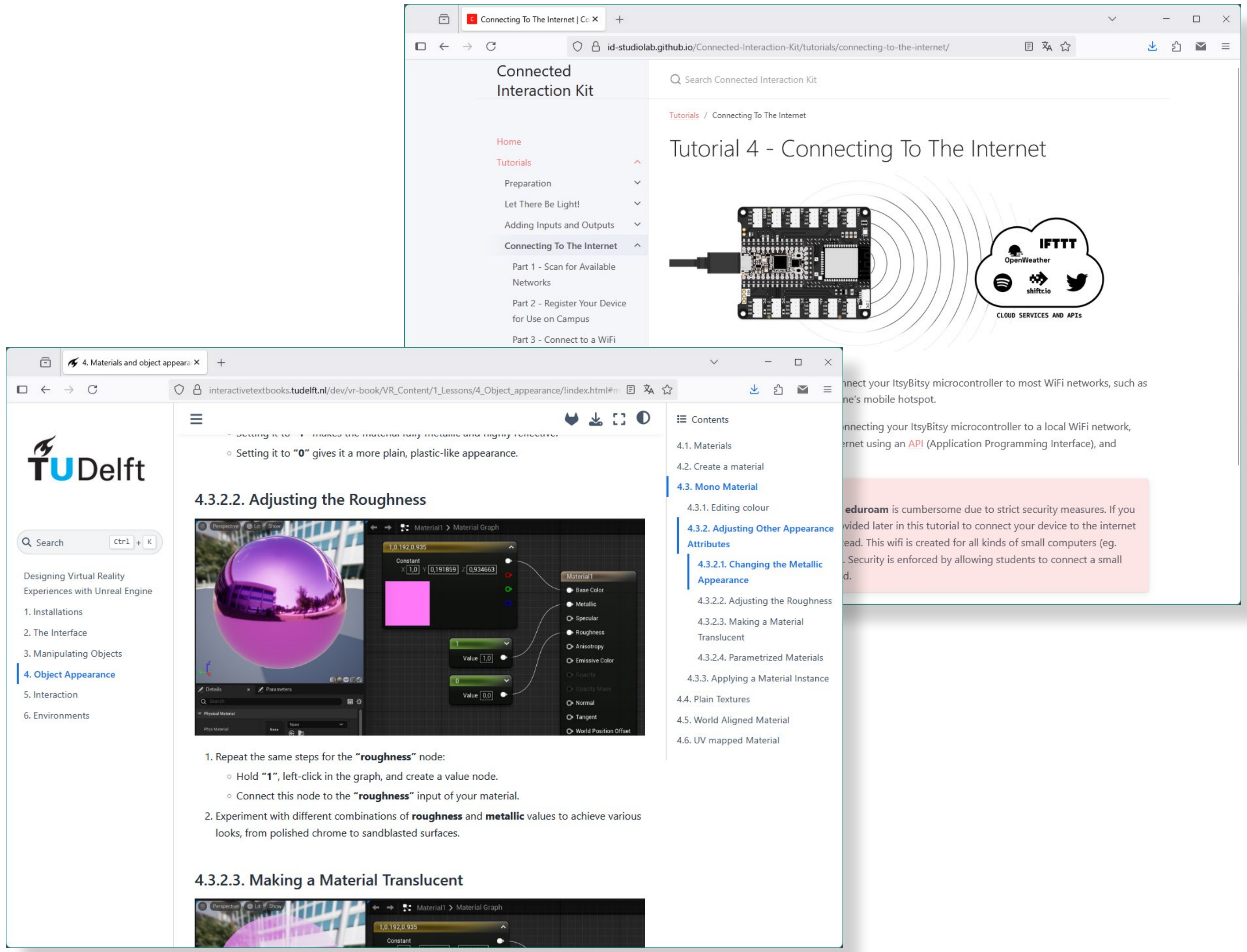


Figure 90. Educational resources that will be a part of the toolkit: Unreal Engine tutorials (left) and Connected Interaction Kit tutorials (right).

4.3 Designing toolkit components

This section will dive deeper into the toolkit's components and their design.

4.3.1 Immersive Heritage Design Deck

To bring together the insights from this contextual analysis and make them useful throughout the design process, I translated the examples and design implications into a deck of cards – the Immersive Heritage Design Deck (Figure 92). This card deck is meant to support the design process in various ways: by inspiring ideas, helping communicate key topics with others, and testing concepts against the identified design implications. Its development is in line with what participants in the user tests asked for: more concrete examples, inspiring use cases of XR in cultural heritage, and a better sense of what the technology can and can't do. The full card deck can be found in appendix G.

Designing the card deck

Two versions of the card deck were developed. The first iteration was created alongside the literature review and based on its findings. This version was then used throughout the design process – in interviews, discussions, and brainstorming sessions (Figure 91). After using the deck both on my own and with others, I created a second iteration that was better adapted to the needs of the design process.

Iteration 1

The first version of the card deck (Figure 93) was developed alongside the literature review. Key insights from the reviewed papers were written down and organized into individual cards, each with a title, relevant image, category, and one or more labels. The title and image were meant to quickly communicate the main idea of the card and grab attention, without needing to read the full content.

Figure 91. The first version of the Immersive Heritage Design Deck being used during an interview; the expert was asked to pick out the most relevant opportunities and obstacles.

Applications

Be inspired by previous projects that combined XR and TUIs

Design implications

Discover the opportunities and challenges within your solution space

Figure 92. Mockup of the final version of the Immersive Heritage Design Deck.

Figure 93. The first iteration of the Immersive Heritage Design Deck contained technology-, application-, challenge-, opportunity-, and storytelling-cards.

The cards were divided into five categories:

- **Applications:** Examples of museum exhibitions or research projects using XR and/or TUIs. These cards included a short description along with any mentioned strengths and limitations.
- **Technologies:** Cards that explained specific technologies that could be useful for the immersive heritage experience or toolkit. Like the application cards, these included pros and cons where relevant.
- **Storytelling:** Focused on how to create compelling narratives within exhibitions. Each card gave a brief explanation of a storytelling approach or consideration.
- **Opportunities:** Highlighted design possibilities or features that could positively influence the final experience.
- **Obstacles:** Pointed out challenges or limitations that need to be addressed when combining XR and TUIs in heritage contexts.

Each card was also tagged with one or more of four labels to help group and navigate them:

- **Cultural Heritage (CH):** For insights related specifically to heritage content and context.
- **Extended Reality (XR):** For insights involving XR technologies.
- **Tangible User Interfaces (TUI):** For insights related to tangible interaction.
- **Development (Dev):** For points related to the design and development process of heritage experiences.

This first version of the card deck was used in expert interviews and during the design process of the calculator case study. Based on this experience, a second version of the deck was created to better suit the needs of the design process.

Iteration 2

After using the card deck, several changes needed to be made to make the card deck better suited to the design of immersive heritage experiences (Figure 94). The following adjustments were made:

- **Categories were revised:** Applications proved valuable during ideation, offering inspiration for new ideas. Technologies, on the other hand, were rarely used—most of their pros and cons already appeared in

Figure 94. The second iteration of the Immersive Heritage Design Deck contained application- and design implication-cards.

other cards, and the design process of the case study showed that you usually already have a good overview of the technologies available to you. Storytelling, opportunities, and obstacles often overlapped and had unclear distinctions. These were merged into one category: Design Implications, focusing on how insights could be applied in the design process and what questions they might raise.

- **Labels were updated:** The original generic labels weren't helpful, as nearly all cards related to cultural heritage, XR, or TUIs. Instead, new labels – Technology, Narrative, and Interaction – aligned with the three design lenses used in the design process of the case study, making cards more useful during different stages.
- **Sources were added:** While the first version relied on a Notion database for references, this was impractical for broader use. Cards now include references, and the toolkit provides a complete reference list for easier access to source material.
- **Cards were refined:** The first version included many insights gathered early in the project. After testing and applying the cards in practice, it became clear which were truly useful. Some cards were removed or merged to reduce clutter and improve clarity.

Using the card deck

Both iterations of the card deck were used throughout the design process. The first version played a role during ideation and brainstorming, helping to generate new ideas and refine existing ones. It was also used in expert interviews to spark conversations around what elements they considered most important. In discussions with others – such as my supervisors – the cards helped communicate which aspects I found relevant and meaningful. They made abstract conversations about concepts or design directions more concrete and grounded. The second iteration of the deck was also used in group brainstorming sessions with students. It encouraged fresh discussions that led to redesigned features, new directions, or reconsidered ideas.

So how do you use the card deck? There's no fixed method and that flexibility is its strength. It can be tailored to different stages of the design process. You can work with the full set or filter by the tags (technology, narrative, interaction), depending on what's relevant at the moment. While I envision several possible use cases, users are encouraged to adapt the deck in ways that work best for them. If a new method helps you in your immersive heritage design process, that's a success in itself.

Some possible use cases include:

- **Brainstorming:** Application cards can serve as inspiration, either to spark entirely new ideas or to refine existing ones by learning from prior examples. Design implication cards can also be starting points: what happens if you begin your ideation with one of these insights? Alternatively, they can be used to evaluate and improve concepts already on the table.
- **Discussions:** The cards can guide conversations, clarify goals, and help align team members. Design implication cards can be used to identify shared priorities and articulate why certain design decisions were made. They provide a kind of argumentation that supports both collaboration and reflection.
- **Concept evaluation:** Use the cards to quickly assess ideas. Comparing your concepts with the cards can highlight their strengths and reveal areas that may need further development.

4.3.2 Digital building blocks

The goal of the digital building blocks is to help designers jump into prototyping more quickly by simplifying the technical side of things. Instead of starting from scratch every time, users can use these ready-made components as a foundation – saving time and energy that can be used exploring their own ideas and interactions.

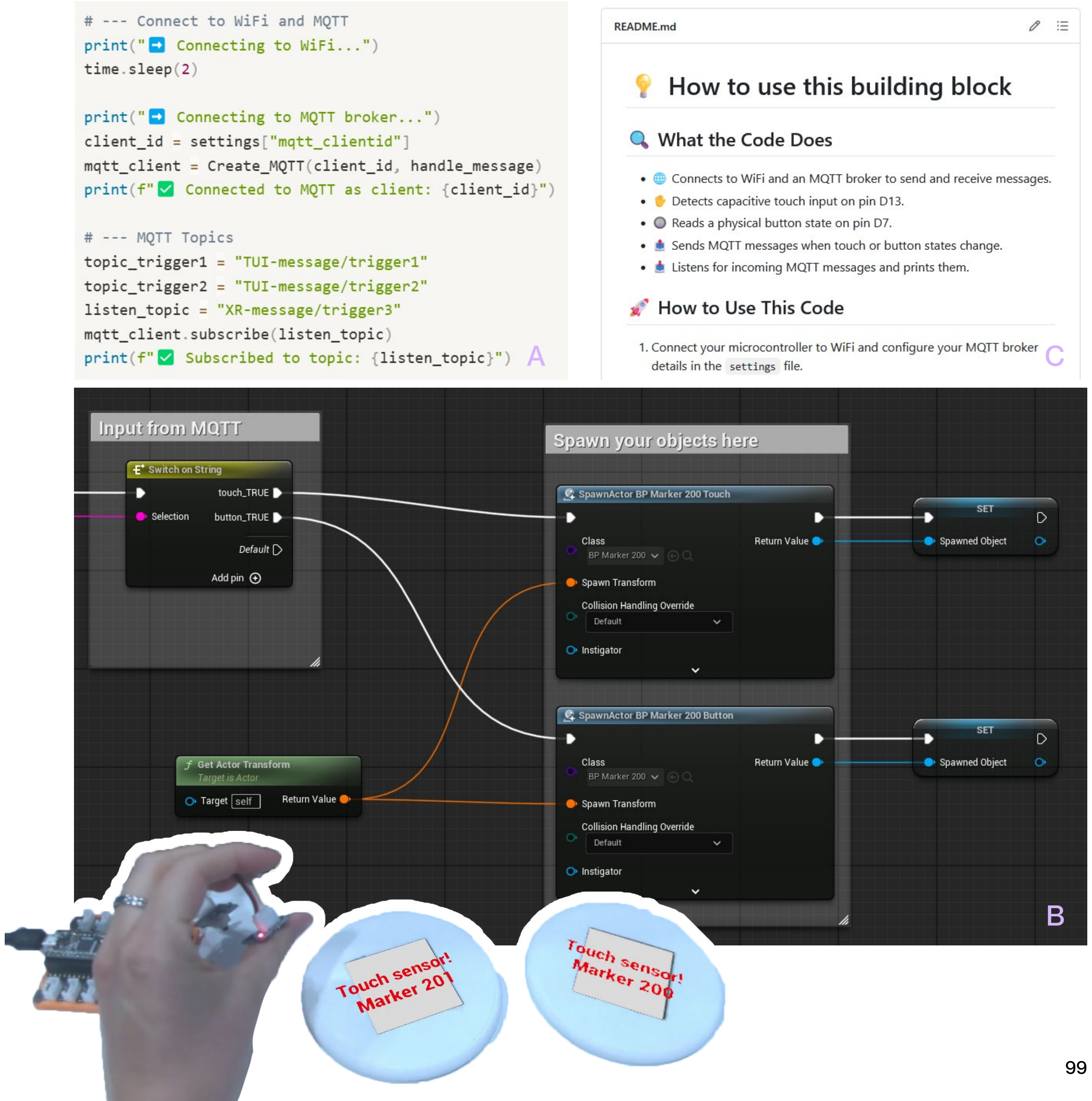
The first part of these digital building blocks is the Connected Interaction Kit. This kit not only includes the electronics needed for prototyping, but also comes with a database of tutorials and basic code snippets for each component. The Tangible MR Heritage Toolkit would expand this database to include tutorials on how to connect these electronics with Unreal Engine, by providing examples and starter code for both CircuitPython and Unreal Engine.

As an example, I've created one of these digital building blocks based on key technical elements from the case study – things that took a lot of time to figure out, but that would be useful to have as a starting point for others. These include:

- Connecting an ItsyBitsy microcontroller to Unreal Engine via an MQTT broker and enabling two-way communication.
- Spawning XR objects using Varjo markers.
- Changing which XR objects are spawned on markers, based on input from MQTT.

I developed a CircuitPython script and an Unreal Engine project that work together to demonstrate these three elements (Figure 95). They're simplified versions of the ones I used in the Calculator's Desk prototype, and I've structured the Unreal Engine event graph in a way that makes it easy to find, understand, and adjust each part. This setup lets users experiment with these interactions without having to dive too deep into complex code right away. And once they're more comfortable, they can start adapting and building on it to suit their own projects.

Figure 95. Example of a digital building block. It consists of A) a code for the microcontroller and B) an annotated Unreal Engine Project. These resources are collected and further explained in C) the GitHub repository.



4.3.3 Digital workbook

The previously described toolkit components can be used at different moments in the design process. But to really help users get the most out of those tools, they also need some structure to guide them along the way. That's where the digital workbook comes in (Figure 96). It's a Miro board that follows the design process outlined in Figure 89 and helps users stay organized as they move through each phase.

The workbook is divided into separate pages, each one focused on a different step in the design process (Figure 97). On each page, users can find relevant methods, suggested activities, and interactive links that lead them to detailed worksheets for each activity. These worksheets are there to support them step-by-step. Users are also encouraged to document their process and reflect on key takeaways from each activity. This helps them stay focused on the current task, while also maintaining a clear overview of their overall progress in the workbook.

I envision the following activities throughout this design process, which should be developed further in next iterations of this toolkit:

1. Heritage research

This first step helps users dive into their topic and build a better understanding of the historical context. By the end of this phase, users should have a clearer idea of the heritage theme or artifact their design will center on.

Activities:

1.1. Heritage-focused desk research

Offers support for conducting background research from a heritage perspective—especially helpful for designers with little experience in this area.

1.2. Interviewing heritage experts

Helps users identify and approach experts, and guides them in preparing meaningful questions.

1.3. Auto-ethnographic museum research

Supports users in visiting and reflecting on museums to better understand the context they're designing for.

2. Technical tutorials

This phase introduces users to the technical tools they'll be working with. After completing it, they'll have a basic understanding of prototyping with both the Connected Interaction Kit and Unreal Engine for XR.

Activities:

2.1. Unreal Engine XR tutorials

Based on the Advanced Prototyping minor's tutorial book, this teaches the first steps in designing XR experiences.

2.2. Connected Interaction Kit tutorials

Includes starter tutorials from the original kit and extra content on integrating electronics with Unreal via MQTT and other digital building blocks.

3. Design vision & scope

Here, users define their design goal and set the boundaries for their project. By the end, they'll have a clear direction and criteria to guide their decisions.

Activities:

3.1. Defining a design vision

Helps users combine early research and the design brief into a clear vision.

3.2. Design criteria

Guides users in translating their goals and insights into concrete design requirements.

4. First round of ideation

This step is about generating ideas and exploring possible directions. It helps focus the following exploration and gives shape to early concepts.

Activities:

4.1. Brainstorm techniques

Provides methods for structured ideation.

4.2. Ideation with the Immersive Heritage Design Deck

Offers ways to use the card deck to spark ideas.

4.3. Design directions

Supports users in grouping ideas and choosing a direction to explore further.

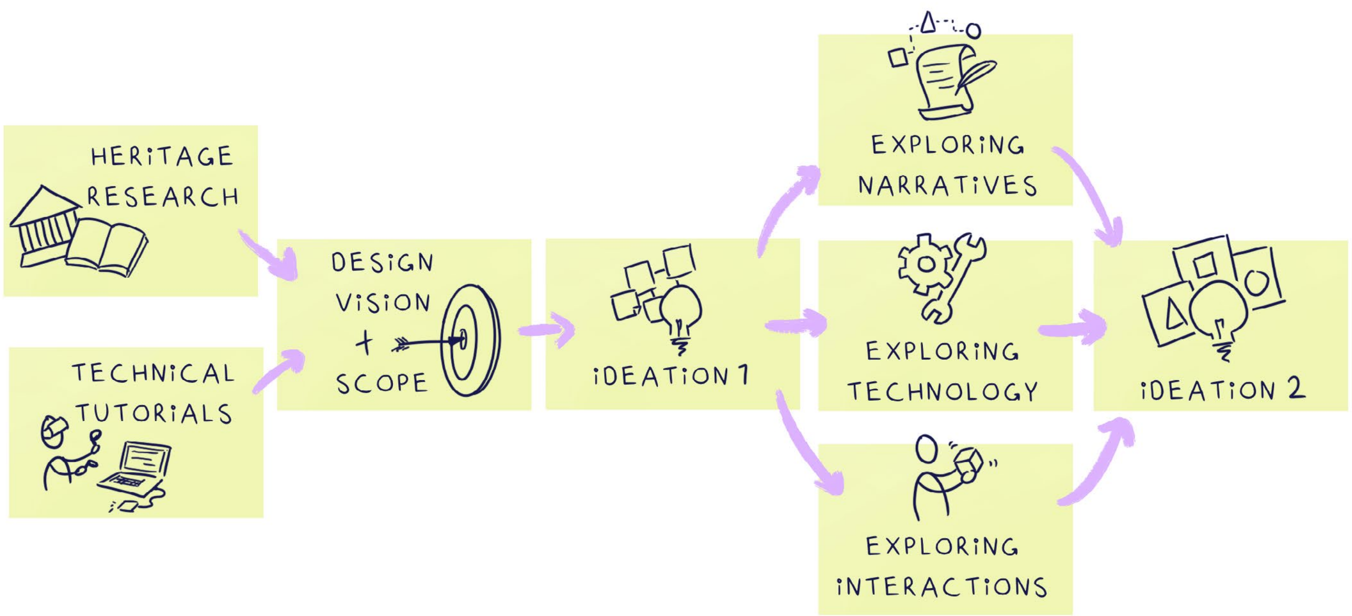


Figure 96. Structure of the digital workbook. The full workbook can been seen in appendix H.

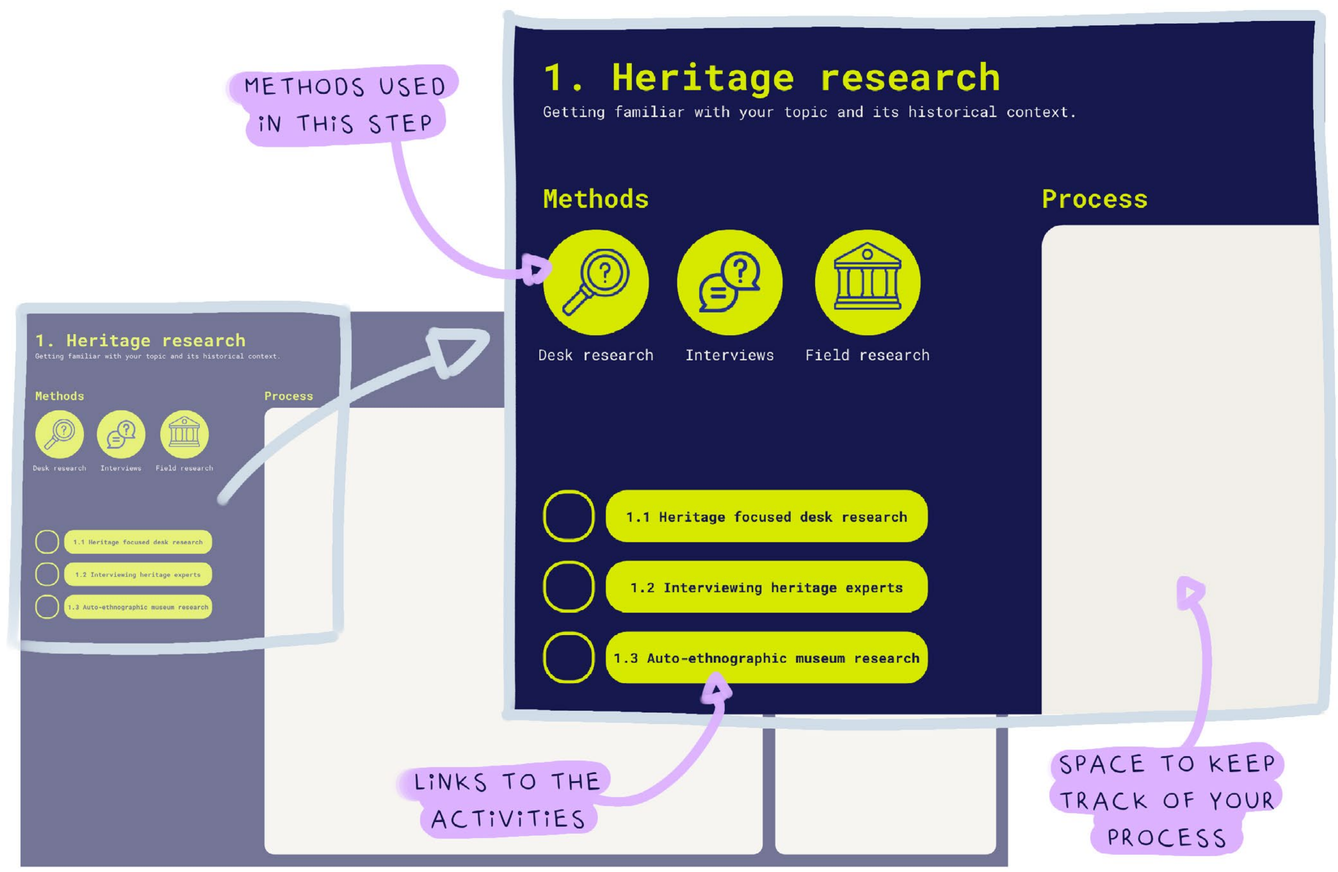


Figure 97. A page from the digital workbook. Users can document their design process in the blank spaces.

5. Exploring narratives

Focuses on uncovering the story behind the artifact—what makes it meaningful, and how to make that resonate with future users.

Activities:

5.1 Historical timeline

Helps users map key events and developments related to their topic.

5.2. Establishing narratives

Supports the translation of the timeline into meaningful narrative for the experience.

6. Exploring technology

Here, users test out technical possibilities to see what's feasible and meaningful. The goal is to understand the capabilities and limitations of the tools.

Activities:

6.1. Technological experiments

Encourages hands-on exploration of how XR and tangible elements can be combined to create meaningful interactions.

7. Exploring interactions

This step is about the user experience—what interactions feel natural, engaging, or meaningful, and how tangible elements affect that.

Activities:

7.1. Experiential Characterization

Teaches users how to performs and analyze the Experiential Characterization user tests to evaluate interaction qualities.

8. Second round of ideation

In this final step, users apply everything they've learned to come up with new, refined ideas. By the end, they'll have selected a concept to take forward into development.

Activities:

8.1. Brainstorm techniques

Provides methods for structured ideation.

8.2. Ideation with the Immersive Heritage Design Deck

This time, users can use the deck not just for idea generation, but to evaluate concepts against design implications.

8.3. Concept selection

Guides users in choosing a final concept based on how well it meets their design criteria.

4.3.4 Start guide, packaging, and materials

Lastly, I designed the package the user would receive. Since most of the toolkit is digital, there needed to be a clear way to access that content. However, because the card deck is a physical element, it felt important to bring everything together in one cohesive package. To do this, I created a start guide that matches the size of the large cards and fits neatly in the same box (Figure 99), helping users keep everything organized. Together, this package forms the HIT-KIT (Heritage through Immersive Technologies Kit), which is designed to be used as an add-on to IDE's Connected Interaction Kit.

The start guide introduces the toolkit, its components, and its intended users. It also includes a QR code linking to the GitHub repository (Figure 98), which hosts all digital materials, including CircuitPython code, Unreal Engine projects for the digital building blocks, and a link to the Miro board containing the workbook. This GitHub repository can expand as more digital building blocks and supporting resources are developed.

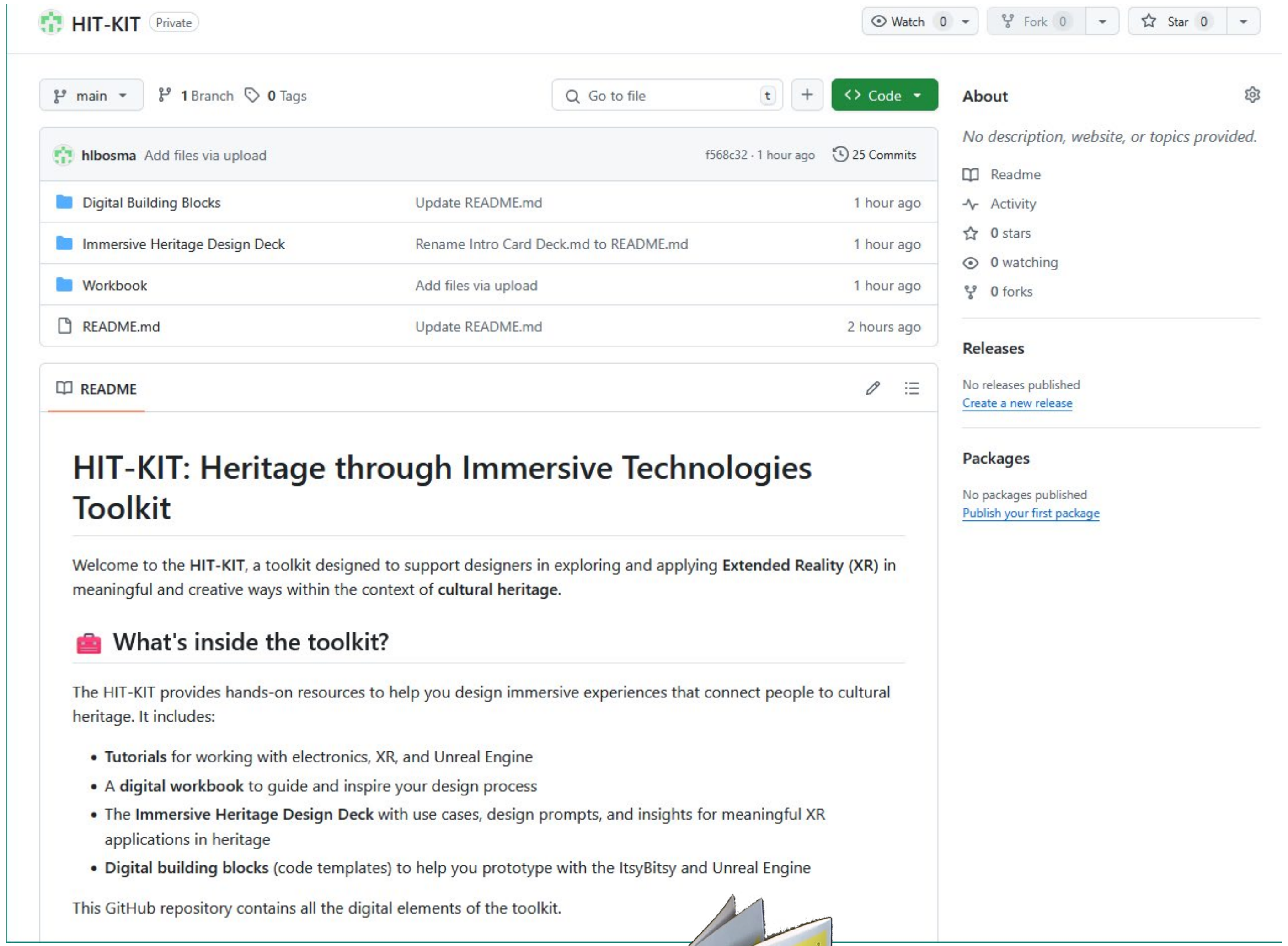


Figure 98. The GitHub repository. It can be accessed here.

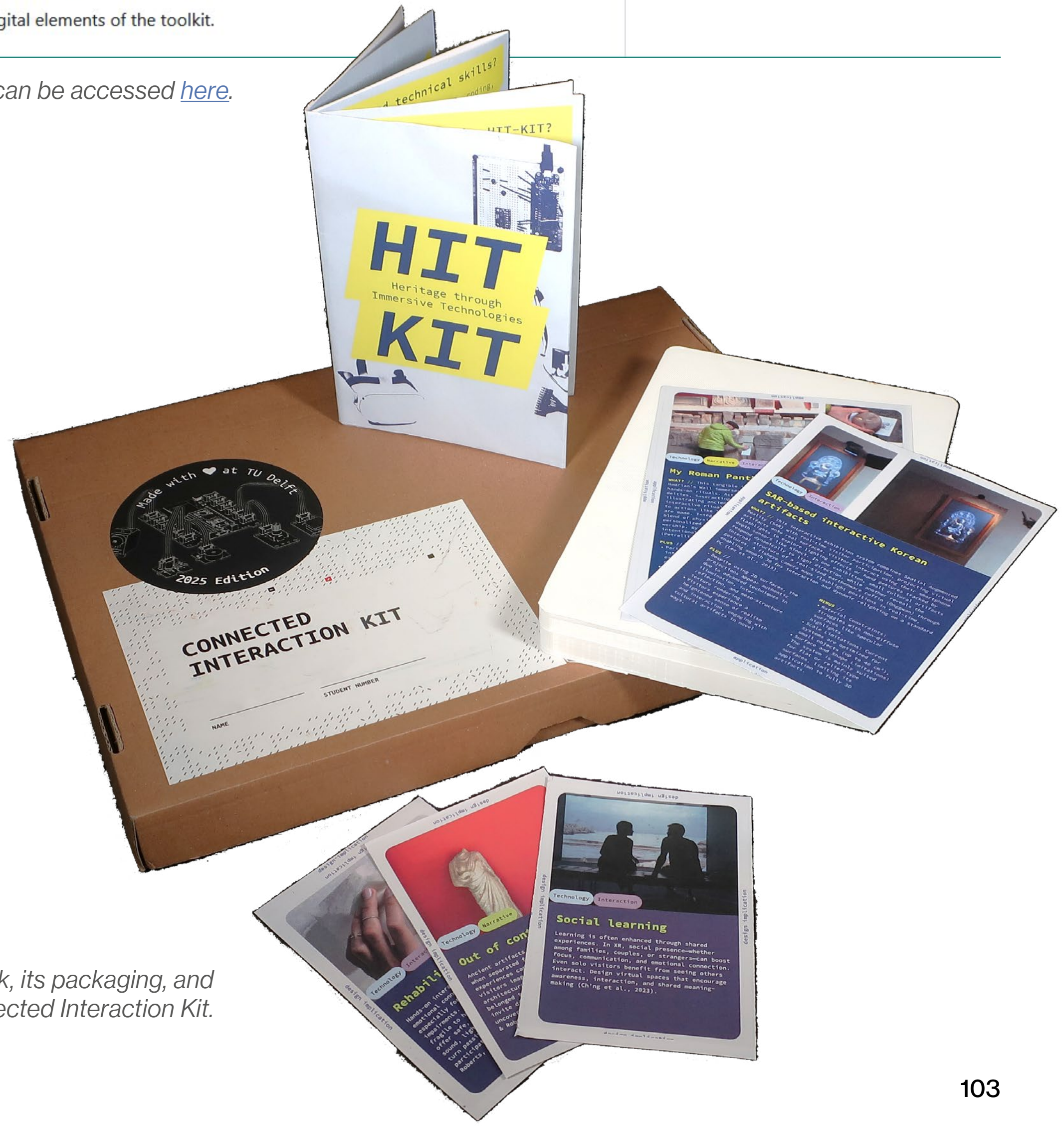


Figure 99. The start guide, card deck, its packaging, and the Connected Interaction Kit.

4.4 Final Design: The HIT-KIT

The final design of the conceptual toolkit is the **HIT-KIT** (*Heritage through Immersive Technologies Kit*). It's designed as an add-on to IDE's Connected Interaction Kit, helping designers create meaningful experiences around cultural heritage through the combined use of Extended Reality and tangible interactions. Whether you're new to XR or just unsure how to combine physical and digital interactions, the HIT-KIT offers tools, guidance, and inspiration to support you throughout your design journey.

Figure 101 shows how the HIT-KIT is typically used: A designer may begin with a spark of inspiration—wanting to create an immersive experience that brings cultural heritage to life through Extended Reality. However, XR technologies can feel unfamiliar or overwhelming. The designer might be curious about what's possible, but unsure where to start or how to apply the tools in a heritage-focused project.

This is where the HIT-KIT comes in. When added to the Connected Interaction Kit, it offers practical support, inspiration, and hands-on resources to help the designer shape and realize their immersive heritage concepts.

The HIT-KIT consists of four core components (Figure 100), each supporting different stages of the design process:

1. **Step-by-step tutorials:** To help the designer get started with XR and electronics, the HIT-KIT includes beginner-friendly tutorials. These resources lower the barrier to entry and allow users to gradually build prototyping confidence as they expand their skills.
2. **Digital workbook:** The design process is structured through a digital workbook, hosted on Miro. It guides the designer through each step—from early research and ideation to experimentation and prototyping. Each page outlines specific activities and provides clickable worksheets that offer guidance. The designer can also document key takeaways and decisions directly within the workbook, helping maintain an overview of the entire project.
3. **Immersive Heritage Design Deck:** The card deck provides design prompts, inspiration, and examples that translate abstract insights into concrete design considerations. It supports ideation, facilitates communication with stakeholders, and encourages reflection on the meaningful use of XR in heritage.
4. **Digital building blocks:** To support early prototyping, the HIT-KIT includes pre-made Unreal Engine projects and CircuitPython scripts. These templates simplify the technical side of connecting tangible components with XR environments. These blocks are designed to be easy to understand, adaptable, and expandable based on the needs of the project.

By the end of the HIT-KIT process, the designer will not only have developed a concept for an immersive heritage experience—they will also have acquired technical skills, gained a better understanding of XR's affordances, and explored how to meaningfully combine tangible and digital elements in the heritage domain.

The HIT-KIT provides structure, inspiration, and technical building blocks to support designers in navigating unfamiliar territory, while still allowing for creativity and personalization. It is a flexible and expandable toolkit that enables designers to bring immersive cultural heritage experiences to life.

Figure 100. Physical components of the HIT-KIT in use.

Figure 101. Using the HIT-KIT.

4.5 Evaluation

I wrapped up the design of the conceptual toolkit by reflecting on the design criteria I had defined earlier. For each one, I checked whether it had been met – either fully in the current prototype or likely to be met with further development. Since the toolkit is still in a conceptual phase rather than a finalized product, it's important to make that distinction. A full breakdown of this reflection can be found in appendix I.

Looking at the crucial criteria, the integration of XR and TUI, as well as optimization for modest technical setups, are already fulfilled in the current prototype. The criteria for supported coding and built-in learning resources aren't fully realized yet, but they would likely be met if the toolkit were further developed and the full set of activities and materials were added.

Among the important criteria, the card deck successfully addresses the need for inspiration through examples. The criteria for narrative construction and lofi prototyping tools would also be covered once the full set of activities is developed and more digital building blocks are added.

The only criterion that hasn't been met is the one focused on modular, reusable components. That said, this is something that could be integrated in future development – for example, by adapting the digital building blocks so they can easily connect with interchangeable physical elements.

Overall, this reflection shows that the toolkit has a strong foundation and meets most of the key requirements. It presents a promising starting point for further development into a fully functional design resource.

4.6 Discussion

Designing the toolkit based on my own immersive heritage project gave me valuable, hands-on insights into what designers might need when working with XR and tangible interfaces in heritage contexts. That personal process formed a strong foundation for the toolkit, but also introduced limitations. The design process I followed reflects just one way of working and was shaped by a very specific case: analog calculators. A different topic or design style might have led to different challenges and tools. To make the toolkit more widely applicable, future iterations should explore how other designers approach similar projects, and adjust the toolkit to support a broader range of methods and subjects.

The **Immersive Heritage Design Deck** became a helpful tool for bridging research and practice. It translated literature into design implications in a tangible, accessible format. But the deck currently leans heavily on more experimental academic sources than practice-based lessons from real museum settings. Including more practice-based cases would enrich the deck and make it more relevant to these institutions. Additionally, while the cards reflect peer-reviewed sources, they do not yet use the insights I gained from other parts of my research and design process. This was a deliberate choice to maintain academic reliability, but it also limits the scope of perspectives included. A future iteration could include blank or customizable cards, allowing users to document and integrate their own observations and experiences into the design process. Finally, not all cards are equally thorough, making comparisons difficult. A more standardized evaluation method, like the MUSETECH model (Damala et al., 2019), could improve consistency and depth.

The **digital building blocks** were designed to help users jumpstart technical prototyping. However, they currently focus on a small part of what's possible – mostly interactions involving Varjo markers and MQTT messaging. This made sense for the calculator case study but leaves out many other valuable interaction types. Exploring two-way communication between Unreal Engine and the Connected Interaction Kit, for instance, would open up more creative possibilities. Another gap is the lack of fully developed **tutorials**. Without well-tested, step-by-step guidance, it's unclear whether designers – especially those new to coding or XR – will be able to use the tools confidently.

Finally, the **digital workbook** offers a helpful structure for guiding the design process, and was shaped by both my project and earlier user testing. But the specific activities within that structure are still mostly based on my own work. It's uncertain how well these activities apply to other types of projects or working styles. Some steps may be unnecessary in other contexts, or important ones might be missing. Interestingly, I also included activities I hadn't done myself but believe would have been useful – especially ones involving expert support around heritage and storytelling. In future development, these activities should be co-created with heritage experts to ensure they are historically accurate and practically useful for designers.

5. Conclusion

This thesis explored the potential of combining Mixed Reality and tangible interactions within the domain of cultural heritage, resulting in both a design prototype and a toolkit intended to support future designers in similar challenges. By combining technical exploration, narrative design, and educational tool development, this project contributes to the growing intersection between technology and cultural heritage. The results highlight both the promise and the complexity of designing for tangible mixed reality, and lay the groundwork for future designers that aim to create more intuitive, meaningful, and accessible immersive experiences.

This chapter summarizes the key contributions of the project, reflects on its limitations, and offers recommendations for future development and research. It ends with a personal reflection on the design process of this project.

5.1 Contributions

One of the core contributions of this project is the integration of MR and tangible interaction in a cultural heritage context. By moving away from traditional XR controllers and instead embracing tangible interactions, the project offers a more natural and intuitive way for users to engage with heritage content presented through XR. This is especially valuable in museums, where many visitors may be unfamiliar or uncomfortable with high-tech interfaces.

A key outcome of the thesis is the development of the HIT-KIT (Heritage through Immersive Technologies Kit). The HIT-KIT supports designers in creating meaningful heritage experiences that combine physical and digital elements. The toolkit includes beginner-friendly tutorials, a digital workbook to guide the user through the design process, a card deck to offer inspiration and support, and digital building blocks that allow for quick prototyping. Whether someone is new to XR or simply unsure how to bridge the gap between tangible and digital interaction, the HIT-KIT offers tools, guidance, and inspiration to support the entire design journey.

The toolkit was developed and evaluated through the case study of The Calculator's Desk—an immersive heritage experience that brings together storytelling, physical replicas, and digital augmentation. This case not only shows how narrative and technology can merge in a museum context, but also helped shape the tools and methods that make up the HIT-KIT.

5.2 Limitations

The biggest limitation is that the toolkit is still largely conceptual. It functions more as a structured outline than a complete and fully operational resource. While some components (like one of the building blocks) have been created and tested, the majority of the content still needs to be developed and evaluated.

Furthermore, the toolkit is strongly based on my own design process, with limited input from other designers beyond the user testing sessions. It remains unclear how effective or relevant the HIT-KIT would be when applied to other design challenges, or by designers with different working styles or levels of experience.

Lastly, the development process relied heavily on TU Delft-specific resources, such as 3D scanning facilities and technical support from the XR Zone. While this is appropriate for the initial target audience (IDE students), broader implementation—especially within museums—would require adaptations based on the tools, skills, and infrastructure typically available in those environments.

5.3 Recommendations

To build on the current work and realize the full potential of the HIT-KIT, several steps are recommended:

- **Further develop the toolkit:** Expand its components and build more digital building blocks, particularly around two-way communication between tangible electronics and XR environments. This will allow for more complex, responsive interactions.
- **Broaden the target audience:** In future iterations, focus on museum professionals and exhibition designers. Explore their workflows, challenges, and available resources to understand how the toolkit can be adapted to their needs and constraints.
- **Apply the methodology to other narratives and artifacts:** Test the scalability and flexibility of the design approach by applying it to different heritage objects or historical themes.
- **Evaluate the toolkit over time:** For example, integrate it into a design course within IDE and track its use throughout a full project. This would provide deeper insights into what the toolkit contributes to the process, what needs refinement, and how it supports learning and creativity.

5.4 Reflection

This project has been one of the most challenging yet rewarding experiences of my entire study. Looking back, I'm genuinely proud of what I've achieved—especially considering how many completely new skills I had to develop along the way. Before this project, I had never worked with XR at all, so starting this project felt both exciting and overwhelming. One of my personal ambitions from the design brief was to develop these new technical skills, and I can confidently say that I achieved that.

One of the biggest challenges I faced was switching between two different design tracks: the toolkit and the immersive experience. At times, it felt like I was investing so much time into the heritage experience without knowing exactly why—especially since the end product was supposed to be a toolkit. This sometimes made me question the value of all those hours spent on the experience. But in hindsight, I now realize that the toolkit could never have existed without that case study. It provided not only the foundation, but also many of the practical insights that later became part of the HIT-KIT. In fact, I probably could've used a toolkit like mine at the start of my own project!

That might actually have been the biggest challenge of all: I was essentially designing for a context I had never worked in before. I had no prior experience with either XR or heritage design, so a large part of the process was spent simply trying to understand the field and find a way to make it work. In a way, I ended up being part of the target audience for my own toolkit—something that added complexity but also made me aware of what kind of support such a toolkit should provide. I imagine that if a more experienced designer had taken on this project—someone already familiar with XR and heritage—they might have been able to focus more directly on developing the toolkit itself, shaping it for a wider audience, and creating a more polished final product.

What I really appreciated about this project was that I got to work on both a practical and a conceptual level. I created a tangible museum experience that others can explore, while also thinking about how such experiences could be better supported in the future. Even though the HIT-KIT is still in a conceptual phase, I clearly see the value in it. Especially at the beginning of this project, I found it incredibly hard to get started without any design method or support. XR felt full of endless possibilities, but I had no idea how to get started. The approach I eventually developed helped me structure my thinking, explore what was feasible within my own skills, and slowly build confidence in designing for this field.

This process wasn't just about the outcomes I delivered, but also about how I grew as a designer. I learned how to navigate uncertainty, how to design in a completely unfamiliar domain, and how to create something that could help others facing the same hurdles. That, in itself, feels like a meaningful result.

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Use of generative AI

Generative AI was used in this thesis to support various parts of the design and writing process. ChatGPT provided coding support and assisted with paraphrasing some sentences of the written text. Sora was used to generate visual content such as UV maps for certain props. No sensitive or personal data was included in any prompts. All AI-generated outputs were carefully reviewed, edited, and integrated by me.

Appendix

Content

A. Project Brief

DESIGN FOR our future

TU Delft

Personal Project Brief – IDE Master Graduation Project

Name student Hanne Bosma **Student number** 4,858,905

PROJECT TITLE, INTRODUCTION, PROBLEM DEFINITION and ASSIGNMENT
Complete all fields, keep information clear, specific and concise

Project title A Tangible Interaction Toolkit for creating Customized Mixed Reality Experiences in Industrial Heritage

Please state the title of your graduation project (above). Keep the title compact and simple. Do not use abbreviations. The remainder of this document allows you to define and clarify your graduation project.

Introduction

Describe the context of your project here; What is the domain in which your project takes place? Who are the main stakeholders and what interests are at stake? Describe the opportunities (and limitations) in this domain to better serve the stakeholder interests. (max 250 words)

Digital technologies are increasingly being used in the field of cultural heritage. Mixed Reality (MR) technologies, such as Augmented Reality (AR) and Virtual Reality (VR), are changing the ways that cultural heritage, including industrial heritage, is experienced and understood. For instance, by projecting artifacts into users' real-world environments, these technologies enhance visitor engagement and offer deeper and more immersive experiences. They play a crucial role in ensuring the preservation, promotion, and dissemination of cultural heritage.

In museums, MR technologies create immersive environments that enable innovative presentations of content, which would not be possible otherwise. Visitors can safely explore and interact with fragile artifacts, and missing pieces can be digitally reconstructed to form a cohesive narrative that connects the artifact with its historical context. In this way, MR creates a deeper connection with cultural heritage.

While MR technologies have been extensively applied to decorative cultural heritage artifacts and historical archaeological sites, there is a noticeable gap in research regarding their use for industrial heritage or scientific instruments. These artifacts are often dynamic in nature, with the most intriguing aspects hidden within their internal mechanics. It is challenging to show such details to museum visitors without risking damage to historical instruments. MR offers a promising opportunity by enabling exploration of an artifact's different layers in a non-invasive manner, preserving the original piece while allowing deeper understanding of its intricacies. Tangible User Interfaces (TUIs, figure 1) can enable visitors to interact with these MR experiences in less complex and more user-friendly ways.

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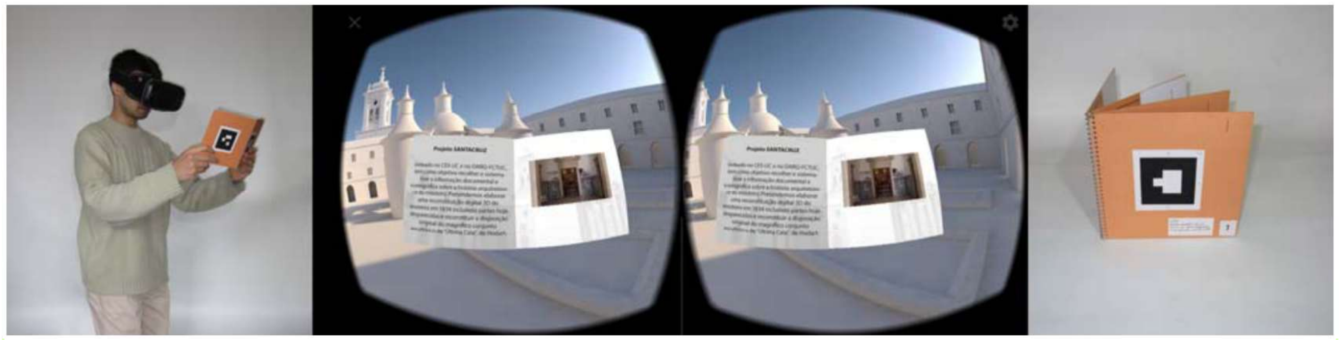


image / figure 1 VR prototype using Tangible User Interfaces

image / figure 2 Mechanical Calculator

TU Delft

Personal Project Brief – IDE Master Graduation Project

Problem Definition

What problem do you want to solve in the context described in the introduction, and within the available time frame of 100 working days? (= Master Graduation Project of 30 EC). What opportunities do you see to create added value for the described stakeholders? Substantiate your choice.
(max 200 words)

Sensory and performative engagement has the potential to enhance learning and create a deeper connection with the history of an artifact. However, working exclusively in VR does not always provide the level of interaction needed for exhibitions to deliver an effective (learning) experience. This limitation is often a result of the difference between interacting with objects in the real world and in the virtual world.

A promising approach to address this challenge are Tangible User Interfaces (TUIs), which provide physical representations of digital content, allowing users to interact with virtual media through tangible artifacts. Studies have shown that the tactile sensations of TUIs could provide more compelling and natural interactions than traditional controllers.

This graduation project will focus on developing a Mixed Reality prototype that uses TUIs to create an immersive experience centered on industrial heritage. The prototype will be created for historical electro-mechanical calculators (figure 2).

The insights gained from this case study will be generalised and used to develop an MR+TUI toolkit. The goal of this toolkit is to enable other designers to develop their own customizable MR experiences with TUIs. This toolkit aims to make this process more accessible, requiring minimal prior knowledge of coding.

Assignment

This is the most important part of the project brief because it will give a clear direction of what you are heading for. Formulate an assignment to yourself regarding what you expect to deliver as result at the end of your project. (1 sentence) As you graduate as an industrial design engineer, your assignment will start with a verb (Design/Investigate/Validate/Create), and you may use the green text format:

Design a toolkit that enables designers with minimal coding knowledge to create their own immersive experiences by combining Mixed Reality and Tangible User Interfaces, through the development of a MR+TUI experience to explore the material properties of industrial heritage artifacts.

Then explain your project approach to carrying out your graduation project and what research and design methods you plan to use to generate your design solution (max 150 words)

After doing initial research, this project will go through two main design cycles. First, I will explore both traditional and digital methods of showcasing industrial heritage artifacts. I will try to speak to experts on MR, HCI in museums, and electro-mechanical calculators. I will also explore the context of designing toolkits. Next to this, I will develop my prototyping skills in Unreal Engine and Circuit Python.

The first design cycle will focus on developing an MR prototype with TUIs using connected micro-electronics to enhance parts of the material experience of vintage electro-mechanical calculators. This prototype will determine the scope of the toolkit. The second design cycle will focus on developing an MR+TUI toolkit, based on this prototype.

Both design cycles will consist of multiple iterations in which I frame the design goal and requirements, ideate on possible solutions, develop prototypes and test these prototypes with relevant stakeholders.

Project planning and key moments

*To make visible how you plan to spend your time, you must make a planning for the full project. You are advised to use a Gantt chart format to show the different phases of your project, deliverables you have in mind, meetings and in-between deadlines. Keep in mind that all activities should fit within the given run time of 100 working days. Your planning should include a **kick-off meeting**, **mid-term evaluation meeting**, **green light meeting** and **graduation ceremony**. Please indicate periods of part-time activities and/or periods of not spending time on your graduation project, if any (for instance because of holidays or parallel course activities).*

Make sure to attach the full plan to this project brief.
The four key moment dates must be filled in below

Kick off meeting	6 Feb 2024
Mid-term evaluation	3 apr 2025
Green light meeting	26 mei 2025
Graduation ceremony	27 juni 2025

In exceptional cases (part of) the Graduation Project may need to be scheduled part-time. Indicate here if such applies to your project

Part of project scheduled part-time	
For how many project weeks	
Number of project days per week	

Comments:

Motivation and personal ambitions

Explain why you wish to start this project, what competencies you want to prove or develop (e.g. competencies acquired in your MSc programme, electives, extra-curricular activities or other).

Optionally, describe whether you have some personal learning ambitions which you explicitly want to address in this project, on top of the learning objectives of the Graduation Project itself. You might think of e.g. acquiring in depth knowledge on a specific subject, broadening your competencies or experimenting with a specific tool or methodology. Personal learning ambitions are limited to a maximum number of five.
(200 words max)

This project combines my love for museums and the history of technology with designing practical prototypes. I really enjoy working in the fuzzy front end of the design process: exploring the complex context of a problem and figuring out how to frame the solution space to create the most value. Even in those early stages, you can make prototypes that are impactful. I personally prefer working on those exploratory prototypes over focusing on polished, final embodiment designs.

During the project I want to challenge myself to keep working together with others. Their thoughts can provide valuable insights, keep me motivated, and inspire new ideas.

While I have experience with interactive elements (e.g., Arduino), MR and Circuit Python are new to me. This will be challenge, but I'm excited to learn and develop these new skills.

I also want to improve my project management skills. This is my first time planning an entire design project by myself. My goal is to create a realistic schedule with smaller design sprints and deadlines to distribute the workload evenly, stay on track and within the hours, and keep my motivation up.

B. Extended history of the calculator

Shown below is the extensive version of the historical timeline of calculators.

Prehistoric times

Hands

We learned to count with our 10 fingers. This is why we still use a decimal or base-10 system today that counts in tens (10, 100, 1000, etc.) With some creative use of your fingers and joints, you can also count higher than 10, as shown in this medieval math textbook (Houston, 2023).

Tally sticks

The earliest tools used for arithmetic were tally sticks – simple wooden rods with notches carved into them. People used these notches to keep track of things like days passing or goods received. The oldest known example is the Lebombo bone, which dates back to around 35,000 BCE (Houston, 2023).

Ancient times

Counting boards

Counting boards are the earliest known devices used for performing both addition and subtraction. They were the precursors to the abacus and worked by placing loose pebbles or beads on a marked board to represent numbers. These boards were likely used to keep track of quantities, trade, and financial transactions. The oldest known example is the Greek Salamis Tablet, dating back to around 300 BCE (Houston, 2023).

Abacus

An abacus is a simple counting tool used to perform arithmetic calculations. It consists of a frame with rods or wires, each holding a series of movable beads that represent numbers. The abacus has been used across many cultures since ancient times – dating back to Mesopotamia. In Europe, they remained common until the 17th century but gradually fell out of use with the adoption of the Hindu-Arabic numeral system, which made written calculations much easier (Houston, 2023).

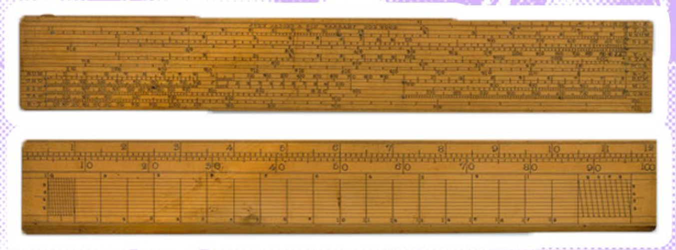
Today, abacuses are still used in countries such as Japan and China, both as a tool for teaching basic math concepts and as an aid to enhance mental calculation speed. In fact, in 1946, a contest was held between a Japanese abacus and an American electromechanical calculator, where the abacus outperformed the calculator in addition, subtraction, and division (Houston, 2023).

17th century

Napier's Bones

Napier's Bones is a manual calculating device used to simplify multiplication and division. It uses a set of numbered rods, each marked with a multiplication table, allowing users to perform calculations by aligning and adding partial products (Houston, 2023).

The tool is named after John Napier, inventor of the logarithm, who published a description of them in 1617. However, the tool had already been invented centuries before by the famous Persian mathematician al-Khwārizmī (Houston, 2023).



Gunter's Scale

Around 1620, shortly after John Napier's invention of logarithms, Edmund Gunter developed the logarithmic scale. By adding this and other trigonometric scales onto a ruler, he created a tool that allowed users to perform calculations such as multiplication and division. Gunter's scale was mostly used for navigational calculations (Houston, 2023).

Slide rule

A slide rule is a mechanical calculating device used primarily for multiplication, division, and other functions like roots and logarithms. It consists of sliding scales with logarithmic markings, allowing quick and approximate calculations without the need for manual computation. It was invented in 1622 by William Oughtred, who combined two Gunter's Scales to make calculations easier. Slide rules were the most commonly used calculation tool in science and engineering until the introduction of the scientific pocket calculator in the 1970s (Houston, 2023).

Rechenuhr

Wilhelm Schickard's Rechenuhr (German for "calculating clock") was a mechanical calculator invented in 1623. It is considered one of the earliest known mechanical calculating machines, capable of performing basic arithmetic operations like addition and subtraction using rotating gears, cylinders, and a set of Napier's bones (Houston, 2023).

Schickard described the device in a letter to his friend, the astronomer Johannes Kepler, but never completed its development after his prototypes were destroyed in a fire. The concept was rediscovered in 1957 and reconstructed based on the surviving letters (Houston, 2023).

Pascaline

The Pascaline, invented by Blaise Pascal in 1642, was the first fully developed mechanical calculator. It used a system of interlocking gears and wheels to perform addition and subtraction, making it a practical tool for arithmetic and accounting. Its innovative carry mechanism allowed numbers to be automatically carried to the next dial when a wheel turned from 9 to 0, enabling faster calculations (Houston, 2023).

Pascal designed the machine to assist his father, who worked as a tax official. He created three versions of the Pascaline, each tailored to different purposes – accounting, surveying, and scientific work – with each model using different numerical scales. Although the Pascaline was not a commercial success due to its high production cost, it laid the groundwork for future mechanical calculators (Houston, 2023).

Stepped Reckoner

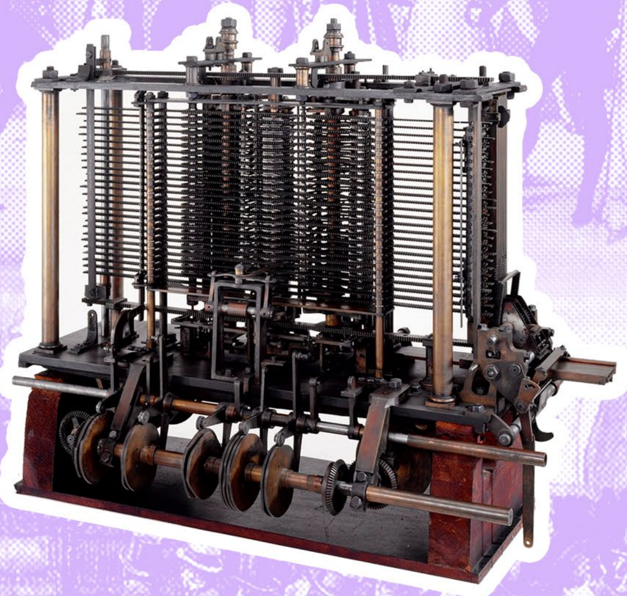
Inspired by the Pascaline and Pascal's unpublished writings, Gottfried Wilhelm Leibniz invented his own mechanical calculator, the Stepped Reckoner, in 1673. It was capable of performing all four basic arithmetic operations: addition, subtraction, multiplication, and division (Houston, 2023).

Although the machine never reached a level of reliability suitable for everyday use, its innovative stepped drum mechanism became a key component in many later mechanical calculators (Houston, 2023).

19th century

Thomas Arithmometer

Invented by Charles Xavier Thomas de Colmar in 1820, the Arithmometer was created to assist with the extensive calculations required for his role as general manager of the French army's supply store. It could perform all four basic arithmetic operations, powered by Leibniz's stepped drum mechanism. As the first commercially successful mechanical calculator, it became widely adopted in offices and businesses, representing a significant advancement toward the automation of arithmetic calculations (Houston, 2023).



Analytical Engine

Charles Babbage's Analytical Engine, designed in the 1830s, is regarded as the first conceptual design for a general-purpose mechanical computer. It featured an arithmetic logic unit, memory, and the use of punched cards to control operations, laying the foundation for modern computing. Although never completed in Babbage's lifetime, the engine was groundbreaking (Swaine & Freiberger, 2024).

Ada Lovelace, an English mathematician and the daughter of poet Lord Byron, is often considered the first computer programmer. She worked closely with Babbage and wrote detailed notes on the Analytical Engine, including an algorithm to compute Bernoulli numbers. This algorithm is recognized as the first ever intended for a machine, earning Lovelace her title as the first computer programmer (Swaine & Freiberger, 2024).

Odhner Arithmometer

While repairing a Thomas Arithmometer, W.T. Odhner decided to replace the heavy and bulky Leibniz wheel with a lighter, more compact pinwheel mechanism. This innovation led to the creation of the Odhner Arithmometer in 1873 – a smaller, more efficient, and affordable mechanical calculator. Its improved design made mechanical computation more accessible and sparked the widespread use of pinwheel-based calculators throughout the late 19th and early 20th centuries (Leipälä, 2003).

Cash register

James Ritty invented the first mechanical cash register in 1879 to prevent employee theft at his saloon. Known as "Ritty's Incorruptible Cashier," the device recorded sales and tracked transactions using a system of levers and gears, similar to the mechanical calculators of its time. It laid the foundation for modern point-of-sale systems and later evolved into the widely adopted cash registers produced by the National Cash Register Company (National Museum of American History, n.d.-b).

Comptometer

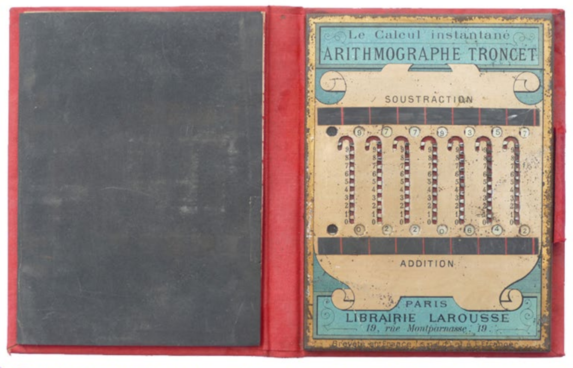
In 1887, Dorr E. Felt invented the Comptometer, a groundbreaking calculator based on early prototypes he built from macaroni boxes during a Thanksgiving holiday. It was the first successful key-driven mechanical calculator, allowing users to enter numbers directly by pressing keys – significantly increasing speed and efficiency compared to earlier designs (Smithsonian, n.d.-b).

Its ease of use made it especially popular in business and accounting, supported by effective marketing and specialized training through Comptometer Schools. The direct-input mechanism went on to influence many later electromechanical calculators (Norman, 2025).

The Comptometer remained influential for decades and marked a key transition to electronic computing when, in 1961, it became the first mechanical calculator to incorporate an all-electronic engine with the release of the ANITA Mark VII. This development bridged the gap between mechanical and electronic calculator technology (Houston, 2023).

The Millionaire

The Millionaire calculator, introduced in 1893, was the first commercially successful mechanical calculator capable of performing direct multiplication. Unlike earlier machines that relied on repeated addition, it used a mechanical multiplication mechanism to deliver results more quickly and accurately (The Computer Museum, n.d.).



Adders

Adders (also called slide calculators) are simple mechanical devices designed to perform basic arithmetic, primarily addition and subtraction. They were invented Louis Troncet in 1892, who called it an Arithmographe. Typically operated with a stylus, adders use sliding or rotating mechanisms to manipulate numbers displayed through small windows (Smithsonian, n.d.-a).

Adders were popular in the early to mid-20th century for their portability, ease of use and affordability. They were widely used before the rise of inexpensive electronic calculators for quick, everyday calculations (Smithsonian, n.d.-a).

20th century

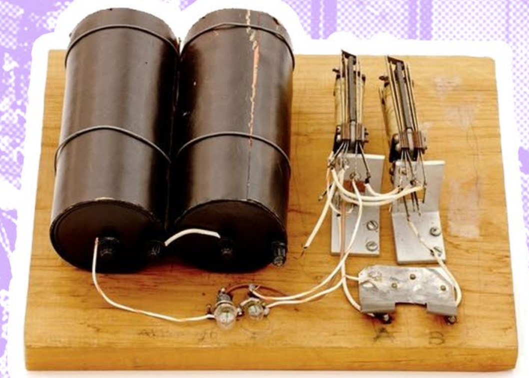
Electromechanical calculators

Electromechanical calculators, developed in the early to mid-20th century, combined traditional mechanical components with electric motors to automate arithmetic operations such as addition, subtraction, multiplication, and division. These machines offered greater speed, accuracy, and ease of use compared to fully manual calculators (Houston, 2023).

Leading manufacturers like Friden and Monroe produced models that merged the internal mechanisms of arithmometers with the extensive keypads of comptometers. Widely used in offices, engineering, and scientific work, these machines played a vital role before the rise of electronic calculators – often operated by women whose behind-the-scenes calculations supported major achievements, including America's first crewed orbital spaceflight (Houston, 2023).

E6B flight computer

The E6B flight computer, developed in the 1930s by the U.S. Navy, is a circular slide rule used by pilots for in-flight navigation and flight planning. It allows for quick calculations of wind correction, ground speed, fuel burn, time en route, and other essential flight parameters. Despite the rise of digital tools, the E6B remains a standard backup in aviation due to its reliability and simplicity. Many flight schools still train students on the E6B today, making it one of the few analog calculators still in regular use in the 21st century (Valerio, 2015).



Model K

In 1937, George Stibitz developed one of the first relay-based calculators, that marked an early step toward digital computing. Using telephone relays – electromechanical switches that open and close circuits – it could perform binary addition. The prototype was named "Model K" by Stibitz's wife, since the prototype was created in their kitchen (Houston, 2023).

Following prototypes led to more advanced relay-based machines that allowed remote operation, laying foundational concepts for modern computers and networking (Houston, 2023).

Curta

The Curta calculator, invented by Curt Herzstark and released in the late 1940s, was a compact, hand-cranked mechanical device capable of performing all four basic arithmetic operations. Often considered the first true pocket calculator, it used a mechanism similar to those in earlier arithmometers but miniaturized to a single stepped drum (Houston, 2023).

Herzstark conceived the idea in the 1930s but began fully developing it while imprisoned in a Nazi concentration camp during World War II. Encouraged to complete the design as a potential gift for the Führer, he did so in hoping to save his own life (Houston, 2023).

The Curta found a niche among contestants in sports car rallies, who used it to calculate times and distances. Its durability and precision made it ideal for the rough conditions of motorsport, where early electronic calculators struggled (Houston, 2023).

Casio 14-A

The Casio 14-A, released in 1957, was the first all-electric, relay-based calculator. It was roughly the size of a desk and used 342 electromechanical relays to perform the four basic arithmetic operations, replacing traditional mechanical components. Despite its high cost, it became a success. The 14-A was known for being quiet, reliable, and durable and was widely adopted in government offices, financial institutions, and general business use (Houston, 2023).

Sumlock ANITA

The ANITA Mark VII and VIII, released in 1961 by the British company Sumlock Comptometer, were the first commercially available all-electronic desktop calculators. They used vacuum tubes and cold-cathode tubes instead of mechanical or relay-based parts to perform calculations silently and efficiently (Houston, 2023).

Sharp QT-8B

The Sharp QT-8B, released in 1970, was the first mass-produced battery-powered, portable electronic calculator, making electronic calculation more accessible and mobile (Tout, 2004).

HP-35

The HP-35, released in 1972, was the world's first handheld scientific calculator. Unlike basic calculators of the time, it could perform advanced functions such as trigonometry, logarithms, and exponentiation. It became incredibly successful among engineers, scientists, and students and ended the 350 year long usage of the slide rule in engineering (Houston, 2023).

Casio fx-7000G

The Casio fx-7000G, released in 1985, was the world's first graphing calculator available to the public. It featured a LCD capable of plotting mathematical functions, along with programmability and a wide range of scientific functions (National Museum of American History, n.d.-a).

21th century

21st century calculators

In the 21st century, calculators have become seamlessly woven into the fabric of everyday digital life. Rather than existing as separate devices, they are now built into the tools we use daily—whether it's a simple calculator app on a smartphone or advanced computational software like Excel, MATLAB, or WolframAlpha. While physical calculators still hold a place in education, particularly in math classrooms and exams, they too have been fully digital for decades. The age of analog calculators has long passed, closing a remarkable chapter in the history of human computation.

C. Statement Cards

Analog calculations are fascinating
Users are fascinated by the concept of analog calculations, as opposed to the digital way of calculating that they're used to.

- **p3:** *"It's fascinating to see this other way of calculating. I've never seen this analog way before."*
- **p4:** *"It's kind of cool that it's analog, it's like different."*
- **p2:** *"Most unique? That you can actually calculate with it. The function itself isn't new, but the mechanical way it works makes it feel unique."*
- **p1:** *"[The most unique aspect is the] more mechanical, playful way of calculating."*
- **p3:** *"[The most unique aspect is] that it's like analog. It's not digital. It's doing all of the work on its own."*
- **p4:** *"[The most unique aspect is] the fact that it's physical. No screen, nothing."*
- **p2:** *"I think it's cool that you can make something so mechanical that does what we normally expect a computer to do."*
- **p2:** *"It feels new to me because I've never used one. What's new is the interaction. It's just a different way of doing math."*

The interaction is more meaningful than the outcome
Users value the activity of interacting with an artifact more than the result of this interaction.

- **p2:** *"I would use it for the activity, not the end result."*
- **p3:** *"I think it's just fun to like actually interact with it, and play around with it, and just seeing that something is happening."*
- **p2:** *"I'd probably just start randomly adding things. Like, two plus two—I know how to do that [in my head]—but now I have this thing, and I can see how it works [on here]."*
- **p3:** *"[It's] so much fun. I completely forgot what I was calculating, to be honest."*
- **p1:** *"I didn't understand it right away. It felt a bit too far removed from what I'm used to, but because it wasn't about an important end result, it didn't matter much."*

Tangibility adds to the experience
Users enjoy interacting with a tangible object.

- **p1:** *"I'm excited to use it! I love new gadgets."*
- **p1:** *"It was nice to have something in my hands; the stylus really made me excited."*
- **p3:** *"It's nice to hold."*
- **p4:** *"It's very engaging because you have to do a lot yourself."*

Replicas should preserve the essential qualities of the original artifact
Users tend to value a replica less if it lacks the elements they appreciated in their interaction with the original.

- **p3:** *"[The replica is] inauthentic ... The nice things from the old calculator are no longer there. Now it feels like a cheap knockoff."*
- **p4:** *"It's not an exact replica, because some functionalities are missing. Not all of those are essential, but some nice elements are not there in the replica ... I think the eraser [of the original] is quite unique and I would like to have that here as well."*
- **p3:** *"I'm missing out on a lot of experiences with the replica—the colors, size, functionality. Now it feels more like a toy."*
- **H:** *"Do you think the replica could replace the original?"* **p2:** *"Not really—I'd really miss the subtraction function. Without that, it's not a full calculator. And I just like that the original is made of metal—that feels much nicer."*

People enjoy playful interactions
A sense of playfulness makes the interaction more enjoyable for users.

- **H:** *"And now you can play with it."* **p3:** *"I'm very excited for that!"*
- **p1:** *"[The most unique aspect is the] more mechanical, playful way of calculating."*
- **p3:** *"It's so much fun to play with the numbers and the stylus!"*
- **p2:** *"I also like the interaction itself. It's fun that you use a little pen. It really feels like a toy."*
- **H:** *"What makes it fun?"* **p3:** *"Just playing with the numbers. I think just moving a little pencil and being like, 'I will reset and actually do some calculations'."*
- **p1:** *"Without playfulness, it would have been boring."*
- **p1:** *"As long as it's playful enough, confusion is less of a problem."*

Users imagine the artifact's original context
Users tend to imagine the original context the artifact was used in, even if they're not familiar with its history.

- **p1:** *"The tin material creates a retro vibe. At the time, was a futuristic way of calculating."*
- **p3:** *"I think it gives me like a professional vibe just because I imagine someone using it to calculate in like their daily business. I imagine someone in the 1950s using it. Unfortunately, I imagine a man."*
- **p3:** *"I just like thinking about the people using it."*

Something unknown is new and unique
Users consider unknown artifacts and technologies to be new and unique, because they're not familiar with it, regardless of the actual age or uniqueness of the artifact.

- **p2:** *"Despite prior knowledge that something is old, it can still feel very new if you're not familiar with it."*
- **p1:** *"[The most unique aspect is the] novel way of doing calculations."*
- **p1:** *"The way of calculating feels new. You can see that it's old, but you don't know the concept."*
- **p2:** *"But it still feels new to me, even though I know it's actually an old object."* **H:** *"What makes it feel new?"* **p2:** *"I've never used anything like this before. I had never even heard of it."*
- **H:** *"And what makes [the sliding mechanism] unique?"* **p3:** *"I just have never seen it like this before."*

Comparisons can make an experience more negative
Users often feel curiosity, fascination, and excitement when interacting with an artifact for the first time. With similar artifacts that follow, their focus tends to shift toward comparing them to the first—often noticing flaws or differences more critically.

- **p1:** *"Overall, the feelings with this second machine were less intense."*
- **p3:** *"I was disappointed because I compared it with the other calculator and I liked that one better ... It's not as much as the other one ... It works less elegantly than the previous one."*
- **p1:** *"Since I already knew how it worked, it was less confusing. But also less fascinating. Maybe I actually needed that confusion."*

Unfamiliarity is strange
Users often see unfamiliar things as strange or unusual.

- **p1:** *"It's something old that you don't completely know, so it's also a bit strange."*
- **p2:** *"It's strange: [It's] a different way of calculating than I would use."*
- **p4:** *"It's strange: [It's] non-intuitive compared to current calculators. [I'm] not used to analog calculators."*
- **p1:** *"It's strange: [It's] a different way of addition than I'm used to."*

The design behind the artifact is interesting
Users are interested in how an artifact has been designed and manufactured.

- **p3:** *"I wanted to know how [the replica] is made and how it works, because it's obviously hand-made."*
- **p4:** *"Oh, it's so developed. It's crazy that you can do that ... The design behind [the original]—How do you come up with it? ... For example like this pocket for the stylus. That makes it also look really like thought through."*
- **p2:** *"It's very "manufactured"—a little metal object with tiny details. I can't imagine how someone would make this by hand."*

Novelty can make interaction frustrating
If an artifact is too different from what the user is used to, the interaction may become overly challenging and lead to frustration.

- **p1:** *"What I found less pleasant: I didn't understand it right away. It felt a bit too far removed from what I'm used to ... It's too novel to use and understand how it works."*
- **p4:** *"I get confused. It's a very non-intuitive way of doing the calculation."*
- **p4:** *"[I experienced] some frustration that it wasn't working as I expected."*
- **p1:** *"I suddenly can't do math anymore!"*
- **p1:** *"Confusion is only fun if you can see a way out."*

Professionalism is judged by looks
An artifact's design influences whether users perceive it as a serious tool or as a toy.

- **p2:** *"[The original] looks more serious, which makes me trust it more."*
- **p2:** *"[The original] looks professional and feels reliable ... It feels like a tool due to its size and weight."*
- **p2:** *" [The original] feels much more professional—like something you'd really use to calculate ... It just looks more serious—especially with the text and labels."*
- **p1:** *"[The original's] colors give it a professional and businesslike appearance."*

Unfamiliarity sparks curiosity
The user's curiosity is sparked by the unfamiliarity of the artifact, making the experience more fascinating.

- **p4:** *"I'm curious. I mean, I don't know, because it's so weird."*
- **p1:** *"At first, [I experienced] mostly curiosity, because it's a completely different way of calculating. You mentioned an abacus earlier, but this is really something else. The curiosity was strong, and I love discovering new things."*
- **p3:** *"I experienced fascination as well, because it's something that we don't use at all anymore. It's just like one of these calculators on your phone in a sense."*
- **p1:** *"Confusion combined with curiosity basically became fascination."*
- **p4:** *"It's so weird, that it's fun!"*

Mixing old & new elements sparks fascination
Users find artifacts more unique and engaging when they blend familiar elements with something new—whether in their physical design or the story they tell.

- **p1:** *"It's a unique way of calculating that I wasn't familiar with, but it vaguely resembles an abacus. The combination of something new and vaguely familiar makes it feel strange."*
- **p3:** *"[The most unique aspect is] the mix of old and new."*
- **p1:** *"It feels futuristic, but retro at the same time. I think that's because it's made of tin, which makes it feel old. But because you can do something new with it — calculating in a special way — it also feels futuristic."*

A functioning artifact is exciting
Users are pleasantly surprised when the artifact actually works when they interact with it.

- **p4:** *"You get surprised when it actually works ... [The artifact is the] most pleasant when it works."*
- **p3:** *"It's exciting to see it actually working."*
- **p2:** *"It does work, and that's fun."*

A playful look invites playful behavior
When an artifact resembles a toy, users are more likely to treat it as one. Conversely, if users engage with an artifact as if it were a toy, they're more likely to perceive it as such.

- **p2:** *"The original artifact feels like a tool. The replica feels like a toy, and you feel more inclined to play with it."*
- **p2:** *" It really feels like a toy. I wouldn't really use it as a 'real' calculator."*
- **H:** *"And what makes it feel like a game?"* **p1:** *"It's the way you use it."*
- **p1:** *"Because it works differently and is more mechanical, it feels more playful."*
- **p1:** *" I think the stylus especially is what makes it feel like a game."*
- **p2:** *"It's fun that you use a little pen. It really feels like a toy."*

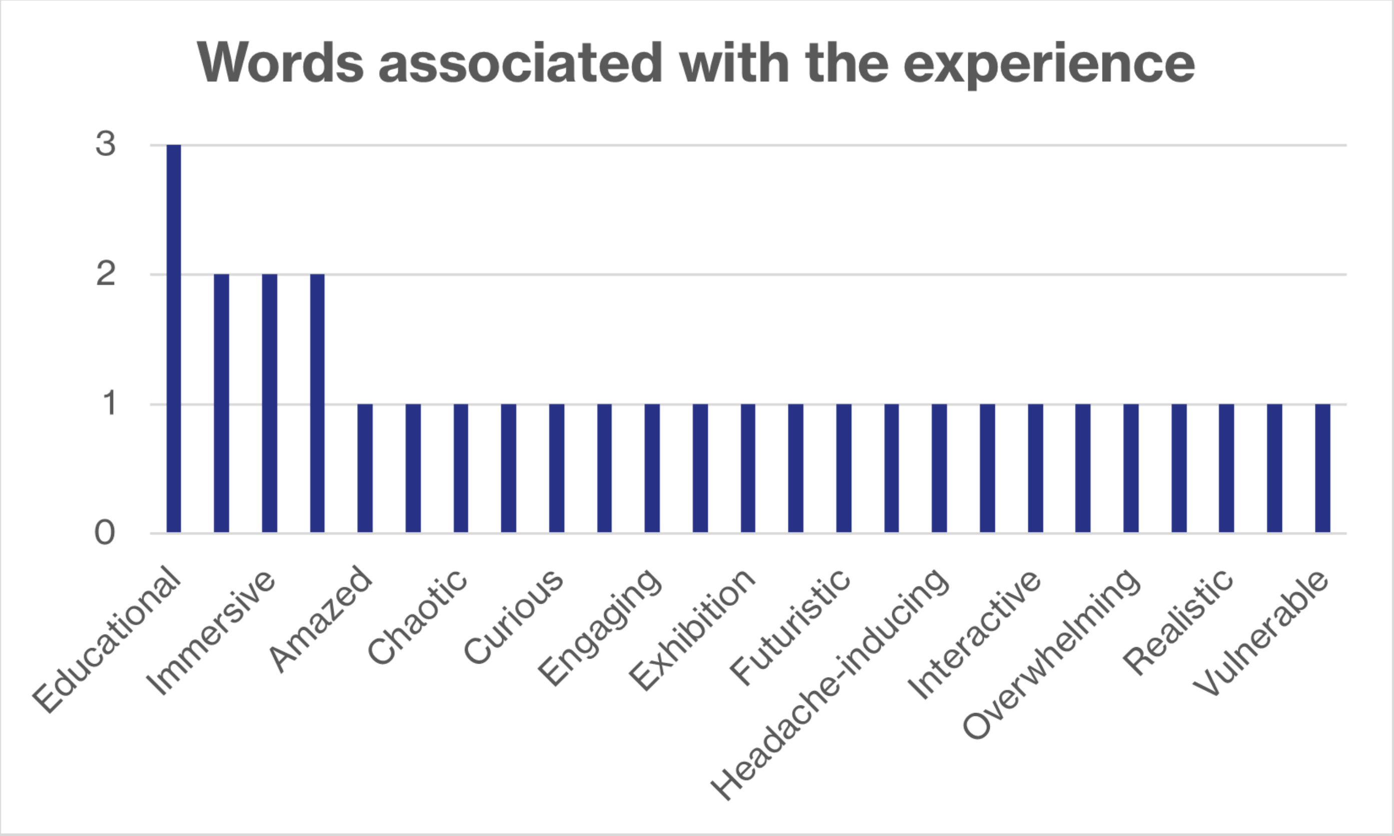
Confusion can trigger exploration
Users enjoy a sense of confusion that makes them want to explore the artifact further.

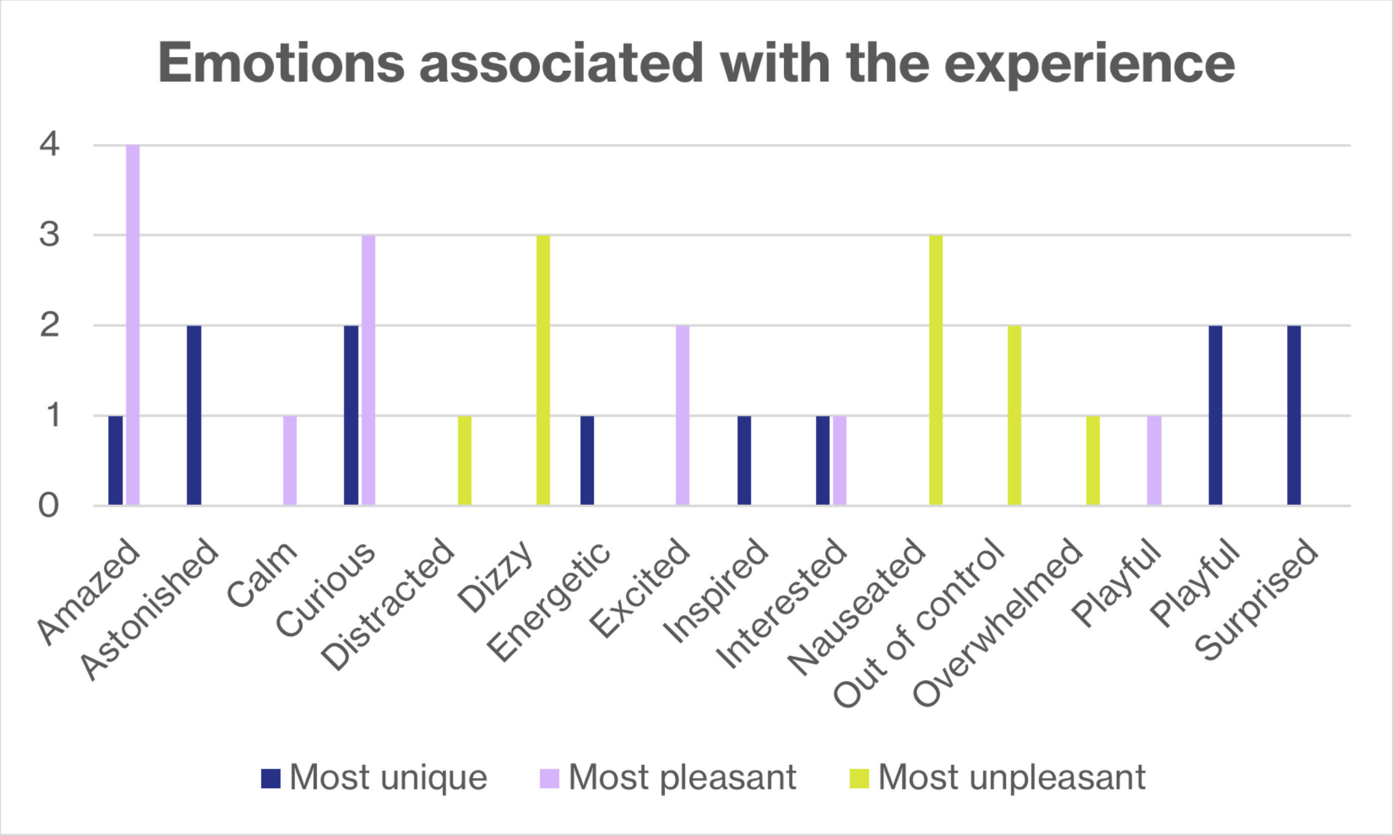
- **p2:** *"Because you don't fully understand how it works, you want to explore it. Curiosity plays a big role. You keep going because you're intrigued. I'm just using it, but part of the fun is not fully understanding it yet."*
- **p2:** *" I understand it even less than the other one, which makes it more entertaining."*
- **p1:** *"Since I already knew how it worked, it was less confusing, but also less fascinating. It was still fun to use, but there was less curiosity. Maybe I actually needed that confusion."*
- **p1:** *"Confusion combined with curiosity basically became fascination."*

D. Bodystorming results

Prop	Arithmometer (1870s)	Adder (1960s)	Slide rule (1960s)
Light	Candle / oil lamp	Hanging lamp / light up ad	Desk lamp
Pen	Fountain pen + ink	Pencil	Mechanical pencil
Cigarettes	Cigar / pipe	Cigarettes + ashtray	Cigarettes + ashtray
Drink	Tea	Coca-Cola	Coffee
Paper	Ledger	Notepad	Notebook
Music	Grammophone	Radio	Record player
Desk	Big, wooden	Counter	School desk
Picture frame	Painting of family	Family picture	Vacation picture with friends
Poster	World map	Handwritten ad	NASA poster
Book	Leather bound encyclopedia	Binder with prices	University book

E. Analysis user tests





F. Criteria Calculator's Desk

Criteria	Description	Criteria met?
Physical interaction without controllers	The system must support direct interaction with tangible interfaces, eliminating the need for VR controllers.	Yes. Users can interact with the experience through tangible props.
Interactive artifacts	The experience must provide users with embodied interaction with functioning artifacts, either originals that will be 'sacrificed' for the experience or replicas.	Yes. Users can interact with both visual and functional replicas.
Tactile responsiveness	Tangible components must provide physical feedback and feel rewarding to manipulate, even if they do not perfectly reproduce the original artifact's mechanical behavior.	Yes, but not all props' feedback mimic that of their original counterparts. More types of physical feedback could be included.
Historical context of artifacts	The experience must connect artifacts to their historical context and show the relevance to us today.	Yes. Artifacts are clearly connected to their historical context.
Multiple levels of engagement	The experience must include both brief, intuitive interactions and optional deeper content layers to support different user interests.	Yes. Users can just look around or explore each object and its information in more detail.
Emotional resonance	Replicas must be designed to trigger similar emotional responses even if they cannot fully match the aesthetic or material qualities of the original artifact.	Yes. Participants in the final user test responded in similar ways as the participants in the experiential characterization test.
Balancing unfamiliarity and usability	The interaction design must include some unfamiliar or surprising elements to stimulate interest but must also remain easy to understand without prior instruction.	Yes, depending on the user. Some users found the experience very easy to navigate, while others struggled more.
Contextualizing replicas	The replica must clearly be presented as an interpretive tool, not a one-to-one reproduction.	Yes. The design of the props clearly demonstrated that they're replicas.
Sensory feedback	Audio and visual cues could be integrated to simulate authentic user interaction and support engagement with the original devices.	Yes, partly. Visual cues have been integrated, but there are no audio cues yet.
Gamified elements	Gamification mechanics could be used to spark curiosity.	No. Would be a good addition to the experience.
Multi-user and social functionality	The spatial setup and interface design could accommodate multiple users interacting simultaneously, encouraging discussion and collaborative learning.	No. Would be a good addition to the experience.

G. Immersive Heritage Design Deck

The full version of the Immersive Heritage Design Deck is shown on the following pages.

application

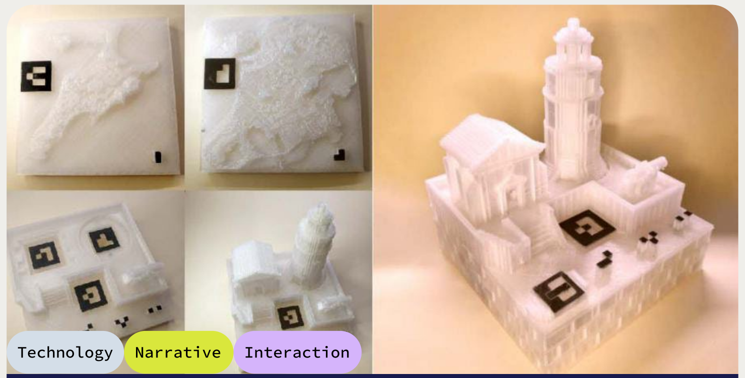
Technology Narrative Interaction

Immersive exploration of ancient Egyptian artifacts

WHAT? // An immersive experience for exploring ancient Egyptian artifacts, focusing on a mummified cat. Users interact with 3D-printed replicas for tactile feedback (TUIs) and engage in conversational dialogue with a virtual curator (SUIs). Features include realistic touch-based exploration, speech-guided storytelling, and a customizable learning path (Cannavò et al., 2024).

PLUS //
- Using TUIs and SUIs together significantly enhances user experience, making VR more engaging, immersive, and effective for CH.
- Both interfaces independently improve engagement, but TUIs are especially valuable for tactile realism.

application



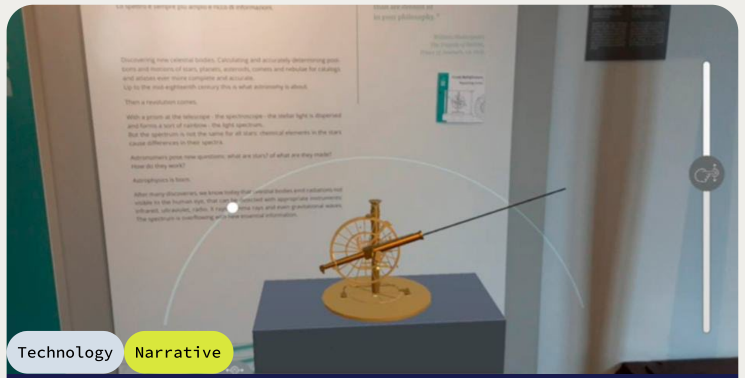
Technology Narrative Interaction

Virtual Guia Fortress Playset

WHAT? // The Guia Fortress Playset is a stackable, interactive model for exploring the Guia Fortress in Macau SAR, China. It features layered maps representing different historical periods and key structures like the church and lighthouse. A tangible boat marker triggers animations, including day/night cycles, lighthouse lights, and cannon firing. Made from 3D-printed and DIY materials, it offers an engaging, hands-on learning experience (Cardoso, 2021).

PLUS //
- Developed using accessible materials and technologies: affordable materials, flexible, marker-based solutions, and open-source software.

application



Technology Narrative

MARSS project

WHAT? // The MARSS Project enhances the Museo Astronomico di Brera (MusAB) with AR-based digital storytelling, making historical astronomical instruments more accessible. Visitors explore interactive 3D models, animations, and gamified narratives, revealing the scientific and cultural impact of astronomy. AR overlays enrich explanatory panels and physical artifacts, offering a dynamic, immersive experience guided by a dedicated app (Spadoni et al., 2022).

PLUS //
- Increased visitor engagement and time spent in the gallery.
- AR storytelling enhances learning and retention.
- Complex concepts become more accessible through AR.
- Interactive, narrative-driven experiences resonate with visitors.
- AR offers a scalable alternative to guided tours.

MINUS //
- Static AR Content lacks dynamic elements, making the experience less engaging.
- Poor angles can make viewing uncomfortable over time.
- Extended AR sessions may lead to fatigue and reduced focus.
- Misalignment between visuals and narration disrupts learning.

application

Technology

Reconstruction of the Celtic Druid Head

WHAT? // The Celtic Druid Head, a renowned Iron Age artifact (450–50 B.C.), was digitally scanned and reconstructed to restore missing details. Using symmetry-based methods and shape prediction algorithms, the well-preserved left side guided the recreation of lost sections. The enhanced model was integrated into AR environments with realistic lighting, allowing viewers to explore it in historical contexts, such as a reconstructed Celtic sanctuary (Haindl & Sedlacek, 2016).

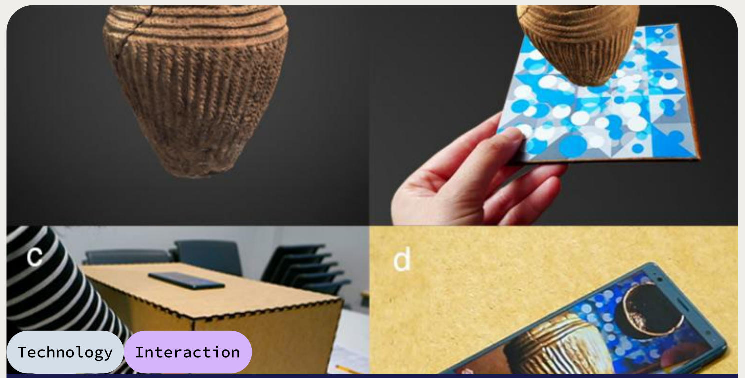
PLUS //
- High-quality replicas of the druid head can be created using 3D printing for museum displays.
- Augmented reality setups allow visitors to explore the artifact in immersive environments
- Archaeologists can use the model to hypothesize about the cultural and historical contexts of its creation and use.
- Art historians can analyze the chiseling techniques, material choices, and ritualistic significance of the artifact.

SAR-based interactive Korean artifacts

WHAT? // This interactive exhibition system combines Spatial Augmented Reality (SAR) with real-time visitor participation, projecting virtual artifacts onto real surfaces. Visitors interact using their smartphone flashlights to explore lighting effects or hand gestures tracked by depth sensors like Kinect. In one exhibition, small cultural artifacts respond dynamically to light direction, while another reveals the internal structure of a real-sized earthenware coffin (Onggwan) through gestures. A fisheye camera maps flashlight positions in real-time, enabling smooth 30 fps interaction and dynamic relighting on a standard PC (Lee et al., 2015).

PLUS //
- Despite using 2D surfaces, the projections appear authentic due to advanced techniques in illumination, inter-reflection, and meso-structure texture rendering.
- Visitors experience a heightened sense of realism and interaction, engaging with cultural artifacts in novel ways.

MINUS //
- Material Constraints: Struggles with non-diffuse surfaces like specular highlights.
- Scale Limitations: Current systems are optimized for small objects (up to 40 cm²),
- Surface and Shape Limitations: The system is mainly suited for flat or relief-type surfaces, limiting its application to fully 3D artifacts.



ARcheoBox

WHAT? // This tangible AR interface lets users pick up, handle, and explore digitized historical artifacts naturally and interactively. Using 3D scanning and photogrammetry, it creates high-quality virtual replicas, offering close encounters with objects typically kept behind glass. This immersive approach makes history more accessible and engaging (Kobeisse, 2021).

PLUS //
- Enhances engagement, accessibility, and educational value of historical artefacts.
- Encourages knowledge sharing within a broader community.

Tangible VR Book

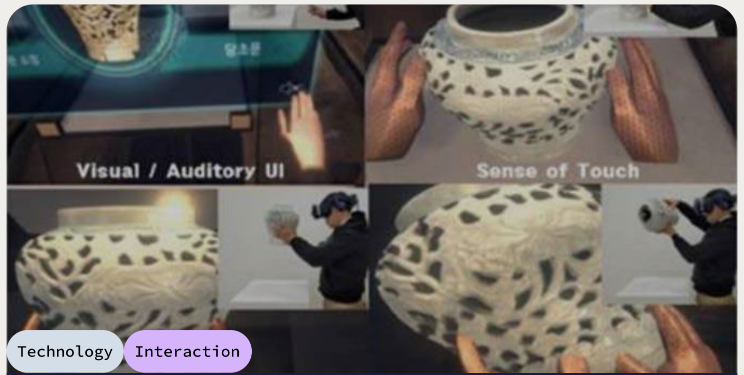
WHAT? // The VR Book is a tangible user interface (TUI) designed as a physical book with thick pages, each featuring visual markers that trigger interactive digital experiences. Users can navigate 360° reconstructions, inspect 3D models, and enter virtual environments via tangible portals. Key interactions include page turning, a physical slider for content browsing, and dynamic portals for immersive exploration. Successfully used for cultural heritage reconstructions, such as the 1834 Monastery of Santa Cruz (Cardoso, 2021).

PLUS //
- Developed using accessible materials and technologies: affordable materials, flexible, marker-based solutions, and open-source software.

Chinese Traditional Wheelbarrow Game

WHAT? // VR Wheelbarrow Challenge is a puzzle-based VR game where players navigate diverse terrains while operating a virtual traditional Chinese wheelbarrow. Using VR controllers, players push, balance, and maneuver through obstacles with realistic feedback. Featuring four terrains inspired by Chinese geography, the game challenges players to reach endpoints while maintaining balance and control (Guojun et al., 2023).

PLUS //
- The game bridges historical practices and modern technology, offering a unique lens into the ingenuity of traditional Chinese farming tools.



HMD-Based Multisensory VR System

WHAT? // This system blends high-precision 3D scanning, sensor-equipped 3D-printed dummies, and bare-hand interaction to create a seamless multisensory experience. By replacing traditional controllers with hand-tracking technology, users can naturally manipulate virtual objects with full 6 degrees of freedom. Tactile feedback is enhanced through sensors embedded in 3D-printed dummies, replicating the texture and shape of real artifacts. Synchronized audiovisual and touch inputs ensure an immersive experience, eliminating sensory delays. The system integrates a hand-tracking module for real-time interaction and a dummy-object module that links physical replicas to their virtual counterparts (Kim et al., 2023).

PLUS //
- Enhanced realism: Natural bare-hand interaction and tactile feedback increased presence.
- Improved immersion: Multisensory content deepened emotional engagement and focus.
- Higher preference: Users favored the realistic, hands-on VR experience.

VR Time Travel

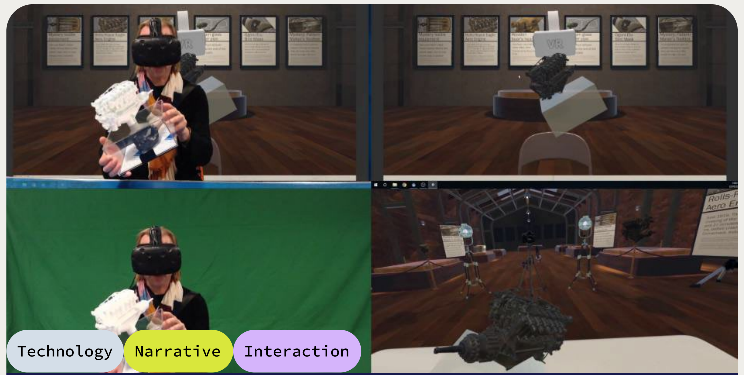
WHAT? // This VR experience brings ancient sites and artifacts to life, allowing users to explore history remotely. Featuring high-detail 3D reconstructions, it makes inaccessible locations—like Ancient Olympia—virtually available. The Temple of Zeus and its statues are digitally restored using historical research and Kinect 2 head tracking, offering multiple viewing angles. Designed for classrooms and museums, it provides an interactive, immersive way to engage with ancient history beyond traditional exhibits (Plecher et al., 2019).

The Loupe: Text-Based AR

WHAT? // The Loupe is a wooden magnifying lens embedded with an iPhone. It enables visitors to:

1. Examine objects up close using image recognition technology.
2. Access digital content (text, images, or animations) relevant to recognized objects (Van Der Vaart & Damala, 2015).

PLUS //
- Different visitor types used the Loupe in varied ways, aligning with their engagement styles.
- Many visitors spent more time looking at objects because of the Loupe's additional information.
- Even basic visual content, such as simple .gif animations, had a strong impact on visitor engagement.



VRtefacts

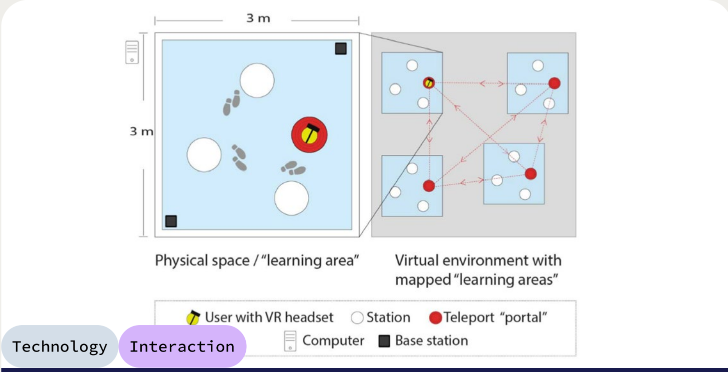
WHAT? // VRtefacts is an interactive VR experience that lets visitors touch, move, and examine 3D-printed or scanned artifacts while crafting personal stories. By exploring rescaled objects with varied textures and weights, visitors develop deeper connections with museum pieces. The experience is structured for storytelling, encouraging participants to record and donate their interpretations for future audiences. Passive haptics ensures alignment between physical and virtual objects, while a host guides visitors through the journey (Spence et al., 2020).

PLUS //
- Visitors were generally more engaged with 3D prints than 3D scans. Tactile interaction amplified engagement and a sense of reality.
- Participants valued tactile interaction, which fostered deeper personal connections and storytelling.

Technology Interaction

Tangible Weaving Experience

WHAT? // Weaving Time is an interactive installation that immerses visitors in the craft of Incan weaving. Featured in The Incas, Treasures of Peru exhibition, it allows visitors to create and extend a digital tapestry by selecting and arranging pattern tiles on a table. A shuttle mechanism slides across the table, adding the chosen designs to a projected tapestry that wraps around the room. As each new row is woven, the tapestry shifts, creating an evolving, collaborative artwork that brings Incan textile traditions to life (Gagarín, n.d.).



Technology Interaction

Tangible VR learning areas

WHAT? // This VR learning environment blends tangible interaction with immersive navigation, allowing users to walk freely while engaging with digital and physical objects. Symbiotic stations create a seamless link between virtual and real spaces, enhancing engagement. Users navigate via restrained teleportation within a 3m x 3m area, moving between persistent learning stations that offer 3D asset interaction, information access, and haptic feedback. This approach optimizes space, reduces costs, and enriches spatial memory, making it ideal for museums and heritage sites (Zhang & Lopez Silva, 2020).

PLUS //
- By integrating restrained teleportation, tangible interactions, and reusable stations, the proposed demo offers an immersive, cost-effective, and engaging way to explore cultural heritage.

Technology Narrative

A History of Enterprises

WHAT? // This project uses storytelling, VR, and interactive technology to make industrial heritage engaging and relatable. Narratives guide visitors through recreated industrial spaces, blending fictional storytelling with real historical events for an emotional connection. A 3D VR experience showcases the 30-year evolution of Grupo Antolin, from a small automotive workshop to mass production, using Oculus Rift and 360° VR. Interactive dioramas combine real car parts with virtual elements, while videomapping animates historical spaces and manufacturing processes, creating an immersive, multisensory experience (López & Cruz, 2021).

PLUS //
- Integrating storytelling with immersive technologies is highly effective for educating the public about industrial heritage.
- This approach not only preserves cultural memory but also makes history accessible and engaging for diverse audiences.

Technology Narrative

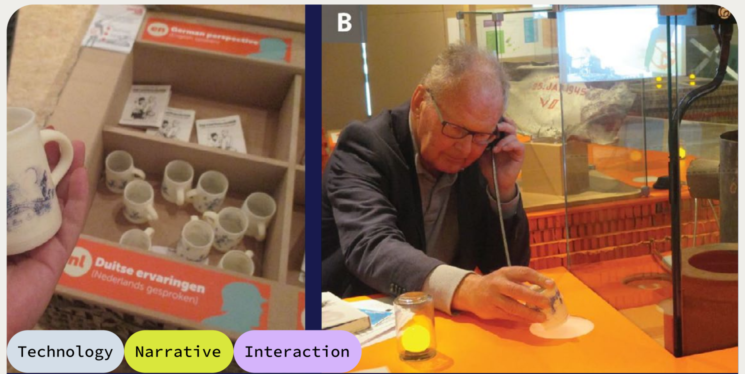
Gamified Greek art

WHAT? // This AR-enhanced museum experience combines physical artifacts with virtual elements to boost engagement. Visitors interact with virtual guides—ancient gods brought to life—who present riddles and tasks, unlocking historical insights as they navigate the museum. Using smartphones or tablets, the AR system tracks statues via Unity 3D and Vuforia, displaying digitally restored versions with original colors and missing parts. This gamified approach offers a hands-on way to explore ancient Greek art, conservation techniques, and cultural history (Plecher et al., 2019).

Technology

Spectare Device

WHAT? // Spectare is a modern XR stereoscope inspired by 19th-century designs, displaying stereo photos, 360° visuals, and immersive soundscapes. It uses 2D barcodes for object detection, reducing smartphone processing demands. Made from cardboard or wood, it provides a cost-effective way to explore cultural heritage, enhancing engagement with stereo and 360° reconstructions (Cardoso, 2021).



Technology Narrative Interaction

The Atlantic Wall: Smart Replicas

WHAT? // The Atlantic Wall Exhibition in The Hague featured a physical city map with displays showcasing historical objects, documents, and models. A separate narrative layer enriched engagement through eyewitness stories. To enhance immersion, smart replicas of historical objects acted as keys to unlock digital content, allowing visitors to experience the exhibition from a personalized, overarching perspective (Marshall et al., 2016).

PLUS //
- Visitors found the objects engaging and aesthetically interesting, appreciating their connection to the historical narratives.
- Museum staff and visitors noted that without the smart replicas, the exhibition felt incomplete. Initially intended as an additional interactive layer, the replicas became an essential part of the experience.

MINUS //
- Some only activated content in areas of personal interest, resulting in fragmented storytelling rather than a complete perspective.
- Visitors did not necessarily find them easier to use than other interactive systems.

Technology Narrative

Views of the Past

WHAT? // This VR experience brings the Forum of Augustus to life through interactive storytelling and environmental narrative design. Visitors explore a 3D reconstruction filled with historical fragments, everyday objects, and narrative snippets, transforming the space into a "living place." Using a stereoscope VR device, visitors trigger VR scenes as they move through Trajan's Market, where artifacts from the Forum are displayed. The system uses Bluetooth-enabled Beacons to adapt the experience in real-time, immersing visitors in the reconstructed past (Petrelli & Roberts, 2023).

PLUS //
- Immersive visuals and narratives deepen appreciation of past environments and social life.
- Artifacts evoke daily life, making history feel tangible.
- VR conveys grandeur, letting visitors experience historical structures' scale firsthand.
- Visitors felt physically and socially present in the historical setting.
- Short, personal stories resonated more than factual descriptions.

MINUS //
- Some narrative fragments from the game lacked relevance to the exhibit.

Technology Narrative Interaction

My Roman Pantheon

WHAT? // This tangible interactive installation at a museum along Hadrian's Wall immerses visitors in Roman religious culture through hands-on rituals. Acting as Roman citizens, visitors make offerings to deities, interacting with artifacts that respond to their choices, illustrating ancient beliefs and practices. A specially designed interactive ritual lamp serves as the core of the experience, reacting to actions like lighting up at commands and extinguishing when offerings are made. Integrated sensors and computational units create a seamless blend of physical and digital interaction, guiding visitors through a personalized ritual where they choose deities and engage in symbolic worship. By physically performing these acts, visitors connect with the intentionality and cultural significance of Roman religious traditions (Petrelli & Roberts, 2023).

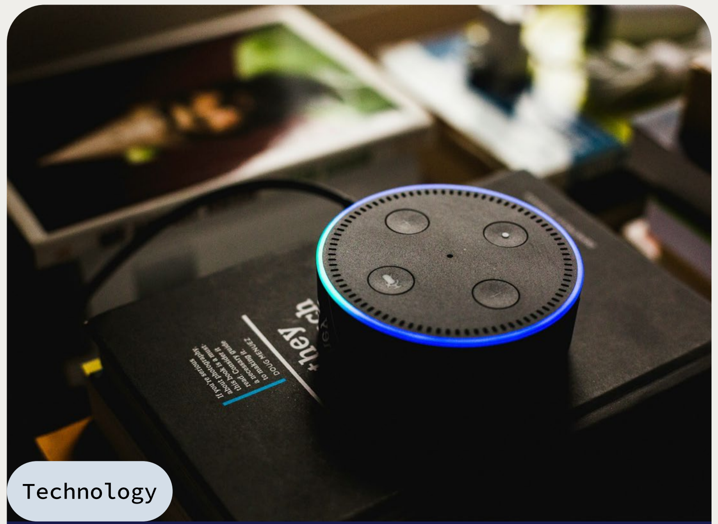
PLUS //
- Participation turns the visit into an interactive, exploratory journey, deepening cultural connection.
- Physical engagement and ritual context immerse visitors in Roman religious practices.
- Touch strengthens personal connections, while offerings evoke ritual significance.
- Visitors felt culturally immersed through hands-on involvement.

Technology

Virtual humans for storytelling

Virtual humans can act as engaging narrators or guides in XR heritage experiences, helping to personalize interactions and bring stories to life. When using them, consider how realism in movement, eye contact, and facial expressions affects user trust and immersion. Striking the right balance is key—too little realism can break engagement, while too much can lead to the uncanny valley (Cannavò et al., 2024).

design implication



Technology

Speech interfaces for natural interaction

Speech User Interfaces (SUIs) can make interactions in XR heritage experiences feel more intuitive and conversational. By enabling users to ask questions or share preferences naturally, SUIs support more flexible and personalized exploration (Cannavò et al., 2024).

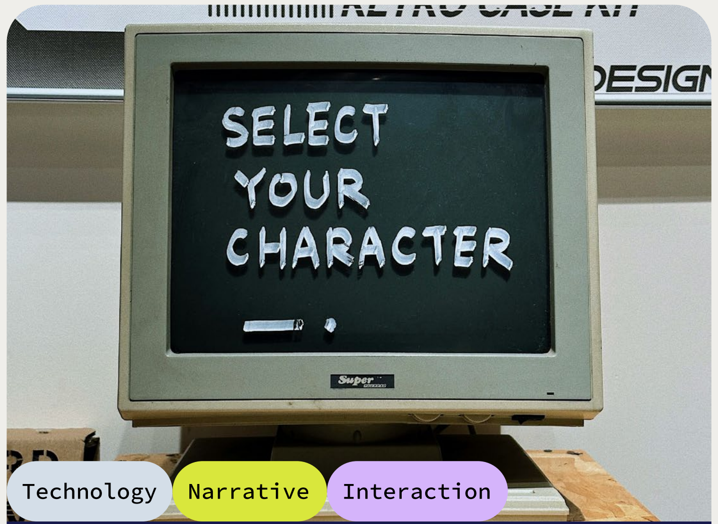
design implication

Technology Interaction

Exploration of artifacts

XR enables experts to visualize and explore both historical and contemporary perspectives of cultural heritage, gaining new insights and knowledge. It allows researchers to hypothesize about an artifact's original appearance and function while offering innovative methods to study craftsmanship, rituals, and materials (Bekele et al., 2018; Haindl & Sedlacek, 2016).

design implication

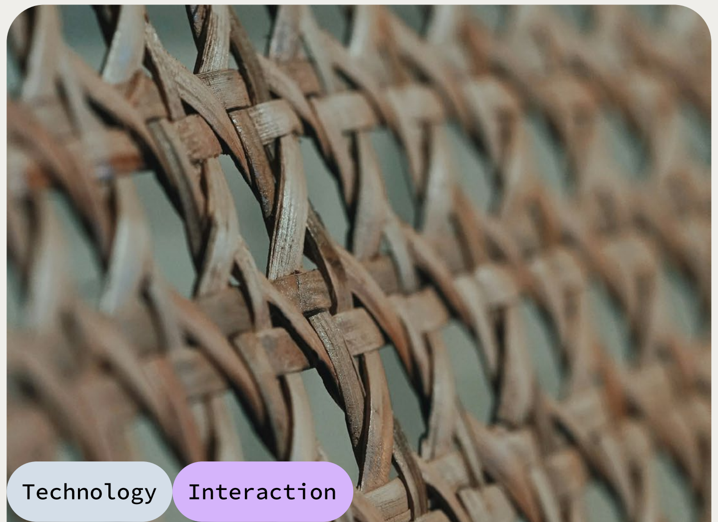


Technology Narrative Interaction

Personalization & autonomy

Digital experiences give visitors the freedom to explore content at their own pace and based on their interests. Design XR interactions that allow for choice and flexibility—whether through branching narratives, adjustable depth of information, or self-guided navigation—to create more meaningful and user-centered experiences. (Cannavò et al., 2024).

design implication



Technology Interaction

Artifact complexity

Highly detailed artifacts can pose challenges for scanning, rendering, and interaction in XR. When designing with intricate objects, consider how much detail is necessary to convey meaning, and how simplification or abstraction might support usability without losing cultural significance (Bekele et al., 2018).

design implication

Technology

Technology vs heritage

There's a risk that immersive technologies may draw attention away from the artifacts themselves, prioritizing novelty over meaning. Consider how technology can enhance interpretation and address real curatorial goals—ensuring the cultural significance remains central, not secondary (Bekele et al., 2018).

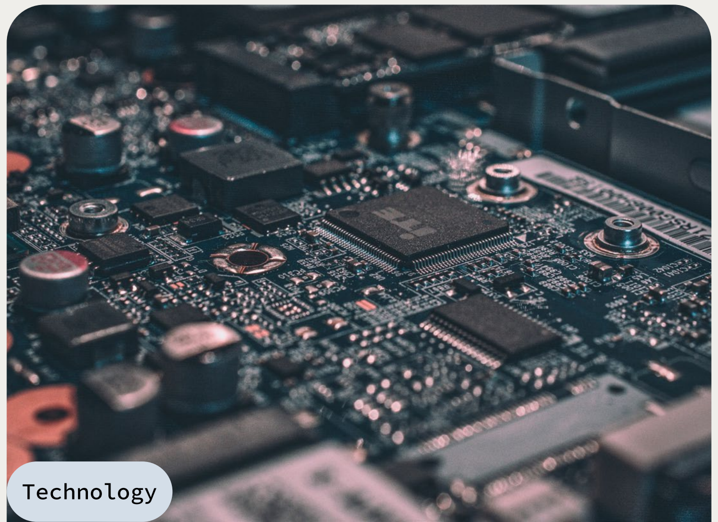
design implication

Technology Interaction

Access to inaccessible artifacts

XR can provide valuable access to cultural heritage when physical interaction isn't possible—whether artifacts are too fragile, off-limits, or located far away. Design with accessibility in mind, using XR to create meaningful, respectful encounters that preserve both the object and the visitor's sense of connection (Bekele et al., 2018).

design implication



Technology

Technological limitations

Creating XR experiences often demands significant resources—from specialized programming to high-fidelity visuals—making it costly and complex for many museums. Consider scalable and reusable approaches that can help institutions manage these demands while still delivering meaningful experiences (Van Der Vaart & Damala, 2015).

design implication

Technology Narrative Interaction

Enhancing learning

Immersive XR experiences can make historical sites and artifacts more accessible and memorable by engaging users through visual storytelling and interactive exploration. Replacing static, text-heavy formats with dynamic content can improve understanding and retention—especially when a sense of presence helps users connect emotionally with the material (Bekele et al., 2018; Innocente et al., 2023; Spadoni et al., 2022).

design implication

Technology Interaction

Immersion within technical limits

VR can powerfully simulate real-world experiences, but achieving high immersion depends on sensory fidelity—like visual realism, spatial audio, and responsive interaction. Be aware of current technological constraints and find creative ways to maintain presence and engagement, even when perfect realism isn't possible (Cannavò et al., 2024).

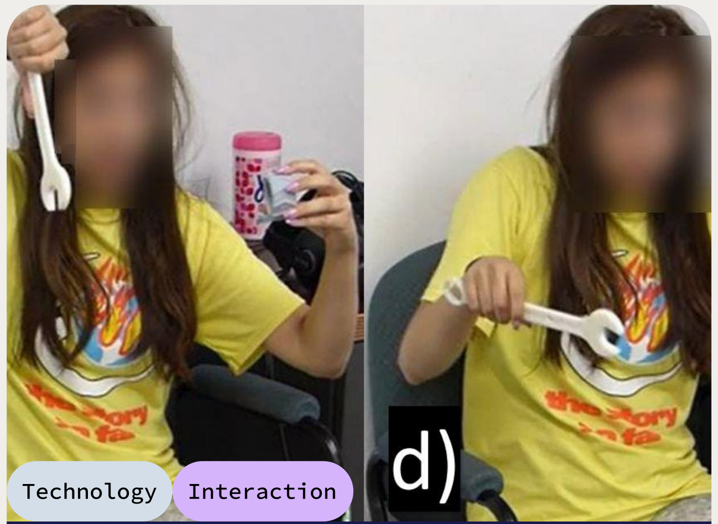
design implication

Narrative

Valuing the ordinary

Everyday, mass-produced instruments—essential for understanding scientific practice—are often overlooked in favor of visually impressive or historically significant objects. This bias towards aesthetic and uniqueness risks losing an essential part of science's history. Consider how these "ordinary" tools can offer valuable context and help tell a more complete story of scientific history (Lourenço & Wilson, 2013; Petrelli & Roberts, 2023).

design implication

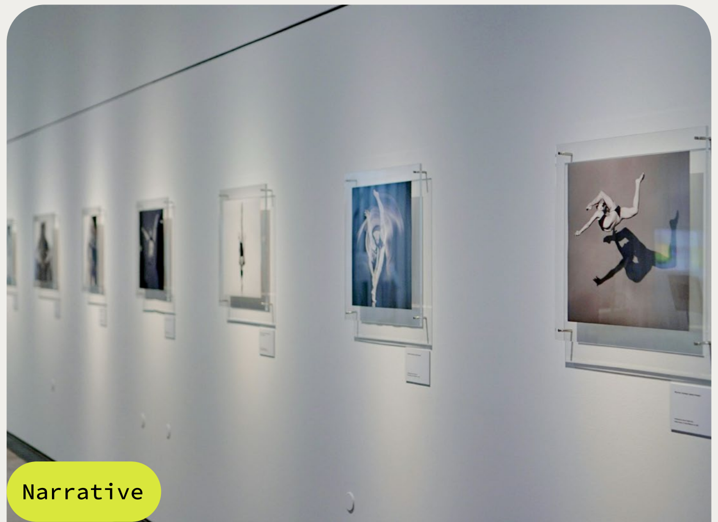


Technology Interaction

Interaction through props

Physical props can make virtual interactions feel more natural by replacing standard controllers with tangible objects that match the look and function of their digital counterparts. Consider using props that reflect virtual items and, where possible, reconfigurable elements that offer flexibility without sacrificing realism or increasing cost (Moran-Ledesma et al., 2021).

design implication

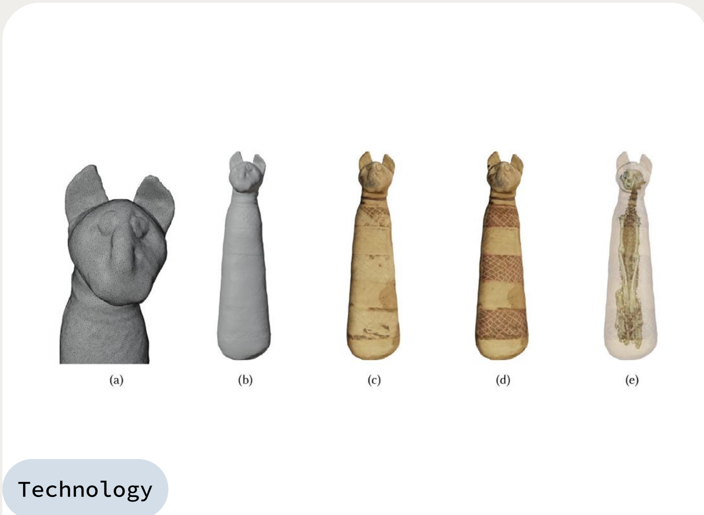


Narrative

Enhancing readability

Well-written texts can draw visitors deeper into objects, not away from them. Keep text short and clear, avoid jargon, and break it into manageable sections. Use engaging language—like questions or vivid imagery—to spark curiosity without overwhelming the experience (Van Der Vaart & Damala, 2015).

design implication



Technology

Reconstructing artifacts

XR can help users explore restored versions of cultural heritage—recreating damaged, lost, or hidden details for better understanding. By using AR or digital replicas, fragile or hard-to-access artifacts become available for public engagement, offering new ways to connect with the past (Bekele et al., 2018).

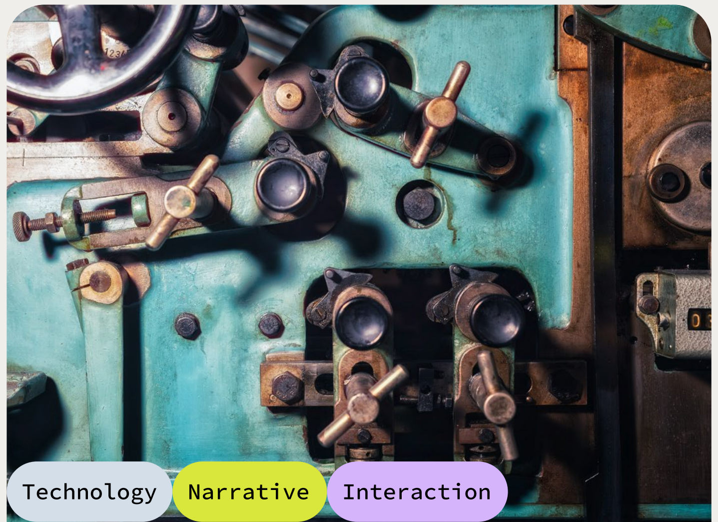
design implication

Technology Narrative Interaction

Cultural and environmental presence

In XR, visitors can explore more than just historical architecture—they can experience how spaces were used through the inclusion of everyday objects and embedded narratives. When designing, think about how furniture, tools, and personal items, paired with contextual storytelling, can bring historical environments and their inhabitants to life (Petrelli & Roberts, 2023).

design implication

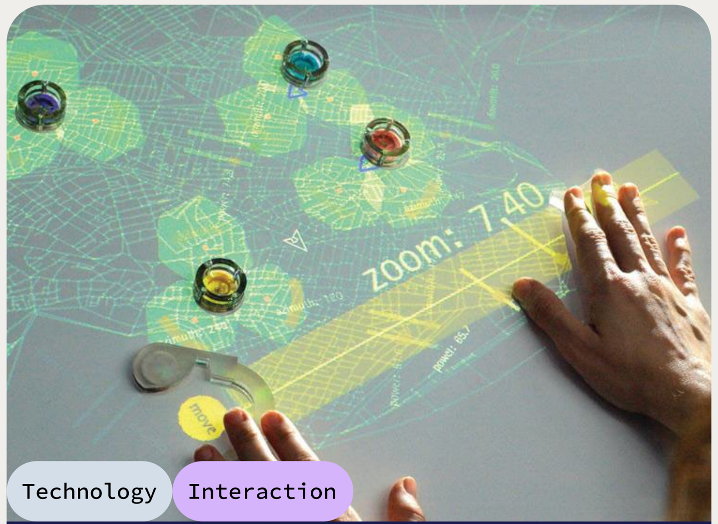


Technology Narrative Interaction

Functionality over material authenticity

Visitors often judge scientific and technological exhibits by how well they explain complex concepts—not by whether the object is original. In XR experiences, models or simplified representations can sometimes be more effective than authentic artifacts (Hampp & Schwan, 2015).

design implication

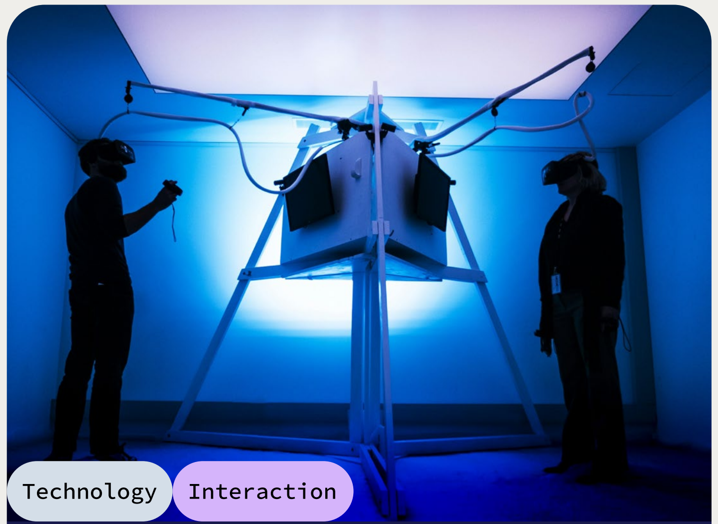


Technology Interaction

Perceptual coupling

A successful tangible user interface depends on strong perceptual coupling—where physical objects and digital responses feel tightly connected. When designing, focus on real-time feedback and aligning input and output spaces, so users experience the interaction as seamless and intuitive, rather than disjointed or delayed (Cannavò et al., 2024; Ishii et al., 2012).

design implication

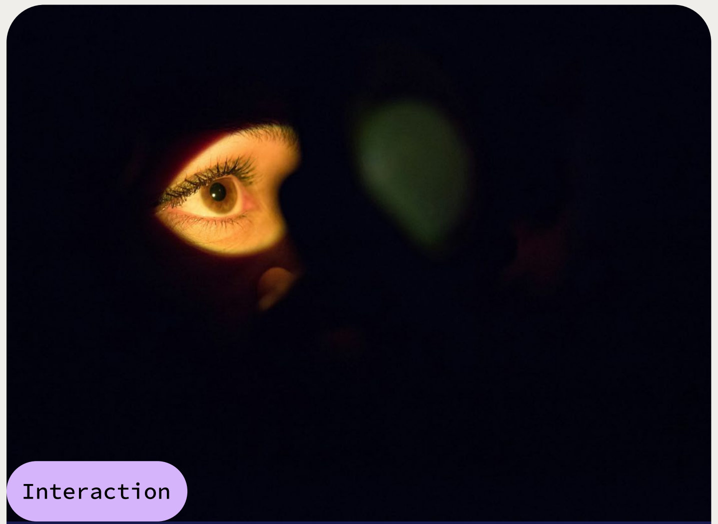


Technology Interaction

Social presence and communication

A strong sense of co-presence in XR relies on smooth, meaningful communication. Barriers like delayed responses or unclear feedback can break that connection. Designing for reciprocity (action-response exchanges) helps users feel acknowledged, emotionally connected, and truly present with others or virtual characters (Ch'ng et al., 2023).

design implication

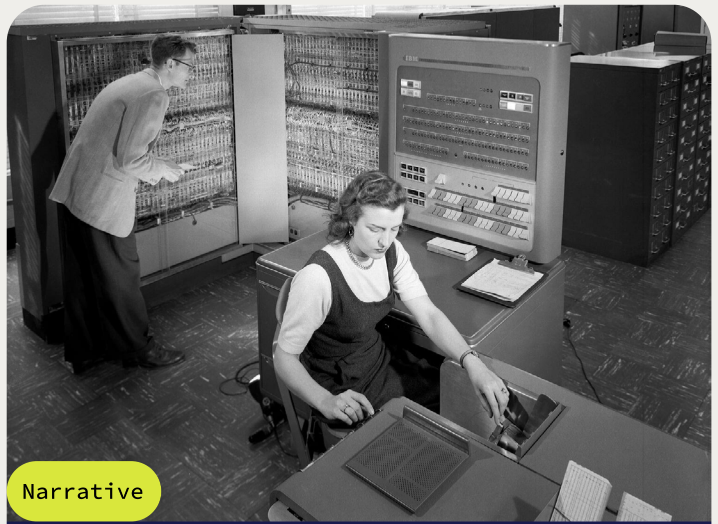


Interaction

Attention limitations

Users can only process one thing at a time, and their attention spans are short. In XR experiences, avoid overwhelming users with too much information or too many simultaneous elements. Guide focus intentionally through pacing, visual hierarchy, and clear interaction cues (Van Der Vaart & Damala, 2015).

design implication



Narrative

Narrative-driven heritage

Visitors connect more deeply with scientific heritage when it's framed through stories, not just facts. A meaningful object isn't defined only by what it is, but by the life it has lived—who used it, how, and why it mattered. Use narrative-driven interactions to reveal the human side of scientific progress (Faria et al., 2015; Lourenço & Wilson, 2013; Marshall et al., 2016).

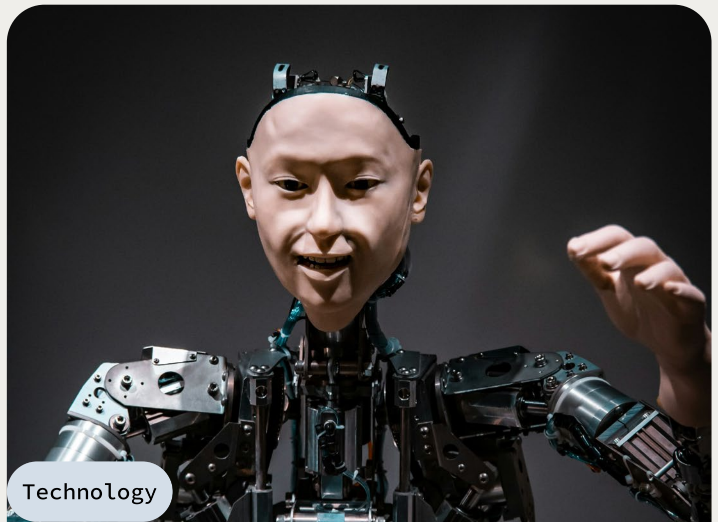
design implication

Technology Interaction

Technological skepticism

Not all museum visitors are equally comfortable with new technologies—some may be hesitant that affect how they engage. When designing XR or interactive experiences, consider a range of user preferences and offer clear, approachable entry points to build trust and ease of use (Bekele et al., 2018).

design implication



Technology

The uncanny valley effect

Virtual humans that are almost—but not quite—realistic can create discomfort, known as the uncanny valley effect. Watch for inconsistencies like stiff movement, unnatural facial features, or gestures that don't match speech. Careful attention to detail helps maintain trust and immersion in the experience (Cannavò et al., 2024).

design implication

Narrative

Heirs to the past

Scientific heritage isn't just about preserving objects—it's about helping people see themselves as part of an ongoing story of discovery. Create meaningful connections with the past, showing how science has shaped our understanding of the world and our place in it (Lourenço & Wilson, 2013).

design implication

Technology Interaction

Shared realism

Users tend to enjoy XR experiences more when they feel a strong social connection, rather than when objects look highly realistic. Prioritize social presence and meaningful interaction, especially during tasks, as these can make virtual objects feel more natural and engaging (Ch'ng et al., 2023).

design implication

design implication

Technology Narrative

Enhanced storytelling

XR can bring artifacts to life by layering historical and scientific context directly onto them. Use narrative-driven overlays to help objects explain their own significance and illustrate abstract ideas. This approach can make complex topics—like scientific heritage—more accessible, engaging, and easier to understand (Spadoni et al., 2022).

Narrative Interaction

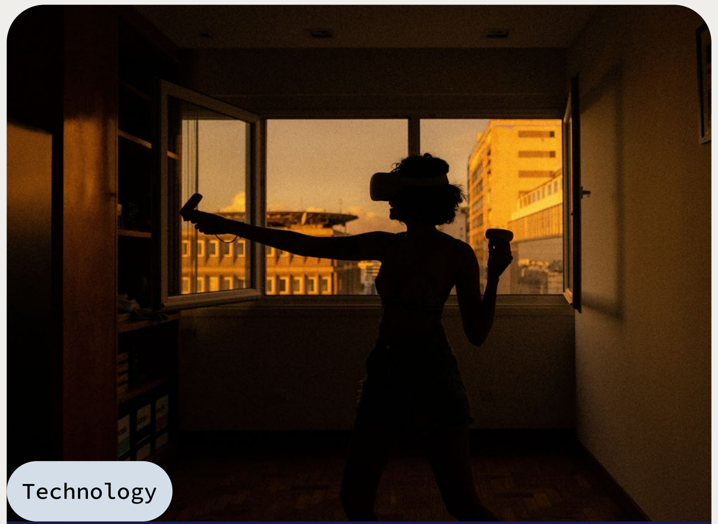
Balancing artifacts and information

Visitors naturally shift attention between artifacts and the information provided about them. Effective XR experiences blend interaction with objects and engagement with interpretation in a way that supports understanding without overload. Design with pacing, clarity, and focus to help users make meaningful connections (Van Der Vaart & Damala, 2015).

Technology Narrative

Out of context

Ancient artifacts can feel distant or unclear when separated from their original context. XR experiences can bridge this gap by helping visitors imagine the social, cultural, and architectural worlds these objects once belonged to. Design interpretive layers that invite dialogue with these “opaque” artifacts, uncovering their deeper significance (Petrelli & Roberts, 2023).



Technology

Limited mobility

Head-mounted displays (HMDs) can be challenging to use in crowded or busy environments. Limited mobility, spatial constraints, and the need for supervision can affect the experience. When designing for public settings, plan for restricted movement and think about how to keep interactions comfortable and safe (Giariskanis et al., 2022).

Technology Interaction

Rehabilitation of touch

Hands-on interaction supports learning, emotional connection, and accessibility—especially for visitors with visual impairments. While real artifacts may be too fragile to handle, replicas paired with XR offer safe, effective alternatives. Adding sound, lighting, and other sensory elements can turn passive viewing into active, memorable participation (Kim et al., 2023; Petrelli & Roberts, 2023; Spence et al., 2020).

Technology Interaction

Social learning

Learning is often enhanced through shared experiences. In XR, social presence—whether among families, couples, or strangers—can boost focus, communication, and emotional connection. Even solo visitors benefit from seeing others interact. Design virtual spaces that encourage awareness, interaction, and shared meaning-making (Ch’ng et al., 2023).

Interaction

Sensory mismatches

When a physical prop doesn’t match its digital counterpart in size, shape, or feel, it can lower immersion. To maintain a believable experience, ensure that tactile elements align closely with visual and interactive cues in XR. Consistency across senses helps users stay engaged and grounded (Spence et al., 2020).

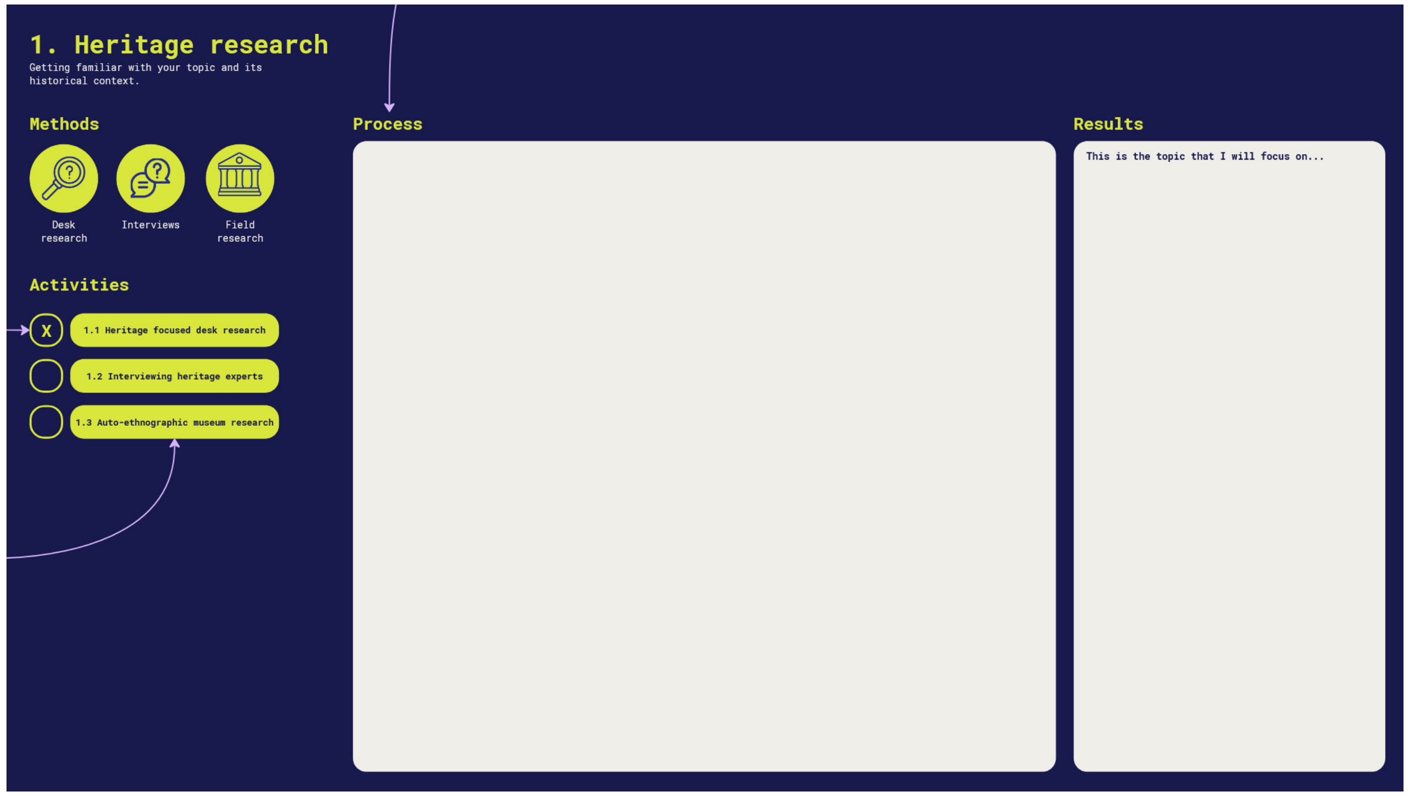
Technology Narrative

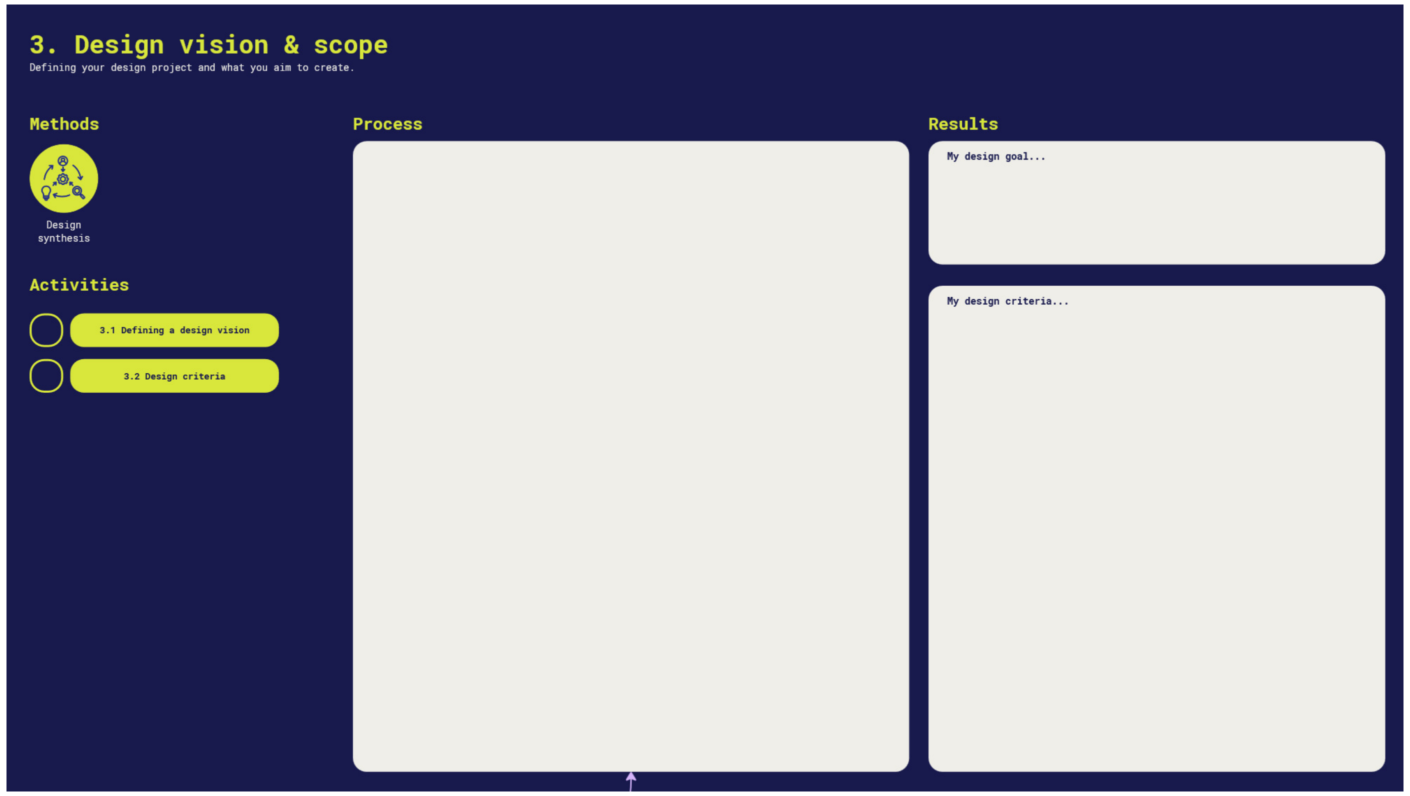
Gamification

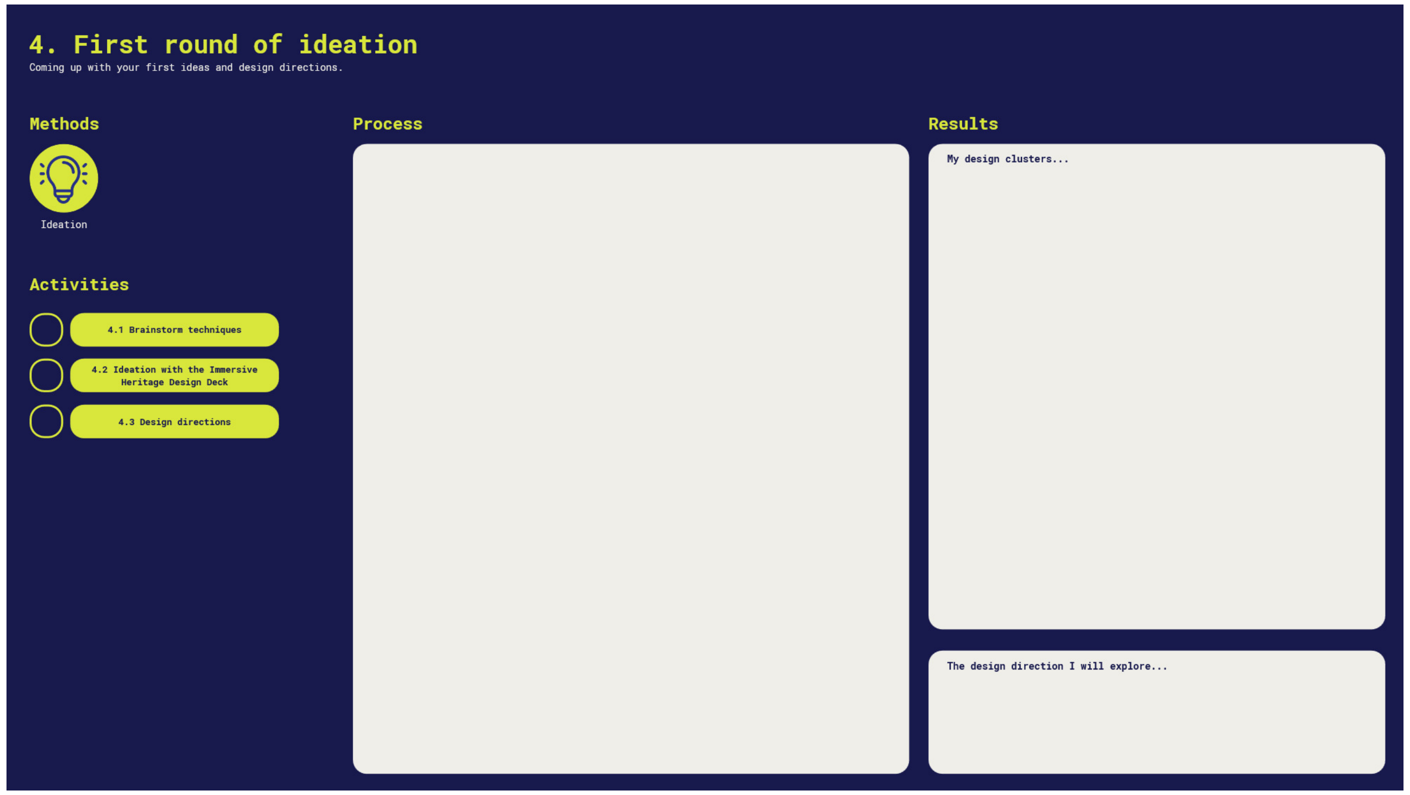
Interactive elements like quizzes, challenges, and scavenger hunts can make museum visits more playful and memorable. Seamlessly integrated XR can turn history into hands-on exploration. Gamification—through rewards, leaderboards, and progress tracking—encourages problem-solving, repeat visits, and deeper engagement with content (Ribeiro et al., 2024).

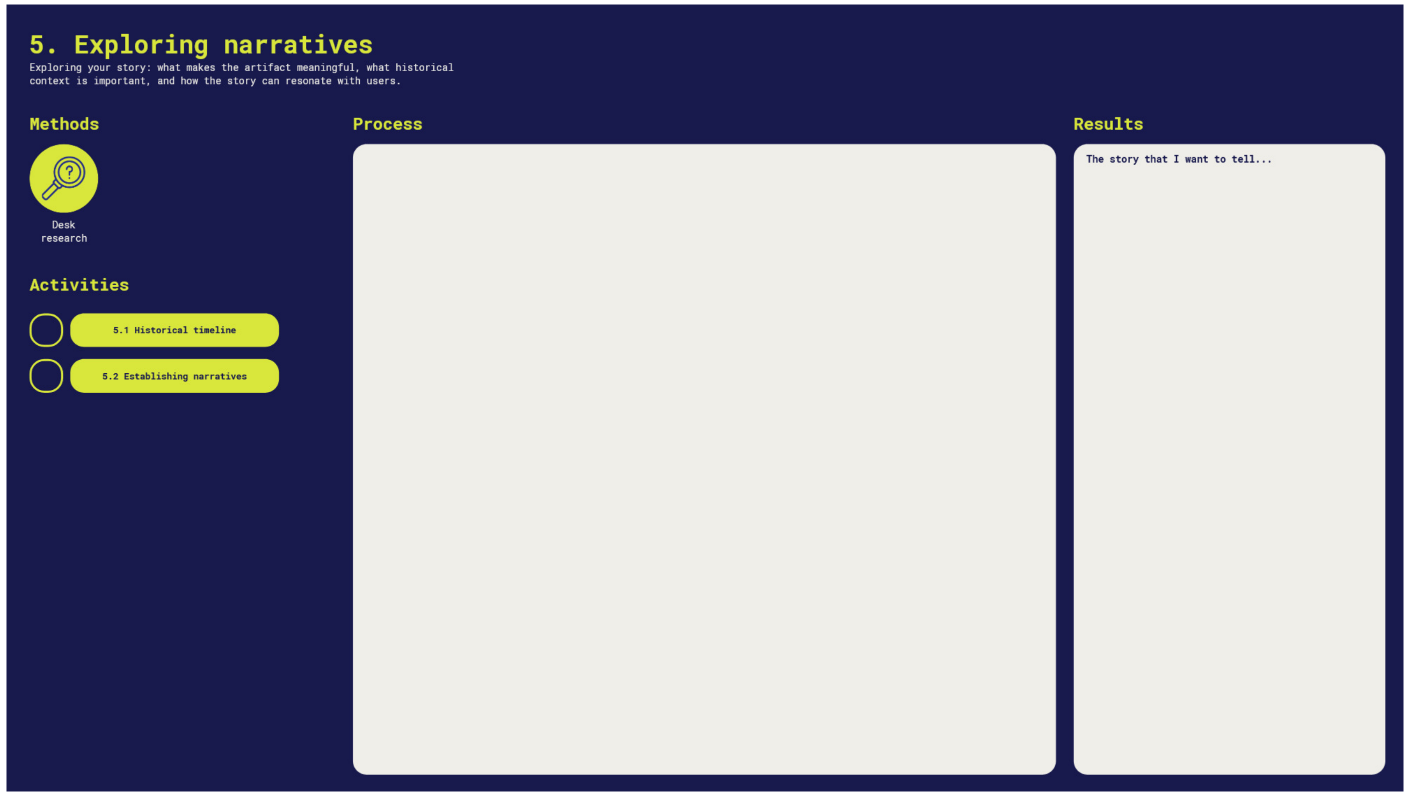
H. Digital workbook

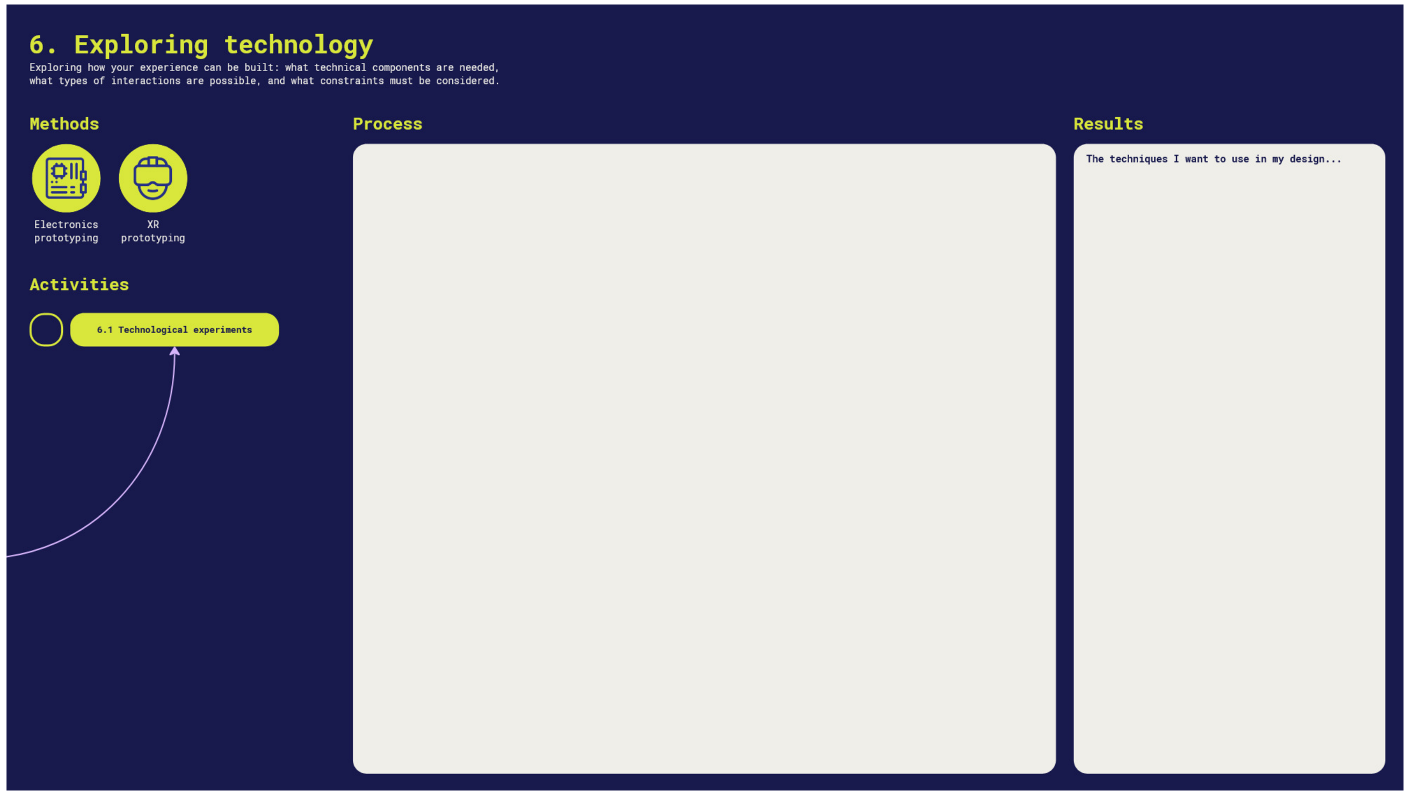
The full workbook can be viewed here.

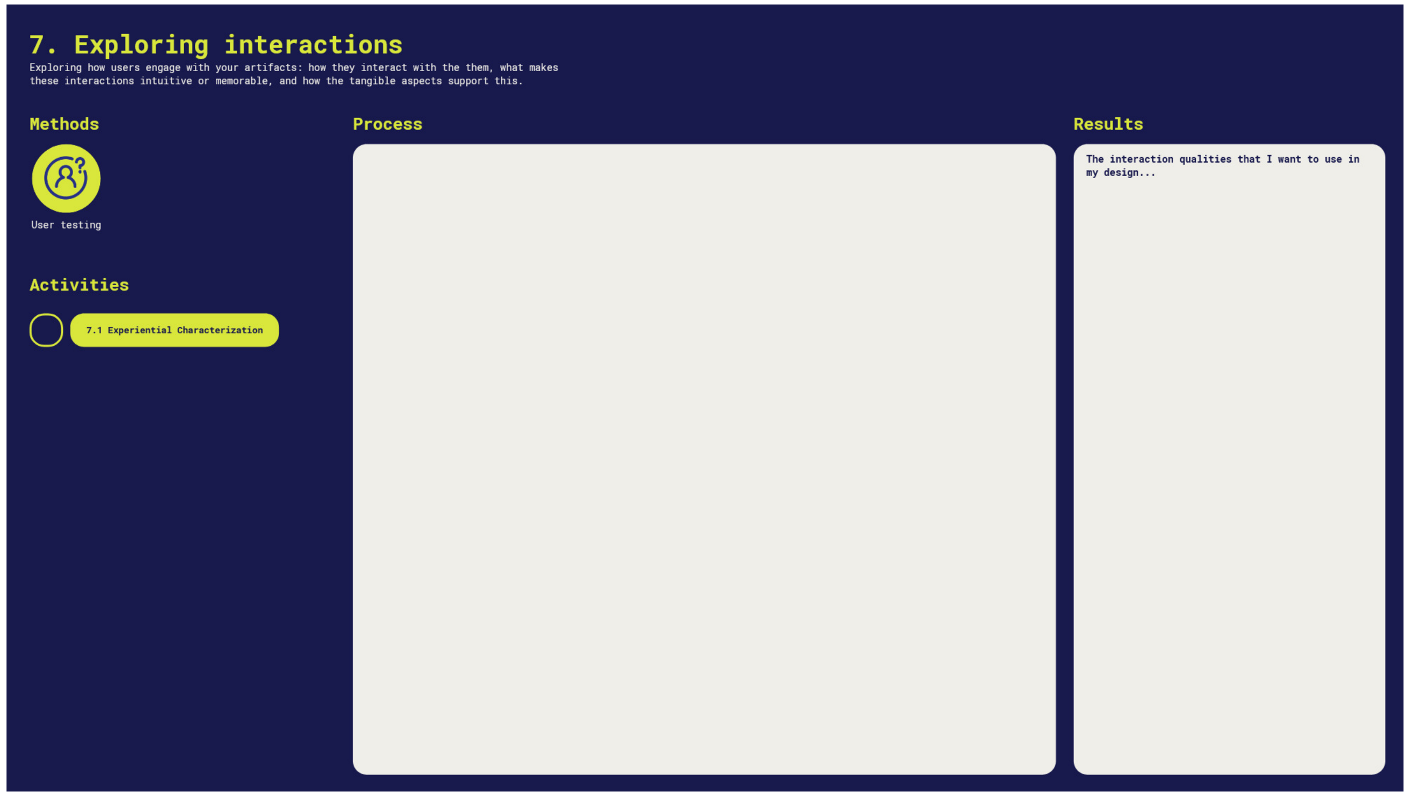







5. Exploring narratives
Exploring your story: what makes the artifact meaningful, what historical context is important, and how the story can resonate with users.
Methods
Desk research
Activities
5.1 Historical timeline
5.2 Establishing narratives
Process
Results
The story that I want to tell...


6. Exploring technology
Exploring how your experience can be built: what technical components are needed, what types of interactions are possible, and what constraints must be considered.
Methods
Electronics prototyping
XR prototyping
Activities
6.1 Technological experiments
Process
Results
The techniques I want to use in my design...


7. Exploring interactions
Exploring how users engage with your artifacts: how they interact with the them, what makes these interactions intuitive or memorable, and how the tangible aspects support this.
Methods
User testing
Activities
7.1 Experiential Characterization
Process
Results
The interaction qualities that I want to use in my design...


8. Second round of ideation
Use the insights from your exploration to come up with concepts.
Methods
Ideation
Design synthesis
Activities
8.1 Brainstorm techniques
8.2 Ideation with the Immersive Heritage Design Deck
8.3 Concept selection
Process
Results
My concepts...
The concept that I will develop...

I. Criteria toolkit

Criteria	Description	Criteria met?
Supported coding	The toolkit must support designers with limited coding expertise in coding in Unreal Engine and CircuitPython by offering templates and instructions.	Yes, if concept is developed further. Users are supported through tutorials, activities and digital building blocks.
XR and TUI integration	The toolkit must provide modules that allow designers to connect CircuitPython interactions to responses in Unreal Engine with minimal configuration.	Yes. Digital building blocks can be used for this.
Built-in learning resources	The toolkit must include instructional guides, templates, and examples to support onboarding and inspire use.	Yes, if concept is developed further. The digital workbook provides these resources.
Optimized for modest technical setups	Experiences must run on hardware currently available for students at the TU Delft.	Yes. All technology used is available to TU Delft students.
Narrative construction	The toolkit should support users in selecting relevant heritage artifacts and narratives.	Yes, if concept is developed further. Selection is supported by narrative exploration.
Lofi prototyping tools	The toolkit should include quick, low-tech prototyping methods that allow users to experiment in early design phases.	Yes, if concept is developed further. Digital building blocks provide a start.
Inspiration from examples	The toolkit should provide examples and case studies of successful tangible Mixed Reality experiences to inspire throughout the design process.	Yes. The Immersive Heritage Design Deck can be used for this.
Modular, reusable components	Designers could be able to construct experiences using pre-built components (digital and physical) that can be reused and adapted for different artifact scenarios.	No. Digital building blocks could be transformed into modular components, by attaching physical elements to these digital resources.

TU Delft