Touching the Past:
Developing and Evaluating Tangible AR Interfaces for Manipulating Virtual Representations of Historical Artefacts

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PhD
2022

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A thesis submitted in partial fulfilment of the requirements of the University of Northumbria at Newcastle for the degree of Doctor of Philosophy

Research undertaken in the Faculty of Arts,
Design & Social Sciences

2022

In Loving Memory of My Father

...I know you'd be very proud

ABSTRACT

Tangible User Interfaces (TUIs) and Augmented Reality (AR) are two advanced technologies that are becoming highly integrated into the cultural heritage domain, TUIs give physical form to manipulate digital information, while AR allows superimposing virtual objects in the physical environment. The common sign "do not touch" is visible on every museum visit to alert visitors not to touch the collections on display. This practice-led thesis aimed at developing and evaluating *ARcheoBox,* a *walk-up-and-use* tangible augmented reality prototype that would 'bring historical artefacts to life' using a collection of Bronze Age artefacts from the Northumberland National Park in the North East of England. While tangible interactions became widely and successfully implemented in museums, exhibits are still site-specific and theme-specific, on the other hand, ARcheoBox employs generic physical objects as tangible AR interfaces that offer physical access to otherwise inaccessible artefacts removing any physical barriers encountered using more common touch screen interface.

The thesis follows a Research through Design (RtD) methodology; supported by the researcher's reflective practitioner lens and co-designing which involved multiple stakeholders in the design process. The practical contribution of this thesis '*ARcheoBox*' demonstrates the implementation of tangible AR interfaces for manipulating virtual representations and interacting with interpretation of historical artefacts in augmented reality. ARcheoBox was installed as a stand-alone exhibit at The Sill: National Landscape Discovery Centre.

The theoretical contribution of this thesis proposes a conceptual framework that contributes original knowledge to the literature on developing and evaluating tangible AR interfaces for manipulating virtual representations of historical artefacts. The conceptual framework presents four core themes: Interactivity, Learning, Engagement, Usability. The core themes encompass four main concepts: Tangible Interfaces, Gesture Interactions, Mapping, and System Usability. The four main concepts are aligned to 10 key aspects where each aspect is defined and contributes with design characteristics for ARcheoBox. These key aspects inform the future design space of tangible AR interfaces, and aid to guide the design process of developing and evaluating tangible AR interfaces for manipulating virtual representations of historical artefacts.

Keywords:
Tangible Interfaces; Augmented Reality, Interaction Design; Design Research; Virtual Representations, Historical Artefacts, Digital Cultural Heritage.

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ACKNOWLEDGEMENTS

During the course of my PhD, I have crossed path with many people who influenced my studies in one way or another. First, I would like to express my greatest appreciation to my principal supervisor Dr Heather Robson, who offered me great support; for sharing her vast experience and her encouragement during challenging times in my PhD. I'm also thankful to Dr Andrew Richardson, my second supervisor, for his continuous support.

I want to thank Northumbria University for their support throughout my doctoral research and to whom I am extremely grateful for giving me the opportunity to fulfil one of my dreams.

I also would like to thank all the staff at Northumberland National Park and the Sill: National Landscape Discovery Centre who have provided great support and amazing resources at all stages of my PhD research. Particular thanks to Andrew Mitchell and Chris Jones, thanks for your trust, kindness and encouragement.

A big thank you goes to my external examiner Dr Florian Echtler from Aalborg University and my internal examiner, Dr Marco Mason from Northumbria University in Newcastle for their time and effort in examining my thesis.

This thesis is dedicated to my father — A great man who gave everything to his family, *you are greatly missed.*

DECLARATION

I declare that the work contained in this thesis has not been submitted for any other award and that it is all my own work. I also confirm that this work fully acknowledges opinions, ideas and contributions from the work of others.

Any ethical clearance for the research presented in this thesis has been approved. Approval has been sought and granted by the University Ethics Committee on December 10, 2019, October 22, 2020, June 15, 2021, and August 4, 2021.

I declare that the Word Count of this Thesis is 41,670 words.

Name:

Signature:

Date:

GLOSSARY

Augmented Reality (AR). An immersive experience that superimposes virtual 3D objects upon a user's direct view of the surrounding real environment, generating the illusion that those virtual objects exist in that space (Azuma, 1997).

Tangible User Interfaces (TUIs). A term that was first coined by Ishii and Ullmer in 1997. Tangible user interfaces give physical form to digital information, employing physical artifacts both as representations and controls for computational media (Ishii and Ullmer, 1997).

Tangible Augmented Reality (TAR). An interface where a virtual object is registered to a (tangible) physical object; the user can interact with virtual objects by manipulating the corresponding tangible object (Kato et al., 2001).

Tangible Gesture Interaction. The use of physical devices for facilitating, supporting, enhancing, or tracking gestures people make for digital interaction purposes (Hoven and Mazalek, 2011).

Co-design. The practice of co-design is a creative activity applied at different stages of the design process. It is also referred to as the creativity of designers and of the people who have not been trained in design working together in the design development process (Sanders 2000).

Virtual representations of Historical Artefact. A 3D model that represents a three-dimensional understanding of an object, which provides a detailed mesh of archaeological material and an efficient record of its structure and texture.

Generic Proxies. I used the term generic proxies in this research to refer to the use of cylinder-shaped physical objects as tangible interfaces to manipulate virtual objects in an Augmented Reality (AR) environment.

ARcheoBox. A *walk-up-and-use* tangible augmented reality prototype. ARcheoBox allows museum visitors to manipulate virtual representations and interact with interpretation of historical artefacts using tangible augmented reality.

1. INTRODUCTION

Overview

The thesis follows practice-led research and examines the application of tangible interfaces and augmented reality to interact with a collection of Bronze Age artefacts from the Northumberland National Park (UK). The visitor will be able to hold a real object in their hands, rotate it and examine it from all angles, explore its initial state and unearth its narrative using generic physical proxies and unique interaction techniques in AR. An innovative feature of this research is the *walk-up-and-use* approach which allows the visitor to have an immediate interaction with the exhibit without requiring any special equipment such as a head-mounted display or handheld controllers. The visitor can engage with virtual representations of historical artefacts intuitively enabling an intuitive and immersive experience while removing any physical barrier between the visitor and the historical artefacts.

This research was motivated by my combined interest in pursuing further studies on a Ph.D. level to become a researcher, in order to expand my horizon as a designer beyond artefacts design and understand how digital technologies can influence visitors' interactions with historical artefacts and inspire them to learn about the past. In Addition, museums were witnessing a surge in experimentation with digital technologies to develop interactive exhibits and capture visitors' attention. Hence, this thesis addresses my passion for effectively investigate digital technologies to explore their potential to deliver engaging experiences in heritage context.

1.1 Research Context

Museums have created a distance between heritage collections and visitors, where artefacts are shielded behind glass cases, and "do not touch" signs. Starting from curatorial exclusivity and elitist practices to more practical reasons such as to keep away visitors from physically interacting with artefacts due to their fragile nature and to avoid exposing them to potential damage. However, museum studies have helped shape a new perception towards touch in museums and acknowledged the importance of connecting with objects. Museology (Chatterje, 2008), (Pye, 2007) has emphasised the importance of materiality to engage with artefacts and highlighted that, it is through touch sensation that visitors can engage and learn about the past (Spence, 2007).

Digital technologies applications in the cultural heritage domain keep developing to support museums' wider vision to remain relevant and engage visitors with heritage collections. These applications range from interactive touch displays, virtual reality, 3D printing and smart artefacts. While several solutions have been explored by museums to facilitate physical interactions with virtual objects by producing 3D printed exact replicas of their collections to allow visitors to touch and inspect artefacts intricate details. However, 3D printing faces certain limitations associated with production cost, complex 3D modelling which requires specialised or trained staff, an approach that sometimes cannot be afforded by smaller cultural institutions. Additionally, the majority of museum exhibitions would require the visitor to download a mobile application or operate an uncomfortable gear such as head-mounted displays that would disrupt the momentum between the visitor and their experience with the exhibit. Hence, research into more intuitive interfaces for manipulating virtual representation and interacting with interpretation of historical artefacts presents an opportunity for incorporating more expressive mediums for visitors, offering them richer experiences when exploring historical artefacts.

1.1.1 The Technology

Tangible User Interfaces (TUIs) (Ishii, 1997) enable users to physically interact with digital content, bridging the gap between physical and digital worlds while benefiting from humans' innate skills to grasp and manipulate physical objects (Ishii, 2008). Further studies also suggest that passive real-world tangible props can benefit users through spatial relationships between interface and objects, e.g., in neurosurgical planning (Hinckley, 1994).

Augmented Reality allows to overlay virtual representations into the physical space (Azuma, 1997), while Tangible AR combines AR content with tangible input devices, typically through printed flat markers with visual patterns (Billinghurst et al., 2008). The commercialisation of VR headsets such as google cardboard and Oculus Rift encouraged further research around tangible proxies to better understand how to connect the physical world to the virtual environment and allow a closer to reality user experience. Several studies have shown that tangible proxies for instance in VR, can enhance user interaction with virtual models (Muender et al., 2019), (Feick et al., 2020), (Hettiarachchi et al., 2016). Similarly, in the domain of cultural heritage, virtual manipulation of historical artefacts is becoming a popular research area as more interest arises in engaging the public using physical manipulation of museum collections, for instance through the use of HoloLens and 3D prints (Pollalis et al., 2017), (Spence et al., 2020), (Ramkumar et al., 2019). However, fewer examples emerged from the literature for developing physical objects (generic proxies) for AR except (Jiménez Fernández-Palacios et al., 2017), and in heritage context (Kalinda et al., 2020).

In this research, I developed ARcheoBox, a *walk-up-and-use* prototype, offering a hands-on experience using readily available physical objects (generic proxies) which also enables more accessible and affordable interfaces trade-off for AR to manipulate virtual representation and interact with interpretation of historical artefacts. Furthermore, the generic proxies have embedded interactions to interact with the interpretation, allowing the visitor to stay engaged with the object in hand without breaking the interactions to switch to another device such as a touch screen. Additionally, Augmented Reality (AR) as a medium allows the visitor to see their hands, and adjust their body movement to acquire a certain perspective while exploring the artefacts, for example, to move their head backward or forwards to look closer into more details. Therefore, augmented reality offers a more natural setting versus a Virtual Reality (VR) system, where the user is secluded from their physical surroundings as all objects are set in the virtual environment. By having the real world as a tangible reference, it amplifies the effect of holding the actual artefact in hand and therefore improves the user's perception of the artefact and enhances their interaction experience.

1.1.2 The Sill: National Landscape Discovery Centre

In 2017, Northumberland National Park Authority opened *The Sill: National Landscape Discovery Centre* on Hadrian's Wall in the UK (Figure 1) designed to inspire people of all ages to explore the stunning landscape, and the rich history of Northumberland. The Sill features a permanent exhibition, a temporary exhibition, event spaces, a café, a modern Youth Hostel, a rural business hub, and a shop specializing in local crafts and produce. The Sill is considered a gateway into Northumberland National Park (The Sill, 2019).

Figure 1: The Sill: National Landscape Discovery Centre – Permanent Exhibition.

As part of the National Park to embrace technology, in Summer 2018, The Sill organised the Digital Landscapes Exhibition. The Digital Landscapes exhibition incorporated several interactive technologies such as augmented and virtual reality, in addition to data dashboards of live datasets collected by National Park Rangers. The exhibition was split into three main areas; Digital for Adventure, Digital for Learning and Digital for Conservation. From maps to apps, walking to cycling, the exhibition would showcase how technological advances can encourage users to explore and interpret the landscape. The visitors could explore different areas of the landscape using virtual reality or engage with hands-on exhibits such as an Augmented Reality sandbox. The digital officer at The National Park stated that: "*The Sandbox was, without doubt, the most popular exhibit throughout the 12 weeks exhibition, we received many* *messages from people following their visit".* Following Digital Landscapes, the Sandbox was re-branded for inclusion in the permanent exhibition. In the following year (Summer 2019), the National Park continued exploring new technologies, and they introduced a 3D holographic display of archaeological artefacts at The Sill. The display content was created using end-to-end reality capture and digital delivery platform which enabled to the production of 3D photogrammetry models of Bronze Age artefacts uncovered during archaeological excavations in the Ingram Valley.

1.1.3 Framing the Research

To frame the research and develop a better understanding of the workings of this collaborative research, I visited The Sill and had an initial meeting (October 2019) with three members of the staff, a digital officer, a GIS officer, and a volunteer officer. This initial visit allowed me to gain an understanding of the variety of exhibits at The Sill (Figure 2). Through the conversations and after a tour of The Sill, I started to identify several opportunities that promise to deliver an innovative and more engaging visitor experience and bring Bronze Age artefacts to life (more details are described in the Capture phase in the methodology chapter (see section 3.2). Additionally, ongoing excavations at the National Park and explorations of new sites that are under study mean that this research project would have the potential to have long-term benefits in terms of future excavations and the dissemination of the archaeological finds to the general public.

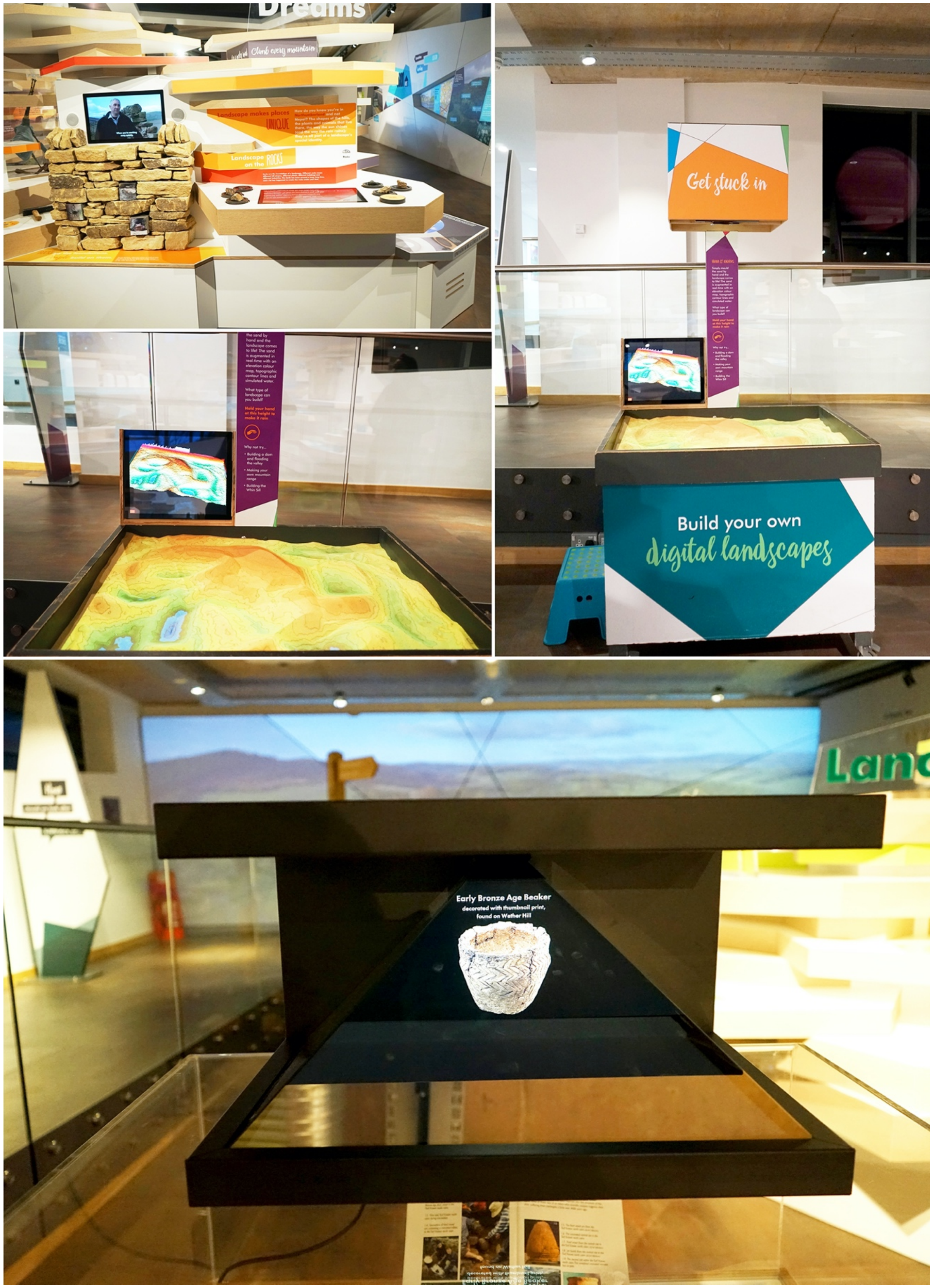

Figure 2: Digital and interactive exhibits at The Sill: National Landscape Discovery Centre.

1.2 Research Questions, Aims and Objectives

The key aim of this research project was to understand how tangible interfaces and augmented reality can engage the visitors' and enhance their interaction experience with virtual representations of historical artefacts. Additionally, the research aims to facilitate public access to historical artefacts, which could also encompass a wide range of audiences including: heritage experts, researchers, school groups, and life-long learners. Hence, the following aims and objectives have been identified:

1. To develop a *walk-up-and-use* tangible AR prototype to manipulate virtual representations and interact with interpretation of historical artefacts in an intuitive manner and without operating an additional device such as head-mounted displays and handheld controllers.
2. To develop and evaluate a conceptual framework that can formalise the design process for developing and evaluating tangible AR interfaces to manipulate virtual representations of historical artefacts.
3. Apply co-design methodology to develop a tangible AR prototype.

The significant impact that digital technologies and in particular tangible interfaces and augmented reality have had on the cultural heritage sector raises several important questions. Thus, this research addressed the following research questions (RQ):

1. R.Q.1: How can Tangible Augmented Reality engage museum visitors with virtual representations of historical artefacts?
2. R.Q.2: How do we present Tangible Augmented Reality to a casual user, without requiring any uncomfortable technology such as head mounted displays?
3. R.Q.3: What is the visitor experience of this novel tangible AR prototype versus traditional displays such as touch screens and dioramas?

I aimed to answer the first research question by adopting a co-design methodology that is centred around generating design ideas with the heritage experts (see section 3.4). The second research question revolves around the design process of a tangible AR prototype (see section 4.2). And the third and final research question is addressed by conducting an in-situ prototype study with The Sill visitors.

In this research, I adopted Research through Design (RtD) and co-design methodologies, for the domain of interaction design to evaluate the user experience of manipulating virtual representations of historical artefacts following a user-centered approach. Throughout my research through design approach, I created a series of prototypes in an iterative process to develop a tangible augmented reality prototype. The design process was guided by highly collaborative stakeholders including cultural heritage professionals and archaeologists. The multidisciplinary nature of the research led to a combination of several methodological approaches which was guided by the innovative and technological nature of the research itself which deals with the application of digital technologies to a specific museum case.

1.3 Research Contribution

This research contribution to knowledge is in two folds: The practical research contribution constitutes a tangible augmented reality prototype for manipulating virtual representations and interacting with interpretation of historical artefacts, co-designed with heritage experts, resulting in ARcheoBox, a *walk-up-and-use* prototype exhibited at the Sill: National Landscape Discovery Centre in Hexham, UK. The theoretical research contribution consists of a conceptual framework that is evaluated and refined by analysing the data collected from ARcheoBox in-situ study, which could benefit interaction designers, heritage professionals, and researchers in the field of design and human-computer interaction.

1.3.1 Practical Research Contribution

As a practice-led Ph.D., this research presents a tangible augmented reality prototype that incorporates Tangible Interfaces (generic proxies) and Augmented Reality (AR) with three interaction techniques (*Move, Rotate, Flip*) and output modalities in AR (*Zoom, Select, Switch*) to manipulate virtual representations and interact with interpretation of historical artefacts. The practical outcome of the prototype called ARcheoBox is based on a collection of Bronze Age artefacts that were excavated from the Northumberland National Park and later laser scanned using photogrammetry techniques to create the 3D models. The 3D models of the historical artefacts were later integrated as the content for the augmented reality application.

ARcheoBox is intended to offer museum visitors a hands-on experience to learn about archaeological interpretation while engaging with physical manipulation of virtual representations of historical artefacts. With this aim, I co-designed and developed ARcheoBox with the heritage experts and conducted several user studies with heritage experts and end-users. I first developed a proof-of-concept ARcheoBox 1.0 and tested it with the heritage experts to elicit their feedback on the use of a tangible AR prototype to manipulate virtual representations and interact with interpretation of (Bronze Age) historical artefacts. The insights and design recommendations generated from these methods resulted in ARcheoBox 2.0, a *walk-up-and-use* prototype that responds to the challenges linked with inaccessible historical collections and supports unique interactions with virtual representations of historical collections for museum visitors. Another important feature of this research is embedding physical objects (generic proxies) with three interaction techniques (*Move, Rotate, Flip*) as output modalities in AR (*Zoom, Select, Switch*) using gesture interactions to interact with interpretation of the historical artefacts. Additionally, the practical research contribution also demonstrates the potential of generic proxies as physical interfaces which allow making "anything something different" that can be applied to any historical artefact collections. This approach can engage, heritage experts, researchers, school groups, and small communities in acquiring and sharing knowledge on local heritage using low-cost devices, which could also boost the sense of belonging to a shared cultural heritage for local communities.

1.3.2 Theoretical Research Contribution

One of the research questions raised in this thesis is how to employ tangible AR interfaces to engage museum visitors with virtual representations of historical artefacts. While virtual objects are widely accessible online via 3D modelling platform website such as Sketchfab, the historical artefacts remain distant from the visitors' hands, therefore a conceptual framework for tangible AR interfaces can contribute towards a better understanding of how to design such systems and enables wider adoptions across different cultural institutions. This research theoretical contribution offers a conceptual framework that identifies key aspects that contribute with a set of design characteristics that can be incorporated into the design of tangible AR interfaces to manipulate virtual representations and interact with interpretation of historical artefacts. Initially, the conceptual framework was constructed based on the data collection and analysis of several studies in this thesis, using co-design interviews with heritage experts and prototype user evaluation questionnaires. Eventually, the in-situ study served as a real-world case study and enabled the evaluation and refinement of the framework based on the visitors' responses.

The conceptual framework aims to formalise the design process for developing and evaluating tangible AR interfaces in cultural heritage context and contributes original knowledge to the field of tangible AR to manipulate virtual representations of historical artefacts. The conceptual framework is comprised of four core themes (Interactivity, Learning, Engagement, Usability) and four main concepts (Tangible Interfaces, Gesture Interactions, Mapping, System Design). The main concepts are aligned with 10 key aspects: *Manipulation, Control, Feedback, Communication, Rewarded Experience, Making Connection, Accessibility, Visibility, Efficiency, Consistency*. The key aspects are defined and contribute with a set of design characteristics that can be considered in the design and implementation process of tangible AR interfaces.

1.4 Thesis Structure

The thesis consists of seven chapters. Chapter 1 provides an overview of the research context and how the collaborative relationship with the Northumberland National Park and The Sill: National Landscape Discovery Centre formed an essential component for co-designing a tangible AR prototype for manipulating virtual representations and interacting with interpretation of historical artefacts. Chapter 1 also presents the research aims, objectives, and questions, in addition to the research's practical and theoretical contributions. The structure of the research process is illustrated in Figure 3. In chapter 2, I present an extensive contextual review, introducing the literature relevant to this research, beginning with the origin of augmented reality, followed by drawing on research in tangible user interfaces, I then situate the research within cultural heritage and emerging technologies. In chapter 3, I describe the research methodologies for developing tangible AR prototype for manipulating virtual representations and interacting with interpretation of historical artefacts and discuss the varied methods that contribute to design research.

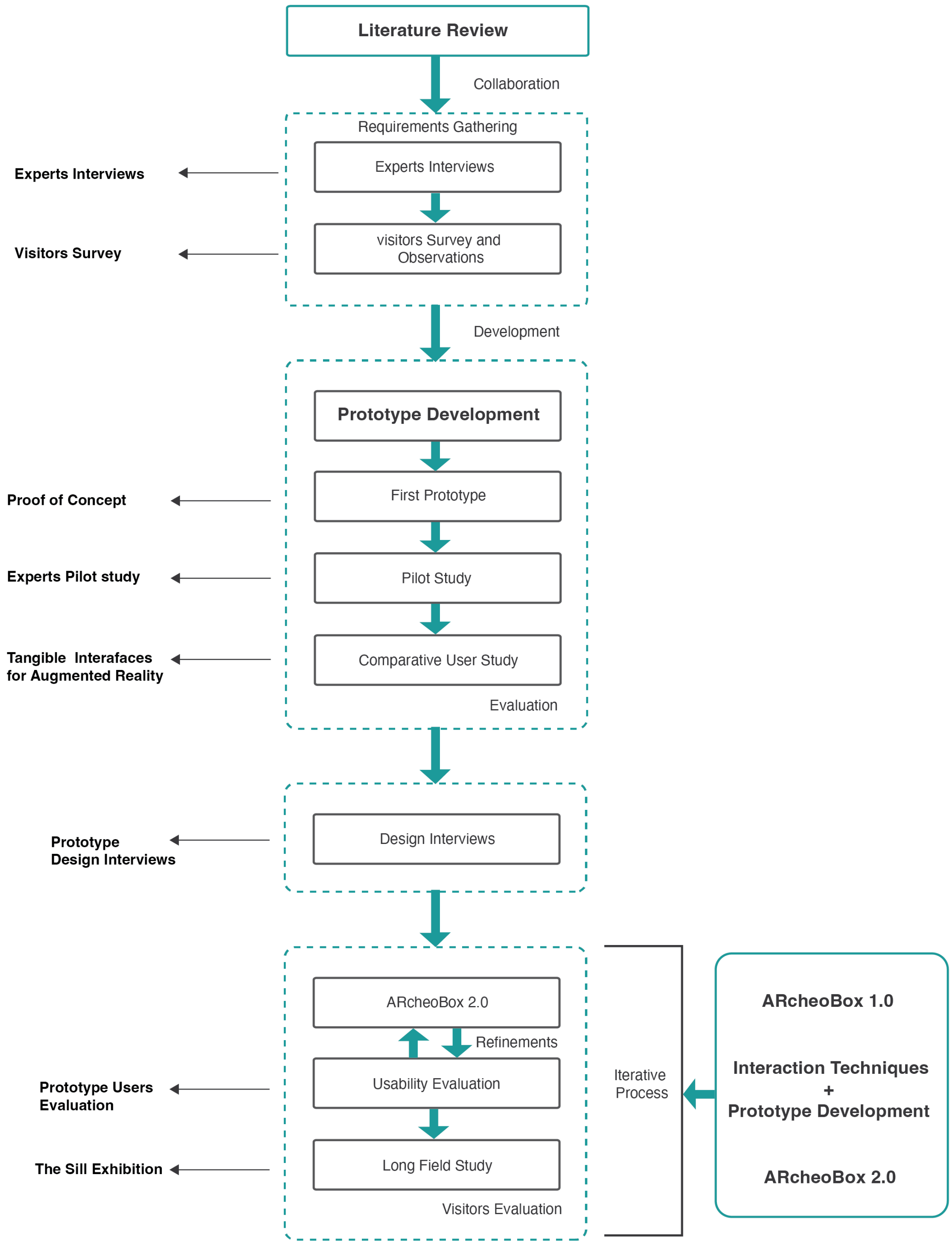

Figure 3: Structure of the research process.

In chapter 4, I describe ARcheoBox iterative design process and the co-designing journey with the heritage experts. In addition, I give a detailed description of the several prototype designs and technical implementation that led to the final prototype (ARcheoBox 2.0). In chapter 5, I present three user studies and discuss their findings in regards to the research practical contribution (ARcheoBox) and theoretical contribution (conceptual framework) to support the development of tangible AR interfaces for manipulating virtual representations and interacting with interpretation of historical artefacts. Chapter 6 presents my reflections on the overall research process. Finally, in chapter 7, I summarise the research contributions and share my thoughts on the research limitations, as aspirations for future work.

Summary

This chapter has introduced my research context, research aims, objectives and questions, practical and theoretical contributions, and thesis structure. The research is situated across multiple HCI fields, mainly tangible interfaces, augmented reality, and interaction design and within the context of cultural heritage. The research context is set with The Northumberland National Park's visitor centre, The Sill: National Landscape Discovery Centre in Hexham, UK. Through my research aims, objectives and questions, I defined my methodological approach, which includes co-designing with the heritage experts, as well as applying research through design to combine my practical skills as a designer with research skills to achieve a unique interactive experience with historical artefacts that can be shared with a wider community of designers and researchers, while also serves as a guide for cultural institutions to create intuitive and engaging visitor experiences that can overcome existing limitations surrounding access to historical artefacts.

2. CONTEXTUAL REVIEW

Overview

The contextual review chapter introduces three main related areas of work which frame the research background, these areas are associated with Tangible User Interfaces (TUI), Augmented Reality (AR), and Cultural Heritage and Emerging Technologies. I first review Augmented Reality and Tangible User Interfaces, two fundamental and well-established fields in HCI to gain a better understanding of early TUIs and AR applications and frameworks. Cultural Heritage and Emerging Technologies review section presents project examples from different digital applications as well as design approaches in museums, galleries, and outdoor cultural sites such as virtual reality, augmented reality, smart objects, and 3D prints. Through the collective of this contextual review, I aim to situate my research with previous works and identify the gaps in the literature and how my research can help to address them.

2.1 Augmented Reality Evolution from Fiction to Reality

Before Augmented Reality (AR) became a reality, Frank Baum envisioned a pair of augmented reality spectacles in his novel “The Master Key”. Baum’s protagonist, a 15 year old boy named Rob, and while experimenting with electricity, he accidentally awakens the *Demon of Electricity* who offers him three gifts. For the last one of the three gifts, the demon gives him the “Character Marker”, a unique pair of spectacles. The demon starts to explain their function:

> …“I give you the Character Marker. It consists of this pair of spectacles. While you wear them everyone you meet will be marked on the forehead with a letter indicating his or her character. The goodwill bears the letter 'G', the evil the letter 'E'. The wise will be marked with a 'W' and the foolish with an 'F'. The kind will show a 'K' upon their foreheads and the cruel letter 'C'. Thus,

> you may determine by a single look the true natures of all those you encounter" (Baum, 1901, p94).

While Baum's vision of augmented reality is still far from predicting a person's good or bad nature using today's technologies. Augmented reality surpassed the pages of the novel and transited to reality when fifty years later, the cinematographer Morton Heilig introduced to the world the first virtual reality machine "The Sensorium Machine", an immersive, multi-sensory theatre experience using 3D images, sound, smell, and seat vibration to create an illusion of reality during watching a film (Heilig, 1962). In 1968, Ivan Sutherland created the first head-mounted display "The Sword of Damocles". In his essay "The Ultimate Display", Sutherland goes further by giving a glimpse of the future by describing an AR display:

> "The user of one of today's visual displays can easily make solid objects transparent—he can "see through matter!" (Sutherland, 1965, p507).

In 1990, Tom Caudell and David Mizell coined the term augmented reality at Boeing Computer Services Research (Caudell and Mizell, 1992). They created a head-mounted see-through AR display that superimposed instructions through high-tech eyewear and projected them onto multipurpose, reusable boards.

2.1.1 Augmented Reality

Augmented Reality (AR) allows for computer-generated information properties to be overlaid onto the real environment, enabling the user to experience virtual elements as if they have had real-world properties. Azuma (1997) defines augmented reality as follows:

> Augmented Reality (AR) is a variation of *Virtual Environments* (VE), or Virtual Reality as it is more commonly called. AR allows the user to see the real world, with virtual objects superimposed upon or composited with the real world. Therefore, AR supplements reality, rather than completely replacing it. Ideally, it would appear to the user that the virtual and real objects coexisted in the same space, (Azuma, 1997, p2).

In augmented reality, visual information complements the physical space and does not obscure the user environment, while in virtual reality the user is completely immersed in new unfamiliar territory, completely reliant on the information provided through the virtual device.

As per recent augmented reality statistics and facts[1], by 2023, there will be an estimated 2.4 billion mobile augmented reality (AR) users worldwide, with market shares of global AR/VR spending on the consumer market worldwide in 2020 has reached 3.7.4%. The rapid development in computer technologies has allowed the adoption of augmented reality in many disciplines, ranging from education, health, automotive, entertainment, and most recently in the field of medicine due to the advancement in computer processing and tracking technology. Early research projects into augmented reality have focused on integrating electronic systems into the physical environment. Digital Desk (Wellner, 1991) is one of the pioneering projects, which demonstrated a way to merge physical and digital documents by using video projection of a computer display onto a real desk with physical. Mackay (1998) explored the concept of “Interactive Paper” which links directly to relevant computer applications instead of replacing paper documents. The project aims at creating a seamless transition between physical world components and virtual world applications. Consequently, the experience of augmented reality applications has completely transformed from being an individual experience to a shared experience among multiple users, this leads the way to several research projects exploring the potential of augmented reality in collaborative work environments (Vinot et al., 2014). Such approach allows multiple users to share the same augmented reality environment in real-time without the requirement of a head-mounted display.

2.1.2 Mixed Reality and the Collaborative Interface

Milgram et al. (1994) positioned augmented reality along the mixed reality spectrum (Figure 4) in what he identifies as the Virtuality Continuum. On one end of the spectrum, there is the

[1] https://www.statista.com/topics/3286/augmented-reality-ar (accessed April 11, 2020)

real environment where we perceive physical objects, as they exist in the real world. On the far end of the spectrum, there is the virtual environment where virtual objects exist in the virtual environment as in the case of wearing immersive gear. Oculus Quest is an example of a virtual reality headset where the user is transported into another space independent of his physical environment. Along the spectrum also exist the Augmented Virtuality stage, in which we engage with the virtual world using physical objects to establish interactions with the virtual world. For example, in the case of The Nintendo Wii and the Microsoft Kinect which allow a user to affect a virtual environment by emulating their interactions in a real environment.

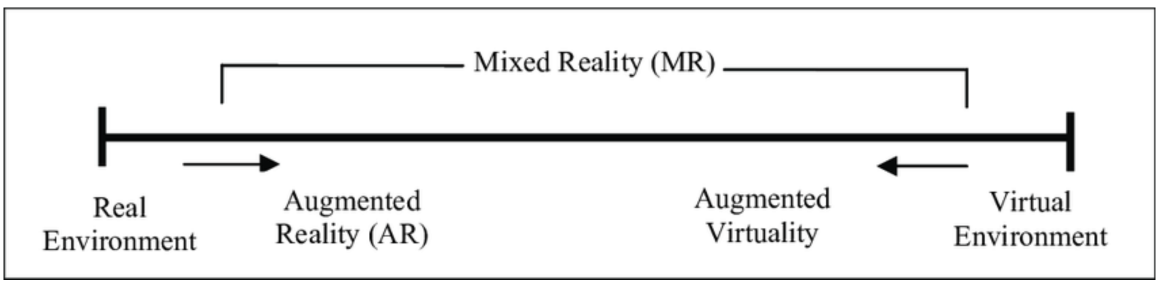

Figure 4: Mixed Reality on the Reality-Virtuality Continuum. (Source: Milgram et al., 1994).

Billinghurst and Kato (1999) argued that Virtual Reality created a barrier between the user's real-world and their interaction within the physical space. They suggested the use of Mixed Reality as a tool to enhance remote and face-to-face collaboration, specifically to support 3D interactions in Computer-Supported Collaborative Work (Figure 5). This approach allowed users to interact with each other and the real world at the same time as the virtual content. Furthermore, Billinghurst et al., (2000) introduced Shared Spaces to showcase how augmented reality supplemented by spatial 3D objects, can function as an effective interface to support multiple users at the same time and in the same location to interact in both the real and virtual world. Shared spaces allowed users to directly manipulate virtual objects by manipulating several marked cards with fiducial patterns augmented with virtual objects on them, in parallel users can still refer to physical objects such as notes and diagrams at the same time while viewing and interacting with virtual objects.

Figure 5: AR collaborative environment. (Source: Billinghurst et al., 2000).

Another application of mixed reality interface was developed by Billinghurst, Kato, and Poupyrev (2001) in the "MagicBook", an interface that used a real book to transport users seamlessly between real and virtual world, or between co-located and remote collaboration. The interface uses vision-based tracking to superimpose virtual models into the actual book, which allows multiple users to experience the same virtual environment either from an egocentric (AR) or an exocentric (VR) perspective (Billinghurst et al., 2001).

2.1.3 Markers Technologies and Authoring Tools

Augmented reality technologies are characterized in two main categories: Location-based and vision-based. Location-based AR uses the real physical environment to navigate the AR interface using geo-based markers. As an example, Pokémon Go[2] is the first popular and most successful location-based AR game. Vision-based AR is a registration and tracking approach that determines camera pose using data captured from optical sensors (Billinghurst, Clark, and Lee, 2014), for example, when a physical object is viewed via a camera pose. Today AR has gained a lot of momentum due to the minimal computational power required which became widely available in smartphones and tablets. Additionally, several augmented reality SDKs have been introduced to the market which allowed for augmented reality applications to be easily available to those who are interested in developing their AR applications without requiring a lot of programming experience. For example, using Vuforia Engine[3] and Wikitude SDKs[4] through smartphones, Google Glass, etc.

[2] https://www.pokemongo.com/en-gb (accessed April 12, 2020)
[3] https://engine.vuforia.com/engine (accessed April 12, 2020)
[4] https://www.wikitude.com (accessed April 12, 2020)

2.1.4 Marker-based AR

Marker-based AR is based on 2D images markers called fiducial markers and uses image tracking within the camera range for detecting and augmenting 2D images, which allows AR apps to then overlay the virtual 3D objects accurately on the markers. An example of marker-based AR is ARToolKit, a software library which provides a visual programming environment for developing Augmented Reality (AR) applications using computer vision algorithms to calculate the position and orientation of the camera in relation to the 2D marker (Kato and Billinghurst, 1999).

2.1.5 Marker-less-based AR

Marker-less AR differs widely from marker-based AR because it uses different features within the natural surroundings of the space. Marker-less AR uses a combination of a camera and a sensors system to accurately detect the scenery, which enables an AR application to integrate virtual objects into a real environment in real-time. An example of marker-less AR is Vuforia object target[5] detects scanned features of the 3D object, which is created by scanning a physical object using the Vuforia Object Scanner and enables 360° augmented reality visualization around physical objects. On the other hand, the model target[6] requires a 3D/CAD model by recognizing object geometry used for detection to superimpose virtual information over the 3D object. Other hardware supports the integration of augmented reality in the real world, such as gyroscope and GPS tools can be also used to determine the position in the physical world and overlay large objects into a room[7].

2.2 Tangible User Interfaces – Back to the Real World

The Marble Answering Machine (Figure 6) is one of the early conceptual Tangible User Interfaces prototypes that links the physical and digital worlds. In 1992, Durrell Bishop, while a student at Royal College of Art (RCA) in London, he developed the prototype, which aimed at integrating computing in everyday objects. Later it became an inspiration for Ullmer and Ishii (1997) who describes its function:

[5] https://library.vuforia.com/content/vuforia-library/en/articles/Training/Vuforia-Object-Scanner-Users-Guide.html (accessed April 12, 2020)
[6] https://library.vuforia.com/features/objects/model-targets.html (accessed April 12, 2020)
[7] https://www.ikea.com/gb/en/customer-service/mobile-apps (accessed April 12, 2020)

... "The user can *grasp* the message (marble) and drop it into an indentation in the machine to play the message". Although, The Marble Answering Machine remained a conceptual prototype and did not materialize except through video animation[8]. The materialization of phone messages through marbles demonstrates the possibilities of coupling bits and atoms, which paved the way for a new vision around Tangible User Interfaces" (Ullmer and Ishii, 1997, p3)

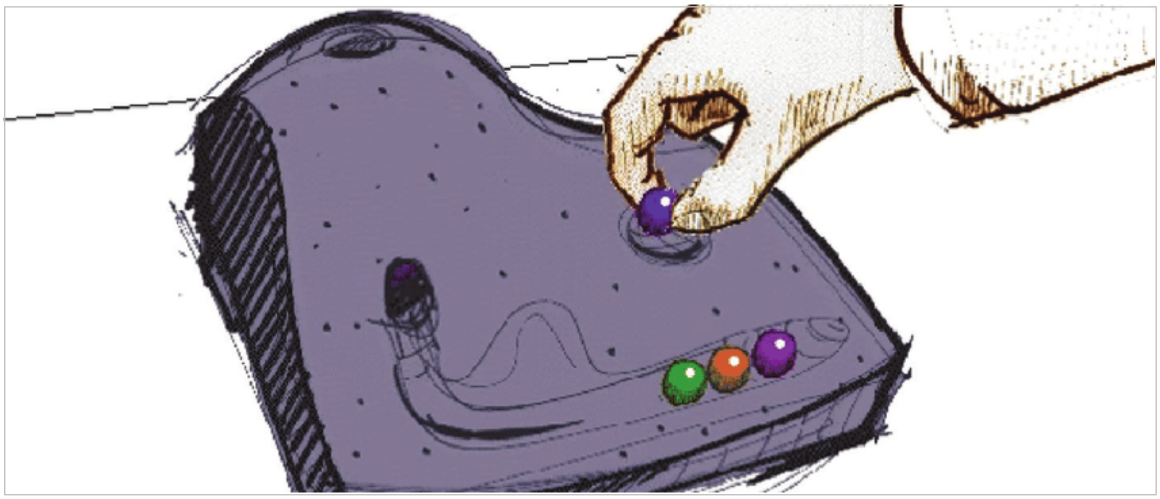

Figure 6: Marble Answering Machine, Durrell Bishop, RCA. (Source: Ishii & Ullmer, 1997).

Three years later, and ahead of the surfacing of Tangible User Interfaces (TUIs) paradigm, the concept of Graspable User Interfaces was introduced by Fitzmaurice, Ishii, and Buxton (1995) in *"Laying the Foundations for Graspable User Interfaces"* bricks – an input system that allows direct manipulation of virtual objects through physical handles using two-handed interactions, offering a seamless blend between the physical and virtual worlds (Figure 7). The bricks prototype was developed using GraspDraw and ActiveDesk, modeled after a drafting table, bricks are overlaid on top of the graphical interface, and once moved, the graphics can be moved, rotated, and scaled.

[8] Message box by Saul Hardman, a student at Plymouth University developed a working prototype of Durrell Bishop's The Marble Answering Machine. https://www.youtube.com/watch?v=Zg5EBTkOG2k&feature=emb_logo (accessed July 30, 2020)

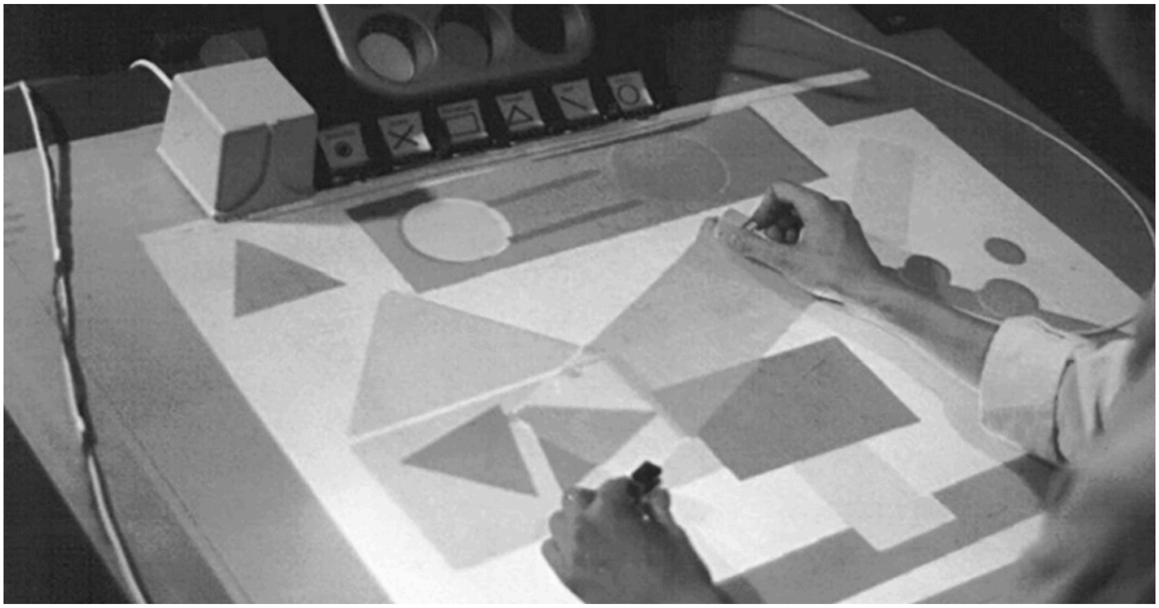

Figure 7: Bricks system (Source: Fitzmaurice, Ishii and Buxton, 1995).

The authors classify input devices as being space-multiplexed or time-multiplexed. In the instance of space-multiplexed, users can perform multiple interactions simultaneously like when driving a car, each interaction has a dedicated transducer controlling a specific task. As opposed to the computer mouse, which uses time-multiplexing to control multiple virtual tasks. The Graspable User Interface aimed to introduce new design spaces based on existing skills of humans' abilities gained from using GUIs and therefore as a means of augmenting the power of conventional Graphical User Interfaces.

2.2.1 Ishii and MIT Tangible Media Lab

In their 1997 ACM CHI conference paper, Hiroshi Ishii and Brigg Ullmer coined the term "tangible bits". The core concept of TUIs is tied to the notion of coupling between physical objects with digital content. At a time when GUIs dominated Human-Computer Interaction field, there were few explorations on how to combine the world of physical and digital to create a unique Human-Computer Interaction experience. One of the first TUIs prototypes that emerged from MIT Tangible Media Lab is the metaDESK, a system of interaction for graspable physical objects (Figure 8). The metaDESK uses an application called Geospace to navigate a geographical space of MIT campus, once the Dome (phicon) is placed on the desk, a two-dimensional map of the MIT campus appears underneath the desk, the Dome then behave as a physical handle for navigating the map, both the 2D desk-view and 3D lens-view are correspondingly transformed by rotating the Dome object (Ullmer and Ishii, 1997). To couple the physical objects with digital data, the authors borrowed basic principles from the HCI theory of affordance (Norman, 1988). The components of metaDESK consist of a desk, a projected graphical surface; an active lens, and an arm-mounted flat-panel display. For example, the magnifier functioned similarly to how a traditional magnifier would work, which supports the user's intuitive interactions.

Figure 8: The-metaDESK-system-overview. (Source: Ullmer and Ishii, 1997).

The authors illustrate how the GUI "menus" and "handles" are instantiated as TUI "trays" and "phandles" (physical handles). The diagram (see Figure 9) showcases the mapping of GUI widgets into physical space. For example, the GUI "window" is substituted by a physical lens" which further emphasizes the TUIs idea of seamlessly coupling people, digital information, and the physical environment.

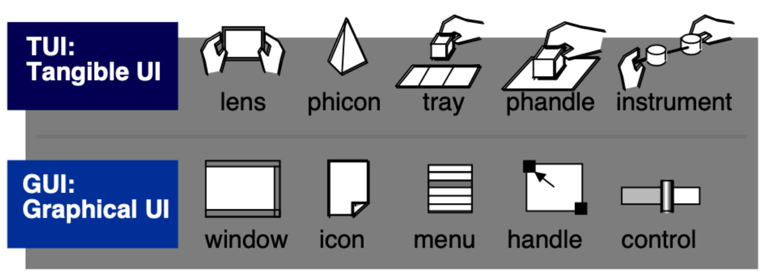

Figure 9: TUI instantiations of GUI elements. (Source: Ullmer and Ishii, 1997).

Furthermore, MIT Tangible Media Lab developed multiple TUIs projects showcasing the use of physical objects to interact with digital information. The musicBottles installation by Ishii, et al., (2001), uses glass bottles as "containers' and "controls" for digital information, the bottles can be moved above a special table to play audio tracks and display coloured lighting effects (Figure 10). The objective of the installation is to create a simple and unassuming interface that uses everyday objects; therefore, the interface would blend seamlessly into the user environment and afford more natural interactions.

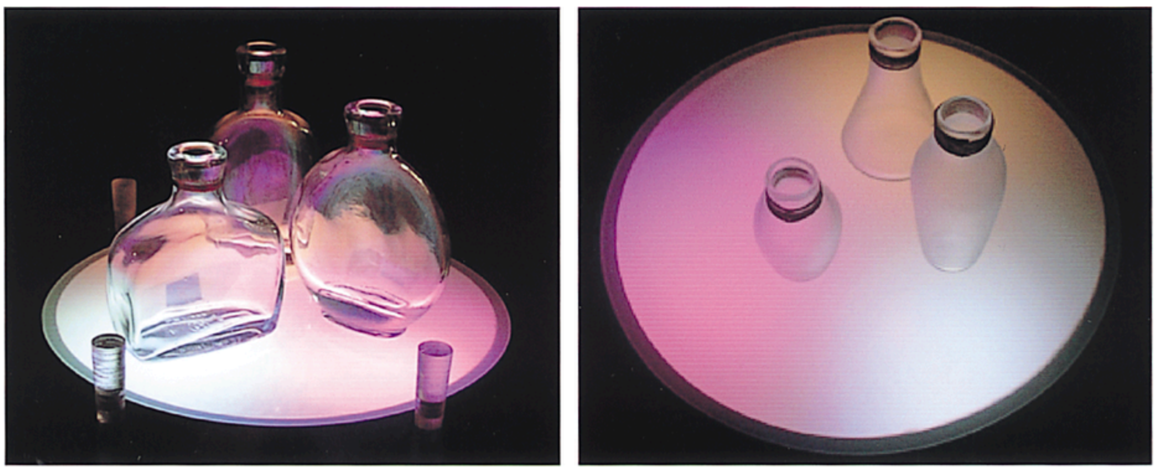

Figure 10: The musicBottles installation. (Source: Ishii et al., 2001).

Beyond the coupling of physical objects with digital information and promoting intuitive interfaces, other projects at MIT Tangible Media Lab explored a new trend in digital storytelling. Mazalek et al. (2002) suggest that creating a multi viewpoints story using TUIs allows the user to experience collaborative interactive storytelling. The tangible multiple viewpoints system explores how the mixture of physical objects and augmented surfaces can act as a tangible interface for the different character viewpoints in an interactive story, by using tangible elements as a navigational tool into the story world offering multiple viewpoints to the character perspectives. "As the story unfolds, the system gathers information about which characters a user has been interacting with, and makes decisions about what segments to present next based on this knowledge", they also state:

> “When developing a story for a new delivery channel, it is important to consider both the form and environment in which it will be conveyed to its audience". (Mazalek et al. 2002, p. 402)

Almost ten years later, Ishii (2008) recognized the divide that still exists between the world of bits and the world of atoms, he states:

> “At another seashore between the land of atoms and the sea of bits, we are now facing the challenge of reconciling our dual citizenships in the physical and digital worlds. Our visual and auditory sense organs are steeped in the sea of digital information, but our bodies remain imprisoned in the physical world” – *Hiroshi Ishii* (2008).

Although the tangible representation allows the physical embodiment to be directly coupled to digital information, it has a limited ability to represent a change in many materials or physical properties (Ishii, 2008). As designers, if the distinction of physical and digital will be a mere impossible in the future, we need to consider the design sphere and elements that need to be in place to describe such space. The design challenge is a seamless extension of the physical affordances of the objects into the digital domain (Ishii and Ullmer, 1997).

2.2.2 Tangible Interactions and TUIs Frameworks

After Tangible User Interfaces became a firmly grounded and explored domain encompassing multiple disciplines, researchers in HCI acknowledged that the limitations of addressing tangible interfaces and called for an emphasis on interaction design. Hornecker and Buur (2006) advocated for a shift in terminology from tangible user interfaces to tangible interactions to put emphasize not only interface design but also the interaction design aspect as well. Eva Hornecker (2015) describes some of the features that tangible interactions approaches should include:

- Tangibility and materiality of the interface
- Physical embodiment of data
- Whole-body interaction
- The embedding of the interface and the users' interaction in real spaces and contexts

Following the distinction between tangible interfaces and tangible interactions, TUIs researchers established several frameworks and paradigms that defined TUIs theoretically. From emerging frameworks by Ullmer and Ishii (2000) and taxonomy for tangible interfaces (Fishkin, 2004) to the TAC paradigm (Shaer *et al.*, 2004) and framework on physical space and social interaction (Hornecker and Buur, 2006). This section will prominently highlight one of the early frameworks developed by Holmquits et al., (1999) which will be used later as a building block for my research for understanding, developing, and evaluating a generalizable approach to tangible user interface for cultural heritage. Holmquits et al., (1999) characterize the process of accessing virtual data through a physical object using the term "T*oken-based*". The framework is devised into three different, nonetheless intertwined classifications:

- *Containers* are physical objects with generic form and do not hold resemblance to digital information it contains. For instance, *mediaBlocks* (Ullmer et al., 1998) are small wooden blocks with no inherent computational properties; the blocks allow access to digital information through several inputs and outputs ports. The user can insert the mediaBlocks into a slot linked to a whiteboard where drawings from the whiteboard can be later printed through a desktop printer.

- *Tokens* are physical objects that hold a resemblance to digital information. *WebStickers* (Ljungstrand et al., 2000) *is a token-based* interaction system that allows users to access web pages through tokens (Figure 11). Users attach barcode stickers to objects on small post notes, which are linked to a URL web address associated with that barcode. In this case, the user can use the properties of any object to find a certain web address.

- *Tools* are physical objects, contain computational properties, allowing for manipulation of virtual representations, such as the case in *Bricks* system (Fitzmaurice et al., 1995) and metaDESK (Ullmer and Ishii, 1997). Both systems use tangible user interfaces to manipulate digital objects on a surface that holds a resemblance to digital information, for example in Bricks, users can rotate and scale graphical objects in conjunction with two physical bricks. With metaDESK, the user can use a magnifying glass to navigate and zoom into MIT campus map analog to magic lenses. Nevertheless, the authors acknowledge that the line between these three categories can sometimes blur …" since when a physical object is attached to a virtual, direct manipulation of virtual properties using the physical representation might become possible" (Holmquist et al., 1999).

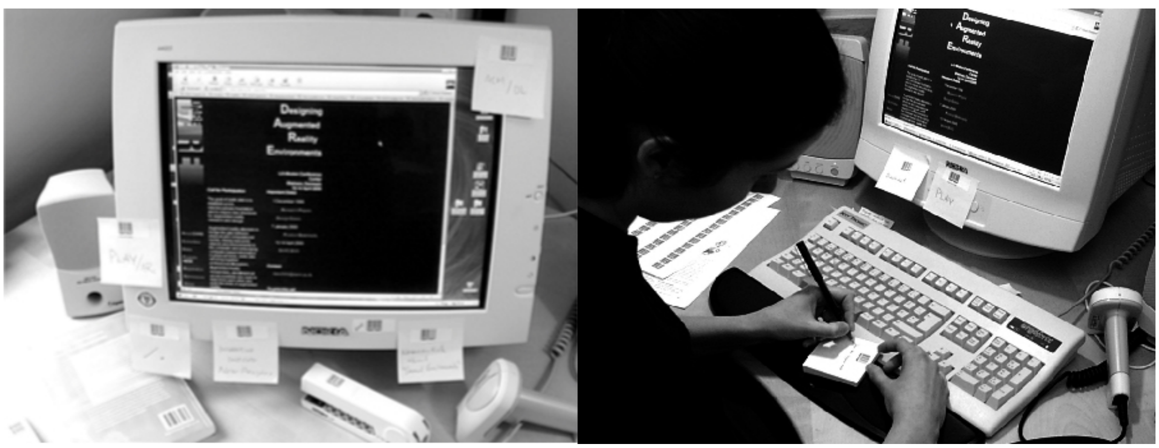

Figure 11: *WebSticker* Post-It notes with printed barcodes. (Source: Ljungstrand et al., 2000).

The concept of tokens to access digital information has also been explored in museums context as well; Ciolfi and McLoughlin (2011) used tokens to give visitors access to interactive content as part of the visitor-guided tour around an open-air museum. Additionally, Wakkary and Hatala (2007) project ec(h)o, a TUI wooden cube coupled with navigational information guides visitors around the museum collections via audio content. Visitors can access content based on their corresponding spatial location.

2.2.3 The Future of Tangible User Interfaces

As described by Holmquist (2019), tangibles user interfaces (TUIs) are considered one of the cornerstones of modern HCI research. However, the lack of implementation of these technologies in a commercial context remains one of the barriers to making TUIs more available for the consumer market "*TUIs have many benefits and opportunities, but there are also impediments to their mainstream adoption*" (Holmquist, 2019). Additionally, at the ACM CHI 2019 conference, Holmquist co-organized a panel to discuss the past, present, and future of tangible user interfaces, in the presence of many academics and industry pioneers including Hiroshi Ishii, the panel presented a few themes that can be regarded as potential successful steps to better the field of tangible user interfaces. Here, I briefly present these themes that emerged from the panel discussion as noted by (Holmquist, 2019):

- ***Users*** are always at the center of any successful technological product or experience, so it is most important to create a personal and socially engaging tangible user experience.

- ***Embodiment*** as an additional layer in TUIs user experience, which can engage all of the six human senses. By incorporating additional components, TUIs can offer a more embodied experience of digital systems and merge intuitively into human activities.

- ***Materiality*** is what distinguishes TUIs from GUIs, the ability to build an interface from any material like plastic, wood, glass, metal, or even dynamic materials such as liquids.

- ***Process*** of development in TUIs requires a lengthier evaluation that is far more cumbersome than what is required in web applications. Similar to GUIs components that facilitate producing graphical interfaces quickly, the production of standardized tangible UI components can facilitate building physical interfaces.

- ***Scalability*** relates to the economical and realistic value that resides in tangible user interfaces, once such value is perceived by the market, as in the case of buying the new iPhone, people will be more ready to invest.

- ***Sustainability*** in relation to electronic waste already forms a concern from an environmental perspective; prompting TUIs to create interfaces using sustainable and recyclable components could reduce electronic junk.

- ***Impact*** of many technologies that were initiated in research labs, today is evident with consumer products such as smartphones and the Internet of Things. TUIs are in a promising position to have a similar impact being a technology that is well experimented and validated within the research community.

- ***Inspiration*** remains one of the driving forces behind the continuous development of tangible user interfaces. Ishii describes his creative approach to research as putting new glasses that let you see the world differently.

Twenty-three years after Ullmer and Ishii first coined the term "Tangible Bits", researchers can still identify many challenges facing the tangible user interfaces research community. These challenges arise from lacking the right theories or frameworks to identify directions, methods and results. At TEI2020, Kristina Höök acknowledged the need for an "evolutionary pressure" (Figure 12) and called for taking the next step in tangible user interfaces research as stated in her Facebook post:

> "Sometimes a research field needs some form of "evolutionary pressure" to take the next step. Pressure needs to come at least from two (?) directions: (1) requirement on a coherent theory that explains the field's ideals, methods, results, and (2) on the other end, engaging with reality (users' needs, business models, need for practical tools) as it is (even when annoying). Maybe?" (Kristina Höök, 2020).

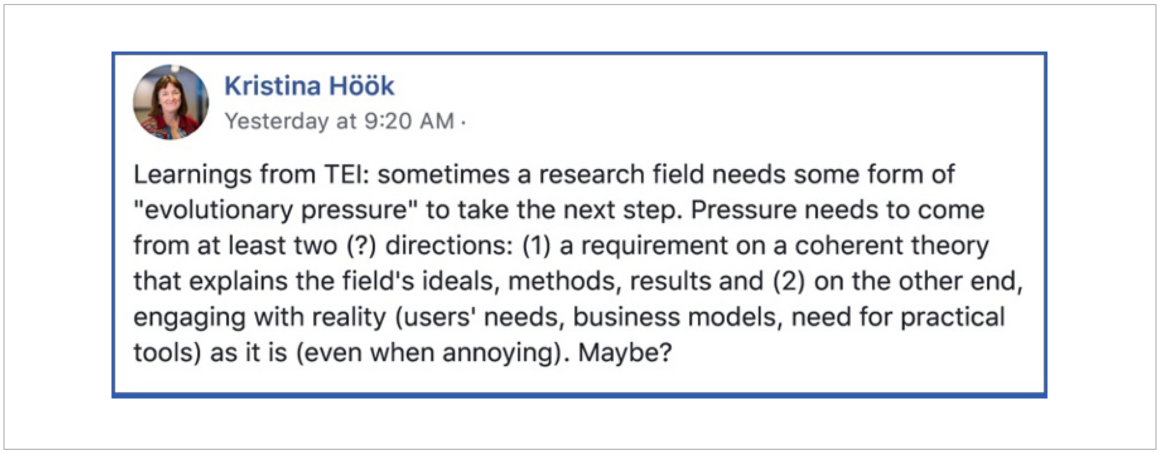

Figure 12: Kristina Höök. TEI 2020 Conference. [Facebook]. (Accessed February 12, 2020).

The vision for the future of tangible user interfaces is jointly celebrated by academics and the industry, however, experimentations and explorations in the research community remain a great source of inspiration and progress for tangible user interfaces.

2.3 Tangible Augmented Reality

Tangible augmented reality (TAR) interfaces combine the rich display of augmented reality (AR) with the intuitive manipulation and interaction of physical objects, providing a seamless and intuitive interaction between the real and virtual worlds (Billinghurst et al., 2008). In Tangible AR interfaces, each virtual object (3D character) is coupled to a physical object (paper card) where the user interacts with virtual objects by manipulating the corresponding tangible object (Figure 13).

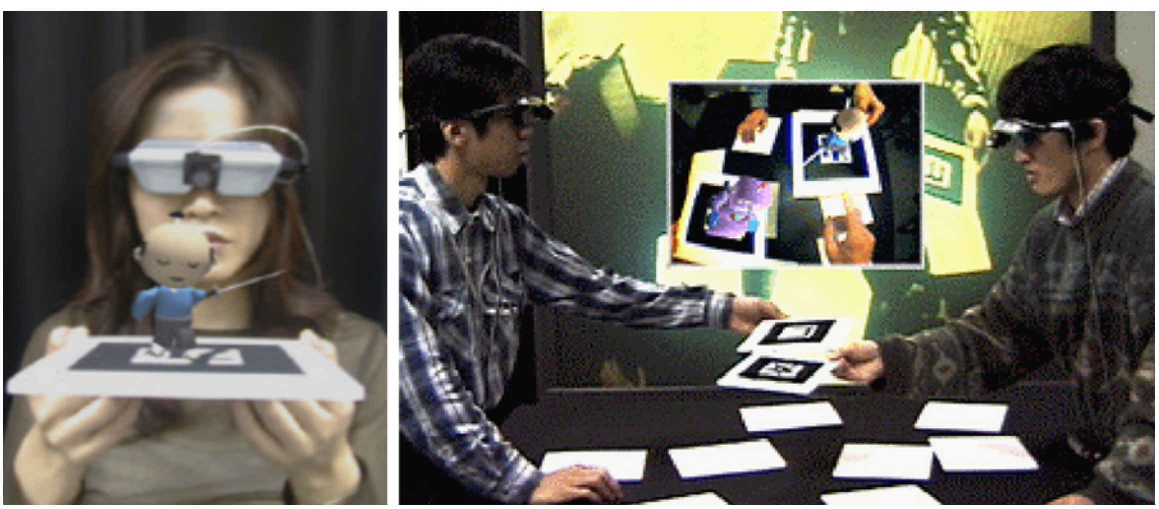

Figure 13: Users interact with virtual objects. (Source: Billinghurst et al., 2008).

2.3.1 Augmented Physical Interactions

Researchers in tangible augmented reality have adopted previous interactions techniques to support early tangible augmented reality interfaces, combining early lessons in augmented reality (AR) applications (Kato et al., 2000) and tangible user interface (TUIs) design principles (Ishii & Ullmer, 1997). This section describes some of the tangible augmented reality (TAR) interactions principles as stated by Kawashima et al. (2001).

- Object affordances should match the physical constraints of the object to the requirements of the task.
- The ability to support parallel activity where multiple objects or interface elements are being manipulated at once.
- Support for physically based interaction techniques (such as using object proximity or spatial relations).
- The form of objects should encourage and support spatial manipulation
- Support for multi-handed interaction.

The Magic Paddle developed by (Kawashima et al., 2001) is a tangible augmented reality interface where users can move and manipulate virtual objects in a virtual scene using a physical paddle. Magic Paddle is comprised of a book, a large piece of paper, a cardboard paddle, and an HMD device (see Figure 14). The Magic Paddle application allows the user to arrange furniture pieces in a virtual room. Users copy and transfer objects from the book pages onto the large piece of paper (virtual room) using the paddle as the physical interaction device.

A great deal of Tangible augmented reality interfaces is rooted in HCI affordance theory (Norman, 1988) which supports the familiarity of everyday objects and its advantages for the user to make the associations between physical objects and augmented space. In that regard, Billinghurst et al. (2009) state:

> ”In an AR experience, there is an intimate relationship between 3D virtual models and physical objects these models are associated with. This suggests that one promising research direction may arise from taking advantage of the immediacy and familiarity of everyday physical objects for effective manipulation of virtual objects”. (Billinghurst et al., 2009, p. 15).

Figure 14: The Magic Paddle. (Kawashima et al., 2001).

The rapid developments in augmented reality SDKs and easy access to 3D printing technologies fostered more experimentation in the field of tangible augmented reality, more recently Mann and Fryazinov (2019) printed tracking pattern onto 3D printed object to create 3D printed AR marker to visualise an artefact, the experiment shows promising results and a glimpse into of the future of augmented artefact.

2.4 Cultural Heritage and Emerging Technologies

UNESCO defines heritage as “our legacy from the past, what we live with today, and what we pass on to future generations” (UNESCO, 2009). From this statement, the mission to create, preserve and conserve digital heritage becomes a necessity as new forms of human knowledge are established through digital channels. As indicated in previous sections, the advances in digital technologies and access to handheld devices allowed for rapid technological growth in multiple domains. The cultural heritage sector was no exception; we can see the implementation of interactive technologies in exhibition design as early as the 2000s in an attempt to reshape the museum experience and engage visitors with heritage collections. The variety of cultural assets whether in museums or open-air heritage sites created exhibitions that incorporate interactive guided tours, 3D visualisation of artefacts and historical monuments, and virtual archaeological sites. This section describes interactive exhibitions that employ augmented and mixed reality applications, as well as tangible interactions. Also, it aims to describe how some of these exhibitions have paved the way to understand the role of interactive technologies in exhibition design and outline the relationship between artefacts, technology, visitors, and space; to better understand and enhance the visitor experience, as well as the role it plays in fostering different roles within heritage intuitions.

2.4.1 Augmented and Mixed Reality Applications

Early applications of augmented reality focused on creating personalised experience for visitors, for instance, Vlahakis *et al.*, (2002) developed Archeoguide, an augmented reality mobile AR for outdoor archaeological sites based on user profile and behaviour, it uses a handheld device, a laptop, and a head-mounted display. Archeoguide provides personalized tours for heritage sites and uses tracking, mobile computing, and 3D visualization to reconstruct ruins of archaeological sites (Vlahakis et al., 2002).

Following on the trend of personalised content for museum visitors, Damala et al. (2008) developed an augmented reality mobile application hosted at the Museum of Fine Arts in Rennes (Figure 15). The hand-held experience uses marker-based AR, to overlay virtual content over paintings. During the visit, the visitor points the webcam towards the paintings to augment 2D or 3D virtual objects. The user can then access these objects interactively by using a touch screen to access further digital documents such as text, audio, and video).

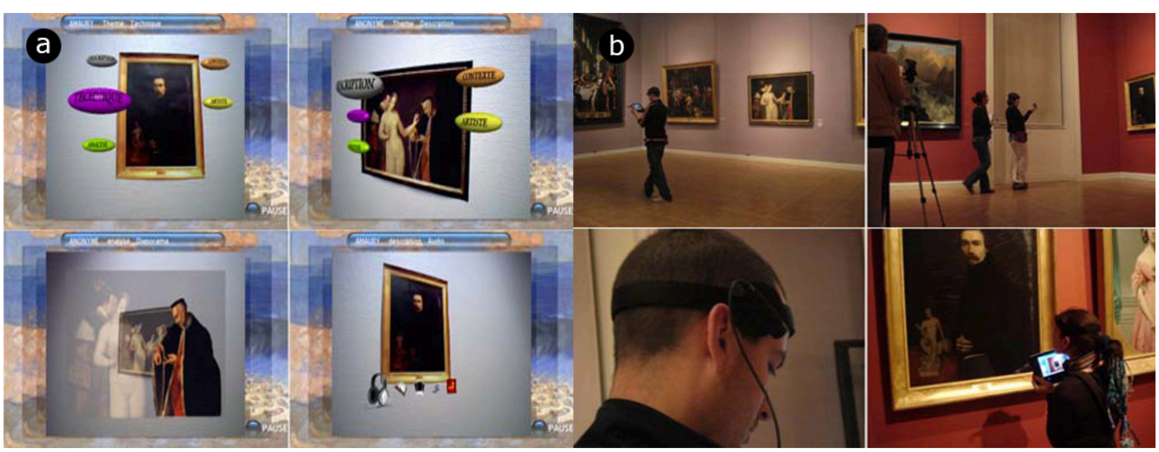

Figure 15: a) Painting’s navigation b: user observation. (Source: Damala et al., 2008).

Keil et al. (2013) created a web app that integrates AR as non-linear storytelling tool. Two versions were developed (Adult, Child). Keil et al. (2013) explain that AR is not seen as a stand-alone application, nor does it replace the entire landscape of existing mediators. Instead, AR is integrated as another medium, part of a comprehensive and coherent framework based on personalised interactive non-linear storytelling on mobiles. Keil et al. (2013) argue that the current use of AR due to its novelty often takes the shape of technological proofs-of-concept aimed at illustrating the potential of AR and leaving AR role in the preexisting Transmedia landscape unaddressed.

As part of an EU project, CHESS (Cultural Heritage Experiences through Socio-personal interactions and Storytelling)[9]. CHESS completed projects in multiple world-renowned cultural institutions across Europe such as the New Acropolis Museum and L'Espace de Cité in France bringing together researchers from multidisciplinary backgrounds to create visitors-oriented experiences through the use of personalised interactive storytelling, and mobile technologies for interactive games and AR applications. For instance, Katifori *et al.*, (2014) created an AR application for museum visitors to explore museum artefacts by pointing a tablet to a statue, then visitors can see superimposed virtual representations as well as read text and listen to audio annotations.

The SHAPE and Disappearing Computers was another EU-funded initiative that highlights the potentials of integrating digital technologies into people's lives to enhance their interactions with the outside world for people to engage and collaborate beyond computer screens. One example of the SHAPE project in museums and galleries, is an installation at the HUNT Museum in Limerick, Ireland that led to create hybrid public environments that allow visitors to actively interact with physical and digital spaces (Ciolfi and Bannon, 2002). Furthermore, the project highlighted the importance of collaborative explorations and participatory design between museum professionals. The project resulted in gaining a thorough understanding of the way visitors navigate through an exhibition and interact

[9] CHESS stands for Cultural Heritage Experiences through Socio-personal interactions and Storytelling. Further details about the project are available through this link: http://www.chessexperience.eu (accessed April 14, 2020)

around the objects on display which is considered an essential component in designing effective museum installations (Ciolfi and Bannon, 2002).

2.4.2 Tangible Interactions and Rapid Prototyping Techniques

Touch in museums keeps gaining importance and being acknowledged in museum studies as it aids in developing a deeper understanding and appreciation for objects (Dudley, 2010). Digital Technologies also offered visitors the opportunity to get closer to artefacts by simulating touch through several technological systems. This section reviews tangible interactions in the context of cultural heritage. A major European-funded projects The MeSch [10] (Material EncounterS with digital Cultural Heritage) aimed at designing and developing innovative platforms for tangible interactions for museums using the Internet of Things approach (i.e., embedded microprocessors, sensors, and actuators into physical objects). Petrelli et al., (2013) suggest that embedding digital information in physical objects helps deliver a richer experience for visitors of cultural heritage sites, bringing back the focus on physical objects without shifting focus from the objects themselves or being distracted by digital technology. For instance, in "The Hague and *the Atlantic Wall* – War in the City of Peace" exhibition set in a historical war museum, smart objects (Soldiers diaries) are activated based on the relevant content (two enemies diaries) which connects the two objects together and unlocks more visual narrative, indicating that the tangible interfaces when associated with a context creates for more meaningful tangible exhibit. "Voices from Fort Pozzacchio"[11] (Figure 16) a MeSch project, also highlights how technology can serve as a complementary layer and seamlessly integrated into the exhibition to form a part of a holistic design as described by Petrelli, (2019):

> "As designers of interactive installations for cultural heritage, a holistic design approach invites us to consider and use many sensorial aspects that are often overlooked, but that are fundamental to creating a memorable experience". (Petrelli 2019, p. 39)

[10] meSch stands for Material Encounters with digital Cultural Heritage. Further details about the project are available through this link: https://www.mesch-project.eu (accessed April 11, 2020)

[11] https://www.mesch-project.eu/voices-from-fort-pozzacchio/

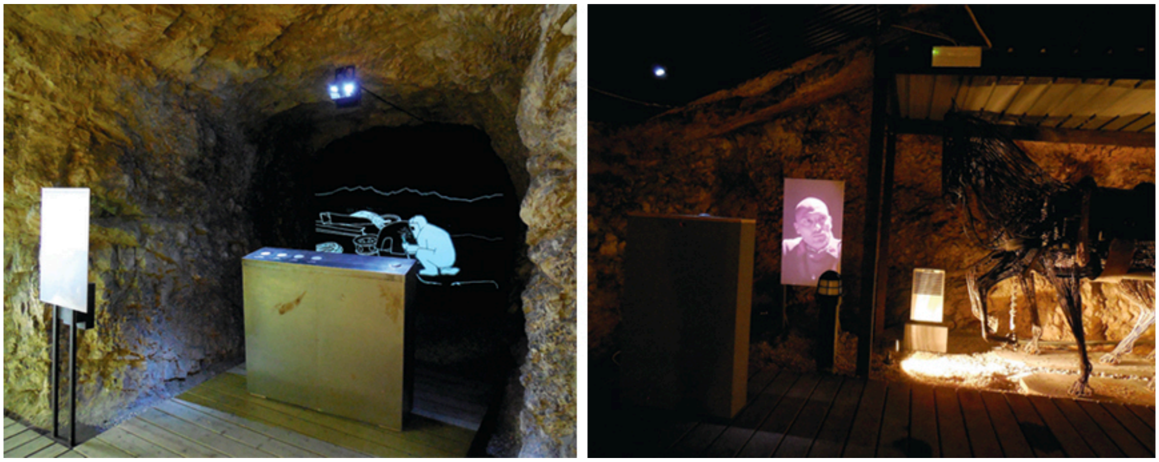

Figure 16: A station at the “Voices from FoPozzacchio” exhibition. (Source: Petrelli, 2019).

The Loupe (Figure 17) is a handheld augmented reality application in the shape of a wooden magnifying glass which augments museum objects with additional content such as text, audio, and two 2D animations using an augmented reality application (Van Der Vaart and Damala (2015).

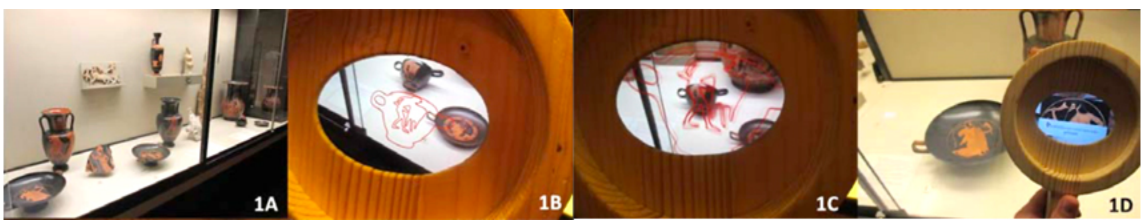

Figure 17: 1a-1d: The Loupe Interface. (Source: Van Der Vaart and Damala, 2015).

Dima et al. (2014) suggest haptic augmented reality as an approach to create a tactile experience by evoking direct haptic interaction with the physical artefacts (Figure 18). The authors suggest that the interaction afforded by the 3D printed replica and a haptic pen helps create an immersive experience and foster a deep understanding of the object as it simulates a sense of touching the original artifact, rather than having visual cues and to develop. Additionally, User evaluation between the 3D replica and haptic device revealed that haptic interaction using the 3D printed replica produced a more rich experience than the haptic device. Dima et al. (2014) state:

> “Our interaction with the world around us is embodied and multi-modal and we make sense of the world by enacting in it. Enactive knowledge is direct, in

the sense that it is natural and intuitive, based on the perceptual array of motor acts". (Dima et al., 2014, p. 5).

Figure 18: Lewis Chess piece behind the glass and 3D replica. (Source: Dima et al., 2014).

Tanenbaum et al. (2010) argues that most tangible experiences focus on system outcome rather than on developing an experience where objects become storytelling tools to express meaningful connections rather than focusing on system functionality. The authors attached RFID tags to ten objects which are triggered via a wearable interface called The Reading Glove, that allows users to listen to audio narration attached to objects. Tanenbaum et al. (2010) states:

"Stories told through objects have the potential to engage senses not ordinarily invoked in traditional storytelling experiences". (Tanenbaum et al., 2010, p. 2)

3D printing has also become a trend to simulate tangible interactions for museum objects, and it gained immense popularity as it provides an exact replica of the original artefact and enables visitors to physically manipulate objects, replicating thousands of collections. The benefits of using 3D printing to foster engagement and enhance visitor experience has been widely studied (Di Franco et al., 2015, Echavarria and Samaroudi, 2018). Also, 3D scanning which are that become widely adopted by museums and cultural institutions. It enabled museums to produce and manage an online repository of their collections over platforms such as Sketchfab[12] that leveraged 3D printing of a whole museum collection.[13] For instance, John Schofield, an archaeologist along with other researchers at the University of York, England, printed "vocal tract organ" that plays vowel sounds through a 3-D-printed replica of a larynx. for ancient Egyptian scribe Nesyamun, helping to bring 3000 old mummy[14] voice back to life The researchers think that approximating a long-dead voice, even with an admittedly imperfect simulation, could help museums make history more accessible. Additionally, 3D printing has been utilized to help the visually impaired visitors to experience museum collections via a touch experience; Touching the Prado[15] exhibition in Madrid reproduced six of his famous paintings through 3D printing, thanks to technology and innovation; these paintings can be touched and experienced by visually impaired visitors. Touching the Prado aid visually impaired visitors to engage with the physical aspect of the paintings and develop a heightened perception of the artworks. D'Agnano *et al.*, (2015) developed Tooketo, a smart ring that allowed visitors to navigate a 3D printed model of the façade of the church of San Michele in Isola by moving their finger over the tactile surface, making art explorations accessible to the visually impaired (Figure 19). The system involves 3D printed façade with NFC sensors and a smartphone application. When visitors touch the surface, the ring detects the NFC tags and connects them to the application wirelessly, which in turn activates an audio track related to the corresponding section on the 3D façade.

[12] https://www.sketchfab.com (accessed on April 14, 2020)
[13] https://www.youtube.com/watch?v=aC557aqSD_U (accessed on April 14, 2020)
[14] https://www.scientificamerican.com/article/3-d-printing-gives-voice-to-a-3-000-year-old-mummy (accessed on April 15, 2020)
[15] https://www.smithsonianmag.com/innovation/please-touch-art-3-d-printing-helps-visually-impaired-appreciate-paintings-180954420/?no-ist (accessed on April 15, 2020)

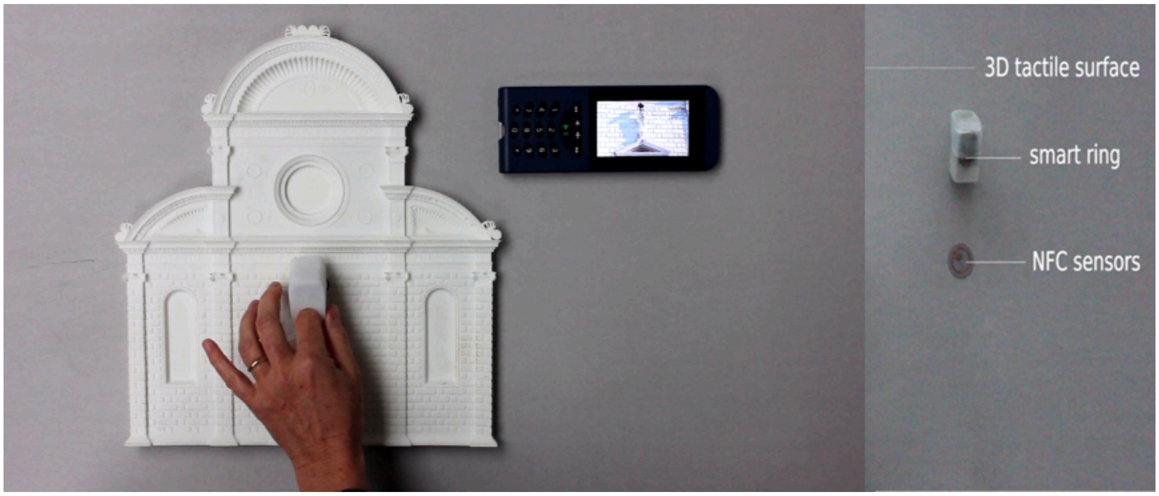

Figure 19: Tooketo system. (Source: D'Agnano et al., 2015).

From smart artefacts to 3D printing replicas, tangible interactions remain an evolving domain, as new technologies are developed, researchers, museum professionals, designers, and developers will be working together to investigate how can tangible interactions be firmly situated within the cultural heritage sector and how to it can behave more than an extra technological layer. The reviewed projects and systems have served as a road map in guiding my research in exploring a new territory for tangible interactions in cultural heritage that is not specific to a certain theme but in fact can serve as a widely accessible solution.

2.4.3 Digital Applications for Archaeology

The application of digital technologies (see Table 1) also encompass archaeology; studies from the early nineties (Reilly, 1990) have called for the incorporation of digital technologies in archaeology to enhance archaeologists' workflow and assist them in their tedious tasks such as sorting artefacts fragments and analysis of findings. This section aims to review digital tools and workflows developed for the purpose of presenting, analysing, and recovering artefacts. Digital archiving, virtual reality reconstructions, and 3D printing are few of several new technologies that are employed to help archaeology experts uncover the past hidden secrets[16], analyse, preserve and organise their findings whether in the laboratories or excavation sites.

[16] DigiArt employs aerial 3D data capture via scanners and drones using techniques such as laser detection (LIDAR), automatic registration, and 3D visualization, resulting in 3D representation of cultural artefacts collections within a virtual museum space. http://digiart-project.eu/ (accessed April 13, 2020)

This section presents four categories of technologies that influenced the archaeological field. In recent years, we observed a surge in the 3D visualization and reconstruction of historical sites and monuments with the aid of photogrammetry and laser scanning, resulting in virtual site reconstructions.

- Virtual reality for virtual reconstructions is one of the most common technology applications in archaeology, due to its ability to reconstruct lost historical sites and monuments. Additionally, Virtual 3D models are easily shared among archaeologists via online platforms which makes knowledge easily transferable among the research community. Vote et al., (2002) explored the use of Virtual Reality (VR) technologies by exploring Petra archaeological site by developing a VR Cave immersive environment (Figure 20). Vote et al., (2002) suggest that Virtual Reality (VR) can aid archaeologists to visualize, as well as interact with archaeological excavation data for analytical tasks, using a three-dimensional model with an situ site virtual representations to provide a contextual inquiry environment.

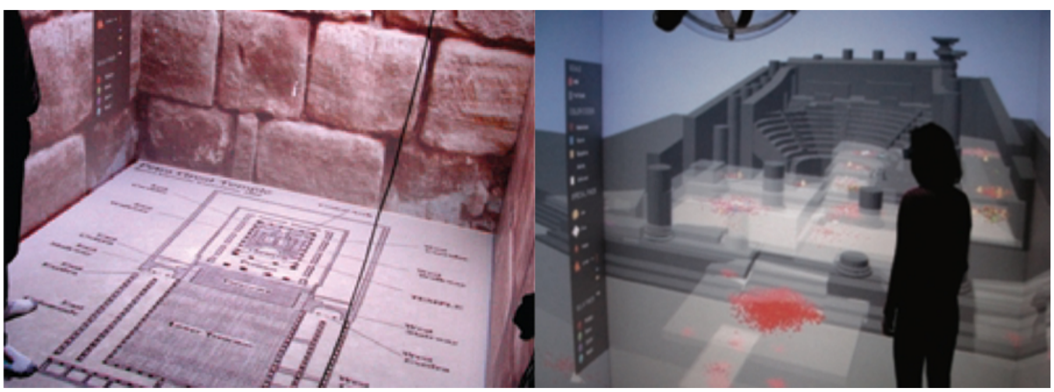

Figure 20: VR Cave immersive environment. (Source: Vote et al., 2002).

- Mixed Reality (MR) was utilised by Benko et al (2004) to simulate archaeological dig conditions and enable remote sites collaboration among archaeology experts. The system named VITA (Visual Interaction Tool for Archaeology), is a collaborative mixed reality system that works as a remote station of an archaeological dig (Figure 21). Archaeologists have access to a high-resolution display, a tracked handheld display, and a multi-user, multi-touch, projected table surface and can use a tracked glove, speech commands, and the multi-touch sensitive surface to collaborate by jointly navigating, searching, and viewing data. The system uses existing archaeological analysis methods with new techniques to combine 2D information from an excavation site, such as sketches, photographs, and notes with 3D models of objects and the excavation site. However, VITA system requires to have a high command of using multiple technological tools, as well as a cumbersome amount of wearable equipment to be able to navigate, explore and engage with information data about archaeology, the system would also require a lot of training and would be very difficult to operate and maintain by archaeologists.

Figure 21: Two users collaborate simultaneously in VITA. (Source: Benko et al., 2004).

- Another Mixed Reality (MR) project to simulate archaeological dig was developed by Human Interface Technology lab[17] (2001) and in collaboration with the Seattle Museum of Art entitled: The Virtual Dig, an interactive learning experience that invites museum visitors to engage in activities to learn about the artefacts' origin and are asked to uncover and examine artefacts found at a new site in the Sichuan province. The visitors would use an ordinary brush and a shovel to reveal several layers and explore artefacts broken shards in the pit, also to interact with the model and attach the broken fragments together to solve the riddle. The installation applies video-based tracking techniques, ceiling mounted cameras, a projection table, a wall screens, then using ARToolKit, the cameras tracked physical shovels used by visitors and projected a 3D virtual model of the shovels onto the wall projection screen.

[17] Human Interface Technology Lab. The Virtual Dig (2001). http://www.hitl.washington.edu/research/sichuan (accessed November 11, 2019)

- ArchAIDE[18], an EU-funded project that aimed at automating the process of sorting pottery and ceramic fragments for archaeologists, developed pottery shreds database management system. ArchAIDE supports the classification of archaeological pottery, (during both fieldwork and post-excavation analysis) where ceramic fragments will be photographed, and their characteristics sent to a comparative collection via algorithms, which activates the automatic object recognition system, resulting in all relevant information to be linked, and ultimately stored within a database that allows each discovery to be shared online.

- 3D printing became a common practice to replicate original artefacts by museums and galleries to offer visitors a hands-on experience; Gaugne et al., (2019) used CT scans data to produce 3D printed models that support archaeological analysis by using HoloLens, an optical see-through augmented reality device to superimpose virtual 3D model into 3D printing replicas using a virtual random-dot mask (RDM). The outcome of the described process is what the authors refer to as visualization of the internal elements of materials.

[18] http://www.archaide.eu/project (accessed April 13, 2020)

Table 1: A list of digital technologies in Archaeology and Cultural Heritage.

Category	Technology	Reference
CAVE	VR Archaeological site	Borba et al. (2017)
	VR 3D models	Jiménez Fernández Palacios et al. (2017)
	VR Historic site visualization	Vote et al. (2002)
Excavation Site	Head-worn Display	Benko et al. (2004)
	Reality-based 3D models	Guidi et al. (2013)
	Tangible interface	Lee et al. (2001)
	VR 3D data recording	Lercari et al. (2018)
	Online virtual museum	Levy et al. (2010)
	3D Web GIS	von Schwerin et al. (2013)
	Mobile AR Application	Vlahakis et al. (2002)
Museum Exhibits	ARToolKit -Virtual dig	HITLab (2001)
	VR Museum Collection	Ciolfi et al. (2002)
	Spatial Augmented Reality	Ridel et al. (2014)
	3D visualization	Madson et al. (2015)
	Augmented reality	Michael et al. (2010)
	Tangible interface	Not et al. (2019)
	Tangible interface	Petrelli et al. (2019)
	Tangible interface	Ryabinin et al. (2019)
	Handheld AR app	Van der Vaart et al. (201
	Tangible interface	Qi Lu et al. (2019)
	AR XML artefacts database	White et al. (2004)
	ARToolKit	Wojciechowski et al. (2004)
Pottery Ceramic Shreds	Mobile Application for Pottery shreds Database	ArchAIDE Consortium (2019)
Artefacts and monuments	AR Application for Landscape	Eve, S. (2012)
	Augmented Reality Cube	Jiménez Fernández-Palacios et al. (2015)
	Artefact's visualization	Leymarie et al. (2000)
	Virtual dig	Polymeropoulou (2014)
	Tangible interface	Reuter et al. (2010)

2.4.4 Museum Visitor Experience: Models and Frameworks

The museum visitor experience has been extensively studied across decades resulting in several models and frameworks which aim to offer structured tools for museum professionals and researchers to examine the visitor experience and understand the visitor behaviour in museums, and their interaction with objects and around exhibitions. Pekarik et al., (1999) used survey data obtained from visitors at nine Smithsonian museums where they identified a list of 14 satisfying visitor experiences. The experiences were categorized into four clusters (object experiences, cognitive experiences, introspective experiences, and social experiences). Dierking and Falk (1992) conceptualised the museum experience from a visitor's perspective using the interactive experience model as a framework to understand the overall museum visitor experience. They suggest that the interactive experience model which focuses on the actions taken by the visitor during their visit, is dictated by three contexts (personal context, physical context, and social context) that need to be considered when analysing the visitor experience.

Similarly, Desmet and Hekkert (2007) introduced a general framework as a tool to compare experiences of using products which includes three distinct components (aesthetic experience, experience of meaning, and emotional experience). These components can be interrelated and dependent on each other. Additionally, the frameworks proposed by the literature consider various dimensions of the visitor experience to play a significant role in shaping their experience, such as the visitor's personal characteristics (i.e., personality, skills and cultural background) along with the object characteristics (texture, shape, colour) as well as the context where interactions take place (i.e., museum, gallery, displays).

2.5. The Future of The Past

According to UNESCO's Charter on the Preservation of the Digital Heritage (UNESCO, 2009), all forms of digital materials including text, databases, images, audio, graphics, software, and web pages that constitute a heritage should be protected and preserved for current and future generations require purposeful production, maintenance, and management to be retained. Therefore, guaranteeing access to heritage collections remains the most significant challenge to digital heritage preservation. To guarantee the continuity of access to heritage material authentic message and purpose are essential.

2.5.1 Heritage Challenges: Accessibility, Preservation, and Conservation

A recent white paper published by the nine Institutes of the DIITET Dept. on "Technologies for Cultural Heritage (CH) Use and Preservation (2019) describes some of the emergent issues facing the cultural heritage sector. Some of these issues are summarised in the following question: How does the future of the past look like? This question reveals further recommendations for many museum professionals and researchers to address these new challenges. I will emphasize two of the recommendations as stated by CNR DIITET AP11 (2019) that will form part of the areas addressed in the thesis.

- Integration of *gesture/ tangible/ speech interaction* and *augmented/ virtual reality*, dialoguing with the Internet of Thing (IoT) sensors and optimizing user interaction capabilities; development of sensors-based, active replicas to support AR applications.

- Development of tools with interfaces *accessible for all*, to support schools, stakeholders, and small communities in acquiring and sharing knowledge on minor/local assets using low-cost devices and open data repositories, boosting the sense of belonging to a common cultural heritage of local communities.

Further to UNESCO advocacy on digital preservation for cultural heritage, CORDIS result pack (2020) features 12 EU-funded projects through Horizon project 2014-2020 that help ensure the preservation of Europe's cultural heritage. The project aims to support innovation in the cultural heritage domain using state-of-the-art technologies, which is leading to the next stage research programme, Horizon Europe. Additionally, in 2019, 26 European countries signed a Declaration of cooperation on advancing the digitisation of cultural heritage [19]. The declaration aims to better use state-of-the-art digital technologies in

[19] https://ec.europa.eu/digital-single-market/en/news/eu-member-states-sign-cooperate-digitising-cultural-heritage. (Accessed April 15, 2020).

addressing risks that Europe's rich cultural heritage is facing, enhancing its use and visibility, improving citizen engagement, and supporting spillovers in other sectors.

> "The digital revolution is leading to new and innovative forms of artistic creation while making culture and heritage more accessible and opening up new ways of enjoying cultural content. Making our cultural heritage widely available in the digital era is vital. It is great news that many Member States will now work closely together to fully leverage the cultural opportunities brought by digital technologies", (Tibor Navracsics, 2019).

Digital Technologies represent of the facets of digital transformation challenges for cultural heritage institutions in terms of the integration of digital in museums' physical domains. According to Finnis et al. (2020) report for Europeana, the term digital transformation designates a transformative contemporary condition for museums in which digital thinking, practices, and tools have assumed a normative presence that penetrates all levels of their operations and function (cited in Mason, 2022, p1). Another central aspect of the digital transformation discourse (socio-technical context) is the centrality of people and understanding the stakeholders' and the visitors' needs to enhance the visitor experience. In this instance, Mason (2022) suggests that digital transformation happens at the design level and is part of the social context. He argues that adopting a human-centered design approach (such as Design Thinking) can foster new competencies and novel ways of thinking (Mason, 2022). Hence, the design of digital/physical visitor experiences within the cultural heritage domain should account for the design of the overall museum experience as an essential component of digital cultural heritage design.

Summary

The contextual review covered extensive literature on Tangible User Interfaces, Augmented Reality, and Emerging Technologies in Cultural Heritage. The review revealed widespread applications of digital technologies in multiple domains with a focus on museums and heritage sites, whether in the form of immersive technologies such as augmented reality, virtual reality, or tangible interaction using smart artefacts and 3D printing. Although at times the technology was seen as an added technological layer and has been argued that it distracts visitors' attention from the actual artefacts, researchers are still keen to create meaningful experiences through personalised and compelling narratives.

The review also revealed a lack of generalisable solutions that would promote the use of tangible augmented reality, since the presented projects particularly focus on theme-specific or specific site exhibits using complex systems and applications. Additionally, theoretical frameworks specific to tangible interfaces in museums remain scarce and mainly address broader considerations on technological interventions in the cultural heritage domain. Consequently, this research aimed to investigate how the use of physical objects (generic proxies) for augmented reality could advocate access to inaccessible artefacts and lead to wider adoption by museums and galleries. Additionally, through the use of generic proxies, I aim to shed the light on how digital technology can be used to enhance the attributes of original artefacts and not replace them. Therefore, a conceptual framework can formalise the design process of tangible AR interfaces for manipulating virtual representations of historical artefacts and aid researchers, designers, and cultural heritage professionals in understanding and guiding the design process to build more engaging tangible AR interfaces for historical artefacts.

3. METHODOLOGY

Overview

This chapter discusses the research methodology. I adopted research through design (Frayling,1993) and co-design with stakeholders (Sanders et al., 2008) in the domain of HCI with a focus on interaction design. In the practice of research through design within HCI, interaction designers explore new problem spaces, codifying understanding through the construction of artifacts (Zimmerman and Forlizzi, 2008). Additionally, I applied pragmatism as a reflective lens for design research which aligns with Donald Schön (1983) theory for design education. Schön (1983) describes practitioners' work as a reflective practice, where reflection in action and reflection on action, are two activities that support the process of developing knowledge through practice. This multi-method approach in the research echoes with Lévi-Strauss (1966) Denzin and Lincoln (1994), and Louridas (1999) ideas of a bricoleur. As a bricoleur, the researcher chooses her research tools depending on the research questions and their context and adheres to different research methods at hand to address real-world problems (Denzin and Lincoln, 1994). Vallgårda and Fernaeus (2015) also suggest that bricolage is a suitable method in interaction design and particularly when designing for tangible and material computing, "…bricolage proposes interesting ways of creating more culturally grounded and material rich artifacts because it operates in-situ and not towards an imagined future", therefore, bricolage encourages an exploratory approach and what is suited for each design situation (Vallgårda and Fernaeus, 2015, p173). The reason for practicing this multi-method approach is driven by the novelty of the research itself which deals with the application of digital technologies to a specific situation (Dalsgaard, 2010). This led me to explore new methods to generate and interpret design ideas through crafting my own research tools to communicate research outcomes.

Through a designerly-researcher (Yee, 2017) viewing lens, I developed a tangible augmented reality prototype combining my background as a practicing designer with research skills and co-designing with the heritage experts to generate prototype design concepts, which were later tested through multiple user studies. Furthermore, this chapter highlights the research activities taken to generate insights on how to design, implement and evaluate the prototype for a Visitor Centre in the North East of England. The research activities initially took place at The Sill: National Landscape Discovery Centre part of Northumberland National Park Authority. The Sill served as the context for my research where the final prototype was on display as a stand-alone exhibit. This approach helped me to forge a good relationship with The Sill staff in various roles and supported the recruitment of research participants at a later stage. The restrictions imposed by the COVID-19 pandemic determined that for an extensive period of the research, it would be conducted remotely. I describe this transition to online methods in more detail in the evaluation and findings chapter (Chapter 5). I also describe the multitude of qualitative methods I adopted in this research in the following sections.

3.1 Methodological Approach (Research Through Design)

Research through Design (RtD) is an established methodology for design research in HCI. To view design as more than just a domain for aesthetic and visual appeal, Zimmerman et al. (2007, 2010) addressed the need to formalise the process of Research through Design (RtD) in HCI. Subsequently, Zimmerman et al. (2007), Zimmerman and Forlizzi (2008) aimed to provide a theoretical lens through which interaction designers can articulate the process of design and analysis of design artefacts that would transform the world from its current state to a preferred state.

> "In Research through Design (RtD), researchers make *prototypes, products,* and *models* to codify their own understanding of a particular situation and to provide a concrete framing of the problem and a description of a proposed, preferred state", (Zimmerman and Forlizzi, 2008, p. 4).

Zimmerman et al. (2007) also developed an evaluation model that hosts four criteria: process; invention; relevance, and extendibility, they described these four lenses as standards through which interaction designers can evaluate an interactive artifact and identify their contribution. Fallman (2003) distinguishes between two types of design research: design-oriented research and research-oriented design. In design-oriented research, the researcher regards the design process as what is being investigated while the artifact implementation is a manifestation of this process. In this research, I am focused on examining the unique user experience of manipulating virtual representations of historical artefacts using the prototype while it unfolds through a User-centered Design (UCD) approach. The User-centered Design (UCD) approach in interaction design is an important aspect of understanding the relationship between designing interactions and users' needs, strengths, and contributions. This is exemplified through the collaborative process and continuously communicating of the research outcomes with the heritage experts.

3.2 Pragmatism as a Reflective Lens for Design Research

Designing for real-world problems lays at the heart of the pragmatism approach. Pragmatism has previously inspired interaction design research (Petersen et al., 2004). Pragmatism places action and reflection in a dialogue, very similar to Donald Schön designing with materials as a reflection conversation (Schön, 1992). This continuous dialogue is important for the type of situated artefacts, as iteration, and evaluation form integral parts of the design process where researchers can go back and forth between different phases of their artifacts design process. Also, there is a growing interest in connecting pragmatism and design research, as both approaches aim to transform the world from its current state to reach a preferred state (Zimmerman et al., 2007).

> "In taking a *grounded* approach, design researchers focus on real-world problems by making things that force both a concrete framing of the problem and an articulation of a specific, preferred state that is the intended outcome of situating the solution in a context of use"(Zimmerman & Forlizzi, 2008, p5).

Pragmatism as an approach offers an advantage for its situatedness and reflective perspectives which provides a qualitative and reflective lens for my methodology. Dalsgaard (2014) makes an argument on how pragmatism can become a conceptual scaffolding for progressing the discourse of design and design practice by drawing on John Dewey's (1859-1952) theory of pragmatism. He highlights the parallel worlds of pragmaticism and design thinking and the convergence between them.

> "As such, pragmatism and design coincide on a fundamental level; one might say that pragmatism is very amenable to designerly thinking in that it offers articulations and insights regarding the notions of *situation, emergence*, and *interaction* that can be employed in understanding the design and users of interactive artifacts", (Dalsgaard, 2014, p. 148).

Additionally, Dalsgaard highlights how pragmatism advocates users as resourceful actors who draw on their situations when using interactive artifacts to make sense and transform their reality.

Several design research models implement Research through Design (RtD) process in which all resonate with the reflective lens adopted in this research. For Schön (1992) the reflective process is continuous through framing the problem, taking action, and then reflecting. Zimmerman et al., (2004) define the most common design process for Research through Design (RtD) in HCI into six phases: define, discover, synthesis, generate, refine and reflect. Another relevant reflective model is Kolb's (1984) Experiential Learning Cycle. Kolb defines the process as a spiral model (Figure 22) where knowledge is attained in a cycle through experience, reflection, experimentation, and conceptualisation. For Kolb, learning takes place when an individual assimilates the experience and then processes it by reflecting on the experience and then proceeding to action where knowledge is attained, and learning happens through the experience.

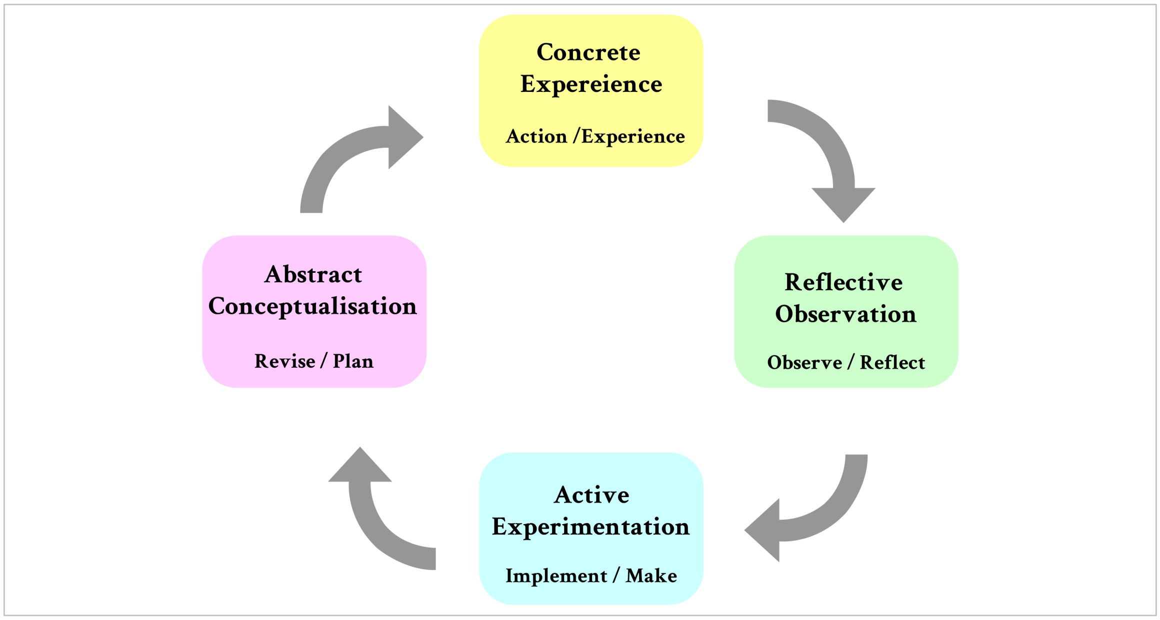

Figure 22: Kolb's Experiential Learning Model. Kolb (1984).

My research design process followed the double diamond model (Design Council UK, 2005). The double diamond model is a design process that was formalised by the UK Design Council in 2005 to facilitate the design process, and it encompasses four stages: discover, define, develop, and deliver along with divergent and convergent thinking. This model was shaped with a User-centered Design (UCD) approach in mind to illustrate the different phases for orchestrating my research design process which led to prototype development. I then characterised these four phases into the following phases: capture, interpret, ideate, and implement. The adopted double diamond model (Figure 23) is hosted under three main components: Research, Collaborate and Build, which represents the overarching umbrella framing the whole design process. The model also demonstrates the various methods that were used in each phase to research, gather information, interpret the findings, collaborate, design, and build the final prototype.

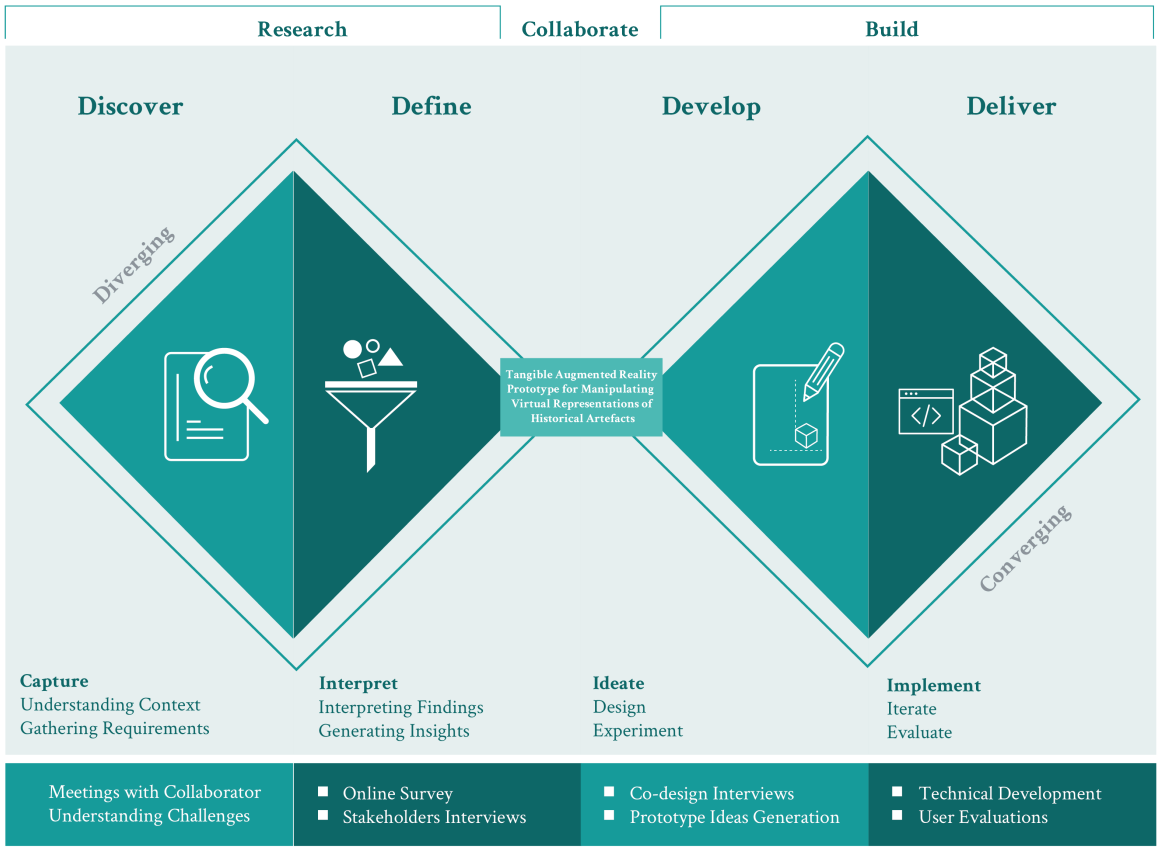

Figure 23: User-centered Design adapted to the double diamond. © Suzanne Kobeisse (2021).

Capture

The capture phase focuses on examining the research context and understanding the challenges around the design process. During the capture phase, I used several requirements-gathering methods such as field visits and observations of the context. During my field visits at The Sill, I focused on developing my understanding of the visitors' interactions with digital exhibits, particularly exhibits that involve tangible interactions. This approach emphasises human-centred principles of the double diamond which includes the understanding of the (socio-technical) context and designing for people. I also organised several meetings with the research collaborators at The Sill and launched an inquiry into what are the challenges of engaging The Sill visitors with virtual representations of historical artefacts. Several meetings prompted discussions around the current use of the holographic display at The Sill which showcases 3D models of Bronze Age artefacts. The holographic display limited the visitors' physical interactions with the historical artefacts and generated less interest in the narrative of the Bronze Age artefacts. At this point, it was essential to capture the visitors' attitude about digital technologies and their interactions with the current digital exhibits at The Sill, as any new digital intervention must pay consideration to the visitor interactions around the interactive exhibitions (Hornecker, 2008).

Interpret

The interpret phase focuses on processing the findings from the capture phase and generating insights that narrow the possibilities to address the design challenges. During the interpret phase, I started developing a clearer idea about the design and technical challenges. It became evident through an online survey and field observations that my design practice and making skills would merge with understanding the visitor's needs and the context itself. I then interpreted my findings through a proof-of-concept to generate further insights with the stakeholders around manipulating virtual representations of historical artefacts. The proof-of-concept provided an opportunity towards defining the research process towards enabling The Sill visitors to have a hands-on experience with virtual representations of historical artefacts and offer them an intuitive and engaging experience.

Ideate

The ideate phase focuses on the design and experimentation with several design concepts using brainstorming, sketching, and low-fidelity prototyping. During the ideate phase, I used co-design with the heritage experts to test as many ideas as possible and address any technical challenges. I went through an iterative design cycle which allowed me to validate the prototype concept at each stage. The iterative cycle plays a role in shaping early design concepts as described by Sanders and Stappers (2014), "Iterative prototyping can be viewed as 'growing' early conceptual designs through prototypes into mature products" (Sanders and Stappers, 2014). Starting with a proof-of-concept paved the way to the development of a tangible AR prototype that is extensively studied through iterative prototyping and tested with stakeholders to validate its effectiveness. The tangible nature of the research allowed for each iteration to inform progress or a step back to assess design decisions, or even change in the design direction. The ideate phase allowed me to communicate my ideas and co-design concepts with stakeholders about different interaction techniques using generic proxies, as well as validate the interface design for the augmented reality application through user testing.

Implement

The implement phase focuses on developing the final prototype, iterations, and evaluating the prototype with stakeholders. During the implement phase, I developed the augmented reality application including the Unity software code development, the narrative content, and interface design features. At this stage, all user requirements for the prototype are achieved and a high-fidelity prototype is presented to stakeholders. Also, I completed feedback sessions with stakeholders to identify any issues with the different aspects of the prototype (i.e., ergonomics and interface design features), which allowed for further iterations based on the insights generated from feedback sessions. At the end of the implement phase, a final prototype was produced and installed at The Sill ready for final evaluation by The Sill visitors.

3.3 Thinking Through Prototyping

> **Prototypes**
>
> …" are design-thinking enablers deeply embedded and immersed in design practice and not just tools for evaluating or proving successes or failures of design outcomes", (Lim and Stolterman, 2008, p2).

Thinking through prototyping constitutes part of my methodological approach (Research through Design (RtD). In Research through Design (RtD), Stappers (2014) describes the multiple roles, that a prototype can embody, one of those roles is such as eliciting discussions with stakeholders, "Prototypes evoke a focused discussion in a team because the phenomenon is on the table" (Stappers, 2014, p6), the topic of investigation becomes an obvious entity, and the involved team can consider the concepts more visibly. The prototyping process is considered a contemplative process between the researcher, the materials, and the physical setting. This approach resonates with Ingold's (Ingold, 2013) ideas of "thinking through making", Ingold considers creativity as an emerging process that forms a continuous dialogue between the maker and materials transformation. Also, in referring back to Schön (1992), where he describes the design process as a dialogical between researcher's reflection, action, and talkback with the materials. In my research, this process is exemplified by the dialogue between the designer-researcher, prototype design materials, and communication with the stakeholders, while emphasising the role of the materials, which allows the designer to experiment with different outcomes, and have tactile evidence of design iterations. I experimented with materials to test different design solutions (here I refer to materials, in terms of sketching, physical prototyping, and Unity software code). Subsequently, materials allowed me to identify any challenges that would arise that sometimes present a turning point in the design process. This dynamic relationship with materials generates insights, which can be expressed and discussed with stakeholders. Sanders and Stappers (2014) describe prototype as "the thing being made is not a forerunner of the future product, but a vehicle for observation, reflection, interpretation, discussion, and expression" (Sanders and Stappers, 2014, p6). Prototypes are a tangible attempt to view a design's future impact so that we can predict and evaluate certain effects before we unleash them into the world. Knowing that prototypes filter certain aspects of a design, we can become more aware of the complexity and responsibility of a design, and hence be more thoughtful about our design decision-making. (Lim and Stolterman, 2008). Prototypes also serve beyond just tangible visualisation of design concepts and system features. They become a thinking tool for the researcher throughout a long iterative process. They can provide instant feedback on unresolved design issues as I refer to them as physical containers for my thoughts. Gill et al., (2011) consider physical models to provide even richer visual information and a more concrete sensory experience with an artifact or a given dimension of an artifact. Stappers (2007) calls for prototypes to form part of generating knowledge where insights can feed into the growth of theory.

> "The designing act of creating prototypes is in itself a potential generator of knowledge (if only its insights do not disappear into the prototype, but are fed back into the disciplinary and cross-disciplinary platforms that can fit these insights into the growth of theory)", (Stappers, 2007, p. 87).

Within the domain of cultural heritage, Mason (2015) suggests that prototypes are a way to externalise ideas for the designing of digital media installations in museums. Prototypes become a common language that facilitates the exchange of knowledge and fosters collaboration between different stakeholders. In the early phase of my research, I did not commit to one specific idea of how the prototype will end up looking, instead, I experimented with several prototypes as an ideation method using the 3D models of the virtual representations of historical artefacts. The prototypes served as a way to interactively externalise design concepts and present them in a comprehendible format to the stakeholders. This approach allowed me to see what is feasible beyond 2D sketching, it also helped the collaborators on the project to familiarise themselves with the potentials of tangible AR and what other opportunities we can build onto from early prototype experimentations. I was also able to survey which design concepts are viable and best suited as a tangible AR approach. As some of the ideas that sounded great at the beginning, started falling apart once they were physically built, this helped me realise any challenges early in the design process and avoid any obstacles throughout a more advanced design stage (see section 4.1.2). Furthermore, designing for augmented reality can add an extra layer of challenges, as the designers need to visualise and conceptualise for 3D space. So far, most design tools such as wireframes are intended for 2D screen-based interactive projects. While research in the domain of AR has been active for over 20 years, the available tools for designing interactions in AR are still limited, thus designers have to rely on 2D sketching. Therefore, I consider using low-fidelity prototyping as an effective method to externalise design ideas, for example, I used physical tools such as cardboard and laser-cut wood, flat AR markers, and 3D printing at different stages of the prototype development process. Prototypes also serve as an important and practical documentation instrument. The researcher can use them to record and keep track of the different decisions made, assess the challenges, and examine the turning points throughout the research. At every stage in the design process, I was able to use the prototype to review different aspects and provided an easier way to communicate with stakeholders because I could refer back to previous iterations. Throughout my Research through Design (RtD) approach, I engaged with prototypes as a manifestation tool to:

- Develop a deep understanding of the technology capabilities and define potential design directions by testing several design concepts.
- Reflect and anticipate any limitations pertaining to tangible interfaces and augmented reality application in a heritage context.
- Showcase and communicate ideas to stakeholders to gain insights into further prototype development.
- Document my design decisions through an iterative process.
- Demonstrate and evaluate design concepts with stakeholders.

3.4 Engaging Heritage Experts in Co-designing Tangible AR Interfaces

During the course of the research, collaboration with the heritage experts was a central component in understanding the context for the prototype being developed. I enlisted the help of Northumberland National Park and The Sill staff who had diverse expertise (archaeologists, cultural heritage professionals, directors, engagement and educational officers, digital/technical officers, and volunteers). The heritage experts possessed a wealth of knowledge about the history of Northumberland National Park and Ingram Valley (North East of England) in particular, where the Bronze Age artefacts were excavated. In addition to the contextual knowledge about the artefacts, I had continuous discussions with The Sill exhibition manager, who is in charge of planning and organising exhibitions at The Sill and was able to provide good insights into understanding The Sill visitor' requirements and their preferences.

Further details about the role of the heritage experts and their involvement at different stages of this research, through co-design sessions (see section 4.2.4) and user studies are described in more detail in the evaluation and findings chapter (chapter 5). Contact with the heritage experts was established from the early stages of the research, especially during the experimental prototyping stage (see section 4.1.2). Co-design and participatory practices for developing cultural heritage projects, mainly for tangible interactive experiences (Petrelli et al., 2018) have been explored to empower heritage experts with technological tools using co-design workshops (Ciolfi et al., 2015). Acknowledging the role of the heritage experts as co-creators rather than simply giving input about the design process (Mcdormett et al., 2014).

This approach would allow for the democratisation of the design process in museums and aims to empower not only heritage experts but also volunteers (Ciolfi and Petrelli, 2016). Additionally, collaboration with the heritage experts also took the form of an inspirational dialogue. I was able to reflect on that dialogue with the heritage experts using sketching, and prototyping, the user studies also elicited meaningful conversations that translated into inspirational outcomes towards design decisions.

3.5 Studies, Participants, and Methods of Data Collection

I conducted seven studies (see Table 2) that formed a substantial component of the user-centered design approach in this research. Table 2 outlines a summary of the research activities, objectives, and data collection methods for each study. I then follow with a detailed description of each study. Study 4, study 6, and study 7 are discussed in more detail in the evaluation and findings chapter (chapter 5). The studies constitute a progression that builds up towards answering the research questions and developing the final prototype. In each study, I collected and analysed the data to inform the next stage in the research.

Participants and Ethical Approval

The collaborative nature of the research with The Sill enabled me to form a long-term relationship with stakeholders who offered continuous support and encouragement throughout the research process. This continuous relationship with stakeholders allowed me to consistently recruit participants in multiple studies and also was helpful in the sense that stakeholders were able to follow the research journey and monitor the progress, as well as give feedback on prototype iterations, address potential problems, and propose new solutions. Participants' recruitment took various forms and included heritage professionals, archaeologists, management staff, volunteers and visitors. I focused on a small sample for the semi-structured interviews to allow in-depth conversations about the research while developing a close engagement with the data. For the online survey, participants were recruited via an invitation posted on The Sill social media channels. For the user studies, participants were recruited using The Sill network of staff, volunteers, and personal contacts. An overview of the sample size for each study is described in Table 2.

The research adhered to the ethics guidelines to ensure that the research process is aligned with all the ethical considerations. The appropriate ethical approval for the entire research was acquired by Northumbria University Ethics Online system on December 10, 2019 (submission reference 20903). The ethics application included information sheets and consent forms for each study. The ethics approval addressed all matters related to ethical conduct to safeguard participants' involvement in the studies and that their data is stored in accordance with participants' data protection under the General Data Protection Regulation (GDPR). Additionally, following the COVID-19 pandemic restrictions, a detailed risk assessment plan including an amendment to the ethics application to resume face-to-face research with participants was submitted and approved respectively in June 2021 and August 2021. More details on the ethics and risk assessment documentation for each user study are discussed in the evaluation and findings chapter (chapter 5).

Semi-structured Interviews

I used semi-structured interviews as a qualitative research approach to conduct one-on-one interviews with the heritage experts. The semi-structured interviews represented part of a triangulation approach for using multi-sourced data. The semi-structured interviews allowed me to have in-depth discussions with the heritage experts and explore their views on the role of digital technologies in enhancing visitor interaction experience with virtual representations of historical artefacts. In a sense, these interviews formed a bridge that links my design reflections during the research process and the stakeholders' anticipation of what is feasible using digital technologies while maintaining the authenticity of the interpretation for the historical artefacts. Additionally, I also used the interviews as a tool to demonstrate the prototype abilities and test different iterations in hands-on sessions, and to generate concept ideas through the co-design interviews. All interviews were audio-recorded, transcribed, and later analysed to identify emergent themes and report on patterns and categories using Thematic Analysis (Braun and Clarke, 2006). During this process of analysis, I was building on the initial concepts that emerged from earlier interviews to arrive at higher-level concepts to support the theoretical contribution.

Table 2: Summary of research activities for each study.

Research Activities	Data Collection Method	Participants	Objective
Study 1 Requirement Gathering	Online Survey	60 visitors	Gather insights about the use of digital technologies at The Sill from the visitors' perspective.
Study 2 Requirement Gathering	Semi-structured interview	Eight heritage experts	Gather insights about the use of digital technologies to answer the overarching research questions.
Study 3 Pilot Study	Semi-structured interview	Eight heritage experts	Evaluate proof-of-concept (ARcheoBox 1.0)
Study 4 Comparative Study	Likert-type Questionnaire and open-ended questions	16 heritage experts	Explore design opportunities for generic proxies as tangible interfaces to manipulate virtual representations of historical artefacts.
Study 5 Co-Design Interviews	Semi-structured interview	Eight heritage experts	Generate design concepts for the prototype.
Study 6 Prototype Demo Study	Likert-type Questionnaire and Open-ended questions	25 heritage experts & public users	Evaluate design features of the prototype.
Study 7 Final Prototype Study	Questionnaire (open-ended questions)	80 Visitors	Evaluate ARcheoBox and refine the conceptual framework

Study 1

- *Objectives:* The first study aimed to gain insights into the visitor perception towards the use of digital technologies at The Sill: National Landscape Visitor Centre and also to establish an overarching understanding of the visitor preferences regarding interactions with interactive exhibits.

- *Methods of data collection:* An online survey was distributed via The Sill internal mailing list and social media channels. The survey questionnaire was composed of two sections, demographic questions (Section A) and general questions (Section B). The general questions addressed the visitor patterns of visits to The Sill, as well as the interactions with interactive exhibits.

- *Outcomes:* The survey questionnaire yielded a total of 68 respondents. In terms of the visitor perception towards the current use of digital technologies at The Sill, results show that 71% of respondents described their experience between good and excellent. In terms of having used one of the interactive exhibits, 68% of visitors stated that they did interact with one or more of the interactive exhibits, and 77.5% of them expressed a positive response in regards to incorporating more state-of-the-art technological exhibits at The Sill.

Study 2

- *Objectives:* Study 2 was semi-structured interviews and aimed at the heritage experts to share their thoughts about the use of digital technologies and more specifically, tangible augmented reality as a technological intervention to engage The Sill visitors with virtual representations of historical artefacts.

- *Methods of data collection*: Semi-structured interviews with eight heritage experts to discuss the advantages of using digital technologies to manipulate virtual representations of historical artefacts. The interviews were audio-recorded and transcribed, and later processed for data analysis. Each interview discussion took around 30 minutes. During the interviews, I asked questions related to the significance of tangible augmented reality prototype to provide an interactive interpretative approach to foster a closer understanding of virtual representations of historical artefacts.

- *Outcomes:* The study provided insights into the heritage experts' expectations of the proposed technology and recognizing its potentials to provide an interactive interpretive approach for manipulating virtual representations of historical artefacts.

Study 3

- Objectives: Study 3 aimed to demonstrate the potentials of a tangible augmented reality prototype to the heritage experts and capture their initial feedback. I presented an early-stage prototype (ARcheoBox 1.0) in a pilot study to eight heritage experts. The prototype intended to provide a demonstration of the technological possibilities and inform further design explorations for the next design phase.

- Methods of data collection: Semi-structured interviews with eight heritage experts to experience the prototype and receive their feedback. The interviews took place at Northumberland National Park's office in Hexham. The sessions were audio-recorded, transcribed, and later data was analysed.

- Outcomes: The initial results revealed that the prototype has great potential as an innovative interpretive approach to interact with 3D models of historical artefacts. Further details on the results of this study were published as a two-page publication in the ACM Symposium on User Interface Software and Technology (UIST'20).

Study 4

- *Objectives:* Study 4 aimed to explore design opportunities for generic proxies as tangible interfaces to manipulate virtual representations of historical artefacts in augmented reality. The study approach was exploratory as I intended to understand whether using an exact 3D-print replica of the original historical artefact or a close-in resemblance (generic proxy) as a tangible interface would influence the visitor's perception of holding the actual artefacts in their hands.

- *Methods of data collection*: A comparative study was conducted to compare four different tangible interfaces in augmented reality (touch screen, flat AR marker, 3D-print replica, wooden generic cylinder). The study took place in November 2020 and was conducted remotely using Microsoft Teams teleconferencing application due to the COVID-19 pandemic restrictions on face-to-face research. The participants answered Likert-type scale questions and open-ended questions.

- *Outcomes:* The study findings revealed that using a generic object such as a cylinder would offer a good trade-off as a tangible interface in augmented reality when access to exact 3D-print replicas is not feasible. Additionally, participants revealed that the cylinder-shaped generic proxy as a tangible AR interface enabled a physical and more compelling experience over the touch screen interface and the traditional flat AR marker. More detailed discussion about the study design, study method, data analysis, and findings are discussed in the evaluation and findings chapter (section 5.1).

Study 5

- *Objectives:* Study 5 aimed to gain insights on what kind of heritage information would engage The Sill visitors with virtual representations of Bronze Age artefacts, and also to identify what design features are desirable for the prototype.

- *Methods of data collection*: Semi-structured interviews with eight heritage experts were conducted remotely. All heritage experts had extensive archaeology and cultural heritage experience. The heritage experts participated in co-design sessions to explore prototype design concepts using a sketching sheet to develop design concepts for the tangible AR prototype. Additionally, the heritage experts answered a set of open-ended questions which were audio-recorded and transcribed for data analysis.

- *Outcomes:* The co-design sessions with the heritage experts resulted in a set of prototype design features which were fed into the next cycle of the prototype iteration. More details on the design outcomes are discussed in chapter 4 (see section 4.2.4)

Study 6

- *Objectives:* Study 6 aimed to test the prototype demo by conducting a controlled experiment. The study evaluated the prototype overall system design including the tangible AR interaction techniques and the augmented reality application features.

- *Methods of data collection*: The study took place at the Northumberland National Park office with 25 participants including heritage experts and public users. Participants were asked to provide feedback on the prototype ergonomics, system aesthetic design, and application interface functions. I developed Liker-type scale questions adopted from Nielsen and Molich

(1990) usability guidelines to measure the system functionalities and participants' satisfaction with the prototype. I also took notes and recorded participants' verbal comments that were transcribed later for data analysis.

- *Outcomes:* The study results showed that the participants describe their experience with the prototype to be intuitive. Overall, participants stated that the prototype offers a great opportunity for making historical artefacts accessible. I was also able to form a set of design recommendations towards improving the design of tangible augmented reality systems for manipulating virtual representations of historical artefacts. For a detailed discussion on the results of this study, refer to the evaluation and findings chapter (see section 5.2).

Study 7

- *Objectives:* Study 7 aimed to evaluate the visitors' overall experience with ARcheoBox at The Sill: National Landscape Discovery as well as evaluate and refine the conceptual framework for developing and evaluating tangible AR interfaces for manipulating virtual representations of historical artefacts.

- *Methods of data collection*: Paper-based questionnaire and digital survey using tablet display. 80 visitors' responses were recorded on the paper questionnaire and 572 visitors participated in the digital survey.

- *Outcomes:* The study findings showed that the visitors expressed positive reactions to what they described as a novel interpretive approach to manipulate virtual representations of historical artefacts. The study findings also present the conceptual framework main concepts and key aspects, which are described in more detail in the evaluation and findings chapter (see section 5.3).

Researching the Context

An additional approach I took as part of my methodology, was to develop a deeper understanding of The Sill as a research context. Gill et al. (2011) acknowledge that the design process is a complex endeavour that requires an understanding of the audience (the 'makers' and 'readers' of prototypes) and the context of use. Through this mindset, I first visited The Sill to attend an introductory meeting and discuss the prospects of digital technologies applications to engage The Sill visitors with virtual representations of historical artefacts. There, I met the digital and technical officers to identify digital technologies opportunities to "Bring to Life" a collection of Bronze Age artefacts using a novel technological intervention. The brief was quite open, and I was given plenty of freedom of how I will interpret it. After the initial conversation about the different technological possibilities, I was offered a general tour of The Sill building and the two exhibition spaces. The first is a temporary events space used for short-term exhibitions, and the second is the permanent exhibition space which includes a unified wooden structure exhibiting different stories about the Northumberland National Park Landscape. Additionally, there are two separate stand-alone exhibits, (an augmented reality sandbox and a holographic display), which represent The Sill digital vision to engage their visitors with the Landscape using interactive technologies.

Thereafter, I incorporated several research tools to acquaint myself with The Sill as a research context. First, I conducted an online visitor survey (see section 3.5), where I asked questions about the visitor demographic base, and also questions about the different interactive technologies at The Sill. Furthermore, I wanted to immerse myself in situ to see how visitors interacted with interactive technologies. The visitor observations are a common approach for examining visitor interactions around exhibitions (Falk et al., 1985). I visited The Sill, where I did observations mainly on the augmented reality sandbox which showcases topography in a hands-on way, as it was very popular with most visitors (adults and children). The augmented reality sandbox simulated three different landscapes in the Northumberland National Park and how they were formed; the undulating landscape of Hadrian's Wall, the rounded hills of the Cheviots, and the sandstone escarpment of the Simonside Hills. The Sill digital officer stated that: "*The exhibit is still the most popular element of our permanent exhibition;*

appealing to both young and old, almost two years since we brought it to The Sill". I followed the observations with a short interview to collate more qualitative data on what mostly triggered visitors about the augmented reality sandbox. I made several field studies which enable me to gather preliminary data that would help in the next stage of the research in which I conducted semi-structured interviews to get more in-depth knowledge about The Sill from the staff perspective. Also collating data on the visitor attitudes towards the different technologies at The Sill, and talking to the staff, not only helped influence my impressions of the space and its people but also fed into my inspirational thoughts in regards to the design process.

3.6 Grounded Theory and Thematic Analysis

Grounded theory is a qualitative research method for data analysis that was developed by Glaser and Strauss (1967). Established in sociology, grounded theory has also been extensively explored in multiple domains in HCI as data analysis method. Grounded Theory consists of systematic guidelines for gathering, analysing, and conceptualising qualitative data to discover patterns and construct theories "grounded" in the data using constant comparative analysis and a cyclical process where data collection and data analysis occur iteratively to derive theory (Charmaz, 2006). The practical implementation which draws on grounded theory in this research is enriched by the triangulation of data using multiple sources of data such as semi-structured interviews and user studies. Additionally, the relevance of the grounded theory method is significant to interaction design research, as it allows to promptly process the outcomes from the data and take simultaneous actions.

I have primarily applied an inductive qualitative analysis approach to the data using thematic analysis as the analytical approach which draws from grounded theory and that is grounded in the analysis of the interviews and user studies. Applying an inductive approach, allowed me to formulate a bottom-up process to data (Charmaz, 2006), leading to the development of a conceptual framework which served to formulate design characteristics for developing and evaluating tangible AR interfaces. The categories and related concepts derived from the data analysis are discussed in more depth in the evaluation and findings chapter (see section 5.3.3, 5.3.4).

Thematic analysis is considered a suitable approach as a qualitative research method for data analysis in HCI. Inductive Thematic Analysis was applied throughout this research to analyse data including participants' interviews and user studies, to identify categories, refine themes, and establish a relationship between themes (Braun and Clarke, 2006). In Thematic Analysis, data is categorised into low-level themes using open coding, examining themes' frequency, and then re-categorising themes into higher level themes. This process is followed by identifying patterns to formulate higher concepts by drawing on each pattern that emerges from the data (Corbin and Strauss, 2008). This continuous cycle for all participants' data allowed me to develop high-level data conceptualisation.

Summary

This chapter presented the research methodological approach, studies, participants and ethics, data collection and data analysis methods, as well as co-designing with the heritage experts. The data analysis methods applied are drawn from grounded theory and Thematic Analysis. Each study structure included the objectives, data collection methods, and outcomes. The three studies (study 4, study 6, and study 7) which influenced and helped answer the research questions are described each in more detail in the evaluation and findings chapter (chapter 5). The rationale behind the selection of these methods is also discussed in this chapter, which sets out the rationale for the methodological direction that forms the basis of the studies conducted in this research providing confidence and rigour in the findings.

4. ARCHEOBOX

Overview

In this chapter, I discuss the prototype design iterations, co-design sessions with the heritage experts, and technical implementation that led to crafting ARcheoBox; a tangible augmented reality prototype for manipulating virtual representations of historical artefacts. The development and implementation of ARcheoBox constitute the practical contribution of this practice-based Ph.D. research. I highlight the decisions made and insights gained from the reflective process of developing the prototype leading to the final prototype exhibition at The Sill. In the next section, I start by describing the collection of the historical artefacts and how they were acquired, design inspirations, and early prototype experimentations, followed by the first version of the prototype (ARcheoBox 1.0) including a pilot study. Continuing with the description of the final version (ARcheoBox 2.0) and how the process between the two prototypes revealed challenges, breakthroughs, and moments of great discoveries.

4.1 ARcheoBox 1.0

In this section the process of acquiring the virtual representations of historical artefacts, the early prototype experimentation, and a proof-of-concept (ARcheoBox 1.0) is presented. The second and final prototype (ARcheoBox 2.0) including the design process, working with AR markers, co-designing with heritage experts, the augmented reality application technical specification and implementation, and finally the exhibition at The Sill is discussed in detail.

4.1.1 Bronze Age Artefacts and Virtual Representations

The Breamish Valley in the North East of England holds some of the best-preserved archaeological landscapes in the Cheviot Hills. The excavations (1994 - 2003) revealed several fascinating Bronze Age food and drinking vessels (Figure 24) which were carefully removed, restored, and conserved for public display at Ingram Valley visitor Centre. Laser scanning and photogrammetry are becoming one of the increasingly popular technologies, especially among museums and heritage sites to reproduce realistic representations of world antiquities and their locations. Making the exchange of knowledge about historical artefacts more feasible and accessible. Sketchfab, the web 3D viewer hosts over 100,000 cultural heritage collections of 3D models that allow users to view the 3D models in 360 degrees. In 2017, Northumberland National Park worked with a company in the North East of England to scan the Bronze Age vessels and generate detailed 3D models with high geometric precision through a combination of 3D scanning and photogrammetry techniques using X Reality hardware and software. I was granted access through the Northumberland National Park Sketchfab[20] account to download and modify the 3D models (Figure 25) to accommodate them with Unity software to develop the augmented reality application.

Figure 24: Bronze Age. (Turf Knowe, Ingram, archaeological excavations, report 4834).

The large urn[21]. The large urn is from Turf Knowe North Cairn, Ingram Farm. It was excavated as part of the Breamish Valley Archaeology Project (1994-2004). Dating to the Early Bronze Age (4,000 Years BP or 2,000 BC), the urn is carefully placed into the structure of the cairn and which contained the remains of an infant who died after suffering from meningitis.

[20] Northumberland National Park. Sketchfab. https://sketchfab.com/NlandNP. (Accessed October 29, 2019).
[21] https://sketchfab.com/3d-models/large-urn-1dbfd70f477e4b1f82de6dd12d7f81a5. (Accessed October 29, 2019).

The Food Vessel[22]. The food vessel from the central cist or stone coffin of Turf Knowe North Cairn, found with a jet bead from a necklace, also dating to the Bronze Age.

Bronze Age Beaker[23]. The reconstructed Bronze Age Beaker (4,200 years old) is beautifully decorated with thumbnail print, found in fragments in a timber timber-lined from a pit on Wether Hill, Ingram Farm, by the Northumberland Archaeological Group. No bodies were found from the coffin due to the acidic soil, but fragments from at least five individual Early Bronze Age pots were recovered.

Figure 25: 3D scans of urn, food vessel, beaker 3D models. © Northumberland National Park.

4.1.2 Early Prototype Experimentations

Throughout this research, the iterative process unfolds through several prototype experimentations. It is through the iterative process that I was able to formulate and test different design ideas in order to progress to the next phases in the design process, Adams (2002) states:

> "Iteration is a significant component of design activity that occurs frequently throughout the design process; and measures of iterative activity were significant indicators of design success" (cited in Lim and Stolterman, 2008, p9).

[22] https://sketchfab.com/3d-models/bronze-age-beaker-33bc8c488f8a4b25a1c4ee7b9989feff. (Accessed October 29, 2019).
[23] https://sketchfab.com/3d-models/food-vessel-c46c48f1e6fc4498bd3670106db3830c. (Accessed October 29, 2019).

The early prototyping phase aimed as an explorative phase to generate insights into tangible augmented reality concepts and explore what are the feasible possibilities that exist in this domain to manipulate virtual representations of historical artefacts. For early experiments set up, I started with a low-fidelity prototype (Figure 26). For my technical setup, I used an iMac (2015) desktop computer and a Logitech (C920) webcam. Software used Included Unity Software24 (2019.3.10f1) and Vuforia Augmented Reality SDK (8.5.9) for the augmented reality application development. I was able to test the AR outcome using the monitor screen, as well as a mobile device (Sony Xperia XZ2).

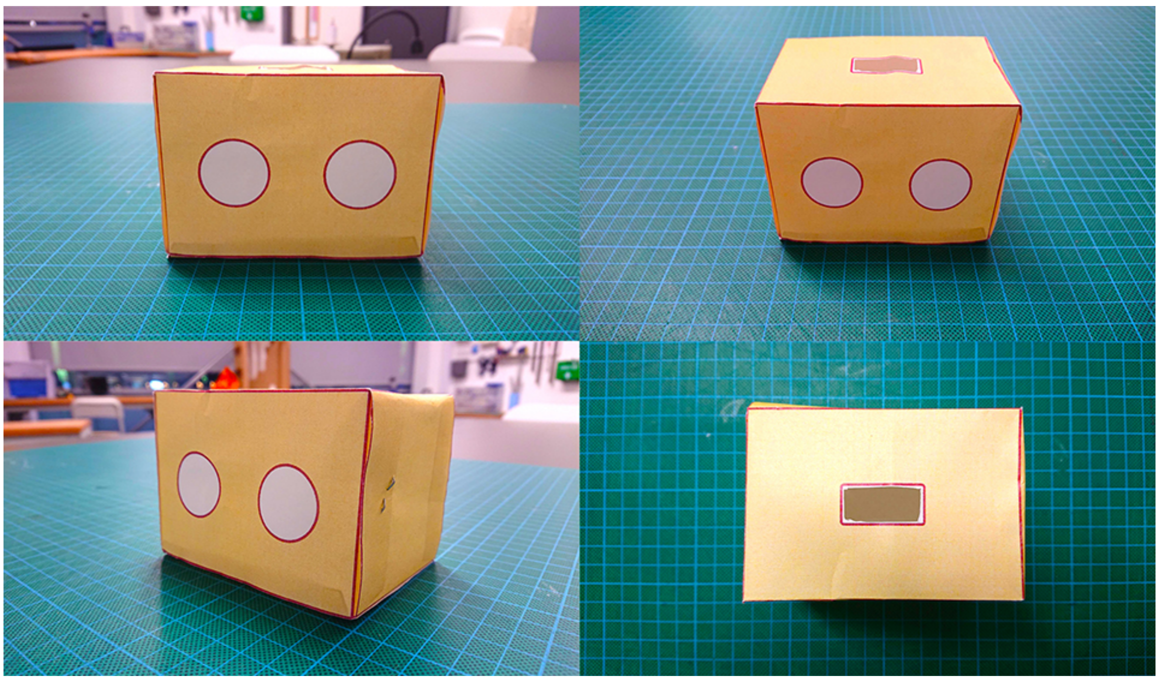

Figure 26: ARcheoBox first low-fidelity prototype made from paper.

I created an AR puzzle game; the physical puzzle pieces comprised of flat AR markers that were augmented into virtual 3D shreds of a Bronze Age large urn. Through this prototype experimentation, I wanted to develop an understanding of how tangible interfaces can promote intuitive manipulation of AR virtual objects (Billinghurst, et al., 2008). I printed four flat AR markers and assembled them to connect like a magnetic effect in the virtual environment, once the flat AR markers are brought together, the virtual 3D shreds disappear, and the full urn is presented (Figure 27).

[24]Unity Software. https://unity.com (Accessed October 30, 2019).

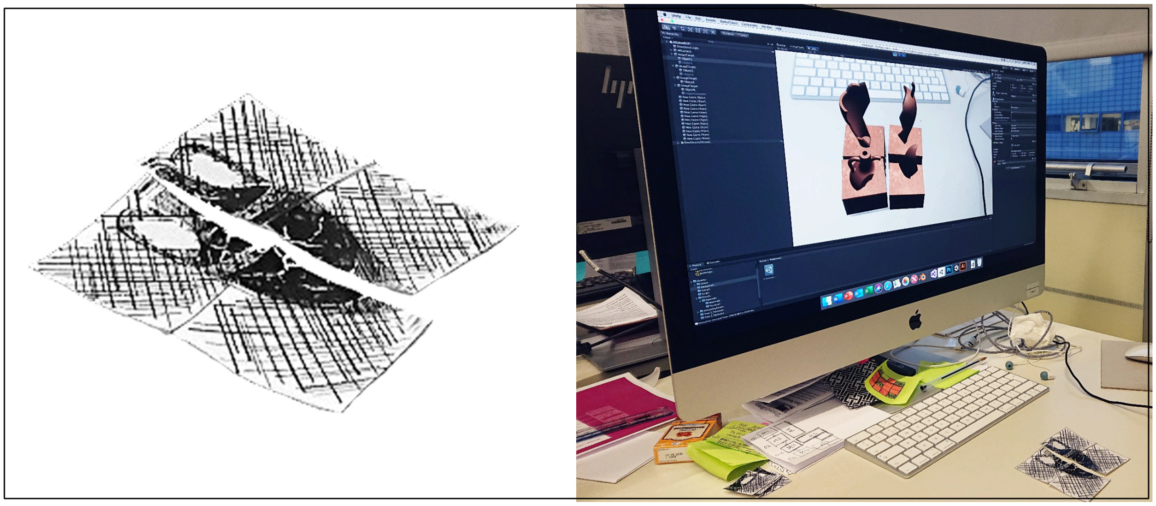

Figure 27: AR markers and AR puzzle virtual 3D objects displayed in Unity software.

After looking into the best practices for developing Vuforia image targets., I experimented with various AR image targets patterns and sizes following Vuforia configuration to achieve the best tracking results for the AR markers. I then built a wooden square puzzle (Figure 28). The puzzle design revealed some ergonomic limitations when moving the square-shaped puzzle pieces, the mechanism was a bit clunky, which I anticipated would create some frustrations for visitors in case I decided to pursue the puzzle concept any further. Nonetheless, the prototype was demonstrated to the digital officer at The Sill to receive some initial feedback. Communicating the design outcomes for prototype experimentation was kept throughout the whole research process in order to identify design opportunities and validate them with stakeholders. Thus far, the early experimentation phase highlights the benefits of externalizing design concepts through physical prototyping to foresee any obstacles before advancing further in the design process.

> "Prototypes in this context can serve as tool for discovery, understanding, and learning. They assist the designers in externalizing concepts in similar ways that drawing or sketches do but they also aid in exposing physical characteristics, opportunities, and constraints that a drawing is unable to provide", (Gill et al., 2011, p674).

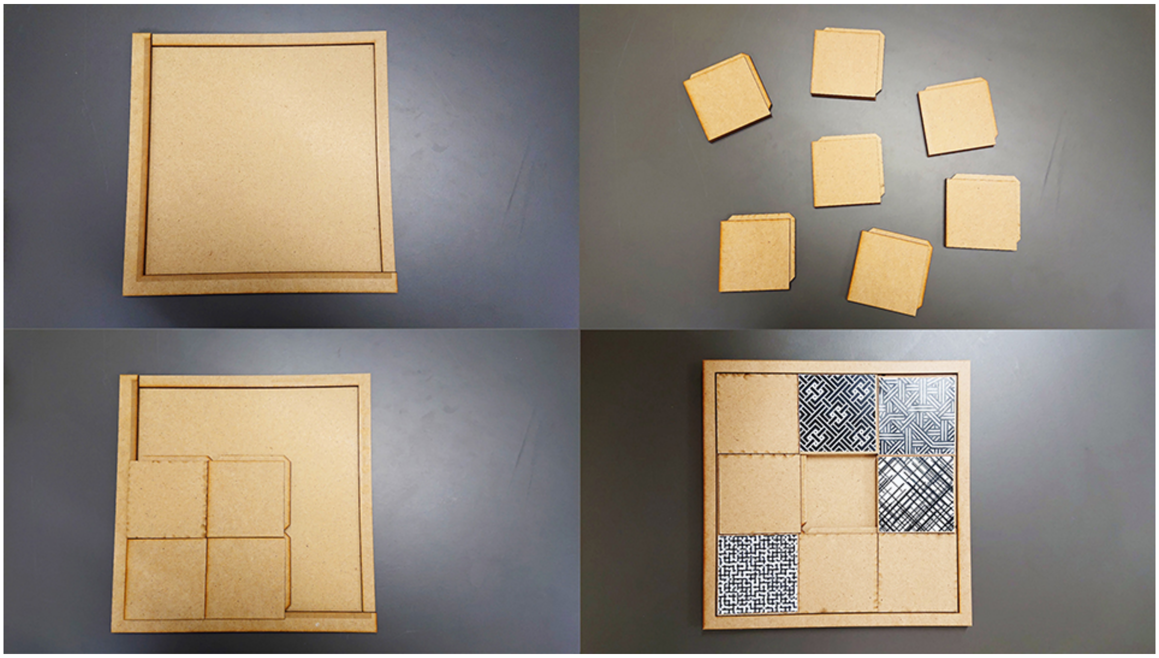

Figure 28: Augmented Reality puzzle prototype pieces put together.

4.1.3 Proof-of-Concept

The first version of the prototype ARcheoBox 1.0 (Figure 29) was developed as a proof-of-concept on the use of a tangible augmented reality as a novel interactive approach that lets users physically pick up and manipulate a digitised version of a real Bronze Age artefact and inspect it closely from all angles to remove physical barriers between museum visitors and historical artefacts. The box consists of a wooden container, L 45cm x W 30cm x H 25cm, constructed from laser-cut parts. Inside the box are one or more flat wooden bricks which have printed augmented reality markers for tracking. The box has a hole cut in the top to allow placement of a display (in this case an Android Sony Xperia XZ2 phone), and two holes on the front to allow users to place their hands and interact with the artefacts. The software was realized using the Vuforia Augmented Reality SDK and Unity Software.

The resulting prototype allows users to reach into the box and grab a flat AR marker, upon which an AR representation of a digitised historical artefact will be positioned. Using tangible interactions users can then manipulate the artefact to inspect it from different sides, bring it closer to see fine and intricate details.

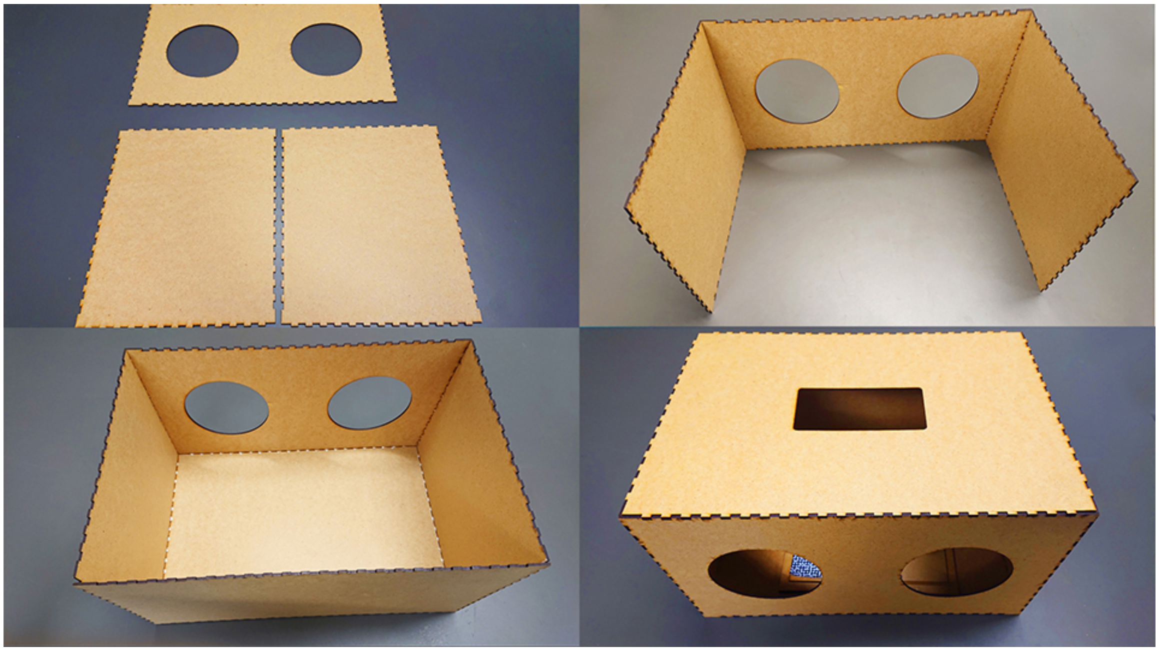

Figure 29: ARcheoBox (1.0) prototype assembly.

4.1.4 Pilot Study

The prototype was tested in a pilot study (Figure 30-31) with eight heritage experts at Northumberland National Park. I used semi-structured interviews to ask the heritage experts about their feedback in terms of the technology application and its benefits to manipulate virtual representations of historical artefacts. The initial feedback indicated that ARcheoBox 1.0 has great potential as an innovative and interpretive prototype to manipulate 3D models of historical artefacts.

Figure 30: A heritage expert manipulating virtual historical artefacts using flat AR marker.

Figure 31: 3D model of a virtual object on top of flat AR marker.

The heritage experts also noted that the prototype is very easy to use since they did not have to download a mobile phone application or wear any additional equipment such as head-mounted displays. Recorded comments from the participants included:

> *"I never experienced anything like this, I can really see the details on the 3D model, it almost feels like seeing the fingerprints made by its original maker" (P1).*

> *"The prototype produced a very realistic representation of these artefacts and enhanced the experience of studying historical artefacts" (P5).*

The pilot study indicated that ARcheoBox successfully allowed the heritage experts to engage with virtual representations of historical artefacts using tangible interactions and augmented reality giving physical access to otherwise inaccessible artefacts. Consequently, I decided to further build on the proof-of-concept by using a 3D-printed replica of the virtual representation for the historical artefact as an AR marker. Participants can pick the 3D-printed replica in their hands as if it is a real artefact. After experimenting with different physical objects as AR markers, it started to be evident that a tangible interface had a great influence on how the participants perceived the virtual representations of the historical artefacts in augmented reality. Hence, I conducted a comparative study to explore design opportunities for generic proxies as tangible interfaces (touch screen, flat AR marker, wooden generic proxy, and 3D-printed replica). The comparative study is described in depth in section 5.1. The next step was the design process and development of ARcheoBox 2.0, including co-designing with heritage experts, the technical development and implementation of the augmented reality application, mapping the tangible AR interaction techniques, and ARcheoBox exhibition at the Sill.

4.2 ARcheoBox 2.0

The second-generation prototype (ARcheoBox 2.0) is the outcome of an iterative design process which was achieved through co-designing activities with the heritage experts. The Sill visitor can place their hands inside the box and experience intricate details and interpretation of Bronze Age historical artefacts by holding and manipulating cylinder-shaped generic proxies (see section 4.2.2). ARcheoBox design iterations were conceptualised using sketches and diagrams (Figure 32- 33). The series of sketches for the box reflect design considerations related to the viewing angle from the tablet camera, with both a tilted and a straight surface were tested to ensure that the distance between the tablet camera and the AR markers is suitable to keep the AR markers in the field of view for the camera and achieve accurate tracking inside the box. The box consists of a wooden container manufactured using laser-cut machinery (Figure 34 and Figure 35). A tablet display (Samsung Galaxy S7 tablet) is placed on top of the box (Figure 36) and two holes are cut in front of the box to allow users to reach in and hold what is inside the box, in this case, wooden cylinder-shaped generic proxies with attached AR markers for tracking.

4.2.1 Thinking Inside the Box

The box presented opportunities for me to explore several interaction techniques using its internal space. From a technical point of view, the box provides a controlled environment to overcome some of the challenges associated with AR markers tracking such as lighting conditions. Additionally, I installed a series of small LED lights attached to the inside top of the box, to help provide good lighting conditions for AR markers tracking as Vuforia recommends that the image targets should be viewed under moderately bright and evenly lit diffused lighting). The concept of interaction techniques inside the box was observed initially when heritage experts were moving the flat AR markers inside the box to track them through the camera. This has led to the considerations around hand movement and how it can relate to the interaction experience with AR inside the box. Then, through formal and informal discussions with the heritage experts, I started exploring how to utilize the new configuration that the box provides to interact with interpretation of historical artefacts using the cylinder-shaped generic proxies as an interface. For instance, left to right is normally left to right, but inside the box, left to the right becomes a relative position, which can be translated into contextual information. I used stop-motion (Bonanni and Ishii, 2009) as an interactive prototyping method to draw on the relationship between the generic proxies' position inside the box and the AR interactions output by changing the AR markers' position inside the box (see section 4.2.2). ARcheoBox showcases the potentials of AR beyond overlaying digital information within the peripheral vision of the user, but also how it enables navigating the 3D space using their bodily movement. To develop the different interaction techniques, I used Unity software as a development tool for the augmented reality application. The Unity code allows virtual objects to appear and disappear based on their relative position to the camera benefiting from the XYZ configuration. The interpretation can be activated by moving the generic proxies on the x, y, or z-axis offering more control over accessing the interpretive content.

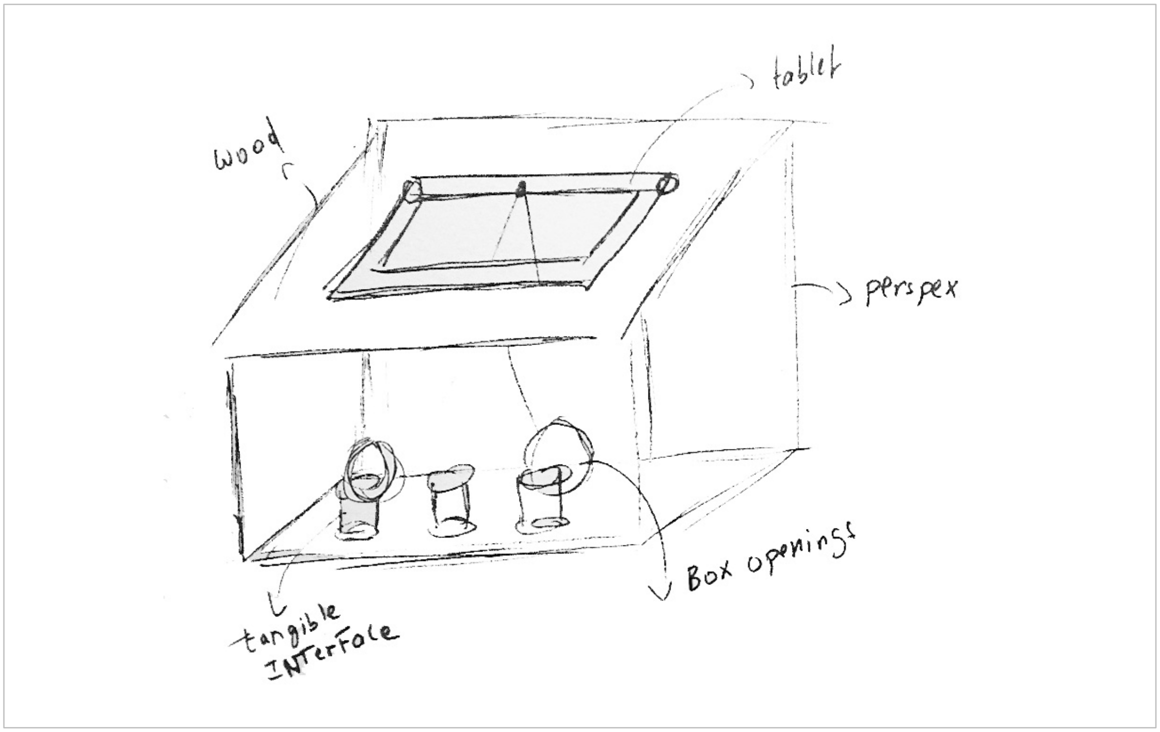

Figure 32: ARcheoBox sketching process.

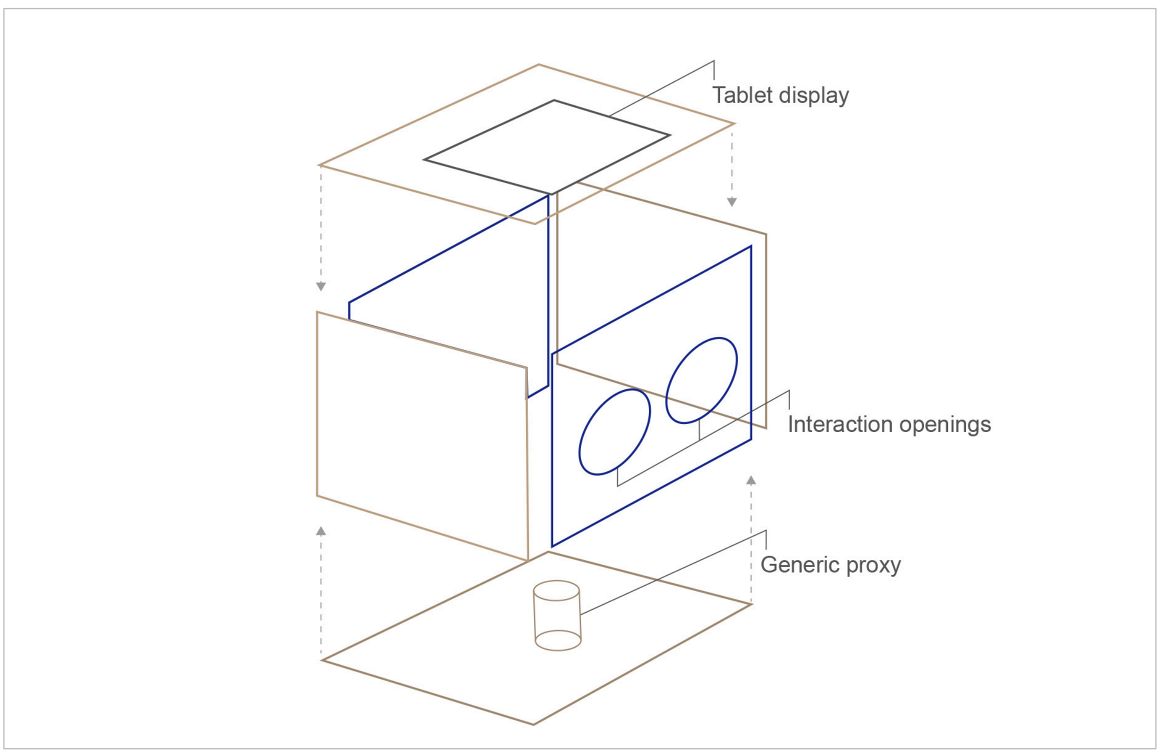

Figure 33: ARcheoBox assembly illustration.

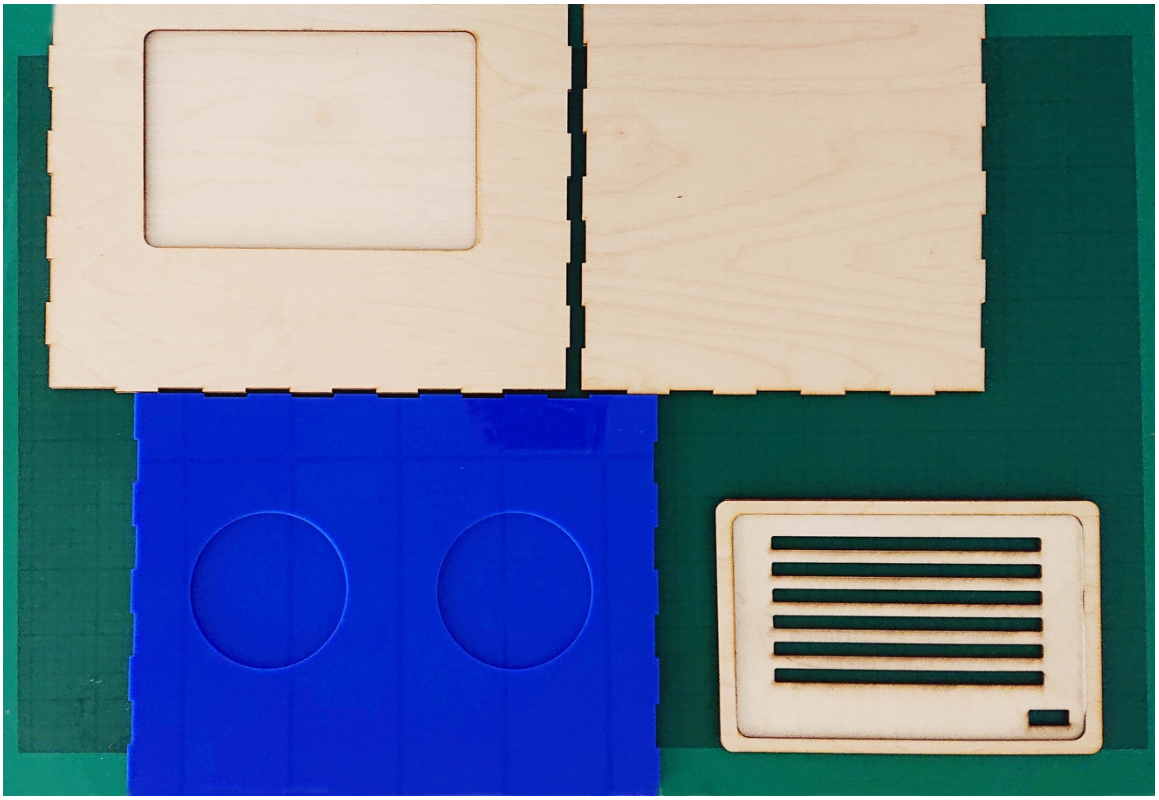

Figure 34: ARcheoBox laser cut parts.

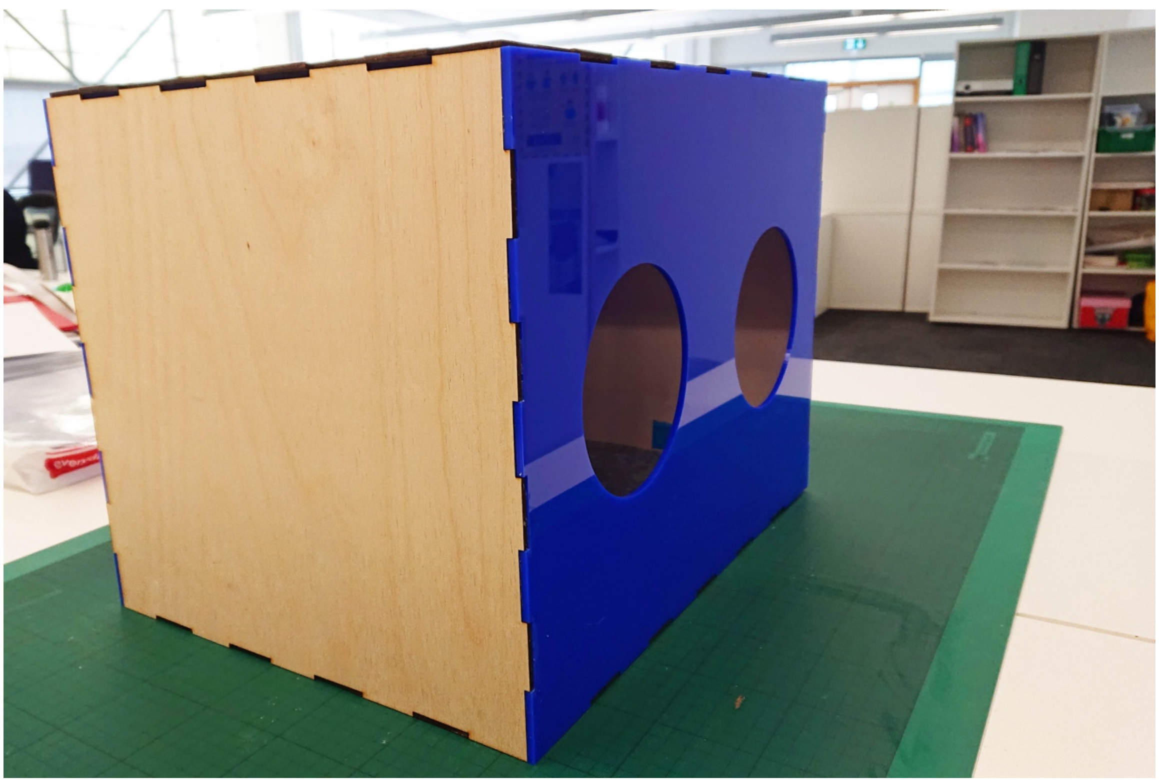

Figure 35: ARcheoBox prototype assembled.

Figure 36: ARcheoBox top view showing tablet display.

4.2.2 Designing the Interaction Techniques

Three interaction techniques were designed and mapped to the generic proxies' position inside the box (Figure 37). They were based on the XYZ coordinate system which is used to locate virtual 3D objects in the virtual environment. The position is calculated based on the distance between the camera and the Vuforia AR markers attached to the cylinder-shaped generic proxy to activate the corresponding virtual content. While Inertial measurement unit (IMU) sensors are used in AR/VR applications to enable the tracking of devices, limited accuracy remains an issue and accurate tracking requires more complex workflow such as specialised hardware and highly hi-tech sensors. On the other hand, when moving the cylinder-shaped generic proxy, Vuforia SDK knows the position and enables the rendering of 3D objects through the camera feed without any sensors.

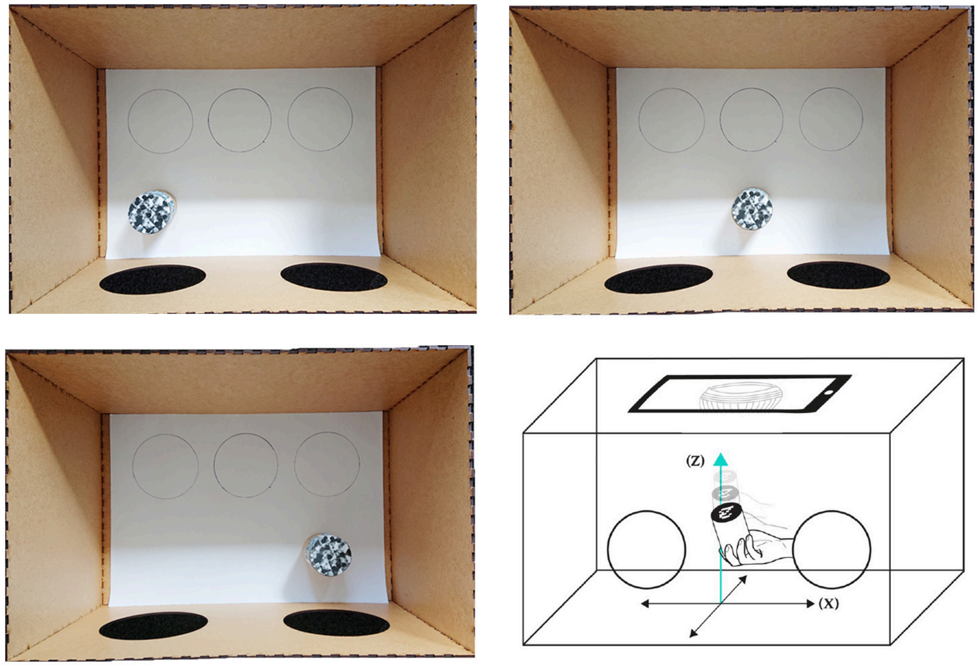

Figure 37: Testing the AR marker position inside the box on the x-axis.

Initial testing revealed that moving the generic proxy on multiple axes could be confusing as the interaction techniques themselves are novel, also assigning content (audio and visuals) to *xyz* axis proved to be problematic and prompted the audio to be called by the software and kept replaying several times. The three interaction techniques (*Move, Rotate, Flip*) are executed using the generic proxy to interact with interpretation (*Zoom, Select and Switch*) (Figure 38). The interaction techniques work by registering the relative position between the camera and the augmented reality marker to display the corresponding virtual 3D model and related interpretive content. The interaction techniques are intended to emulate human hands movements when examining an artefact and studying it from different angles building on human affordances [Gibson 1977] and would be similar to what the user would perform if allowed to handle a real artefact. The expressive mapping between the interaction techniques and output modalities in AR empowered by the user' hands movement to explore virtual representations of historical artefacts produces an intuitive and immersive user experience.

Move. Moving the generic proxy closer to the camera to activate panels including text, maps, and photographs. The audio for the interpretation is also controlled by moving the generic proxy either close to the camera to play it or further away to pause it. This action would minimise any degree of disruption when handling the artefact, in case the user moves the AR maker away from the camera view.

Rotate. Rotating the generic proxy to different sides allows to select various pieces of interpretation about the historical artefacts. The interpretation is attached to two AR markers attached to the sides of the generic proxy.

Flip. Flipping the generic proxy allows to switch between the Explore Mode and Interpret Mode. The flip action is executed by turning the generic proxy into an upside-down position and flipping it back to its original positioning.

While I considered adding visual hints [White et al., 2007] such as text or animations around the virtual 3D model or adding an extra AR marker as a controller [Tan et al., 2001] for the virtual environment, I anticipated that this would have obstructed the handling of the historical artefacts and possibly divert the visitor attention from the task at hand while manipulating the artefacts. Therefore, I refrained from implementing GUI buttons. I wanted to preserve the flow between the visitor handling of the generic proxy and their interaction with the interpretation using the same physical object, by keeping the visitor focused on the artefact as an interface instead of introducing GUI elements via the touch screen.

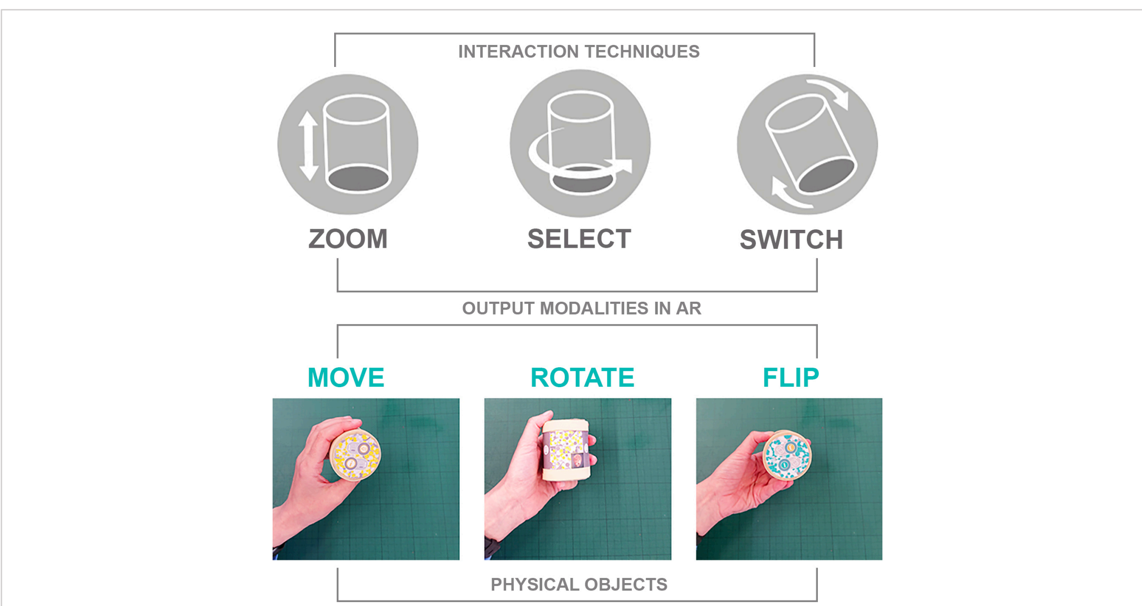

Figure 38: Interaction techniques and output modalities in AR.

4.2.3 Augmented Reality (AR) Markers

In the early phases of the prototype experimentation, I used flat AR markers (Kato et al., 1999) which are still one of the most common modes of interaction for augmented reality, that allow users to explore and manipulate virtual representations from multiple viewpoints. Using computer vision algorithm, the image targets are scanned, and 3D objects are placed in the camera view. Vuforia SDK has made it possible for developers to create image targets[25] by uploading a jpeg or png image to their cloud service which can be later be downloaded and incorporated into Unity software project package. Vuforia image targets use distinct and sharp features with high contrast to be detected by Vuforia Engine and need to be a legible size in order to be recognisable.

Vuforia also enables the use of cylinder targets that can be tracked to overlay virtual 3D objects which are cylindrical in shape. While this could be considered a good approach for tracking cylinder-shaped virtual 3D models. However, the cylinder image targets are calculated as single tracked targets, for instance, cylinder targets composed of several images are tracked as a single target which would allow tracking of one single virtual object at a time. Hence, when using cylinder targets, it wouldn't be possible to track various sides of the cylinder to trigger multiple interpretation when rotating the generic proxy in hand. Therefore, I used several flat AR markers attached around the cylinder-shaped generic proxy, so each AR marker can be tracked independently in the field of view of the camera to allow interaction with different parts of the historical artefacts. Additionally, AR markers work best when applied to flat surfaces to facilitate tracking, although not having enough markers in the field of view of the camera can cause the virtual representations to disappear.

I used flat AR markers in the pilot study as a baseline to test them as a tangible AR approach to manipulate virtual representations of historical artefacts. In the first instance, participants were given instructions on how to track flat AR markers in the camera to view virtual 3D models.

[25] Vuforia Image Targets. https://library.vuforia.com/features/images/image-targets.html. (Accessed October 30, 2019).

In the next step, I explored 3D printing for AR markers to understand if using an exact replica would enhance the experience of manipulating virtual representations of historical artefacts if the AR marker was closer in resemblance to its virtual counterpart. The 3D-print was a replica of the original artefact and was produced using ABS filament with a printed AR graphical pattern attached to the top. After early experimentation with the flat AR marker and 3D-print replica as tangible interfaces, I conducted a comparative user study (see section 5.1) adding cylinder-shaped generic proxies to explore design opportunities for different tangible interfaces and how it can influence the visitor perception of virtual representations of historical artefacts.

4.2.4 Co-Design Process

The co-design interviews aimed to generate insights on what kind of design features and heritage content I can create to engage the users with interpretation of Bronze Age artefacts. I interviewed eight heritage experts remotely using Microsoft Teams teleconferencing application. All experts had extensive archaeology and cultural heritage experience. The heritage experts answered a set of open-ended questions which were recorded and transcribed for analysis. We then identified a set of design features and heritage content. The questions were motivated by two research questions:

1. RQ1: What kind of heritage information would engage users with interpretation of Bronze Age artefacts?
2. RQ2: What are the design features that are useful to incorporate within the tangible AR prototype?

Prototyping for AR is still an exploratory design space with very few tools that exist to help with the ideation process for 3-dimensional and virtual spaces. Consequently, I developed a sketching sheet (Figure 39) to help non-designers such as the heritage experts, brainstorm different concepts for the prototype. The sketching sheet structure contains two sections: the first section, *Interactions in AR*, is to brainstorm concepts for interaction techniques in AR using generic proxies. The second section, *heritage content*, is to compose the artefacts interpretation. The sketching sheet served as an inspiration tool and enabled participants to establish connections between analogue methods of ideation and AR technologies, as well as generate ideas about interaction techniques using generic proxies. Once, the heritage experts identified more specific ideas, we then initiated discussions around potential technological implementation.

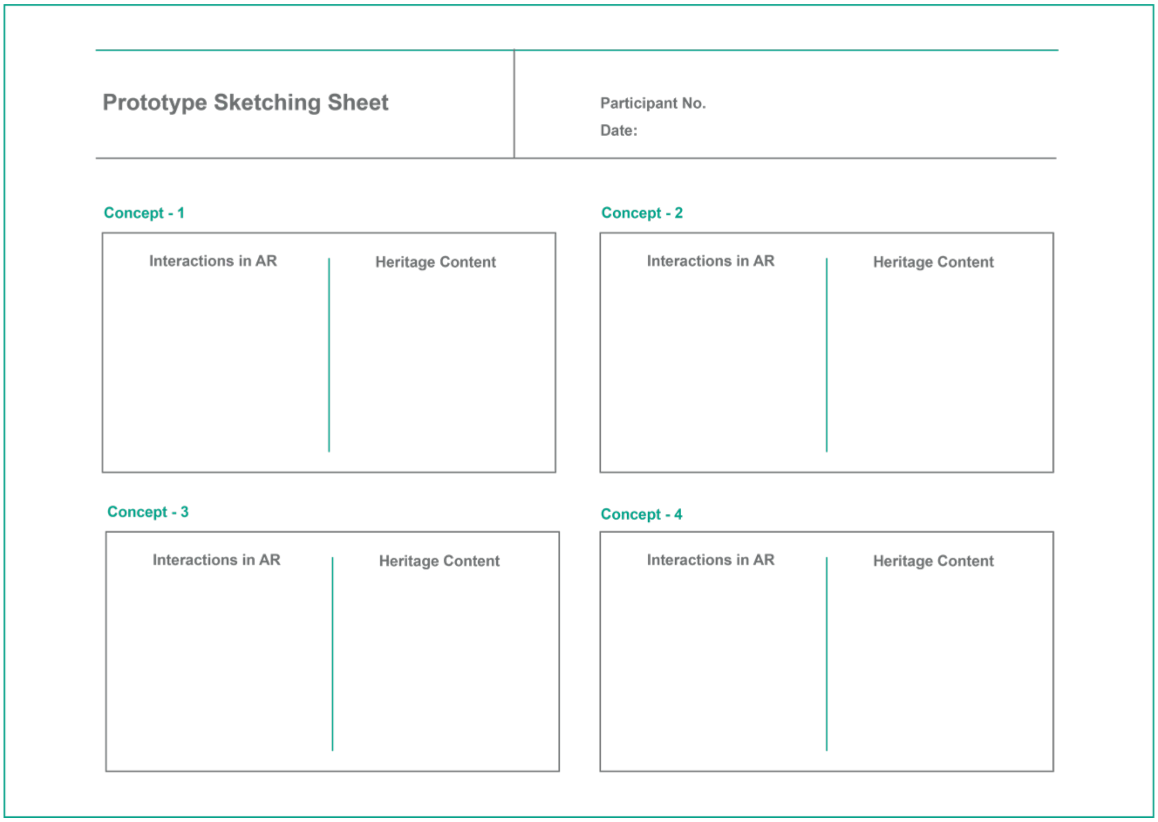

Figure 39: Prototype sketching sheet. © Suzanne Kobeisse (2021).

Heritage Experts Feedback and Insights

The heritage experts stated that limited access to historical artefacts due to their fragility and composition is one of the main challenges for physically exploring them. The heritage experts considered that these challenges could be addressed using a tangible augmented reality prototype. Furthermore, the heritage experts identified additional benefits for the prototype beyond museums exhibitions. This includes knowledge sharing among other experts, supports early career researchers in studying historical artefacts, and provide an opportunity for enthusiastic users to get a closer look and learn more about the artefacts, who otherwise would not have access to them. Based on the feedback and insights gained from the heritage experts co-design sessions, I identified a set of design features.

Design Features and Heritage Content

A common approach for interacting with AR applications in a heritage context is using hand-held devices (i.e., tablets, mobile phones) where visitors scan through the surrounding environment (Madsen, 2015) or aim the device at artworks in the exhibition (Katifor et al., 2014). This approach limits physical interaction with the artefacts, as stated by one of the heritage experts:

> *"Constantly what you're doing with that is making your experience of the artefact through a screen"* (P4).

Through the co-design interviews, the notion of using physical objects (generic proxies) to manipulate virtual representations and interact with interpretation of historical artefacts responded to some of these challenges, as well as they would allow physical access to historical artefacts which wouldn't be previously possible due to museum protocols. Therefore, tangible AR was regarded a more suitable approach for the prototype.

Design Features

Interaction Techniques. The inherent affordances of the physical objects extended to incorporating interaction techniques as output modalities in AR to unlock the artefacts interpretation. The interaction techniques intended to be an expression of the hand gestures when exploring an artefact to interact with interpretation, as one heritage expert suggested:

– *"If you turn it that way you can see it was used for and if you turn it the other way you discover who used it", ..." this would definitely be a new approach than to the traditional panel interpretation looking at it in a glass display"* (P4). –

The experts also highlighted that physically holding an artefact in hand while listening to their interpretation, would enhance the user's understanding of the artefacts interpretation and foster a close connection between the user and the artefacts. The interaction techniques as output modalities in AR would also allow access to multifocal narrative such as artefact manufacturing, use, and community practices. Other suggestions by the heritage experts for interaction techniques included, holding the physical objects over time can result in different types of output modalities in AR.

– *"You are looking at objects in a way where it connects to its landscape and it connects to its context"* (P7). –

Visualisation. In order to support the implementation of the artefacts' context in the virtual environment, the heritage experts suggested incorporating graphical visual and audio assets, such as maps and photographs, as well as audio interpretation and ambient sounds inspired by the landscape such as, recorded sounds of birds from the Holystone Woods in the quiet part of the Coquetdale area in Northumberland. The atmospheric and tranquil soundscape helped paint a beautiful image of the landscape with waterfalls, peaks, and plenty of aged woodlands, enabling the visitor to get immersed in the landscape and feel connected and inspired by the original people who used these artefacts Additionally, the heritage experts also stated that the visitor should be able to explore the virtual representations separately in explore mode to have full appreciation of the details of the artefacts, and then introduce interaction with interpretation in interpret mode.

– *"offering people, the feeling of being there"* (P8). –

Heritage Content

Moving Inside the Box. The box internal structure provides a three-dimensional space to support a spatial configuration that responds to the interaction techniques by calculating the relative position between the tablet camera and the AR markers to display the corresponding content in the virtual environment. Additionally, the box creates defined boundaries that potentially could prevent the user from moving the generic proxies in random directions outside the tablet camera's field of view and losing tracking of the AR markers.

The Narrative. The Breamish Valley situated in the Northumberland National Park, in the North East of England, UK, holds some of the best-preserved archaeological landscapes in the Cheviot Hills. The excavations (1994 - 2003) revealed three fascinating Bronze Age food and drinking vessels which were carefully removed, restored, and conserved. The Bronze Age artefacts date back to the Early Bronze Age (4,000 Years BP or 2,000 BC) and depict important information about the life of the people and their rituals in the Bronze Age. The artefacts contained the remains of an infant who died after suffering from meningitis. Early suggestions indicate that these types of artefacts were used as a funeral pot and contained food to be used by the deceased in the afterlife. In collaboration with the heritage experts, I crafted the heritage content for three Bronze Age artefacts (an Urn, a food vessel, and a beaker). The heritage experts also suggested that the interpretation would be a combination of photographs, short text, which can support text legibility on the screen, as well as audio interpretation which aimed to reduce time spent reading off the screen.

4.2.5 Technical Specifications and Implementation

The augmented reality application used virtual representations of 3D models that were acquired through 3D scanning and photogrammetry techniques. They were scanned and processed using the X Reality hardware and software. Developing the augmented reality application required multiple software. First, I used Blender, a 3D modelling software to process geometric data and reduce the number of polygons into a conceivable size while conserving the smooth texture of the virtual 3D models. I then worked through Vuforia SDK and Unity games engine software to develop the augmented reality application. One of the challenges throughout the development process is designing the image targets. Initially, I experimented with default image target samples provided by Vuforia such as the stones and chips images, since it was important to understand the best practice for designing Vuforia image targets. I then developed and tested several image targets with different abstract graphical patterns. The newly designed image targets offered flexibility to consecutively adjust the graphical patterns to improve image target quality and achieve better tracking performance (Figure 40). Vuforia recognises pattern distinct features with sharp and complex outlines, so changing the pattern colours only wouldn't suffice. Therefore, I had to ensure that the image targets design contained rich details, high contrast and no repetitive patterns. I then uploaded the image targets to the Target Manager to check their star rating of five-star targets, which are then deployed to the Vuforia developer database, to be downloaded and imported into Unity Software scenes (Figure 41).

Figure 40: Experimenting with multiple AR image targets patterns and sizes.

The cylinder-shaped generic proxy incorporated five AR image targets that are attached to the wooden cylinder. The AR image targets on top and around the cylinder are tracked to superimpose the corresponding virtual 3D model, and the AR image target on the bottom of the cylinder is tracked to switch between Explore mode and Interpret mode. To avoid the several AR markers being tracked simultaneously around the cylinder, I added an additional distance of two centimetres between each of the image targets. This would minimize fusion between several AR markers around the cylinder and overlaying multiple virtual 3D models at the same time. At the time of the research, Unity software can accommodate up to eight Vuforia image targets including a wide range of 3D objects within the same scene. The AR camera in the software tracks the image targets (AR markers) which trigger and display the corresponding virtual 3D objects. Additional technical issues were encountered throughout the development process and had to be resolved such as the Unity code itself and how to coordinate it with the output modalities in AR based on the generic proxy position in the real world. This process required continuous testing and building the augmented reality application into the tablet device to verify that the code is working correctly.

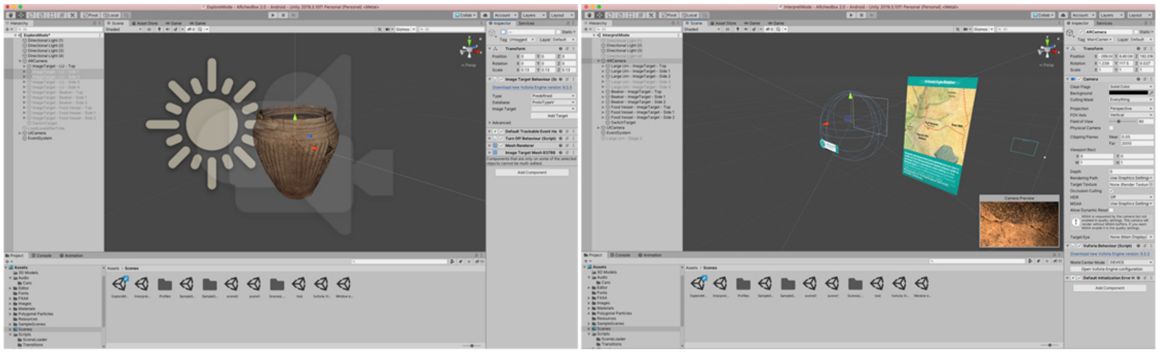

Figure 41: Scenes in the augmented reality application inside Unity Software.

The augmented reality application (Figure 42) functions by allowing the visitor to inspect virtual 3D models of historical artefacts and access different interpretative content using three tangible AR interaction techniques (*Move, Rotate, Flip*). Rather than the conventional flat AR markers most often used in augmented reality applications, I use physical objects (cylinders) as generic proxies, whose shapes resemble the virtual models, but without exactly corresponding to them. The application consists of two modes: "Explore Mode" presents the 3D models and allows the user to fully immerse in their fine details and get a close-up view of the beautifully decorated artefacts with thumbnail print marks. The "Interpret Mode" presents the interpretation of the artefacts. When the user picks up one of the physical objects, they can choose to interact with each interpretation marked on the artefact, for example, photographs, short text, and maps of the national park that showcase the wider context of the landscape. In a similar manner, the user can choose to access audio interpretation.

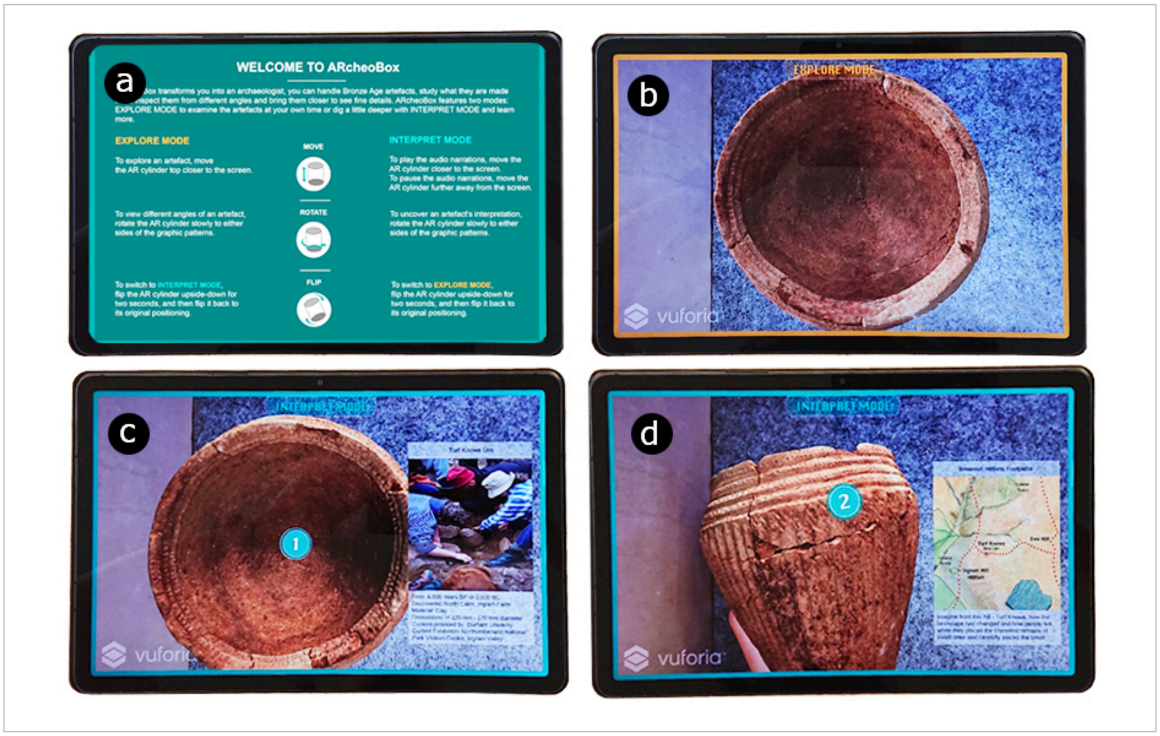

Figure 42: Screenshots from the Augmented Reality (AR) application.

4.2.6 ARcheoBox Exhibit at The Sill

ARcheoBox was showcased at The Sill: National Landscape Discovery Centre in Hexham as a stand-alone exhibit between August 9th and August 22nd, 2021. I designed the exhibit banners and with the help of The Sill staff, I set up the exhibit at The Sill exhibition space. Below is an excerpt of the text included on the exhibition banners to explain to the visitor about the history of the surrounding landscape and ARcheoBox:

> *"ARcheoBox transforms you into an archaeologist, you can handle artefacts, study what they are made from, inspect them from different angles and bring them closer to see fine details".*

ARcheoBox final prototype (Figure 43) was built using timber wood as we wanted the prototype to be sturdy and withstand the large number of visitors who would interact with ARcheoBox.

Figure 43: ARcheoBox final prototype encasing. © Northumberland National Park.

The exhibit banners (Figure 44) also had a visual explanation of how to interact with ARcheoBox. During the two weeks period, I used mixed methods of data collection combining a self-completed paper questionnaire and digital screen survey application to collate the visitors' responses pertaining to their overall experience with ARcheoBox. I gathered 80 questionnaires in which I asked the visitors questions about their overall experience with ARcheoBox, as well as whether they learned something new about the artefacts. The digital survey log recorded 572 visitors that interacted with ARcheoBox. The data from the self-completed paper questionnaire was analysed using Thematic Analysis to identify emerging themes to evaluate visitors' engagement with virtual representations of Bronze Age artefacts using tangible AR prototype. The findings specific details are discussed in chapter 5 (see section 5.3.4).

Figure 44: ARcheoBox Exhibition Banners. © Suzanne Kobeisse (2021).

Summary

In this chapter, I presented the practical output of this practice-based Ph.D. by developing and evaluating a tangible augmented reality prototype for manipulating virtual representations of historical artefacts. I produced two prototypes, ARcheoBox 1.0 and ARcheoBox 2.0, both showcase the iterative process of designing and conceptualising the prototype through co-design sessions with the heritage experts. Also, this chapter discussed the technical implementation and described the final prototype exhibit at The Sill. In the next chapter, I will discuss the evolution of the prototype using three main studies to evaluate the main stages in prototype development. The three studies are presented with the following structure: study design, risk assessment, data collection and analysis, and study findings.

5. EVALUATIONS AND FINDINGS

Overview

In this chapter, I discuss the evaluation and findings of three studies that constituted the main aspect of my research's practical and theoretical contribution. In section 5.1, I describe the study design, risk assessment, data collection and analysis, and findings for a comparative study which aimed to explore design opportunities for generic proxies as tangible interfaces to manipulate virtual representations of historical artefacts in augmented reality. In section 5.2, I discuss the prototype demo study which focuses on testing the prototype user interface design features. In section 5.3, I report on the findings of ARcheoBox visitors' evaluation at The Sill as well as evaluating and refining the conceptual framework for designing and evaluating tangible AR interfaces for manipulating virtual representations of historical artefacts. A number of participants took part in all the three studies which involved heritage experts and staff from The Northumberland National Park and The Sill. Gathering feedback from the same participants across the three studies enabled the participants to consistently reflect critically and carry their input towards the iterative prototype development process, as well as to validate their feedback, creating richer responses in the data.

5.1 Comparative Study

The study aimed to explore design opportunities for generic proxies as tangible interfaces for manipulating virtual representations of historical artefacts in augmented reality. I applied a comparative user study approach using four conditions (Figure 45):

1. C1: Touch screen
2. C2: Flat AR marker
3. C3: Generic wooden cylinder
4. C4: 3D-printed replica of the digital object

Figure 45: The four conditions: touch screen, flat AR marker, wooden cylinder, 3D replica.

5.1.1 Study Design

The study was conducted remotely due to restrictions imposed by the COVID-19 pandemic. The study was set up as a within-subjects experiment and took approximately 30 minutes for the participants to complete. The conditions were performed using a digitised historical artefact, an urn, selected from the collection of historical artefacts excavated at the Northumberland National Park, and dates back to the Early Bronze Age (4,000 Years BP or 2,000 BC). The augmented reality application ran on a Samsung Series S6 Android OS tablet and used Unity (v. 2019.3.10f1), and the Vuforia augmented reality SDK (v.8.5.9). Participants were seated in the purpose-built gazebo where the four conditions were placed on a table. To free the participants from holding the tablet by the non-dominant hand during the process of exploring the historical artefact, the tablet was mounted on an adjustable mechanical arm.

5.1.2 Ethics and Risk Assessment

The study was conducted remotely using Microsoft Teams, a teleconferencing application, due to restrictions on face-to-face interaction with participants during the Covid-19 pandemic. The Northumberland National Park constructed a bespoke purpose-built gazebo at their visitors' centre, and they developed a thorough risk assessment plan, including a method statement to guarantee a secure environment with full safety precautions between participants. Northumbria University research ethics committee approved the study protocols. The pieces of equipment were properly cleaned and sanitized between participants. I also created a remote user study schema (Figure 46) which illustrates the study journey for each participant as part of preparing risk assessment documentation. I recruited participants through Northumberland National Park's internal mailing network and social media channels. All participants were asked to read the risk assessment documentation prior to their attendance of the study and make sure they are comfortable with the measures taken. All participants who completed the study participated on a voluntary basis without any compensation.

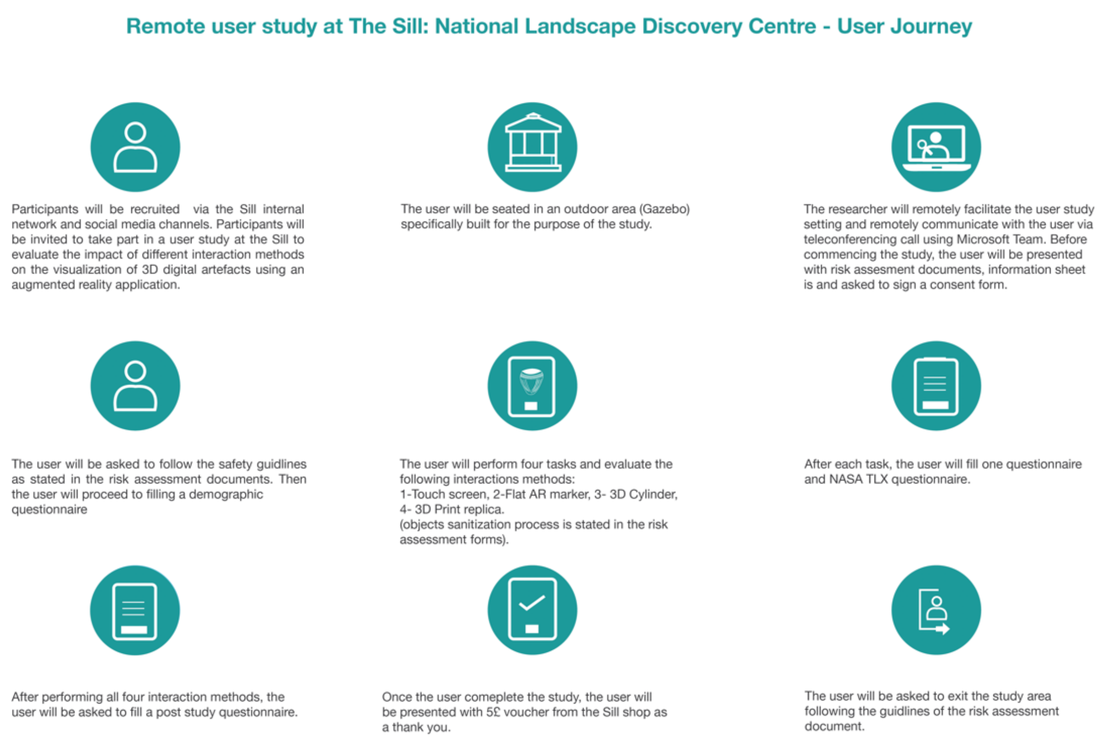

Figure 46: Remote user study schema. © Suzanne Kobeisse (2020).

5.1.3 Data Collection & Analysis

I recruited 16 participants, (eleven females, five males) between the ages of 26 to 56. Regarding employment status, 12 participants (P1-P12) were full-time working professionals, and four participants were domain experts (P13-P16) working on different projects across heritage and conservation in the cultural heritage sector. All participants had previous experience with AR/VR, mainly in museum settings (i.e., AR topographic sandbox and interactive 360-degree films) and reported being very confident to fairly confident in the use of AR/VR. The study was split into three phases (see Table 3). In Phase 1, participants were informed about the scope of the study, were presented with an information sheet, and were asked to sign a consent form. Then, they completed a pre-study questionnaire and indicated their demographic details (age, occupation, etc.) and their prior experience with AR applications.

Phase 2 was split into two phases. In Phase 2.1, each participant was guided to start the experiment by identifying distinct features and cracks on a virtual 3D model of a Bronze Age urn (Figure 47). The conditions were distributed in random order for each participant to avoid bias and the same instructions were repeated across all conditions. While running each condition, participants were asked to answer four questions (1-4). The questions were purposely designed to encourage the participants to actively examine and interact with the artefact.

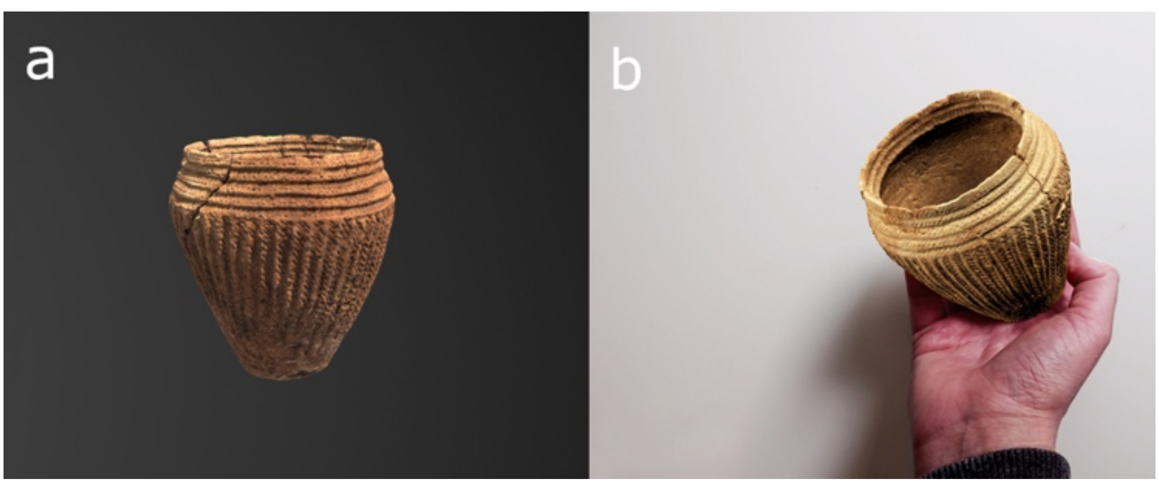

Figure 47: a) 3D scan of the Bronze Age urn; b) The Bronze Age urn 3D model in AR view.

Table 3: Participants – study structure

Phase	Content	Questions
Phase 1 Pre-Study	Information sheet Consent form Demographic data	Basic questions: age, gender, occupation. Questions regarding participants' familiarity with AR/VR applications.
Phase 2 Study	2.1 close-ended questions	1. Can you show me the most distinct feature of the urn? 2. Can you count how many cracks you see along the rim of the urn? 3. Can you show me the biggest crack? 4. How does the urn feel like?
	2.2 5-points Likert-type scale questions and NASA-TLX questionnaire	1. I could easily move or manipulate objects in the virtual environment. 2. Using this interaction method enabled me to examine the virtual 3D model from multiple viewpoints. 3. I felt involved with the visual aspects of the experience. 4. The artefact felt real when using this interaction method. 5. I felt engaged using this interaction method. 6. This interaction method felt natural and intuitive to use. 7. Using this interaction method to interact with historical artefacts was better compared to a traditional museum display.
Phase 3 Post-Study Questionnaire	5-points Likert-type scale questions and Open-ended questions	1. Which interaction method you liked the most? And why? 2. Which interaction method you liked the least? And why? 3. Do you anticipate new purposes for using these interaction methods, if so what kind of purposes?

After completing each condition, in Phase 2.2, participants filled 5-points Likert-type scale questions [Likert, 1932] and NASA-TLX questionnaire [Hart, 2006] to evaluate the workload. The questions were adapted from Witmer and Singer (1998) presence questionnaire. At the end of the study (Phase 3), participants filled out a post-study questionnaire consisting of 5-points Likert-type scale questions and three open-ended questions. The open-ended questions addressed the participants' preferences across the four conditions and what future anticipated purposes of the presented interfaces they can identify beyond historical artefacts exploration. The post-study questionnaire intended to understand whether the four conditions suggest an enhanced user experience for the exploration of historical artefacts compared to traditional observation without tactile interaction.

I analysed the answers of participants responses and accumulated the data into three categories: Positive (strongly agree, agree), Neutral (score 3), and Negative (strongly disagree, disagree). This approach has aided to simplify the presentation of the data and the interpretation of the results (Petrelli and O'Brien, 2018). The next section presents the findings for each condition.

5.1.4 Study Findings

Condition 1: Touch Screen

Participants were able to select, rotate and scale the virtual 3D model and explore it freely using direct on-screen interaction in Sketchfab, a web 3D viewer (Figure 48), where participants can navigate the interface using orbit mode (move camera: 1 finger, pan: 2-finger drag, zoom: pinch in /out, zoom on object, and zoom out: double-tap). I observed that participants noted more details on the outer part of the urn and perceived the urn as less physical.

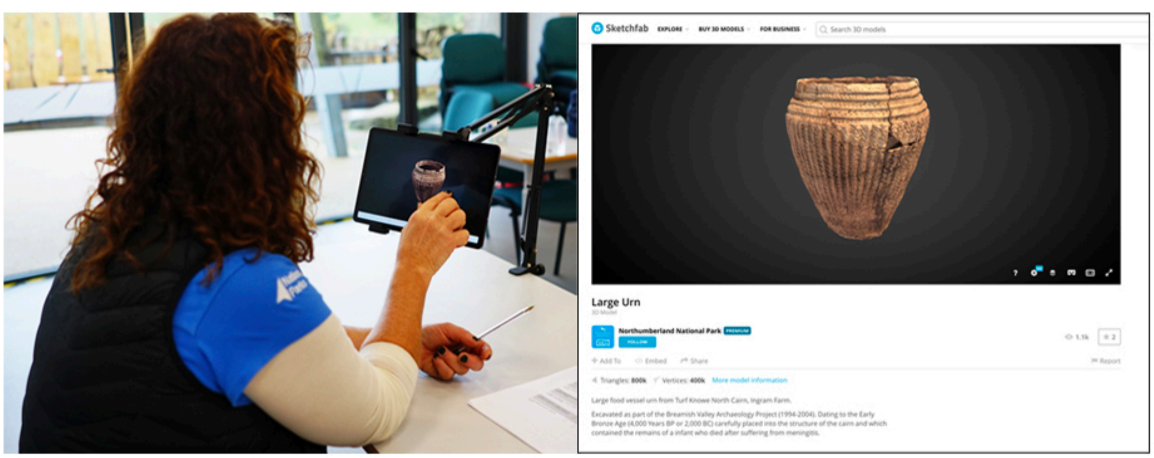

Figure 48: A participant manipulating a virtual urn on a touch screen using Sketchfab.

– *"I feel like interacting with just an image"* (P13) –

– *"The urn feels inaccessible"* (P9) –

– *"The urn seemed distant"* (P10) –

The findings for the touch screen condition are presented in Figure 49. Most participants (14/16) responded positively and stated that the touch screen was easy to use and that they could view the virtual 3D model from multiple viewpoints.

– *"I can view the urn from all angles"* (P15) –

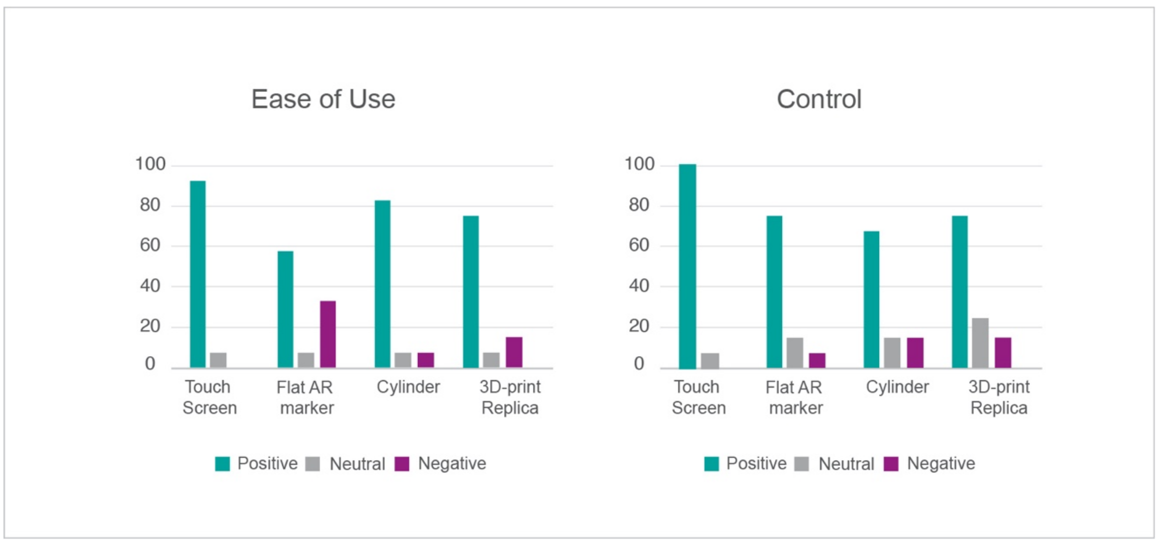

Figure 49: Ease of use and control for the four conditions.

Figure 50: Visual involvement and realism for the four conditions.

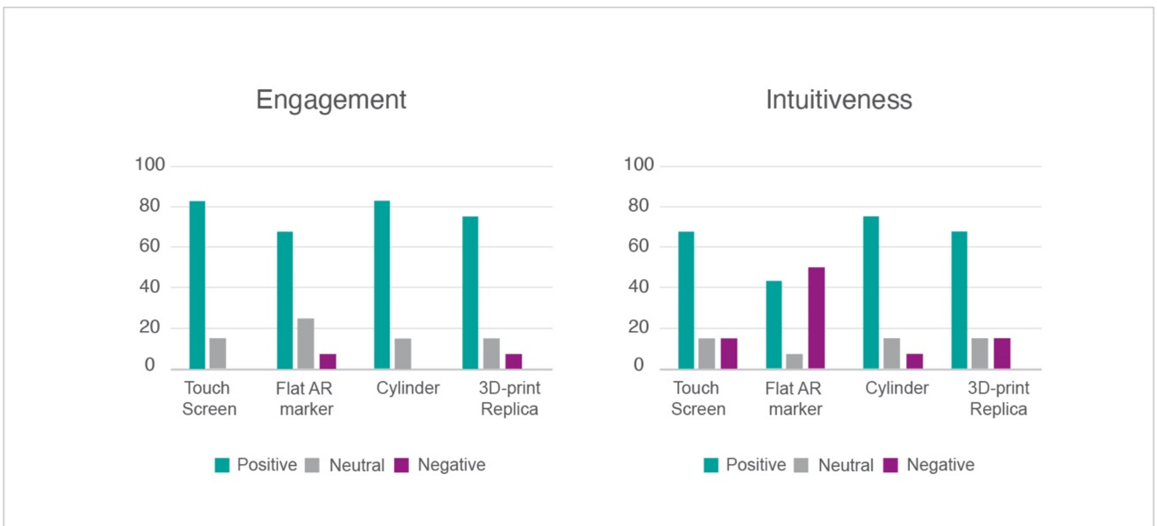

Figure 51: Sense of engagement and intuitiveness for the four conditions.

While 12/16 participants felt involved with the visual aspects of the experience (Figure 50). However, only 5/6 participants felt that the urn was real. Additionally, 14/16 participants felt engaged with the artefact, and (11/16) participants expressed that the method felt intuitive (Figure 51). When answering question 7, phase 2.2 (see Table 3), 12/16 participants were in favour of the touch screen over traditional museum display. Although participants highly rated the touch screen ease of use, they stated that they felt that the virtual 3D model is distant and without any sense of weight. This can indicate that the lack of tangible interactions using the touch screen method has left the participants unable to attach any sense of weight or scale to the virtual 3D model.

Condition 2: Flat AR marker

Participants were presented with a flat square with a printed AR marker attached to a wooden square to provide rigid support, and the 3D digital model was visualized as standing on top of the flat marker (Figure 52). Participants again engaged with the same digitised urn and answered four questions 1-4 phase 2.1 (see Table 3). In response to questions 1-3 phase 2.1 (see Table 3), participants noted more details on the outer part of the artefact, especially the big hole. Also, participants perceived the urn as less physical. In terms of how the urn felt like, participants stated:

– *"I feel like interacting with just an image"* (P13) –

– *"I am aware that I am holding a flat marker"* (P7) –

– *"The virtual model feels light"* (P15) –

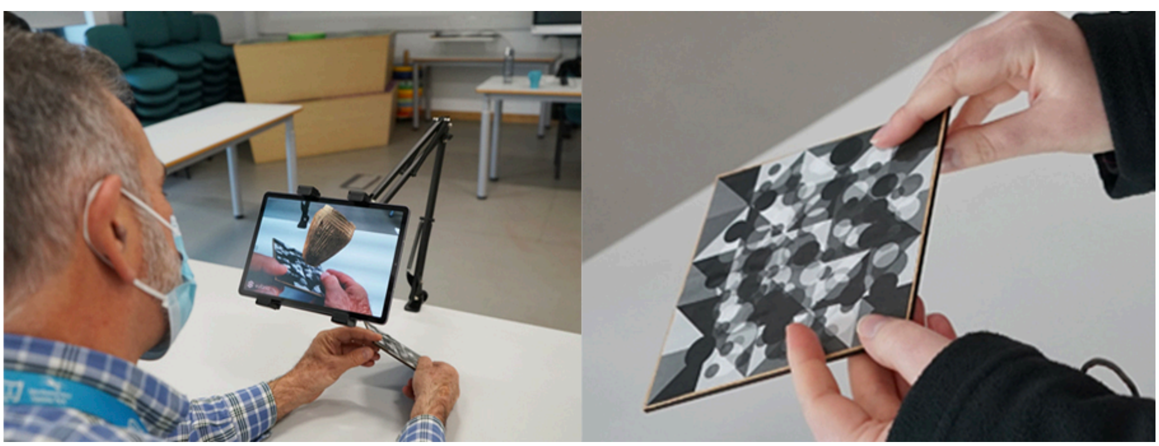

Figure 52: A participant manipulating a virtual urn using flat AR marker.

The findings for the flat AR marker condition are presented in Figure 49. Half of the participants (8/16) responded that the flat marker was easy to use, while 12/16 participants responded that they could view the virtual 3D model from multiple viewpoints, although P1 commented: "I can't see the bottom of the urn". Similar to the touch screen (Figure 50), 11/16 participants felt involved with the visual aspects of the experience, and 7/16 participants considered that the artefact felt real, P3 stated:

– "*I feel that the urn is about to fly*" (P3) –

Additionally, 11/16 participants felt engaged with the artefact, and 7/16 participants stated that the interaction method felt intuitive. (Figure 51). When answering question 7, phase 2.2 (see Table 3), 8/16 were in favour of the flat AR marker over traditional museum display. I postulated from participants' comments, that the lack of weight of the flat AR marker led participants to perceive the virtual object light, almost about to "*fly*" off the flat AR marker. Furthermore, the sharp edges of the square shape of the flat AR marker made participants aware of the shape, and therefore they were not fully able to concentrate on the virtual 3D model.

Condition 3: Generic wooden cylinder

Participants were able to explore the virtual 3D model using a generic wooden cylinder (Figure 53) with an AR marker affixed on top of the cylinder to enable tracking. Participants who answered questions 1-4 phase 2.1 (see Table 3), while handling the wooden cylinder noted more details on the inner side of the artefact and fewer details along the rim of the artefact. In answering question 4 phase 2.1 (see Table 3), Participants stated:

– "*I feel like I am holding the urn in my hand*" (P1) –

– "*I didn't notice I am holding a cylinder*" (P13) –

– "*The cylinder felt true to size of the original urn*" (P9) –

Figure 53: A participant manipulating a virtual urn using cylinder-shaped AR Marker.

The findings for the generic wooden cylinder condition are presented in Figure 49. Almost all participants (13/16) responded positively that the wooden cylinder was easy to use, and 11/16 participants stated that they could view the virtual 3D model from multiple viewpoints. All participants (16/16) felt involved with the visual aspects (Figure 50) and 11/16 participants responded that the artefact felt real (Figure 6). Additionally, (14/16) of participants felt engaged with the artefact and (13/16) responded positively that the interaction method felt intuitive (Figure 51). When answering question 7, phase 2.2 (see Table 3), 13/16 were in favour of wooden cylinder over traditional museum display. I anticipated from participants' comments, that the physicality and weight of the wooden cylinder highly contributed to a better experience, with one participant commenting that they felt more control over the virtual 3D model.

Condition 4: 3D-printed replica

During this condition, participants were presented with a 3D-printed replica (Figure 54) of the digitised urn, with a printed AR marker affixed to the top for tracking. As with the cylinder, they used the 3D-printed replica to move around the urn in any direction and explore it. Answering the four questions 1-4 phase 2.1 (see Table 3), participants noted the ridges on the outer rim and the details on the inside of the artefact. Two participants noted that they perceived the urn to be more fragile when using the 3D-printed replica and were more concerned about dropping it: “But now the urn feels more fragile”. In answering question 4 phase 2.1 (see Table 3), participants stated:

– *"I can feel the ridges on the urn because of the texture on the 3D-printed replica"* (P1) –

– *"I feel connected to the urn"* (P13) –

– *"The urn feels realistic"* (P16) –

Figure 54: A participant manipulating a virtual urn using 3D-print AR marker.

The findings for the 3D-print replica condition are presented in Figure 49. Participants (12/16) responded that the 3D-printed replica was easy to use, and 9/16 participants stated that they could view the virtual 3D model from multiple viewpoints. The majority, 13/16 participants responded that they felt involved with the visual aspects of the experience, and 15/16 participants stated that the artefact felt real (Figure 50). Additionally, 12/16 participants stated that that they felt engaged with the artefact, and 11/16 participants stated that the interaction method felt intuitive (Figure 51). When answering question 7, phase 2.2 (see Table 3), 12/16 participants were in favour of 3D-printed replica over traditional museum display. The participants' feedback that the virtual urn felt more realistic seems connected to the presence of physical ridges on the 3D-printed replica. On the other hand, the 3D-printed replica's high resemblance to the original artefact promoted a sense of handling a fragile object, which could influence their level of immersion if participants would get concerned about dropping the object and damaging it.

Task Workload

The NASA-TLX questionnaire contains six questions to measure participants' perceived workload using six dimensions: mental, physical, temporal, performance, effort, and frustration. The NASA-TLX questionnaire involves two steps. First, participants are presented with a task to reflect upon, and then they are asked to choose which dimension is more related to the workload resulting in 15 paired comparisons. The weighted score is the sum of times each dimension is selected. The weighted score is then multiplied by the raw score for each dimension and then divided by 15 to generate the overall workload per score from 0 to 100. However, the weighting step is excluded to reduce the amount of time needed to administer the NASA TLX questionnaire and analyse the raw TLX responses (Cao et al., 2009; Hart, 2006). Additionally, other studies show no difference is noted when removing weighted TLX scores and that a 15 minutes delay did not significantly affect the workload ratings (Moroney et al., 2003). Therefore, in this study, the use of weighting scales was not included, and I only report the unweighted raw NASA-TLX data (Figure 55).

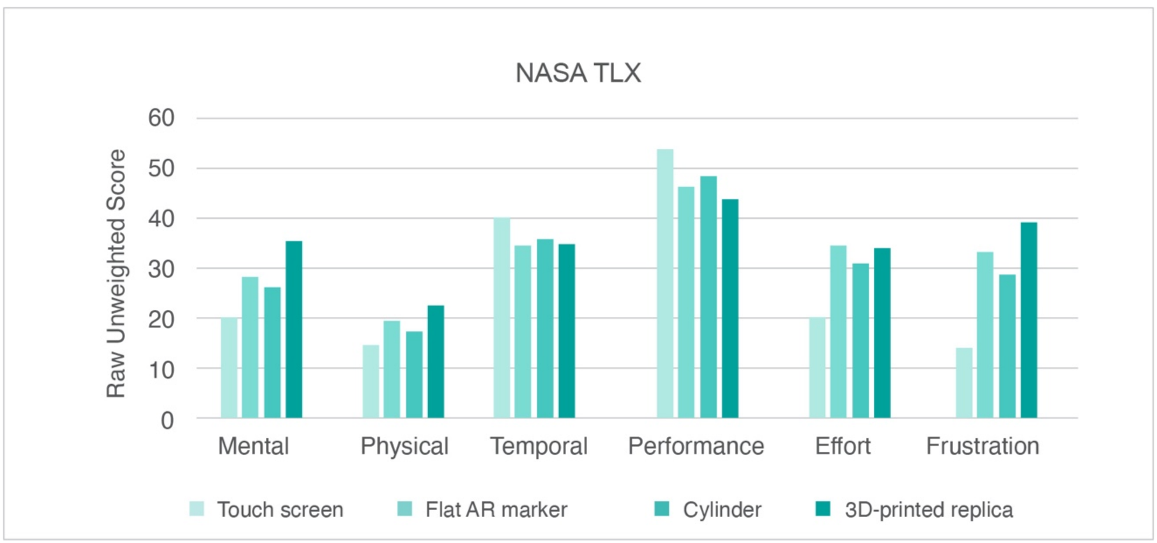

Figure 55: Nasa TLX Raw Unweighted Score.

Participants perceived the mental workload on the NASA TLX using the touch screen as being low, while participants reported a higher level of mental load using the 3D-printed replica. For the flat marker, participants perceived the physical workload and the level of effort higher in comparison to the touch screen and the cylinder. The level of frustration was highest using a 3D-printed replica (60/100), followed by the flat AR marker, cylinder, and touch screen. The touch screen scored higher on performance measures, but no significant difference was noticed between all four interfaces. Across all conditions, the touch screen scored the lowest on the workload, with exception of Temporal measures, an indication that participants might need more time to adjust to the exploration of the virtual artefact through the touch screen vs the other three interfaces. I interpreted these results as being a combination of familiarity with the touch screen being the most familiar interface for most participants, and technical issues with the tracking sometimes being lost due to occlusion or other factors while manipulating the physical objects.

Interface Preferences

I asked participants to rate their preferences using questions 1 and 2 phase 3 (see Table 3) for the interfaces among the four conditions (Figure 56). Interestingly, the touch screen scored highly, where four participants stated that they preferred the touch screen condition, the wooden cylinder came second, the 3D-printed replica came third, and the flat AR came last. Participants' slight preference for the touch screen is characterised by the ease of use; P7 commented:

> – *"The interface is responsive and it was easy to use" (P7)* –

Alternatively, participants (3/16) did not favour the touch screen, (4/16) participants did not favour the flat marker, while (2/16) participants did not favour the cylinder, and (3/16) participants were in less favour of the 3D-printed replica. The participants who did not favour the touch screen and flat AR marker stated, that it was due to the difficulty of tangibly manoeuvring the virtual 3D model. As to why they did not the wooden cylinder and 3D-printed replica, participants stated that they had difficulty keeping the 3D virtual model in screen view. While the results show that a high number of participants favoured the touch screen, which I relate to the familiarity with direct manipulation interfaces, participants still had an appreciation for the tactile experience provided by the cylinder and 3D-printed replica.

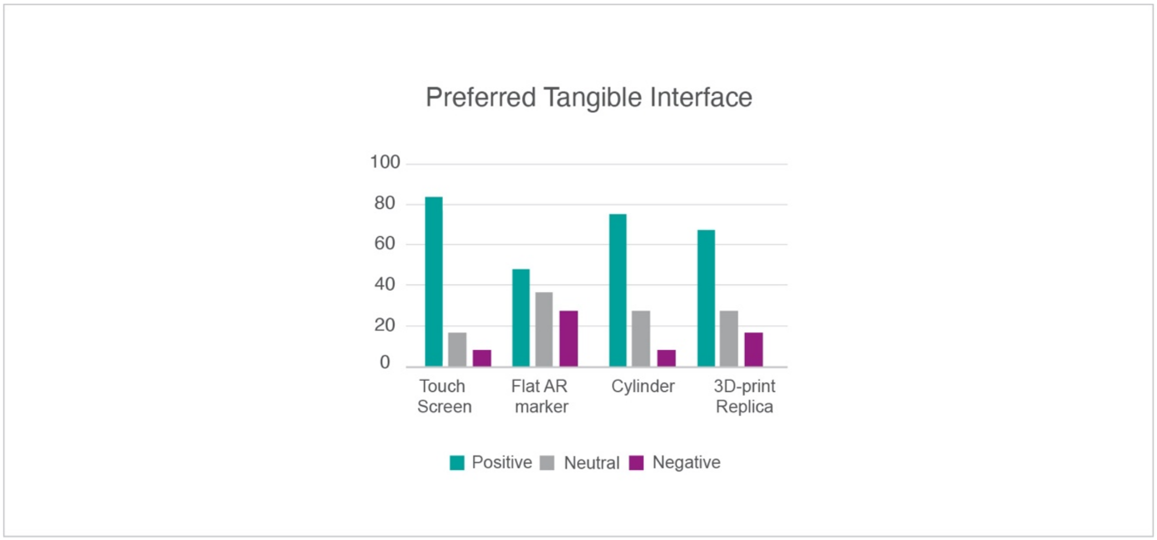

Figure 56: Interfaces preferences for participants.

Below I highlight the design opportunities that occurred from the user study results by exploring four tangible interfaces to manipulate artefacts in AR

Applying Generic Objects as Placeholders for More Complex Objects

This study initial hypothesis is that a 3D-printed replica would offer a more realistic interaction method for AR. However, the results showed that using a more generic object (a cylinder) can achieve a similar effect without the complexity that is required to produce a 3D-printed replica and offer a good trade-off, and potentially represent a larger selection of artefacts, offering an advantage over the standard touch screen and flat AR marker. This indicates that while the 3D-printed replica provided the highest level of realism, the generic cylinder may have enough qualities to make it almost on par. Given that the cylinder can represent more than one object, we argue that it potentially represents a "sweet spot" for tangible interfaces for AR. In this study, I also identified three aspects that can support the interaction methods represented by these four interfaces: Manipulation, Perception, and Immersion.

Firstly, Manipulation. This aspect refers to how easily participants can interact with the tangible interface to view the virtual representations of the historical artefact from multiple viewpoints. Physical interactions emerge at the point of contact with an object and then grasping the object (Wimmer, 2011) as highlighted in HCI theories on affordances (Gibson, 1977, Norman, 1988). Among the four interfaces, the touch screen scored the highest in terms of ease of use and control. Flat AR markers, on the other hand, are the most common type of interaction method for AR. When using the flat AR marker, participants showed excitement for being able to get a closer view of the virtual representation. However, the square shape presented some challenges in terms of interaction, which we attribute to the sharp-angled shape of the marker. The slight preference towards the touch screen and flat AR marker did not come as a surprise to us as we anticipated that the familiarity with both interaction methods and the wide availability of direct manipulation interfaces would instantly appeal to participants. Despite being a generic proxy, the cylinder scored second-highest for manipulation following the touch screen. And even though both, the cylinder and the 3D-printed replica faced issues pertaining to AR tracking stability, if we are able to use better tracking for future versions, this score could potentially become even higher.

Secondly, Perception. This aspect refers to the visual involvement and realism of the interaction method. Participants using the touch screen perceived the 3D model as an image with no sense of dimensions and felt that the artefact was 2D-like and distant. Although the flat marker presented a close view of the 3D model, in this case, participants also perceived the artefact to be distant and less real. Their focus was on holding a square shape and a virtual object stood on top of it. In comparison, once participants picked the cylinder, they stated that they felt that the artefact was in their hands.

– "I can feel it I my hand" (P1) –

Participants at this point perceived the cylinder as if the original artefact was in their hand and were completely involved with the visual aspects of the experience. Finally, the 3D-printed replica was perceived as slightly closer to the actual representation than the cylinder due to the fact that it resembles the real artefact. Notably, the 3D-printed replica scored less on the involvement with the visual aspects. Therefore, we believe that having a 3D-printed replica might lead to distraction from the virtual representation, as participants' perception is affected by what they feel in their hands in terms of shape and texture, instead of having complete focus on what they need to focus on the virtual representation.

Thirdly, Immersion. This aspect refers to the engagement and intuitiveness of the interaction method. The flat marker scored the least in terms of engagement and intuitiveness among the four conditions. The touch screen scored equally to the cylinder, and better than the 3D-printed replica, for engaging with the artefact, but the cylinder was perceived slightly as being the most intuitive, pointing to the fact, that participants become less aware of what they are holding in their hands and were completely immersed with the virtual representation of the artefact.

Designing with Physical Properties and Configurations

Physical properties such as materials have been demonstrated as an important feature for designing tangible interfaces (Jung and Stolterman, 2012), as well as encouraging user engagement through physical interaction (Döring et al., 2012, Dalsgaard et al., 2011). Other properties such as weight and size were also shown to influence user interactions with virtual objects (Kwon et al., 2009), Although testing various physical properties were not addressed in this study, we did notice that certain properties did influence participants' interactions while using the four interfaces. Notably, with the weight, participants interacting with the flat AR marker stated that the virtual representation felt light, as if about to 'fly out' of their hands. Another physical property that was mentioned by participants is size. For example, participants who used the cylinder said that they felt that the virtual artefact fits in the palm of their hands. The study shows strong indications, that the different physical properties such as weight and size of the tangible interface can play an important role in how participants perceive and engage with virtual representations. This opens up opportunities for further configurations that can take advantage of different physical properties that are important when we fashion object. These are (but not limited to) weight, sizes (diameter vs length), and textures (plastic, clay, etc.) or even incorporating different configurations such as additional components that can be assembled in various combinations.

We also provide a summary of the positives and negatives (Table 2), which describes the positive and negative characteristics of each condition. This can serve as a reference guide for interaction designers and researchers, when designing tangible interfaces for AR, specifically when combining physical with a visual exploration of artefacts.

Table 4: Summary of positives and negatives for each condition

	Positives	Negatives
Touch screen	easy to use responsive	low fidelity not realistic
Flat AR marker	familiar stable tracking	low fidelity not realistic
Wooden cylinder	Intuitive good trade-off	non-stable tracking
3D-printed replica	high-fidelity realistic	non-stable tracking complex reproduction

Matching Physical Objects to Virtual Representations

When it comes to interacting with virtual objects in AR, the flat AR marker has so far been the norm. However, the flat marker does not have any tangible qualities that are close in resemblance to the virtual representation. The study results and feedback from participants have shown that the two conditions that overall generated a higher level of realism and intuitiveness were the ones where the physical sensation most closely corresponded to the virtual. For the 3D-printed replica, this meant that what the participant felt in their hand was almost exactly what they saw on the screen. For the generic cylinder, however, the correspondence was less exact, but the similarity was close enough to still generate a positive response from the participants and promote a more compelling experience when manipulating the artefact – "*feeling it in the hand*". This allows participants to feel something very close to what they are seeing in the AR view and allows them to manipulate a virtual object almost as if it was real. This is a contrast to the traditional methods, the touch screen and flat marker, which did not feel as "*real*" to the participants. Furthermore, this indicates that although low-fidelity interfaces might be suitable as an interaction method to view and manipulate artefacts in AR, however, the perception level (realism) and immersion level (intuitiveness) is higher with tangible interfaces that have a close match with the virtual representations.

Limitations

Participants exploring the wooden cylinder and the 3D-printed replica faced some issues pertaining to AR tracking stability, where their hands at times blocked the attached AR markers which led to losing tracking of the physical objects, however, with advancing technologies for AR markers, better tracking would be introduced in future studies, which could potentially improve the overall scores for these two conditions.

5.2 Prototype Demo Study

This study aimed to evaluate the prototype demo design features and augmented reality application functionalities with heritage experts and public users. Zimmerman et al. (2007) acknowledge the importance of the evaluation of the artifact by stating:

> "In evaluating the performance and effect of the artifact situated in the world, design researchers can both discover unanticipated effects and provide a template for bridging the general aspects of the theory to a specific problem space, context of use, and set of target users" (Zimmerman et al., 2007, p497).

5.2.1 Study Design

The aim of the study was to see how the participants responded to the overall prototype design as well as the functions of the three tangible AR interactions techniques. The insights from the study were implemented in the final prototype, which was installed at The Sill to obtain in situ visitors' data (see section 5.3.3). The study was conducted in person once face-to-face research was permitted while adhering to all safety measures to safeguard the participants. The study was set in a controlled environment and took approximately 30 minutes to complete. The augmented reality application ran on a Samsung Series S6 Android OS tablet and used Unity (v. 2019.3.10f1), and the Vuforia augmented reality SDK (v.8.5.9).

Additionally, a photographer took pictures of the participants' interactions with the prototype standing at a 2 meters distance.

5.2.2 Ethics and Risk Assessment

The study took place at the Northumberland National Park Headquarter offices in Hexham. I submitted an amendment to the ethics approval with Northumbria University ethics committee and the application was approved in June 2021 to mitigate the risks associated with the COVI-19 pandemic, where full consideration is given throughout the study in terms of social-distancing, protective face and hands covering, and sanitising. The risk assessment documents included a detailed plan of the study room, and participants were seated in the Annex room with clear marked entrance and exit doors to maintain the COVID-19 safety measures between participants. Both the risk assessment and methodology statement were made available to all those planning to participate in the study stating that it must be read prior to attending. At the beginning of each session, the researcher re-iterated the COVID-19 safety measures that will be taken throughout the study in order to lessen the risk of transmission of the virus. All participants signed a consent form stating that they are comfortable with the measures taken to safeguard the study.

5.2.3 Data Collection & Analysis

The study consisted of 25 participants, 14 females and 11 males, age range 29 - 63, mean age 44.64. Participants were recruited using the affiliated museum network, on a voluntary basis without any compensation. The participants were photographed, and their comments were recorded and transcribed later for data analysis. Participants were given an information sheet explaining the study protocol, then they were asked to sign a consent form and fill a demographic questionnaire.

After a brief introduction to ARcheoBox, participants were left to interact freely with the prototype (Figure 57). Participants were asked to provide feedback on the prototype ergonomics, and user interface aesthetic and functions. The researcher observed the participants' interactions while standing nearby following the COVID-19 social distancing rules and assisted participants by answering questions when needed and also took notes of any comments made by the participants. At the end of the session, participants were asked to complete a questionnaire with 15 Likert-type scale questions Likert, (Likert, 1932). The questionnaire had a five-point Likert Scale questions rated from "Strongly Agree" to "Strongly Disagree", which is consistent with the leading usability questionnaires such as VRUSE Kalawsky, (1999), SUS Brooke, (1996), and SFQ Kizony et al., (2003). Additionally, participants were asked to describe what they most liked and what they liked the least about ARcheoBox and add any further comments to identify any issues that were not covered by the questions. The questions were adapted from Nielsen and Molich (1990) interface design usability guidelines for interaction design and were organised according to five categories:

1. Ergonomics (manipulation, ease of use, and control - i.e., stable tracking, user movement).
2. Performance (efficiency - i.e., alignment of virtual 3D model to the physical object, and the loading time of virtual object in the scene).
3. Perception (comprehension - i.e., understanding of the system and presented information),
4. Immersion.
5. Satisfaction (usefulness and enjoyment).

Figure 57: a) Participant manipulates virtual artefact; b) Participant's hands inside the box.

5.2.4 Study Findings

Despite the novel features of ARcheoBox, it took participants around 30 seconds to get familiar with using the prototype unique interaction techniques. Once the participants understood the principles for interaction, they were comfortable with using the prototype and instantly proceeded to explore the different physical objects and had no issues recalling the interaction techniques. Subsequently, participants reported ease of use, intuitiveness, and enjoyment throughout the study. Additionally, participants stated that they appreciated the tactile sense carried by the generic proxies, which made them feel closer to the artefacts.

The results (Figure 58) from the Likert-type scale questions were grouped according to the interface design usability guidelines by Nielsen and Molich (1990). The results suggest that the majority of participants (92%) stated that the application is clear and visible, where appropriate visual feedback is given to familiarise users with the user interface. The match between the application and the real world also achieved highly with the participants stating that the application corresponded to the real-world environment. The application control yielded favourable results with participants stating that they felt in control when manipulating the historical artefacts. Additionally, participants stated that application functionalities were easy to remember, and that text and visuals were clear and readable. Overall, participants stated that the application is well designed, and the aesthetics of the application are pleasing. Furthermore, all participants stated that they enjoyed the interaction experience, and that the application is useful to explore historical artefacts.

– "I love how it is like holding the artefact and having someone talk you through" (P1) –

– "Sleek and well designed, extremely informative and detailed." (P4) –

– "It is a really fun interactive system that will really help with the different ways individuals learn and interact with objects" (P14) –

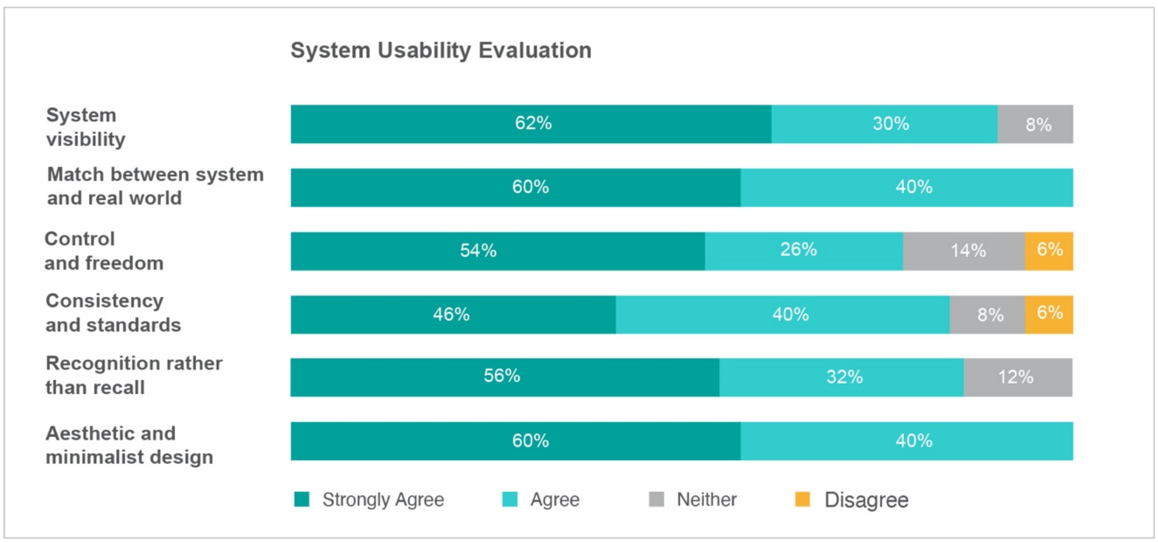

Figure 58: System usability evaluation chart.

I also gathered some valuable comments from the participants to improve the AR application. P20 suggested including hotspot labels for the interpretation. Other suggestions included adding a map of the excavation sites of the artefacts to familiarise non-local visitors with the wider setting of the area. Additionally, participants also stated that having different colours assigned to each interface mode enabled them to easily distinguish between Explore mode and Interpret mode and facilitated their transition from one mode to another. Participants also stated that ARcheoBox offers a great opportunity of making historical artefacts accessible using unique interactions. When asked what they liked most about ARcheoBox, participants stated that the ability to physically hold and manipulate virtual representations of historical artefacts makes brings artefacts to life and makes the whole experience a lot more captivating.

– *"I liked the ability of the system to connect me tangibly to the object, I can hold it, something I can never do with the actual object"* (P3) –

– *"I think this would make a great asset to an exhibition or exploration activities and suitable to all ages"* (P7) –

– *"What I liked is the accessibility side of things, where I don't need to come with my own technology, I don't need to download an app, I put that away and just enjoying the experience". It doesn't require any other interaction from me except using it."* (P8) –

Participants did not state any negative responses when asked what they liked the least about the system besides the previously stated suggestions for improving certain design features related to the prototype AR application.

Design Recommendations

Based on the findings and reflections from the prototype demo study and co-design process with the heritage experts, I will now present three design recommendations that were identified for manipulating virtual representations and interacting with interpretation of historical artefacts.

Communicating Interaction Semantics

The findings show that participants 'felt in touch' with the Bronze Age artefacts because they could hold the artefacts in their hands and interact with Interpretation at the same time. The findings are confirmed by previous research that tangible interaction in museums provide a sense of engagement with exhibits (Note et al., 2019), versus more limited interactions via screen-based touch interfaces. ARcheoBox *walk-up-and-use* approach differs from most immersive museum exhibitions, which require wearing head-mounted displays and handheld controllers. Participants were not required to operate any additional gear, offering an intuitive and engaging user experience for manipulating virtual representations and interacting with interpretation of historical artefacts. From one side, the cylinder-shaped generic proxies shared a familiar resemblance with the virtual 3D models and offered mutual affordances. Moreover, designing interaction techniques as output modalities in AR requires careful consideration in regards to clearly communicating the semantics of the intended interactions between the physical objects (generic proxies) and their output modalities in the virtual environment. Designers can explain the semantics of the interaction techniques to users to test their practicalities. Designers can also provide further visual cues, for example by designing icons related to the different types of output modalities and applying them to the AR markers, which could enhance the learnability of the interaction.

Designing for Immediate Interaction with Artefacts

Participants noted that one of the benefits of using the physical objects (generic proxies) to manipulate virtual representations and interact with interpretation of historical artefacts is the immediate interaction with the artefacts, such as their ability to interact with the artefacts without downloading any applications to their smartphones or operating additional devices such as head-mounted displays or handheld controllers. Accordingly, the following guidelines to design for immediate interaction with artefacts: 1) Re-purposing of physical objects by using a single physical object (generic proxy) whose shape resembles the virtual representation but without exactly corresponding to it, which would enable physical manipulation of multiple historical objects; 2) New way to access archival information by embedding the interaction techniques within the same physical objects (generic proxies) as AR output modalities to interact with interpretation of artefacts. This would minimise the physical barrier that usually exists when users interact via buttons on a touch screen as the user does not need to switch to another device; 3) Customisable interactions, by customising the AR markers on the generic proxies so that each side becomes a potential point for interaction to unearth the artefact narrative. This would enable designers, and museum professionals to alter the contents of the application to fit their exhibitions themes.

Co-designing Tangible AR with Heritage Experts

I incorporated co-design methods in our interviews with heritage experts, to establish design features and heritage content that could engage audiences and '*bring to life'* a collection of Bronze Age artefacts. Co-design provided us with the opportunity to connect with multiple stakeholders, bringing rich perspectives when designing digital technologies for heritage. The heritage experts regarded tangible AR as a medium that could offer museum visitors the opportunity to interact with interpretation in a unique way and enable them to form a connection with the past by holding the objects in their hands. I also worked with other stakeholders from the organisation to audio record some excerpts of the interpretation, bringing a hands-on approach to the community of collaborators as part of the co-design process. I followed an iterative design process, where each prototype iteration was examined to validate the prototype features and elicit conversations through formal and informal discussion. Prototyping for AR is still an exploratory design space with very few tools that exist to help with the ideation process for 3-dimensional and virtual spaces. Consequently, I developed a sketching sheet to help non-designers such as the heritage experts, brainstorm different concepts for the prototype. The sketching sheet structure contains two sections: the first section, *Interactions in AR*, is to brainstorm concepts for interaction techniques in AR using generic proxies. The second section, *heritage content*, is to compose the artefacts interpretation. The sketching sheet served as an inspiration tool and enabled participants to establish connections between analogue methods of ideation and AR technologies, as well as generate ideas about interaction techniques using generic proxies. Once, the heritage experts identified more specific ideas, I then initiated discussions around potential technological implementation.

Limitations

Incorporating interaction techniques not normally associated with generic proxies requires further design consideration. I tried to overcome this limitation by adding visual icons on the AR markers to indicate the interaction techniques and their output modalities in AR. Also, during user observations, I noticed that some participants occasionally lost tracking of the

AR markers. As AR technology keeps advancing, I aim to further investigate different tracking techniques to improve occlusion.

5.3 ARcheoBox In-Situ Study

This study represents the final study and evaluation of ARcheoBox in situ with The Sill visitors. ARcheoBox (Figure 59- 61) was exhibited at the Sill: National Landscape Discovery Centre in Hexham between August 9^{th} and August $22^{nd,}$ 2021. In overall, the exhibition largely received positive feedback from the visitors.

Figure 59: ARcheoBox exhibition at The Sill: National Landscape Discovery Centre.

Figure 60: ARcheoBox prototype stand.

Figure 61: ARcheoBox prototype stand – top view.

5.3.1 Study Design

The goal of the study was to examine how The Sill visitors interacted with ARcheoBox exhibit in situ. As this research is primarily grounded in the field of interaction design, I specifically investigated the design of the visitors' interaction with a tangible augmented reality prototype. The study focused on evaluating ARcheoBox usability features to enhance the interaction experience for manipulating virtual representations of historical artefacts. The study was permitted in person by adhering to all COVID-19 safety measures to safeguard the visitors. The study took place over a period of two weeks including weekends. According to The Sill visitor visit data, the visitor centre was receiving approximately 600 visitors per day. Although The Sill had confirmed that their visitor footfall was much higher pre-pandemic.

At the start of the study, the visitors were left to freely interact with ARcheoBox and they weren't given any specific guidance or instructions besides the written instructions on the banners. The researcher only stepped in and answered questions or provide any guidance when needed. The researcher used informal interviews to capture as many visitors' reactions as possible from the perspective of the visitor interaction experience with ARcheoBox. The visitors wrote down further comments and suggestions about ARcheoBox at the bottom section of the questionnaire (see Appendix 2). This enabled the researcher to incorporate additional logs in the data analysis. The visitors were given an information sheet explaining the research and their participation and were asked to fill out a questionnaire, including questions about their demographics, such as gender, age, occupation, their experiences with AR/VR applications and to describe their overall experience with ARcheoBox.

5.3.2 Ethics and Risk Assessment

The study took place in situ at The Sill: National Landscape Discovery Centre during the COVID-19 pandemic, all visitors and staff followed the required local government guidance regarding safety and social distancing. An additional amendment to the ethics approval was submitted and approved by Northumbria University ethics committee in August 2021. Visitors were photographed while interacting with ARcheoBox and were asked to sign a consent form on the use of their photographs for academic and publication purposes. As with the previous study (see section 5.2.2), risk assessment documents were presented containing details about the Northumberland National Park risk assessment plan, a method statement, and a movement plan illustrating the visitor orientation inside the exhibition space. ARcheoBox was exhibited in the permanent exhibition space which had a one-way system and a limited capacity of 15 visitors. Instructions on 2m distancing, and hand sanitiser cleaning points at entrance/exit points were clearly marked. Pens were also provided for the completion of the questionnaire and were cleaned after each usage.

5.3.3 Data Collection & Analysis

The study data was collected during two weeks period in which ARcheoBox was exhibited at The Sill (Figure 62 - 65). I used mixed methods of data collection combining a paper questionnaire (see Appendix 2) and a self-completed digital screen survey. Additionally, I observed visitors from afar to capture their initial interactions with ARcheoBox. The questionnaire addressed the visitors' overall experience with ARcheoBox, whether they learned something new about the artefacts and the landscape, as well as if they predict other uses for ARcheoBox. Additionally, a digital survey display was placed next to the prototype to rate the visitors' satisfaction including emojis, as well as answering three Likert-type scale questions: 1) after using ARcheoBox, I felt like I interacted directly with the Bronze Age artefacts; 2) I learned something interesting about the Bronze Age artefacts using ARcheoBox; 3) tangible interaction and Augmented Reality for historical artefacts is an engaging approach.

The digital survey application entries (Figure 66) showed that 572 visitors interacted with ARcheoBox, indicating that the visitors actively engaged with ARcheoBox. Overall, 80 visitors (40 female and 40 male) with average age of 42, filled out the paper questionnaire. Occasionally, visitors engaged with the researcher in a discussion about ARcheoBox and the technological approach for manipulating virtual representations of historical artefacts, in which the researcher took notes of their verbal comments, adding more richness to the data, beyond their initial written feedback in the questionnaire.

Figure 62: An adult visitor and a young visitor during ARcheoBox in-situ evaluation.

Figure 63: A young adult visitor during ARcheoBox in-situ evaluation.

Figure 64: An adult visitor during ARcheoBox in-situ evaluation.

Figure 65: An adult visitor and a young visitor interacting ARcheoBox in-situ evaluation.

Sixty-three visitors have university-level education with various occupations, such as teachers, office administrators, engineers, doctors, university lecturers, architects, and local government officers. In terms of previous AR/VR experience, fifty-five visitors had previously used an augmented reality application (i.e., Snapchat, IKEA) or VR commercial headsets and handheld controllers inside and outside the museum context, and although more senior visitors tended to have less AR/VR experience, they were still interested to experience new technologies. By combining multiple methods of several data sources, I was able to develop a broader understanding of the visitor interaction experience with ARcheoBox.

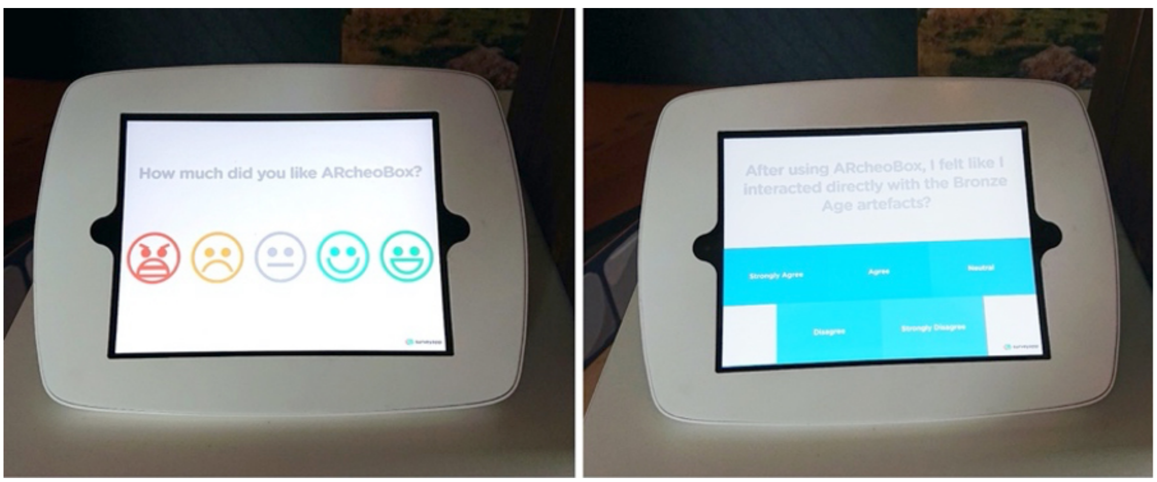

Figure 66: The digital survey app at The Sill: National Landscape Visitor Centre.

The questionnaire responses were analysed using Thematic Analysis to identify relevant themes and evaluate visitors' engagement with ARcheoBox to manipulate virtual representation of Bronze Age artefacts. The raw data was constituted of the transcripts from the visitors' responses to the questionnaire. I used Microsoft Office Excel to transcribe the written text data into an electronic format to facilitate the Thematic Analysis process. I started by reading through the whole transcripts in detail in order to develop an overall understanding of the data direction and explore visitors' additional responses. To ensure immersion and develop a closeness with the data, several readings were repeated to identify recurring concepts and construct potential meanings across the data (Braun and Clarke, 2006). The data was placed in a single column and reviewed to remove any duplicates in the transcripts. Then the cells in Excel were assigned a colour for each allocated theme. As this was an inductive approach, there were no pre-set themes prior to the coding process. This inductive approach led to the development of four core themes. The core themes were also considered in relation to each other and in connection to the overall data interpretation. Initially, the data followed the common coding methods applied in grounded theory (Strauss and Corbin, 1998). First, open coding process to start thinking about the data, and then axial coding by combining codes that share similarities, in order to develop a series of themes and sub-themes, leading to selective coding in order to identify the core themes. The data analysis was concluded when new data brought no additional insight to the overall analysis. Eventually, I identified four core themes which were clearly defined: *Interactivity, Learning, Engagement,* and *Usability* and four main concepts: Tangible Interfaces, Gesture Interactions, Mapping, and System Usability. The main concepts were then aligned to 10 key aspects that contribute with a set of design characteristics.

5.3.4 Study Findings

The study findings reflect insights generated from ARcheoBox in-situ evaluation with visitors at The Sill and how ARcheoBox impacted their overall experience for manipulating virtual representations of historical artefacts. In terms of data findings, the focus was to examine the visitors' actions, reactions and responses to ARcheoBox and how it engages them with virtual representations of historical artefacts, however, the data revealed that learning can occur as part of the experience and would definitely be worth to be further investigated. The framework is illustrated using a visual diagram as shown in Figure 67. The visual diagram indicates four overarching core themes, that encompass the four main concepts which are defined and thoroughly discussed. Hereafter, each main concept is connected to its corresponding key aspect. The key aspects contribute with a set of design characteristics to guide the design process and support the practical implementation of tangible AR interfaces to manipulate historical artefacts. The centre of the visual diagram situates the initial component, which are the artefacts 3D models that can be incorporated within tangible AR prototype using the design characteristics proposed by the framework.

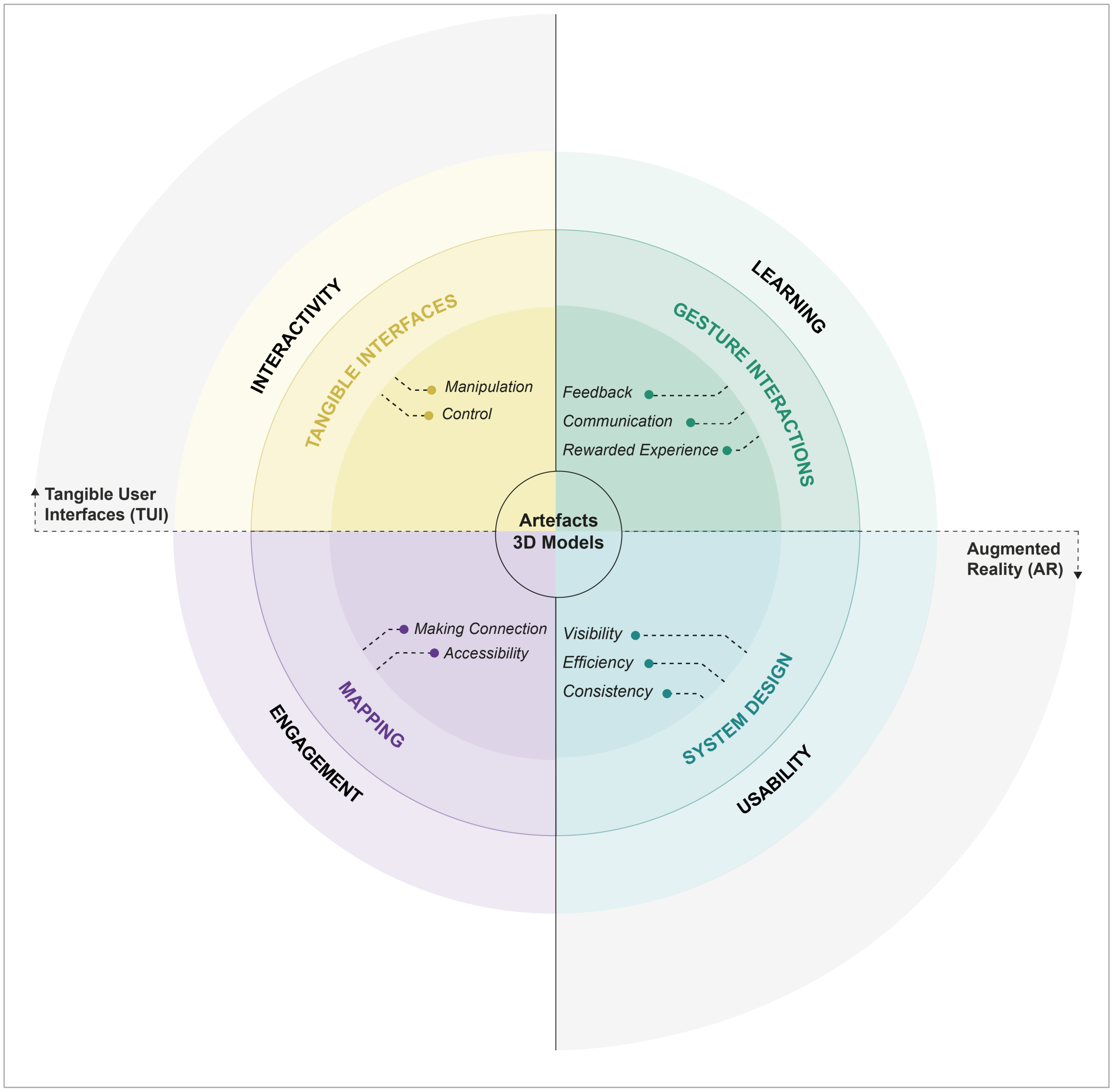

Figure 67: The conceptual framework visual diagram. © Suzanne Kobeisse (2022).

The four core themes (Interactivity, Learning, Engagement, Usability*)* and the four main concepts are shown in Table 5. The core themes were also analysed in relation to each other and with a connection to the overall data interpretation. Each core theme comprises one of the main concepts, which are derived from previous work in the literature. The four main concepts are: Tangible Interfaces, Gesture Interactions, Mapping, System Design. The main concepts are aligned to 10 key aspects: *Manipulation, Control, Feedback, Communication, Rewarded Experience, Making Connection, Accessibility, Visibility, Efficiency, Consistency* (Table 6).

The 10 key aspects are translated into design characteristics to support developing and evaluating tangible AR interfaces for historical artefacts (Table 7). Additionally, excerpts of visitors' quotes are included from the transcripts and integrated into in the final analysis to emphasis elements of the themes and support theory being made.

Table 5: The core themes and the four main concepts.

	Core Themes	Main Concepts
1	Interactivity	Tangible Interfaces
2	Learning	Gesture Interactions
3	Engagement	Mapping
4	Usability	System Design

The first core theme Interactivity refers to the interactive qualities of the prototype. Interactivity theme is defined in terms of three factors elicited by the tangible AR prototype; physical interactions, cognitive interactions, as well as social interactions. Physical interactions offer sensory stimulus and are enriched by allowing the visitor to physically manipulate the historical artefacts using generic physical proxies. Cognitive interactions are supported through the prototype's ability to stimulate interest and provide the visitor with a sense of discovery and fulfilment when exploring the historical artefacts using the augmented reality application, as stated by one of the visitors:

– "great experience, close up view of the artefacts, fascinating" (V31) –

And finally, social interactions are encouraged through the visitors' collective presence enabling conversation about the historical artefacts around the prototype. Interactivity as a core theme comprises the main concept of Tangible Interfaces.

Table 6: The main concepts and the 10 key aspects.

	Main Concepts	Key Aspects
1	Tangible Interfaces	*Manipulation*
		Control
2	Gesture Interactions	*Feedback*
		Communication
		Rewarded experience
3	Mapping	*Making Connection*
		Accessibility
4	System Design	*Visibility*
		Efficiency
		Consistency

Table 7: The key aspects, design characteristics and their implementation.

	Key Aspects	Design Characteristics	Implementation
I	*Manipulation*	Assigning Coherent manipulation for the virtual 3D models in the real-world environment.	This design characteristic is implemented by using cylinder-shaped generic proxies that enable hands-on manipulation of the virtual representation of historical artefacts.
	Control	• Ability to have good physical grasp of the generic proxies. • Ability to inspect the virtual 3D model from different angles.	This design characteristic is implemented by mounting the AR markers around the cylinder-shaped proxies which improves the camera tracking of the AR markers and showcase the artefacts from different angles.
L	*Feedback*	• Link AR interaction techniques to the respective outputs in the AR environment.	This design characteristic is implemented by linking the AR interaction techniques to their AR outputs according to their position. And testing AR interactions techniques are

		• Ensure AR interaction techniques (*Move, Rotate, Flip*) detection by the AR application.	properly detected by the AR application.
	Communication	Incorporating and arranging information (i.e., 3D models, text, audio) within the AR application.	The design characteristic is implemented by incorporating and arranging information related to the historical artefacts, such as the virtual 3D models, text, and audio in the AR application.
	Rewarded experience	Learning novel AR interaction techniques.	This design concept is implemented by introducing ambiguous design qualities which lead to a rewarded experience and strengthening the relationship between the visitors and the physical objects.
E	*Making Connection*	Aligning virtual 3D models to merge correctly with the generic proxies.	This design characteristic is implemented by aligning the generic proxies to their virtual counterparts and integrating the 3D models in the virtual environment to merge with the generic proxies in the real-world environment.
	Accessibility	Creating high-quality scans of original artefacts which allow close inspection of artefacts fine details.	This design characteristic is implemented by producing high quality scans of the virtual 3D models which ensure that the visitor can inspect all the details.
U	*Visibility*	Designing Clear and visible user interface.	This design characteristic is implemented by visual elements to the application interface design which can inform the visitor about the interface status.
	Efficiency	Designing a responsive application through	This design characteristic is implemented by designing a user interface with efficient

		enhanced AR markers detection.	navigation and quick loading of the application. Also optimising Vuforia AR markers with contrasted features to enable effective detection by the camera to display virtual 3D models and information.
	Consistency	Designing user interface with standard functions that achieve similar tasks across the AR application.	This design characteristic is implemented by designing a consistent user interface where the interface follows the same set of functions to achieve similar tasks across different interactions within the AR application.

Tangible Interfaces

The main concept of Tangible Interfaces relates to employing physical objects to manipulate and interact with virtual representations of historical artefacts. The visitors can physically hold and directly manipulate virtual representations of historical artefacts using cylinder-shaped generic proxies. The physical objects serve as an intuitive interface to manipulate the historical artefacts as well as interact with interpretation in AR, which removes the physical barrier between the visitor and the artefacts. The choice of physical objects was considered through early discussions, as well as co-design interviews with the heritage experts to develop a prototype that can overcome current limitations around physical interaction with historical artefacts due to their fragile nature. Consequently, the use of physical objects as an interaction method using generic proxies produced a very positive effect on the visitor interaction experience with the historical artefacts. This concept relates to bodily interactions (Hornecker, 2004) because the visitor's hands are part of the interactions, and their movements translate to in/output through the physical objects. This main concept is aligned to two key aspects: *Manipulation* and *Control*.

Manipulation

The ability to physically manipulate objects is an important aspect of analysing historical artefacts, it is also suggested that in order to fully engage with virtual representations of historical artefacts, it is best to interact via tangible manipulation which can promote thinking through things (Kirsh, 2010). This key aspect demonstrates how visitors can manipulate virtual representations of historical artefacts and view them from different angles using the cylinder-shaped proxies which are based on simple basic primitive shapes. For instance, visitors expressed that by using the cylinder-shaped proxies, they can easily and physically manipulate the virtual 3D models.

– "I like the physical sense" (V66) –

– "Brought me closer to the artefacts" (V76) –

– "Tactile, I could feel the object, not just see it" (V79) –

Additionally, I noted how visitors were able to grasp and manipulate the cylinder-shaped proxies very easily based on the simple basic primitive shapes of the proxies. The system novelty also fostered a sense of positive user experience, as visitors noted:

– "Very good, really impressed, brilliant to get hands on with 3D models" (V18) –

– "Really good, it is a great way to explore artefacts" (V39) –

– "Very interesting, enjoyable, I felt I had new experience and interaction with objects" (V23) –

Control

The cylinder-shaped generic proxies as physical interfaces afforded the visitors to control the historical artefacts by having an interface that responds to their hand movements similar to handling an original artefact. In many instances, visitors related their sense of enjoyment due to the natural affordances ARcheoBox embodied which required no extra gear to operate such as Head-mounted displays or handheld controllers. As expressed by the visitors:

– "I felt I can control the artefacts" (V7) –

– "brilliant to get hands-on with 3D models" (V18) –

The physical objects promoted an intuitive and seamless interface that requires no extra gear to operate such as Head-mounted displays or handheld controllers, enabling the visitors to keep their focus on the objects at hand without having to press any buttons that would distract and interrupt their interactions, for instance, as in the case of using a touch screen interface.

The second core theme Learning refers to learning as it occurred while visitors manipulated the historical artefacts using the tangible AR prototype. The visitors expressed that they learned something 'new' and felt that the prototype enhanced their knowledge about the Bronze Age artefacts, as commented by the visitors: "you can experience what they used to be like and used for" (V15); "educating, very informative and easy to use" (V57); "thought-provoking" (V69); "a good way to learn interactively" (V19); "I really enjoyed finding out what each item was" (V53). Additionally, visitors anticipated that the prototype could apply to other domains such as looking at insects, bones, rocks, and a multitude of historical contexts, "… has a huge benefit to so many walks of life" (V66). Learning as a core theme comprises the main concept of Gesture Interactions.

– "I can also see so many crossovers use such as looking at insects, etc...Can really give insight to new areas." (V4) –

Gesture Interactions

The main concept of Gesture Interactions relates to linking the generic proxies to the interaction techniques as output modalities in AR. Gestures are defined as hand and arm movements that convey information (Quek, 1995). In the context of HCI, gestures can be classified into two categories communicative and manipulative (Pavlovic et al., 1997). The visitor can use three AR interaction techniques (*Move, Rotate, Flip*) to access interpretive content such as text, photographs, maps, and audio, as well as switch between different interface modes in the application (Explore mode or Interpret mode). For instance, the visitor can use three interaction techniques (*Move, Rotate, Flip*) as output modalities in AR (*Zoom, Select, Switch*) to interact with interpretation, such as text, photographs, maps, and audio, as well as switch between different interface modes in the application (Explore mode or Interpret mode). The interaction techniques were considered during early discussions with the heritage experts on how to enhance the visitor understanding of the artefacts and promote reflections while physically holding the artefact in hand. Therefore, the visitor would use gestures that they would perform when manipulating a real artefact. This main concept relates to using gestures for manipulation (Pavlovic, et al., 1997) to facilitate interaction with historical artefacts. This main concept is aligned to three key aspects: *Feedback*, *Communication*, *Rewarded Experience*. Prior works on gestures research suggest that gestures can give richer interaction modality (Matthews, 2006), transform an artefact identity (Fishkin, 2004), as well as animate an object and give it a new life as stated by Vaucelle and Ishii (2008):

> "Those movements carve out a context, giving a thing a certain life. This anthropomorphism or the "identity reinvention" of the controller through manipulation presents itself as a gestural interaction".

Feedback

Feedback is one of the design principles in interaction design, therefore, it constitutes a key indicator of a good user experience. Feedback is achieved by confirming that the user actions are successfully received by the application (Wensveen et al., 2004). The application interface incorporated interface design elements that communicated the results of the visitors' actions such as unlocking interpretation about the historical artefacts using three AR interaction techniques (*Move, Rotate, Flip*). Additionally, the visitors stated that the gestures enabled learning, and brought the artefacts come to life.

– "It made the artefacts come to life" (V27) –

– "A good way to learn interactively" (V19) –

Additionally, the coupling of gestures with tangibles re-enforces learning about the historical artefacts, as research suggests, physical engagement creates involvement and activeness in learning that passive listening or watching does not (Price and Rogers (2004).

Communication

Gesture Interactions are also considered to facilitate communication, which is identified in the literature to improve thinking and the learning process (Hoven & Mazalek, 2011). The interaction techniques as output modalities in AR, enabled sharing of interpretive content such as text and audio to relay information about the historical artefacts, enabling the visitors to contemplate their knowledge about the historical artefacts and hence, aid their learning. The visitors commented:

– "Informative, and more engaging than object in museum display and labels" (V65) –

– "Thought provoking and educational" (V69) –

Additionally, in collaborative settings, Stanton et al. (2001) suggest that gestures can also be performative, especially when combined with tangibles, as their influence stretches beyond the digital space to include the physical space, which allows the visitor to communicate their state or experience to other visitors (Stanton et al., 2001, as cited in Hoven and Mazalek, 2011).

Rewarded Experience

Gesture interactions can enhance the visitor's knowledge about the historical artefacts prompting a rewarded experience. While the prototype advocates intuitive tangible AR interfaces to manipulate historical artefacts, the interaction techniques (*Move, Rotate, Flip)* as output modalities in AR still possessed inherently ambiguous design qualities (Gaver et al., 2003), which aid to promote an inquisitive attitude and drive engagement with new experiences, and subsequently, lead to learning (Dalsgaard, 2008). Initially, the visitors were left to explore on their own, offering them the freedom to unpack the interaction techniques and their output modalities in AR *(Zoom, Select, Switch)*, this process promotes a prolonged engagement with the historical artefacts which in turn deepens the experience and aid learning. As one visitor described it:

– "A new way to learn" (V19) –

Prior research also suggests that systems that may be difficult to learn, but are rewarding to use, particularly for their potential to build physical skills through practiced use (Matthews, 2006).

The third core theme Engagement refers to the tangible AR prototype promoting a sense of engagement by allowing the visitors to hold and manipulate virtual 3D models of historical artefacts. The visitors described their experience to be entertaining.

– "*clever, insightful, and engaging*" (V34) –

– "*this is fun"* (V37*), "Cool"* (V52),

As suggested by Falk and Dierking (2000), entertaining exhibits are considered to be engaging. The visitors also expressed that the tangible AR prototype made the historical artefacts accessible, enabling them to move, rotate, and closely inspect their fine details as if they were handling the original artefacts, prompting a real lifelike experience.

– “*engaging activity and very interesting*
to be able to hold and investigate them” (V36) –

– “you can see all the cracks and feel you're actually
holding, you can look at all bits of it”” (V*37*) –

Additionally, mapping of the virtual 3D models to the generic proxies to explore the historical artefacts and the AR interaction techniques to access interpretation using the physical object as an interface deepened the visitors’ connection with the historical artefacts and offered a seamless experience. Engagement as a core theme comprises the main concept of Mapping.

Mapping

The main concept of Mapping relates to aligning the physical objects to their virtual counterparts by integrating the 3D models in the virtual environment to merge with the generic proxies in the real-world environment. furthermore, a match between the physical objects in hand and the 3D models in the virtual environment can enhance the visitor perception of the virtual representations of historical artefacts (see section 5.1.4) and improve the sense of engagement with the virtual representations of historical artefacts. It is worth noting, that a slight degree of mismatch can occur between the generic proxies and the virtual representations of historical artefacts due to camera tracking of AR markers, however, the visitors haven’t reported any inconveniences due to that issue. This main concept is aligned to two key aspects: *Making Connection, Accessibility*.

Making Connection

The visitors stated that they felt more connected with the historical artefacts using the physical objects, as they were able to hold the artefacts in their hands and take their time to inspect the cracks and pattern details and have a full appreciation of the artefacts. For instance, one visitor stated that seeing the same 3D models of the historical artefacts inside a holographic display didn’t yield any interest to them, as they weren’t able to touch or get closer to explore the artefacts.

– "Engaging activity. "Very interesting to be able to "hold" and investigate them in a way you wouldn't normally" (V36) –

– "Brings Archaeology to life" (V40) –

ARcheoBox ability to enhance the visitors' connection with the virtual representations of historical artefacts is expressed through several visitors commenting that their experience with historical artefacts felt realistic. Technically, this entailed the integration of 3D models into the virtual environment and aligning them with the generic proxies.

Accessibility

The ability to access and touch historical artefacts remains one of the challenging matters for museum visitors. The visitors were able to access otherwise inaccessible historical artefacts through the use of generic physical proxies. The visitors were handling the generic proxies and turning them around as if they were handling the real objects. Additionally, placing the AR markers around the cylinder-shaped proxies improved camera tracking of the AR markers and display of the virtual 3D model, and also helped orient the visitors' hands as if they were handling a real artefact. The 3D model scans of the historical artefacts were produced using high-quality photogrammetry techniques, which enhanced their realism as well, where visitors stated:

– "Interesting, quite cool to see it in real life and how it looked like" (V5) –

– "Fun, interesting, you can see all the cracks and feel you're actually holding, you can look at all bits of it" (V37) –

– "I can see it from all angles" (V53) –

The fourth core theme Usability refers to the user interface design. The augmented reality application should possess a responsive interface, with clear and visible instructions. For instance, optimising AR markers features, and graphical patterns enhances camera detection, which allows faster loading of the virtual 3D models, and hence yields a responsive application. Another important criterion is to have a standard and consistent navigation across the application. For instance, visitors interacted with the AR application using three AR interaction techniques with consistent functions whether using Explore mode or Interpret mode. I also intended to avoid any additional interaction modalities such as pressing buttons using the touch screen, which enabled the visitors to focus on the object in hand. Usability as a core theme comprises the main concept of System Design.

System Design

The main concept of System Design relates to adhering to interaction design principles and following usability guidelines to ensure a good user experience for the augmented reality application. This main concept is aligned to three key aspects: *Visibility*, *Efficiency*, *Consistency*.

Visibility

This key aspect corresponds to introducing visual elements and audio to the application interface design which can inform the visitor about the interface status after each interaction. For instance, the application interface featured corresponding audio tracks and coloured frames on the screen every time the visitors flip the cylinder-shaped generic proxies to switch between two modes in the application. In this case, the visitor can easily recognise which of the user interface mode (Explore mode / Interpret mode) is presented to them.

– "Technically brilliant, cleverly done." (V20) –

Efficiency

This key aspect corresponds to designing a user interface with efficient navigation and quick loading of the application that allows the visitor to complete tasks as easily as possible. For instance, optimising the Vuforia AR markers with high contrast and sharp features can maximise the efficiency of detecting the AR markers which enable the augmented reality application to instantly display the virtual 3D models as soon as the AR markers are detected by the camera resulting in a very responsive application.

Consistency

This key aspect corresponds to designing a consistent user interface. Consistency entails an application user interface that behaves following the same set of functions to achieve similar tasks across different interactions. The interaction techniques (*Move, Rotate, Flip*) as output modalities in AR (*Zoom, Select, Switch*) have similar tasks in both modes (Explore mode and Interpret mode) in the AR application. The functions of the interaction techniques behave similarly whether the visitors want to explore the artefacts, interact with interpretation, or switch back and forth between to modes. This key aspect corresponds to designing a consistent user interface.

Discussion

The analysis of data collected from this study led to a series of observations and reflections. The analysis also enabled the final evaluation to refine the conceptual framework through the practical implementation of ARcheoBox and its impact on the visitor interaction experience which served as a real-world case study. The study findings have also demonstrated that tangible interfaces (generic proxies) coupled with interaction techniques as output modalities in AR using gesture interactions have supported interactivity, engagement, and facilitated learning around historical artefacts, as well as offered museum visitors an intuitive experience that wouldn't be possible using a touchscreen or by looking through traditional museum glass display.

With regards to Tangible Interfaces, the physical objects triggered positive reactions. Through the use of simple primitive objects as interfaces, the prototype afforded a *walk-up-and-use* approach, while still possessing ambiguous qualities that triggered the visitors' curiosity to step in, pick one of the cylinder-shaped generic proxies and manipulate them from different angles conveying a sense of control over the artefacts. This would suggest that designers can consider physical objects as tangible interfaces to leverage human motor skills for interaction with historical artefacts and help remove physical barriers in museums.

With regards to Gesture Interactions, the visitors' responses revealed that the prototype elicited learning by being able to interact with interpretation using the physical objects, for instance bringing the generic proxies closer to listen to audio narration. This main concept was identified from early discussions with heritage experts on how holding physical objects while hearing the interpretation can enhance the visitors' understanding of historical artefacts. This would suggest that designers of tangible AR interfaces for historical artefacts can apply gesture interactions as interaction techniques to promote an active thinking process around historical artefacts. Additionally, prior works suggest that tangible systems with less constraining interaction styles (i.e., such as having the user hands stuck on the keyboard or touch screen) are more likely to foster thinking and communication, while consistently assigning physical movement to interface functions can also support kinesthetic learning (Klemmer et al., 2006).

The visitors stated that they were able to feel connected and have access to otherwise inaccessible artefacts by manipulating the generic proxies to examine cracks, patterns, and view artefacts details from all angles. The key aspects associated with the main concept of Mapping also demonstrated that incorporating high-quality scans of the 3D model in the virtual environment improved the perception of historical artefacts and therefore prompts a realistic experience. Designers can expand the possibilities of Mapping for physical objects and their virtual representations by altering the artefacts conditions, for instance, artefacts can be represented as old and found in the ground, perceived as new shiny objects, or while they are in use. This suggests that designers can consider Mapping to convey the artefacts intangible values, for instance, their material composition or their utility.

In many instances, the key aspects emerged through collaboration with stakeholders, whether during co-design interviews, prototype testing, or informal discussions involving cultural heritage professionals, archaeologists, engagement officers, digital media officers, and end-users. To this extent, the framework put forward a set of design characteristics to implement during the design process and would also be beneficial when working with smaller museums with less resources and experienced teams.

The conceptual framework draws upon relevant prior works in HCI to support the conceptualisation of key aspects to formalise the design process for developing and evaluating tangible AR interfaces to manipulate historical artefacts. Additionally, the in-situ study has demonstrated the possibilities of the framework beyond theoretical framing through a real-world case study and how it impacted the visitors' interaction experience when manipulating historical artefacts. The framework can serve as a guideline for museums including cultural heritage professionals, researchers, and designers, who aspire to build engaging tangible AR interfaces that utilise 3D models of artefacts with the aim to enhance the visitors' interaction experience, as well as facilitate learning about historical artefacts.

Finally, the framework significance is also in its benefits to provide a set of design characteristics pertinent to designing for new technologies such as Augmented Reality (AR), aiding individuals involved in the development of tangible AR interfaces to adhere to a more straightforward process, while maintaining an efficient timeline.

Limitations

The conceptual framework presents keys concepts pertaining to the use of tangible interfaces (generic proxies) to manipulate virtual 3D models of historical artefacts; therefore, it is important to note that the framework aims to help designers, researchers, and cultural heritage professionals in better understanding the design process by providing a set of design characteristics for developing and evaluating tangible AR interfaces to manipulate historical artefacts, and therefore to be taken as proposed guidelines rather than a prescribed formula, where there are possibilities to expand on the key aspects that impact the visitor interaction experience.

Summary

This chapter presented three studies that contribute majorly to this thesis, in terms of both practical (ARcheoBox) and theoretical outputs (conceptual framework) for developing and evaluating tangible AR interfaces to manipulate virtual representations of historical artefacts. The studies structure in terms of study design, ethics, risk assessment, data collection, and analysis, as well as findings, are presented in each section. The first study was a comparative user study that explored design opportunities for generic proxies as tangible interfaces to manipulate virtual representations of historical artefacts in AR. The findings resulted in identifying tangible interfaces that are suitable for interactions in AR to manipulate virtual representations of historical artefacts. The themes that emerged from the study (*Manipulation, Perception, Immersion*) align with the overall concepts of ARcheoBox. The second study is the prototype demo evaluation with 25 participants combining heritage experts and public users to evaluate ARcheoBox and AR application user interface design features.

Finally, the third study is an in-situ study that evaluated the visitors' overall experience with ARcheoBox and allowed for evaluating and refining the conceptual framework. The framework also presents a set of design characteristics that can be implemented during the design process to develop and evaluate tangible AR interfaces to manipulate virtual representations of historical artefacts.

6. REFLECTIONS (on the Research Process)

During my doctoral research, I built on my knowledge and interests to explore the role of digital technologies to foster novel interactions and interpretative approaches to engage with historical artefacts in museums. Firstly, I advanced my experience as a researcher by adopting research methodologies that would adhere to the diverse nature of this Ph.D. level research which is associated with working with advanced technologies. Secondly, I embraced the collaborative opportunities which were presented to me through working with cultural institutions and co-designing with heritage experts. This Ph.D. research journey afforded a great outlet for my creative mind to articulate the findings of research artefacts.

Furthermore, this research also has broadened my thinking as a design practitioner beyond technical capabilities to produce digital artefacts, and to learn how to interpret research discoveries throughout the design process. An additional outcome that unfolded through this practice-based research, is learning about the ability to generate commercial impact from academic outputs. Initially, this step was instigated by the research external partners who expressed an interest in purchasing a licence of ARcheoBox. This step enabled me to connect with numerous networks at the Northumbria University and learn about different industry prospects, and what commercialisation opportunities are available beyond the scope of this Ph.D. research. I believe, this could be a potential research direction that doctoral students can explore if they would like to consider commercial impact at a certain point in their research, since commercialisation is considered a leading example of generating academic impact because it represents an immediate and measurable market acceptance for outputs of academic research (Markman et al., 2008).

In terms of methodological approaches, this thesis incorporated Research through Design (RtD) (Zimmerman et al., 2007), and pragmatism (John Dewey, 1859-1952), as a design thinking tool (Dalsgaard, 2014), through which I used thinking through prototyping to manifest several prototypes through an iterative design process. For my Research through Design (RtD) approach, I adopted the double diamond model (Design Council UK, 2005) to categorise the different phases where my research unfolded into four phases: Capture, Interpret, Ideate, and Implement. Additionally, I hosted these four phases under three main components: Research, Collaborate and Build as an overarching umbrella for the research process. These components also helped me frame certain aspects of my research process and identify the challenges to inform the next step in the design process. Furthermore, I applied Thematic Analysis (Braun and Clarke, 2006) which constituted the main method to analyse data and synthesis the findings for the research user studies. Thematic Analysis also guided me as a researcher to move from the descriptive level of the data to a conceptual level to generate high-level concepts.

Additionally, I advanced my knowledge in developing and evaluating digital artefacts and collaborating with cultural institutions such as the Northumberland National Park and The Sill: National Landscape Discovery Centre. I also explored the role of heritage experts in the design and development process of ARcheoBox as co-creators and learned the value of fostering a participatory approach in my research which resulted in an artefact that could speak to a wider audience and create a richer experience based on the insights of the participants. I conducted seven user studies encompassing participants from different professional backgrounds, this successively offered a broader perspective on what design features the final prototype should embody. The recruitment of a number of participants across all the studies, enabled them to consistently reflect, and monitor their input throughout the prototype iterative process to validate design decisions and outcomes. In acknowledging this important contribution, I was able to continuously test and compare data, using the participants' feedback to serve as a vehicle for documenting the ongoing research process and eventually create richer data analysis over time by incorporating their feedback throughout the analysis process.

Moreover, I followed "Thinking through Prototyping" (Stappers, 2014, Ingold, 2013) approach to externalise my thoughts in a concretised way by conversing with materials, which allowed my ideas to have physical manifestation (see section 3.3). For instance, I could experiment with different AR markers and test the performance of the interaction techniques when linked to their intended outputs in AR. This approach showcased how prototyping can be used to visualise ideas tangibly, as well as empowering my role as a researcher, to support creative efforts toward viable design solutions. Additionally, "Thinking through Prototyping" facilitated my discussions with stakeholders to form an open conversation about the prototype development process, and to test multiple design concepts and prototypes as part of rigorous Research through Design (RtD) process.

I initially built upon my skills and strong attributes as a design practitioner as an interpretive medium to generate practical outputs. Meanwhile, gaining advanced research skills empowered my practice-led research and strengthened my findings to be communicated and shared with the larger research community. By conducting several user studies, I broadened my research scope, beyond exploring the potential of digital technologies to develop digital artefacts, which helped me execute design decisions based on a series of examinable research outcomes. For instance, I submitted my first full article based on the findings of a comparative study (see section 5.1) which I designed to explore design opportunities for generic proxies as tangible interfaces and how it provides an intuitive interaction method to manipulate virtual representations of historical artefacts in augmented reality.

The article reviews supported my ideas about testing different tangible interfaces for AR and led me to continue the development and testing of generic proxies as tangible AR interfaces to manipulate virtual representations of historical artefacts. I then started developing the user interface design features based on the previous study and I conducted a prototype demo study (see section 5.2), where I recruited a wider group of participants to evaluate the prototype. Furthermore, I have been involved with multiple research groups across the university which helped offer feedback and comments at different stages of my research through colleagues and more senior academics. I continuously tried to disseminate my research into publications which enabled me to have my user studies' findings peer-reviewed and assessed by experts in the field. This has significantly improved my academic writing, as well as re-evaluating how I present my studies analysis and data presentation, leading to process-focused research instead of solely focusing on the final outcome.

Upon reflecting on the whole research journey, I strongly believe that adopting diverse methodologies for design-led research in HCI, has enabled my research to be deepened with richer possibilities, where unpredictable outcomes at times were transformative and invited novel directions throughout the research. I considerably became the researcher that is equipped with a set of tools to tackle design challenges along the way and package them as opportunities to advance my research. For instance, I created a sketching sheet for AR to support participants in articulating ideas about heritage content and visualising interaction techniques for the AR environment. Creating a visual method to convey ideas about the prototype was important for non-designers to help them consider the link between heritage content and interaction techniques in AR.

7. CONCLUSION

This chapter considers the emergent research themes, findings and describes the research contributions, limitations, and aspirations for future work. This research journey has been defined by identifying a suitable digital technology application to manipulate virtual representations of historical artefacts in museums. I defined my research methodologies as follows; Research through Design (RtD) to inform an iterative design process, co-designing with heritage experts to ideate to cocreate design concepts, and user-centered design approach to evaluate the prototype.

In Chapter 1, I described the origin of the research, from which I embarked to address the challenges imposed by the restrictive nature of handling historical artefacts in museums and galleries. This was followed by contextualising my research in relation to The Sill: National Landscape Discovery Centre as a host cultural institution to exhibit my final prototype. I also introduced and defined the research objectives with motivated research areas related to tangible interfaces, augmented reality, and visitor engagement with virtual representations of historical artefacts. My research aimed to address a knowledge gap about how to employ tangible augmented reality to engage museum visitors with virtual representations of historical artefacts and also develop a framework to formalise the design process of tangible AR interfaces for manipulating virtual representations of historical artefacts. Hence, the following research questions were addressed:

1. R.Q.1: How can tangible augmented reality engage museum visitors with virtual representations of historical artefacts?
2. R.Q.2: How do we present tangible augmented reality to a casual user, without requiring any uncomfortable technology such as head-mounted displays?

3. R.Q.3: What is the visitor experience of this novel tangible AR prototype versus traditional displays such as touch screens and dioramas?

In answering these questions, three main contributions of this thesis were established:

Research Contribution 1: Created a tangible AR prototype for manipulating virtual representations of historical artefacts, co-designed with heritage experts, resulting in ARcheoBox (2021), a *walk-up-and-use* prototype exhibited at The Sill: National Landscape Discovery Centre. ARcheoBox enables the visitor to physically interact with historical artefacts promoting an intuitive and immersive visitor experience.

Research Contribution 2: Generic proxies as tangible interfaces for AR that can promote access to artefacts and advocate wider adoption of tangible AR for manipulating historical artefacts in museums and galleries. Generic proxies offer an affordable trade-off for bespoke 3D-printed replicas, through a readily available interface for interactions in augmented reality and allow access to otherwise inaccessible artefacts.

Research Contribution 3: A conceptual framework that is based on data collection and analysis of studies conducted throughout the research, and that was refined and evaluated through the analysis of the data collected from the in-situ study. The framework introduces main concepts and key aspects which formalise the design process of tangible AR interfaces for manipulating virtual representations of historical artefacts. Additionally, application of the framework could benefit researchers, designers, and cultural heritage professionals in understanding and guiding the design process to build more engaging tangible AR interfaces for historical artefacts.

In Chapter 2, I conducted an extensive contextual review to situate the research within the domain of Tangible User Interfaces, Augmented Reality, and Tangible Augmented Reality, and understand the formation of theoretical frameworks. The third part of the review highlighted some of the key projects in Emerging Technologies for Cultural Heritage –

focused mainly on tangible interactions, and augmented reality to provide a foundation for digital technologies applications in museums. I presented several projects that showcased how digital technologies and tangibles in particular can enhance visitor experience with heritage collections. I was able to highlight knowledge gap related the lack of generalisable tangible AR interfaces to manipulate virtual representations of historical artefacts and promote wider adoption by museums and galleries., as well as a framework that formalises the design process for tangible AR interfaces to manipulate virtual representations of historical artefacts. The review provided a solid background and informed my understanding of the premise of digital technologies to support human-computer interactions particularly in the domain of cultural heritage.

In Chapter 3, my research methodological approaches and methods that shaped this research were presented by combining Research through Design (RtD) (Zimmerman et al., 2007), pragmatism as a reflective lens (Daalsgard, 2014), and user-centered design approach. By adopting the double diamond model (Design Council, 2005), I was able to create three overarching research components: Research – Collaborate – Build to inform four phases: Capture – Interpret – Ideate – Implement (see section 3.2). This helped me to divide the research process while examining my practice by addressing each research phase, going from requirements gathering to capture the visitor reactions toward the use of digital technologies in a museum and testing a proof of concept with heritage experts, to interviewing and co-design with heritage experts, to developing the prototype to finally evaluation the prototype in situ with the visitors. The careful design of the various methodologies created very rich and explorative directions for my research afforded by approaching methodologies that are suited to address the research challenges.

In chapter 4, I set out the ARcheoBox development phase, including a proof-of-concept, AR ideation techniques, AR markers design, as well as co-designing with the heritage experts. This chapter responds to one of the research questions, on how to design a tangible augmented reality prototype that can be experienced by a causal user, without requiring any uncomfortable technology such as head-mounted displays. I present, the iterative design cycle

(Sanders and Stappers, 2014), and co-designing process, working alongside heritage experts from The Northumberland National Park and The Sill: National Landscape Discovery Centre across multiple user studies. I also discuss the insights gained from exploring early prototypes, conducting a pilot study for early concept validation, and how working with heritage experts has generated feedback that would be transferred into informed design decisions and a more refined and developed prototype.

In Chapter 5, I critically considered the three studies and discuss their study design, ethics ad risk assessment, data analysis, and findings. The studies respond to the following research question: What is the visitor experience of this novel tangible AR prototype versus traditional displays such as touch screens and dioramas? The studies also guided my research to generate the research practical output (ARcheoBox 2.0) and the theoretical contribution (conceptual framework). The first study explored design opportunities for generic proxies as tangible interfaces and how generic proxies can offer an intuitive interaction method to manipulate with virtual representations of historical artefacts in AR which informed the use of cylinder-shaped generic physical proxies as tangible interfaces. The second study evaluated the prototype demo and user interface design features. And in the third study, I conducted an in-situ evaluation of ARcheoBox at the Sill: National Landscape Discovery Centre. The final study contributed to the evaluation and refinement of a conceptual framework which aims to formalise the design process of Tangible AR interfaces for manipulating virtual representations of historical artefacts.

In the following section, I will address some of the research limitations and future work in the area of designing tangible AR interfaces to manipulate virtual representations of historical artefacts, in hope that it can inspire other HCI researchers in the field of interaction design, and digital cultural heritage to continue investigating and developing tools that can enhance the visitor experience with heritage collections in museums and galleries.

7.1 Limitations and Future Work

Tangible augmented reality research relies on utilising the user's ability to physically interact with 3D models in augmented reality. For the past two years, my research timeline was affected by unforeseen challenges as the world experienced an ongoing COVID-19 global pandemic. Face-to-face research was interrupted as we entered a lockdown. At this stage, I was still in the first year of my Ph.D., so I started to consider alternative routes to engage with stakeholders, that are safe but also effective for my research. At one point, I turned to a CHI forum on Facebook to seek advice from other researchers in the field of HCI and tangible interactions (Figure 68). There were very useful insights that arose from the CHI forum discussion. It was also important for me to connect with other researchers who were facing similar research challenges. While some researchers suggested simulating the affordances of tangible objects in VR, a solution that I considered to be outside the scope of my research, other researchers suggested shipping the tangible objects to participants or inviting them to the laboratory to conduct the experiments there following all COVID-19 safety measures. After several discussions with the Northumberland National Park. I decided to conduct a remote user study to explore design opportunities for generic proxies as tangible interfaces in augmented reality. More detail on the remote study design, ethics and risk assessment is available in sections 5.1.1 and 5.1.2.

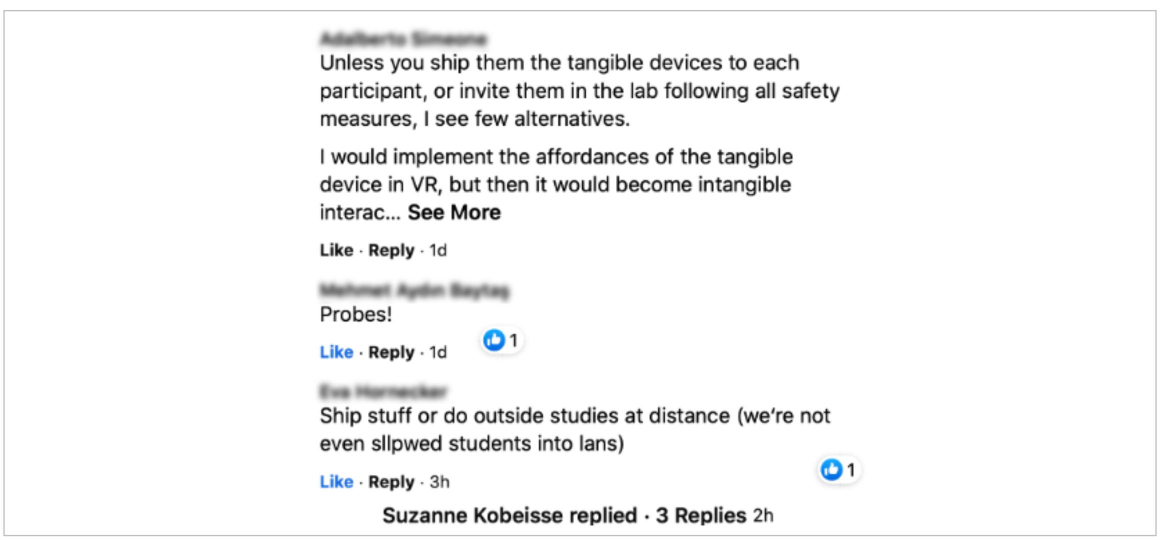

Figure 68: Discussion on remote user studies in Facebook CHI forum. (15 July, 2020).

The research limitations described in the above paragraph affected other aspects of my research, for instance, examining the overall visitor experience at the Sill, thus, I solely evaluated the visitor experience focusing on usability aspects during the visitor's interactions with ARcheoBox. The pandemic has placed limitations on accessing the visitor centre from the period of March 2020 to August 2020 and again from November 2020 to March 2021, while during lockdown easing periods, the visitor centre operated with very limited visitor capacity, which meant that visitors' observations would have yielded very little significance to the research. Additionally, in order to further support the generalisability of ARcheoBox and the accompanying conceptual framework for tangible AR interfaces to manipulate virtual representations of historical artefacts, I would like to incorporate different heritage collections with ARcheoBox and install at various museums and galleries.

Future Work

This research provides a basis for future work which will form part of the ongoing research on tangible AR interfaces to manipulate virtual representations of historical artefacts, including:

Beyond Cylinder-shaped Generic Proxies

This research has shown that cylinder-shaped generic proxies offer a more engaging visitor experience when interacting with virtual representations of historical artefacts over the more traditional approaches such as flat AR markers and touch screens. The research also suggests that generic proxies would offer a good trade-off as tangible AR interfaces and potentially advocate a more generalisable tangible AR interface for manipulating virtual representations of historical artefacts. Future work will examine techniques on how to improve the correspondence between a generic physical object and an AR object. By investigating the mismatch tolerance between the generic physical object and virtual object and how "far" the physical object can deviate from the digital object before it starts feeling unrealistic. This future direction would support further studies on interaction with a wider selection of virtual 3D models in augmented reality.

Developing Additional AR Interaction Techniques

The AR interaction techniques facilitated by gesture interactions required a short period of time before the visitor got familiar with their AR outputs supported in the augmented reality application. From one side, the cylinder-shaped generic proxies shared a familiar resemblance with the virtual 3D models and offered mutual affordances. On the other side, this means that adding AR outputs not normally associated with the cylinder-shaped generic proxies requires further design consideration. Furthermore, future research will examine additional AR interaction techniques using the generic proxies' additional degrees of freedom to explore how additional AR interaction techniques can support different AR outputs. For instance, I am keen to examine how the relative position in the box can be translated to additional information, such as proximity between two generic proxies or moving the generic proxies on a different axis could trigger other contextual information and elicit a further form of interpretation. Another AR interaction techniques property that can be investigated is 'time', for instance holding the generic proxies holding for a certain time frame can be mapped to different AR output modalities.

Longitudinal In-Situ Study

ARcheoBox was evaluated over the period of two weeks at The Sill: National Landscape Discovery Centre in Hexham, UK. The in-situ study was conducted during the COVID-19 pandemic which meant that the visitors' numbers are lower than pre-pandemic. Therefore, a longer in-situ study supported by no COVID restrictive measures would yield a larger number of visitors' enabling ARcheoBox to be experienced by thousands of visitors and generating greater data on the use of tangible AR for manipulating virtual representations of historical artefacts.

A Longitudinal study would also strengthen the possibilities to promote the generalisability of the generic proxies as an interface to manipulate virtual representations of historical artefacts. To continue the legacy of this research, The Northumberland National Park requested to acquire a license of ARcheoBox to continue exhibiting ARcheoBox at The Sill and other National Park venues allowing to plan further research studies on a more permanent basis. This expressed interest is a testimony of the validity of ARcheoBox as a tangible augmented reality prototype to engage The Sill visitors with historical artefacts. Also, this enables me to keep building into ARcheoBox augmented reality application library of virtual 3D models of historical artefacts from future finds at the National Park, or even incorporate other types of artefacts as suggested by studies participants.

7.2 Closing Statement

During my doctoral studies, I set out to rethink access to museums' historical collections using novel applications in digital technologies that would offer an intuitive visitor experience. My fascination with heritage collections and how they are kept behind glass cases, while creating a barrier to uncover the past, propelled me to investigate digital applications in order to give visitor to access to inaccessible artefacts. Using tangible interfaces and augmented reality afforded me to 'bring to life' a collection of Bronze Age artefacts from the Northumberland National Park. This enabled the visitor closer tactile encounters with objects, telling the stories of the people who inhabited this part of the landscape in the North East of the UK. To foster a deeper connection and develop a better understanding of the Bronze Age artefacts that wouldn't have been possible through traditional museum displays, I designed and developed a walk-up-and-use tangible augmented reality prototype in collaboration with heritage experts to engage visitors in museums with virtual representations of historical artefacts. Additionally, I developed a conceptual framework to formalise the design process for developing tangible AR interfaces to manipulate virtual representations of historical artefacts.

Furthermore, the scope of this thesis addressed the domain of cultural heritage and historical collections, however, ARcheoBox premise is not limited to just handling historical artefacts, and application opportunities can stretch to other domains that involve tactile feedback, such as prototyping, architectural models, medical fields, wildlife, etc. Moreover, there are prospects of ARcheoBox can extend to include public outreach and education, in particular for school groups or archival collections, enabling researchers and archaeology enthusiasts alike access to inaccessible collections. In future iterations, the virtual 3D model could be replaced with any 3D model, offering greater flexibility to interact with a larger collection of virtual objects. Consequently, the conceptual framework can be put to use in new contexts and therefore leads to the development of further concepts and key aspects. In that regard, I also believe it is worth examining how the conceptual framework can be utilised to develop tangible AR interfaces that explore domains which require some form of tangibility.

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APPENDICES

The appendices include a list of my Ph.D. publications which constitutes one of the research outputs of this research which was shared with the academic community through conferences presentations. Additionally, the practical outcome of this research was also exhibited at The Sill: National Landscape Discovery Centre. I also included in this section, the list of professional development programme I took part in as part of my research development training, which in no doubt have helped prepare me and shape my thinking as a researcher. Lastly, Appendix 2 includes a survey questionnaire with Th Sill visitor.

Appendix 1: PhD Publications, Presentations, and Training List

PhD Publications

Kobeisse, S., & Holmquist, L.E. (2022). "I Can Feel It in My Hand": Exploring Design Opportunities for Tangible Interfaces to Manipulate Artefacts in AR. *In Proceedings of the MUM'22: Twenty-first International Conference on Mobile and Ubiquitous Multimedia,* 28-36. https://doi.org/10.1145/3568444.3568446

Kobeisse, S. (2021). Touching the Past: Developing and Evaluating A Heritage kit for Visualizing and Analyzing Historical Artefacts Using Tangible Augmented Reality (Graduate Student Consortium). *In Proceedings of the TEI'21: Fifteenth International Conference on Tangible, Embedded, and Embodied Interaction,* 1-3. https://doi.org/10.1145/3430524.3443691

Kobeisse, S., & Holmquist, L.E. (2020). ARcheoBox: Engaging with Historical Artefacts Through Augmented Reality and Tangible Interactions. *UIST '20 Adjunct: Adjunct Publication of the 33rd Annual ACM Symposium on User Interface Software and Technology*, 22-24. https://doi.org/10.1145/3379350.3416173

Exhibitions:

The Sill: National Landscape Discovery Centre. (2021) ***ARcheoBox***. [Exhibition], 09-22nd August 2021, Hexham, UK. https://www.northumberlandnationalpark.org.uk/archeobox-enables-users-to-step-back-in-time/

Conferences & Seminars Presentations

Paper Presentation at The ACM International Conference on Mobile and Ubiquitous Multimedia (MUM'22)
Lisbon, Portugal
November 27-30, 2022
https://www.mum-conf.org/2022/

Graduate Student Consortium Presentation at The ACM International Conference on Tangible, Embedded and Embodied Interaction (TEI'21)
Virtual Event, Salzburg, Austria
February 14-19, 2021
https://tei.acm.org/2021/

Poster Presentation at The ACM Symposium on User Interface Software and Technology (UIST'20)
Virtual Event, MN, USA
October 20-23, 2020
https://uist.acm.org/uist2020/

Guest Speaker at Creative & Cultural Industries Management Program. VA7011 Cultural Heritage & Museums module. Northumbria University. April 22nd, 2021

Professional Development and Research Training

Ethical Training Course; Northumbria University Professional Development and Research Training; October 8, 2019.

Preparing for your Literature Review; Northumbria University Library's Researcher Development Programme; October 28, 2019.

Applying Critical Thinking; Northumbria University Library's Researcher Development Programme; November 11, 2019.

Introduction to Research Data Management; Northumbria University; Library's Researcher Development Programme; November 18, 2019.

Dissertation Planning and Research; Northumbria University Library's Researcher Development Programme; November 20, 2019.

Project Approval: Getting Started; Northumbria University; Professional Development and Research Training; December 18, 2019.

Early Intervention: Career Planning for Postgraduate Researchers; Northumbria University Professional Development and Research Training; April 3, 2020.

Writing with Confidence; Northumbria University; Professional Development and Research Training; April 14, 2020.

Research Philosophies and Paradigms; Northumbria University Professional Development and Research Training; May 13, 2020.

Annual Progression - Preparing for Year 1 Submission; Northumbria University Professional Development and Research Training; May 21, 2020.

How to be an Effective Researcher; Northumbria University Professional Development and Research Training; June 10, 2020.

Careers in Academia; Northumbria University Professional Development and Research Training; June 11, 2020.

Action for Impact Training; Northern Accelerator; July 7 - July 28, 2020.

Teach the Nation to Code - coding workshop; QA.com; October 17, 2020.

An Introduction to Academic Publishing; Northumbria University Professional Development and Research Training; October 19, 2020.

Networking and Making the Most out of Conferences; Northumbria University Professional Development and Research Training; October 20, 2020.

The International Symposium on Mixed and Augmented Reality (ISMAR2020);

Virtual Event; Recife/Porto De Galinhas, Brazil; November 9-13, 2020.

How to Write a Great Research Paper, and Get it Accepted by a Scholarly Journal; Elsevier Researcher Academy; November 17, 2020.

The Significance of 3D-Reproductions for Museums Workshop; TUDelft; November 24, 2020.

Annual Progression: Preparing for the Panel; Northumbria University Professional Development and Research Training; November 25, 2020.

UK Higher Education; Northumbria University Professional Development and Research Training; December 1, 2020.

CV Builder; Northumbria-Sunderland Centre for Doctoral Training; February 24, 2021.

Participatory Action Research course; NINE DTP Doctoral Training Partnership – Durham University, June 7-9, 2021.

Inclusive Academic Futures Project; Northumbria University, June 15 – July 31, 2021.

Postgraduate Researcher Introduction to Teaching; Northumbria University Professional Development and Research Training; June 28 - July 1, 2021.

Writing Up and Submitting; Northumbria University Professional Development and Research Training; October 1, 2021.

Preparing for the Viva: The end is in sight; Northumbria University Professional Development and Research Training; October 26, 2021.

AI & Cultural Heritage; Institute of Advanced Studies; Loughborough University;

Virtual Workshop; March 28, 2022.

Appendix 2: Surveys and Questionnaires

The Sill: National Landscape Discovery Centre
Visitor Experience Questionnaire

This questionnaire is part of a research project at Northumbria University in regards to enhancing visitor experience at the Sill: National Landscape Discovery Centre.
The data collected will not be shared with any organizations outside Northumbria University and Northumberland National Park.
All data is anonymous and will not trace back to you as an individual.

SECTION A: VISITOR PROFILE

1. **What made you visit the Sill? (Please tick all options that apply)**

- ☐ Permanent exhibition
- ☐ Temporary exhibition
- ☐ Program or event
- ☐ Other ___________

2. **How many times have you visited the Sill in the last 12 months?**

- ☐ Once
- ☐ 2-3 times
- ☐ 4-5 times
- ☐ 6+ times

3. **Who did you visit the Sill with?**

- ☐ Alone
- ☐ Friends
- ☐ Family
- ☐ School group
- ☐ Other ____________

4. **How often do you visit cultural centres and galleries?**

- ☐ Once a year
- ☐ 2 - 3 times per year
- ☐ 4 - 5 times per year
- ☐ 6+ times per year

SECTION B: VISITOR EXPERIENCE

5. Please select the areas of the Sill that you have visited today (Please tick all options that apply)

- ☐ Permanent exhibition
- ☐ Temporary exhibition
- ☐ The Green Roof
- ☐ Once Brewed Cafe
- ☐ Other ___________

6. The Sill is a place to:

- ☐ Have fun
- ☐ Learn something new
- ☐ Feel inspired
- ☐ Have new experiences
- ☐ Bring friends and family for activities

7. Have you used any of the interactive exhibits today, e.g.: sandbox, touch screens, or other interactive systems?

- ☐ Yes

If 'Yes', please specify which ones were your favourite

____

- ☐ No

8. How do you describe your attitude towards technology use at the Sill?

- ☐ Poor
- ☐ Fair
- ☐ Good
- ☐ Very good
- ☐ Excellent

9. How strongly do you agree with the following statement: The Sill should provide experiences that allow visitors to interact with artefacts in a different way, i.e.: using state of the art technologies

- ☐ Strongly disagree
- ☐ Disagree
- ☐ Neither disagree nor agree
- ☐ Agree
- ☐ Strongly Agree

10. Based on your experience here at the Sill today, which statement best describes your

plans?

- ☐ Very likely to visit again within the next 6 months
- ☐ Somewhat likely to visit again within the next 6 months
- ☐ Somewhat unlikely to visit again within the next 6 months
- ☐ Not likely at all to visit again within the next 6 months
- ☐ Other ___________

11. Would you recommend the Sill to others?

- ☐ Yes
- ☐ No

If 'Yes', who do you think would enjoy a visit?

____

If 'No', is there any specific reason?

____

SECTION C: DEMOGRAPHICS

12. Indicate your age bracket

- ☐ Under 15
- ☐ 16 - 19
- ☐ 20 - 24
- ☐ 25 - 34
- ☐ 35 - 44
- ☐ 45 - 54
- ☐ 55 - 64
- ☐ 65 and over

13. Indicate your gender

- ☐ Female
- ☐ Male
- ☐ Other ___________

14. What is the highest level of education you have completed?

- ☐ Secondary School
- ☐ Intermediate education (e.g., College)
- ☐ Higher education (e.g., university)
- ☐ Other please state: ___________

15. What is your current occupation?

CLOSING QUESTION

I am embarking on PhD research to help improve the visitor's experience at the Sill. Would you be willing to take part in future research studies that would help improve visitor's experience at the Sill? Your feedback would be really appreciated.

- ☐ Yes
- ☐ No

Name________________________ Phone Number_________________

Email_________________________

THANK YOU FOR TAKING THE TIME TO FILL THIS QUESTIONNAIRE

Visitors Paper Questionnaire Responses

ARcheoBox: ***Hands on the Past***

Participant Identification Number: P3

1. Gender

☑ Female

☐ Male

1. Age: 36

2. What is the highest level of education you have completed?

☐ Secondary school ☐ Intermediate education (e.g., College)

☑ Higher education (e.g., University)

Other please state: MA

4. What is your current occupation?

TEACHER

5. Have you ever used augmented reality (e.g., Snapchat; *Pokémon Go; IKEA catalogue)* applications before? If yes, what kind of augmented reality applications have you used?

☑ Yes

☐ No

If 'Yes', please specify

INTERIOR DESIGN WEBSITE.

1) How would you describe your overall experience with ARcheoBox?

FANTASTIC IDEA, THOUGH A LITTLE CHALLENGING TO ACCESS ALL ITS INFO WITHOUT HELP.

CAN THE "QR CODE" EXTEND ALL ROUND THE CYLINDER SO YOU DON'T LOSE THE IMAGE?

2) Did you learn anything interesting about the Bronze Age artefacts and the landscape?

YES. AND LOVED THE VISUALS.

3) Would you like to see other historical artefacts interpreted using ARcheoBox?

☑ Yes

☐ No

Other, please state:

THANK YOU!

Suzanne Kobeisse, PhD Researcher

ARcheoBox: ***Hands on the Past***

Participant Identification Number: P31

1. Gender

☑ Female

☐ Male

1. Age: 43

2. What is the highest level of education you have completed?

☐ Secondary school ☐ Intermediate education (e.g., College)

☑ Higher education (e.g., University)

Other please state: ________

4. What is your current occupation?

VOLUNTEER COORDINATOR

5. Have you ever used augmented reality (e.g., Snapchat; *Pokémon Go; IKEA catalogue)* applications before? If yes, what kind of augmented reality applications have you used?

☐ Yes

☑ No

If 'Yes', please specify

____

1) How would you describe your overall experience with ARcheoBox?

GREAT EXPERIENCE & A DIFFERENT WAY TO LEARN.

____

2) Did you learn anything interesting about the Bronze Age artefacts and the landscape?

CLOSE UP VIEWS OF ARTEFACTS WERE FASCINATING.

____

3) Would you like to see other historical artefacts interpreted using ARcheoBox?

☑ Yes

☐ No

Other, please state: ________________________________

THANK YOU!
Suzanne Kobeisse, PhD Researcher

ARcheoBox: ***Hands on the Past***

Participant Identification Number: P40

1. Gender

☐ Female

☑ Male

1. Age: 57

2. What is the highest level of education you have completed?

☐ Secondary school ☐ Intermediate education (e.g., College)

☑ Higher education (e.g., University)

Other please state: __________

4. What is your current occupation?

OPERATIONS DIRECTOR

5. Have you ever used augmented reality (e.g., Snapchat; *Pokémon Go; IKEA catalogue)* applications before? If yes, what kind of augmented reality applications have you used?

☑ Yes

☐ No

If 'Yes', please specify

3D FLY THROUGH OF INFRASTRUCTURE PROJECTS - ROADS & BRIDGES

1) How would you describe your overall experience with ARcheoBox?

excellent experience. Brings the archeology to life

2) Did you learn anything interesting about the Bronze Age artefacts and the landscape?

How fragile they are & some could not stand by themselves

3) Would you like to see other historical artefacts interpreted using ARcheoBox?

☑ Yes

☐ No

Other, please state: My experience of recent archeology work, would provide a great living experience of current finds. Would have been great on a recent project I worked on where an archeological dig recovered artifacts. They could have been easily displayed in the local museum.
Excellent !!!

THANK YOU!

Suzanne Kobeisse, PhD Researcher

ARcheoBox: ***Hands on the Past***

Participant Identification Number: G2

1. Gender

☑ Female

☐ Male

1. Age: 20

2. What is the highest level of education you have completed?

☐ Secondary school ☐ Intermediate education (e.g., College)

☑ Higher education (e.g., University)

Other please state: ___________

4. What is your current occupation?

Work in a pharmacy

5. Have you ever used augmented reality (e.g., Snapchat; *Pokémon Go; IKEA catalogue)* applications before? If yes, what kind of augmented reality applications have you used?

☐ Yes

☑ No

If 'Yes', please specify

____

1) How would you describe your overall experience with ARcheoBox?

Very interesting concept, never seen anything like it before. It is engaging and allows you to feel in touch with history + modern technology. When in a museum, it would make you feel like you can take in all artefacts and feel like you're holding them

2) Did you learn anything interesting about the Bronze Age artefacts and the landscape?

The detail of the artefacts on the application

____

3) Would you like to see other historical artefacts interpreted using ARcheoBox?

☑ Yes

☐ No

Other, please state: Flint & maybe bones of animals (dinosaur)?

THANK YOU!
Suzanne Kobeisse, PhD Researcher

ARcheoBox: *Hands on the Past*

Participant Identification Number: 66

1. Gender

☑ Female

☐ Male

1. Age: 53

2. What is the highest level of education you have completed?

☐ Secondary school ☐ Intermediate education (e.g., College)

☑ Higher education (e.g., University)

Other please state: ___________

4. What is your current occupation?

ARCHITECT

5. Have you ever used augmented reality (e.g., Snapchat; *Pokémon Go; IKEA catalogue)* applications before? If yes, what kind of augmented reality applications have you used?

☑ Yes

☐ No

If 'Yes', please specify

IKEA -

1) How would you describe your overall experience with ARcheoBox?

unbelievable - it was a totally mind-blowing experience and has a huge benefit to so many walks of life -

2) Did you learn anything interesting about the Bronze Age artefacts and the landscape?

Yes -

3) Would you like to see other historical artefacts interpreted using ARcheoBox?

☑ Yes

☐ No

Other, please state: But also think about how this technology could not only educate but really help social engagement -

THANK YOU!

Suzanne Kobeisse, PhD Researcher

Super! I like the physical sense of having an application -