A Hands-On, Mobile Approach to Collaborative Exploration and Discussion of Virtual Museum Artefacts

Steven Neale

BSc, MSc

Submitted in fulfilment of the requirements for the degree of

Doctor of Philosophy (Computing and Information Systems)

Submitted to the **School of Computing & Information Systems**

UNIVERSITY *of* TASMANIA

July 2014

Statements and Declarations

Declaration of Originality

This thesis contains no material which has been accepted for a degree or diploma by the University of Tasmania or any other institution, except by way of background information and duly acknowledged in the thesis, and to the best of my knowledge and belief no material previously published or written by another person except where due acknowledgement is made in the text of the thesis, nor does the thesis contain any material that infringes copyright.

Authority of Access

This thesis may be made available for loan, limited copying and communication in accordance with the Copyright Act 1968.

Statement of Ethical Conduct

The research associated with this thesis abides by the international and Australian codes on human and animal experimentation, the guidelines by the Australian Government's Office of the Gene Technology Regulator and the rulings of the Safety, Ethics and Institutional Biosafety Committees of the University of Tasmania.

Signed **Date**

01/08/2014

……………………………………………………………………………… ……………………………

Record of Publications

The following is a list of peer-reviewed publications directly relating to the work that this thesis describes, which were submitted, accepted and published during the course of the work undertaken:

- NEALE, S., CHINTHAMMIT, W., LUEG, C. & NIXON, P. (2014) Facilitating Learning Through Hands-On Engagement with Virtual Museum Artefacts. *Proceedings of the 28th International BCS Human-Computer Interaction Conference (BCS-HCI 2014)*, Southport, UK. September 9-12, 2014
- NEALE, S., CHINTHAMMIT, W., LUEG, C. & NIXON, P. (2013) RelicPad: A Hands-On, Mobile Approach to Collaborative Exploration of Virtual Museum Artifacts. *Proceedings of the 14th IFIP TC13 Conference on Human-Computer Interaction (INTERACT 2013)*. Cape Town, South Africa. September 2-6, 2013

Acknowledgements

Thanks must go to the following people who have been instrumental in ensuring that the past three and a half years actually resulted in a completed thesis:

- At home (UK) and abroad:
  - My immediate family (mum, dad and sister) for constant support.
  - The friends who are always there for me no matter what I do or how long I'm away – particularly Ross Barber, Abbigayle Morris and Simon Lazell.
- At the HIT Lab AU:
  - Soon-to-be-Drs. Mark Brown and Simon Stannus, my HIT Lab AU PhD colleagues, for sharing the adventure / madness.
  - Dr. Robert Rowe and James Riggall for friendship, support, curries, and far too many coffees.
  - Crystal Yoo and Callum Parker for bringing a dimension of excessive fun to the group, for introducing us to the Korean BBQ, and for keeping us grounded.
- At the University of Tasmania and Launceston School of Computing:
  - Julia Mollison for always having the answers and for guidance and advice in countless moments of doubt, stress and confusion.
  - Bruce Andrews, Dr. Matthew Springer, Dr. Dan Rolf, Dr. Mike Cameron-Jones, Prof. Tom Furness, Andrew Spilling, Tony Gray and Christian McGee, and Raelene Nicholas – you've all helped at some point and it all mattered.
  - Other friends and PhD'ers around the campus over the past few years, particularly Belen Yanotti, Catarina dos Santos, YuenYue Tham, Melissa Martin, Sunny and Yang, Yuanhang Liu and Amanda Lunt.
- At the Queen Victoria Museum & Art Gallery, Launceston, Tasmania:

  - Jon Addison and Andrew Johnson for their continual enthusiasm and support for the project, and for providing me with resources and space for my studies at the museum site.
- In Launceston, Tasmania:
  - My friends and team-mates from Northern Rangers Football Club, especially Carlos Castillo, Rich Barker, Mark White, Jimmy Ower, Ben Jones, Uriel Walters, Jon-Anthoney de Boer and all the rest of the guys who played League 1&2 with us over the last three years for plenty of good football and great times – 'Bendypalooza' will live long in the memory.
- In Konstanz, Germany:
  - Prof. Dr. Harald Reiterer and everyone in his HCI research group for allowing me to join them and making me feel welcome there.
  - Stephan Huber, Christoph Gebhardt and Johannes Zagermann in particular for introducing me to the 'bright lights' (and infamous fog) of Konstanz – the Oktoberfest and 'Griechischer Wein' are standout moments.
  - Johannes Dingler and all at the University of Konstanz's Welcome Center for making the most difficult processes incredibly easy.
  - Great friends and fellow PhD'ers in and around Konstanz, particularly Luisa Vega, Ioanna Salvarina, Iva Radisavljevic, Johnathan Oviedo and Maksim Kolikov.
- Finally, huge thanks must go to my PhD supervisors, Prof. Paddy Nixon, Prof. Christopher Lueg and Dr. Winyu Chinthammit, for all their guidance, support and encouragement over the past three and a half years. Thanks for having faith in me to get it done!

Contents

Chapter 1: Introduction

1.1 Research Context – Museums and Their Artefacts

1.1.1 Museums Collections and the 'Community' of Learners

For the visitors who frequent them, museums are a gateway and a window to culture, a place where "children and adults can leisurely browse" exhibitions and displays to discover endless aspects of history and science, and "seek and find meaning and connection" (Falk and Dierking, 2000). The public perception of museums has long been one of "tried-and-true sources of understandable information", and as places where "reliable, authentic, and comprehensible presentations of art, history, natural history, and science objects and ideas" can be digested (Falk and Dierking, 2000). The museum is a place where people can connect with the facts, ideas, cultures, and scientific theories that underpin human and natural history, as well as the modern world that history has shaped.

Besides simply being information sources, for many visitors museums are also associated with the storage and maintenance of physical records and objects. Museums are seen as places where "treasures, both physical and intellectual, are preserved and displayed" for public consumption (Falk and Dierking, 1992), and because of this the strength and importance of museums in society is not just down to the knowledge, but also the collections that they possess (Falk and Dierking, 2000).

The focus of museums has started to change as the information age continues to shape the way people communicate with each other, share information, and learn from and about the world in which they live. Museums have had, and continue to, evolve in order to support the changing characteristics and demands of their audience, an evolution which necessitates "a more sophisticated understanding of the complex relationships between culture, communication, learning and identity" (Hooper-Greenhill, 2007). In order for museums to remain relevant as educational sites, they have to understand the relationship between "the cultural perspectives that [they] produce and the self-identities of learners", and ensure that their message and interpretation speaks to and resonates with their audience (Hooper-Greenhill, 2007).

Building and maintaining this relationship with, and relevance to, an ever-evolving audience is about supporting "the participation of visitors in a wide range of learning communities" (Falk and Dierking, 2000). People often visit museums as part of social groups that are representative of "[their] own unique community of learners", and museum experiences must enable visitors to "pursue enquiries, [make] connections among various contexts, [share] interests with each other, and [learn] how to learn, assist and collaborate with others" in order to encourage groups of visitors to participate and explore museum activities together as part of a community of like-minded learners (Falk and Dierking, 2000).

1.1.2 The Evocative Power of Physical Museum Artefacts

As mentioned in the previous subsection, museum collections have an element of physicality, embodied by the artefacts they possess. Museum visitors expect to be able to "see and learn about" objects that are not part of their everyday lives, such as precious or unusual objects, objects of scientific or cultural importance, or objects that "inspire reverence" (Falk and Dierking, 1992). Physical artefacts, as representations of "both culture and nature", are a central focus in museums' efforts to encourage the active participation of learners "through interaction with [physical] objects" (Hein, 1998).

The importance placed on physical objects is highlighted by Pye (2007) using the examples of religious 'relics' (such as crosses or rosary beads), good luck charms, and "lockets containing a photograph (or lock of hair) of a loved [one]", all of which are physical objects endowed with a sense of power or importance that is transmitted through touch. Physical museum artefacts help to "document the rise of disciplines historically and represent global, natural, and cultural diversity", and when explored through touch can act as storytelling tools that hold secrets and reveal answers for the inquisitive learner (Chatterjee, 2010).

Much of the importance that artefacts are able to transmit is due to the ability of a real, physical thing to "[connect] people across time and culture that they have no tangible contact with otherwise", which gives learners handling, viewing or experiencing an object a "strong personal connection to the past and to the makers and users of the object" (Boyes and Cousens, 2012) (Mastoris, n.d.). This connection that artefacts facilitate between their users or creators and the museum visitors exploring them can evoke deep emotional responses and involvement (Chatterjee, 2007) (Boyes and Cousens, 2012), and it is important that museum professionals realise the power that this "almost magical" experience of touching or handling artefacts can produce (Pye, 2007).

This connection between handler and artefact is potentially an important learning tool in museums. Here, artefacts are "conveyors of knowledge and understanding that inspire discussion, group work and lateral thinking" (Boyes and Cousens, 2012) (Chatterjee, 2010) – exactly the kind of collaborative activities that museums are encouraging their visitors to involve themselves in as part of a group or community of learners. The 'conveying of knowledge' occurs when artefacts are used as "prompt[s]" to memories (whether that be of someone, something or somewhere) and as "a point of departure for learning and creativity" (Mastoris, n.d.). For example, handling "an unfamiliar object" encourages museum visitors to imagine "what it would be like to use it", which in turn "may prompt [a] deeper understanding" of what life, activities, or processes would have been like for the makers, users, or discoverers of the artefact (Trewinnard-Boyle and Tabassi, 2007).

1.2 Research Problem

1.2.1 Understanding Artefacts Through Handling

Existing research has suggested that 'object-based learning' plays an important role in active, experiential learning strategies (Chatterjee, 2010). Physical objects are 3D experiences, "more tactile than a picture or a recording" and often involving moving parts (Mastoris, n.d.), and being able to turn them over and look at them from all sides gives handlers and viewers an increased awareness of physical characteristics such as colour, weight, texture and scale (Boyes and Cousens, 2012).

Besides the experiential benefits of tactile exploration that help handlers to understand the physical properties of objects, museum artefacts in particular can also act as "a 'focal point' that can enhance and disseminate subject knowledge", revealing their history and cultural importance by inspiring the handler and inducing their practical and observational skills (Chatterjee, 2007) (Chatterjee, 2010). This 'conveying of knowledge' that artefacts facilitate, as described in the previous subsection, is especially prominent in collaborative scenarios, where the artefact acts as a focal point and a spatial reference for directing a discussion between a group of handlers as they collaboratively explore and make sense of both its physical properties and its historical and cultural significance.

1.2.2 Limits on Physical Access to Artefacts

However, despite museum collections being full of exciting and valuable artefacts, most of the artefacts in a particular collection will be "inaccessible to the normal visitor", with "relatively few" of the objects that make up a particular collection actually being on display at any given moment (Pye, 2007). In recent years, with the advent of advanced digital imaging techniques and web technologies, museums have begun displaying artefacts from their collections online, but despite being available to anybody with an internet connection, artefacts displayed using digital imagery tend to lack the participatory, tactile qualities of "flesh and blood" objects (Pye, 2007). There are also many scenarios in which, even when an artefact is *on* display, it is still inaccessible – an artefact might be positioned behind barriers, displayed in a glass case, or displayed in low light levels (Pye, 2007).

For collaborative discussions in particular, physical access to artefacts is also affected by location, with two or more potential collaborators often not being in the same location as the artefact, as each other, or both. This can be problematic in scenarios such as discussions of artefacts amongst online communities (digital museum visitors), between curators in different museums around the world, or during long distance lectures, presentations or discussions delivered online.

Staff from the Queen Victoria Museum & Art Gallery (QVMAG) in Launceston, Tasmania described to us an example scenario of museum curators considering the purchase of an artefact from another museum situated overseas. With time, money, and potentially the museum's reputation at stake, it is hugely advantageous for curators to be able to understand the physical properties of artefacts before committing to a decision, even if they are not able to handle them in person. Currently, this is difficult to facilitate using remote-collaborative methods such as video conferencing or the sharing of still digital images.

There is a huge benefit to be gained from manual interaction with museum artefacts. Being able to explore an artefact with the hands gives visitors an understanding of its physical properties and nuances, and allows it to become a focal point for making sense of its historical and cultural associations through active, experiential exploration, particularly as part of a collaborative discussion. But with access to museum artefacts often limited as a result of artefacts and those who wish to explore them being in different locations, this kind of exploration from all sides and angles is not always possible and the vital spatial referencing and physical understanding that handling artefacts provides is lost. This seems like something of a missed opportunity for participatory, collaborative museum learning activities.

1.3 Proposed Solution

1.3.1 A System Designed to Support (Remote) Collaborative Exploration

Providing experiences that support and encourage participatory activities for communities of museum learners is a key objective for museums, as described in *Subsection 1.1.1: Museum Collections and the 'Community' of Learners*, and the reason it should be so is exemplified by the way in which people visit museums. The Australian Museum has estimated that 45-55% of their visitors arrive in the form of family groups, 15% as pairs and partners, and another 15% as organised school or educational groups – that's up to 85% of the visitors to the museum arriving as part of a group, with as little as 15% visiting alone (Black, 2005).

As well as making practical sense to target groups of visitors in so much as that such a large majority of people visit museums together, engaging visitors as partners in collaborative activity also has learning benefits, with adults in particular having been observed to have their "need to know" satisfied by collaborative activities that "[appeal] to their self-concept as independent learners" (Knowles et al., 2005). Museum visitors not only feel that they are learning something independently, but also feel like they are contributing to the learning outcomes of others, which can be a very engaging sensation.

As well as servicing communities of learners, collaboration is also important in that many museum collections "may continue to be of 'deep significance' to the specific communities from which artefacts come" (Pye, 2007). Communities descended from the colonial or indigenous groups that artefacts come from "are increasingly eager to gain access to their ancestral objects", the handling of which provides them with "opportunities for reminiscence and sharing of information", "enables communities to study techniques and materials" and gives community members, young and old, the chance to "regain [and revisit] traditional craft skills and cultural practices" (Pye, 2007).

Unfortunately, as described in *Subsection 1.2.2: Limited Physical Access to Artefacts*, it is not always possible to handle artefacts, which may be behind glass display cases or not currently on display at all, and even when artefacts can be handled it needs to be done gently and sparingly, as contact with the hands can contribute to wear and damage (Pye, 2007). In terms of collaborative exploration, handling also requires that "the person touching be [not only] in the same location as the object", but also as the fellow handler with whom they are collaboratively exploring the object (Pye, 2007).

However, as also mentioned in *Subsection 1.2.2: Limits on Physical Access to Artefacts*, many museums now offer access to digital images of their collections online, making it "possible to view these collections at any time from the comfort of your own home" (Pye, 2007). Rendering museum artefacts digitally as 3D virtual representations potentially allows learners to interact with virtual versions of them, and (to a certain extent) to view and explore them from all sides, which we know from *Subsection 1.2.1: Understanding Artefacts Through Handling* to be of benefit and importance.

As well as using digital viewing techniques to open up artefacts and collections that would not normally be able to handled, the power of the internet as a means of connection and communication between people in different locations (often in real-time) also presents the opportunity for digital museum content to be viewed and explored collaboratively even when being in the same location is not possible, as in the example remote-collaboration scenario described in *Subsection 1.2.2: Limits on Physical Access to Artefacts*.

Thus, the basis of the proposed solution to the research problem is the design of an interactive system that allows museum visitors to collaboratively view and explore digital representations of museum artefacts, even when those visitors are in different (remote) locations.

1.3.2 A System Designed to Support Reality-Based Interaction Principles

As described in *Section 1.1: Research Context – Museums and their Artefacts* and *Section 1.2: Research Problem*, the importance of artefacts to understanding, learning and sense-making is often heavily associated with their physical properties and the ‘3D experience’ of being able to see and explore them from all sides, which is normally only possible through physical handling. Although (as described in the previous subsection) rendering 3D digital representations of museum artefacts would go some way towards facilitating the visual aspects of the experience, any proposed solution should still account for the missing physical qualities and associations of object handling in some way, and offer an alternative means of digitally facilitating the 3D aspects of the experience.

Simply talking about topics and artefacts “does not necessarily imply understanding”, and so the 3D experience is important for ensuring “the most powerful learning” and a “true understanding” of objects (Hooper-Greenhill, 2007). Digital systems are usually based on highly interactive visual stimuli that are often in 3D, but input devices are usually still based on the “point-and-click” principles of the ‘WIMP’ paradigm of 2D “graphical user interfaces based on windows, icons, menus, and a pointing device, typically a mouse” (van Dam, 1997). So, while the visual output of interactive digital systems is often 3D, their continued use of 2D input devices create a paradox between the techniques used to display a 3D digital representation of, for example, a museum artefact, and the techniques that would generally be used to manipulate it.

Unlike the 2D, “transient intermediary” style of a mouse (and keyboard), tangible manipulation is an input and interaction technique that involves using the hands to directly manipulate “material objects that represent the object of interest” (Hornecker and Buur, 2006). Jacob et al. (2008) describe tangible manipulation as one of a number of “new interaction styles” that “[build on] users’ pre-existing knowledge of the everyday, non-digital world to a much greater extend than before” and encompass “themes of reality” including “users’ understanding of naïve physics, their own bodies, the surrounding environment, and other people”. Tangible manipulation (along with other ‘new interaction styles’) therefore serves to bring interaction with computers closer to the experience of interacting with “the real, non-digital world” (Jacob et al., 2008).

Jacob et al. (2008) outline the key elements of what they term "reality-based interaction" in a four part framework that encompasses the following themes from the real world:

1. Naïve physics – the "common sense knowledge" that people have about the physical world,
2. Body awareness and skills – the awareness, control, and coordination people have of and over their own bodies,
3. Environment awareness and skills – the sense and skills people have for negotiating, manipulations and navigating their environment and their surroundings,
4. Social awareness and skills – the awareness that people have of other people within their environment and the skills the have for interacting with them.

Tangible manipulation, by making use of real-world principles, would therefore be a suitable technique for facilitating the 3D experience of interacting with virtual representations of museum artefacts in a digital context, particularly with it being a manual technique that uses the hands and therefore being a good representation of directly handling a real, physical object.

1.3.3 A System Designed to Facilitate Engagement in Learning Activities

The previous two subsections have proposed that an interactive digital system that allows for the (remote) collaborative exploration of a 3D, virtual representation of a museum artefact,using a manual, tangible interaction style would provide a solution to the research problem. Another important concern is ensuring that such a system is useful in a learning context, especially when considering the changing profiles of museum visitors and their expectations of being able to participate and to contribute as groups and communities, as described in *Subsection 1.1.1: Museum Collections and the 'Community' of Learners*. Modern museum audiences are "active, using their emotions and imagination to participate and engage with experiences" (Hooper-Greenhill, 2007), and being "increasingly experienced and educated", they are far less willing "to be passive recipients of wisdom from on high" but are increasingly keen to "participate, to question, [and] to take part as equals" (Black, 2005).

Museum visitors are no longer (and perhaps never were) looking to be 'taught', but are looking for something more experiential from museum artefacts and collections. At the same time, heritage itself has a role to play in "enhancing people's lives and supporting community regeneration", engaging and involving all potential audiences with sites, collections and heritage and "optimising the opportunities for visitors to achieve their full potential" (Black, 2005). This happens not when visitors are told what they should know, but when groups and communities of visitors "can experience and interpret in their own way", a process in which visitors' learning is facilitated by engaging them in activities that "[reflect] the differing needs of different audiences" (Black, 2005).

1.3.4 The Proposed Solution in Summary

To summarise, in the context of museum visitors being inclined to learn a) from the evocative power and inspirational properties of museum artefacts, and b) active participation and engagement as parts of groups and communities, a problem of access arises when:

a) The artefacts themselves cannot be handled, or:
b) When those who want to collaboratively explore and discuss them cannot be in the same location.

To address this problem, an interactive system for exploring and interacting with 3D, virtual representations of museum artefacts has been proposed, based on the following three key points:

1. Support for collaborative exploration of (virtual) artefacts, including in remote-collaborative scenarios,
2. Support for tangible, manual interaction with (virtual) artefacts,
3. Engaging users in a collaborative learning scenario, as opposed to setting out to specifically 'teach' them something.

In realizing these goals, displaying the (virtual) artefact in such a way that collaborators can view and explore it from all sides is vital. Given the capabilities of interactive computer graphics, rendering a 3D digital representation of the artefact that can be rotated and viewed from different angles is the starting point of the proposed system this thesis describes. Such representations are not unfamiliar in museums, where the suitability of visceral interaction "for creating enthusiasm and engagement with challenging topics" (Snibbe and Raffle, 2009) is often exploited. Collections and archives are constantly being updated for digital (and often 3D) display, and interactive projected exhibits featuring digital (again often 3D) imagery are also regularly displayed as parts of collections.

In order to replicate the 3D experience of handling museum artefacts to as great an extent as possible, the visceral, interactive display of (virtual) artefacts from all sides should be combined with a direct, tangible, manual interaction technique for controlling the manipulation of the visuals. Although their smaller form-factor can make them difficult to work with in some scenarios and for more complicated 3D or virtual reality applications (Hürst and Helder, 2011), mobile tablet devices (such as iPads) are ideal facilitators of the required interaction technique, largely based on two reasons:

1. Touchscreen – direct interaction achieved by touching the display means that the visual content responds immediately to the user's intentions. This is important because, in the real-world, objects respond immediately to a handler touching or moving it with their hands, and so the virtual artefact should behave in a similar manner (the importance of the direct coupling and immediacy of input and output spaces will be described in more detail throughout later sections of the thesis).
    a. The screen of a tablet device is also, unlike that of a mobile smartphone device, big enough to still see the display while making multiple and repeated interactions with the touchscreen.
2. Size and shape – like other mobile devices, tablets are light and compact enough for hand-held use, fulfilling the manual requirement of the interaction technique. Holding the tablet in the hands is also representative of holding an artefact in the hands (the importance of representation will be described in more detail throughout later sections of the thesis).

Besides its tangible, manual qualities, the other important and desirable quality of the tablet device is its mobility. The communal, group-learning atmosphere in the modern-day museum "demands new interaction designs for multiple users" (Snibbe and Raffle, 2009) and a departure from traditional 2D desktop (monitor, mouse and keyboard) and kiosk-based exhibits which operate under fixed conditions and where co-participation and collaboration often involve little more than "helping to operate the system or interjecting answers or solutions to a puzzle, often to the frustration of the principal user" (Heath and Lehn, 2010).

The tablet interface's mobility makes it much more suitable for co-participation and collaboration between multiple users, who can operate them freely within the their own personal space. Collaborators can gather around each other from all angles to get a better view of each other's actions on the tablet, can use physical gestures to point things out to each other and make spatial references to draw each other's attention to things that are of interest, and can simply pass the device itself between each other in order to take or relinquish control of the interaction. Interactions that work in group contexts are vitally important for supporting participatory and collaborative learning, especially considering that around "70% of people visit museums and galleries with other people" (Heath and Lehn, 2010), and the importance of these kinds of visual gestures for coordination and spatial referencing in group contexts will be described in more detail in later sections of the thesis (particularly *Subsection 2.2.4: Mutual Access in Collaboration)*.

Another key component of the research problem, as described in Subsection *1.2.2: Limits on Physical Access to Artefacts*, is the common scenario of collaborators being remotely-located – not in the same location as each other or as the artefact they wish to explore and discuss. Tablet devices provide support for a remote-collaborative solution, with their capacity both to run complicated interactive applications and to do so over an internet connection. The proposed solution this thesis describes provides remote-collaborative support for the gesturing and spatial referencing described in the previous paragraphs using interactive, 3D annotations that users can attach to the (virtual) artefact, allowing them to 'point out' different areas of interest to each other. 3D annotation will be described in more detail in *Subsection 4.1.2: Previous Examples of 3D Browser Annotation*, and the 3D annotations developed for the prototype interactive system described and evaluated in thesis will be referred to from here onwards as 'interest points'.

In summary, museums are seen as "sites of spectacle and display", rich and surprising environments that "can arouse curiosity or inspire new ideas" (Hooper-Greenhill, 2007). Collaborative exploration and enquiry are a great way to get people thinking about new concepts, engaging with collections, and engaging with each other in participatory learning experiences, but when physical access to collections is limited – either because of limited viewing angles, artefacts not being on display at all, the artefact being displayed in another location, or being in a different location to like-minded collaborators – the ability to collaboratively discuss, explore, and ultimately understand and make sense of museum artefacts is severely impeded. Museum collections are "wonderful", and should be celebrated with visitors (Black, 2005), not left undiscovered or unappreciated by problems of physical access or differences in the location of those who would be interested by them.

This thesis therefore proposes that manual exploration and collaborative annotation of 3D, virtual representations of museum artefacts using a tablet device facilitates engaging discussions of museum artefacts for collaborators, whether they are remote or co-located, allowing all visitors to actively and collaboratively participate in learning experiences and "to be inspired by what they [might not previously have been so easily able to] discover in the museum" (Black, 2005).

1.4 Research Objectives

1.4.1 Research Question

Discovering whether or not the proposed solution described in the previous section successfully addresses the research problem requires a question to be posed, which through the development and evaluation of the solution can be answered to provide evidence of the suitability of the prototype interactive system for (remote) collaborative exploration and discussion of 3D, virtual representations of museum artefacts.

The research question that this thesis poses and aims answer is:

> *"How can manual interaction with 3D, virtual representations of museum artefacts and interest points using a mobile device help to efficiently facilitate engaging discussions of (virtual) museum artefacts for remote or co-located collaborators?"*

1.4.2 Core Questions

Breaking down the research question into its constituent parts leaves three core questions to be explored:

1. What are the benefits of manual interaction with a mobile device for the rotation, scaling, and marking of interest points on (virtual) artefacts?
2. How efficiently can precise and focused information about (virtual) artefacts be communicated using interest points?
3. How does the combination of manual exploration and marking of interest points facilitate engagement with (virtual) artefacts?

1.4.3 Research Hypothesis

Based on the aforementioned research question, this thesis (and the research it describes) hinges on the hypothesis that:

> *"Manual interaction and annotation with a tablet device, based on real-world principles, is an engaging way of exploring and collaboratively discussing 3D, virtual representations of objects. In the case of oft-inaccessible (virtual) museum artefacts, such interaction techniques offer an experience much more akin to handling physical artefacts than that of the less-engaging digital techniques that are currently used."*

This hypothesis is tested (and the aforementioned research question and core questions answered) through the development of a prototype interactive system based on the proposed solution to the research problem (engaging, manual interaction with virtually represented (museum) objects). This prototype sytem is then evaluated using controlled experiments, during which it is compared with alternative methods of collaboratively exploring and discussing museum artefacts, including using a similarly digital but desktop interface-based approach, and the traditional viewing of physical objects in a glass display case. It's expected that by virtue of being more reality-based, it will be found that the proposed interactive system offers an experience closer to that of physical object viewing (and handling) than its desktop interface equivalent. This process of development, comparative evaluation and answering of the research questions is described in detail in *Chapter 3: Research Methods*.

1.5 Thesis Outline

In this introductory chapter, the motivations for the thesis and the research it describes have been presented, describing the research context (collaborative discussion and exploration of museum artefacts), the problem that the research focuses on (limited access to artefacts due to physical or locational constraints), and the proposed solution to that problem (manual interaction and 3D annotation of virtual representations of museum artefacts using a tablet device). The research objectives have also been presented, including the research question, its constituent core questions, and the hypothesis that the thesis aims to show to be correct.

The remaining chapters of the thesis are presented as follows:

- Chapter 2 – Literature Review:
    - The four key themes that underpin the research are broken down and how they link to each other is described, including:
        - Learning in museums,
        - Collaboration,
        - Reality-based interaction,
        - Engagement.
- Chapter 3 – Research Methods:
    - The methods used to complete the research are presented, including:
        - Research philosophy,
        - Research strategy (the key stages of the project and how they flow from one to the next),
        - Research design.
- Chapter 4 – System Design:
    - An outline of the the prototype interactive system developed as the proposed solution to research problem, including:
        - The basic concepts that the system design is based on,
        - The three key components that make up the system,
        - The prototype system in summary.
- Chapter 5 – Experiment & Results:
    - The in-context study in which the interactive system was evaluated is described, along with the results collected during the process:
        - The experimental design, including an outline of the study, what influenced it, and its data collection methods,
        - The results found and collected during the study, broken down according to the methods used to obtain them.
- Chapter 6 – Discussion:

    - The results outlined in the previous chapter are discussed, interpreted, and categorised according to:
        - What makes a reality-based interaction,
        - How collaboration has been facilitated,
        - What makes an engaging experience,
        - How learning experiences have been facilitated, and
        - What could be considered for future improvements.
- Chapter 7 – Conclusions:
    - Finally, research conclusions are drawn about the suitability of the prototype interactive system as a solution to the research problem, focusing on:
        - Whether the research questions were answered,
        - Whether the research hypothesis was proven or disproven,
        - How the prototype system met some of the challenges and related to some of the frameworks described in earlier sections of the thesis,
        - The importance or relevance of the prototype system as a proposed solution to the research problem, in the context of collaborative discussion and exploration of museum artefacts, and
        - What still needs to be investigated in the future.

Chapter 2: Literature Review

The previous chapter described the problem of limits on access to museum artefacts, caused by numerous display or physical condition and fragility issues. The proposed solution is a tablet-based interface that allows users to manually interact with 3D, virtual representations of museum artefacts, which are hypothesised to be an engaging way to collaboratively explore and discuss virtual objects, and in the context of museum artefacts would provide an experience closer to that of viewing and handling a physical artefacts than current alternatives, such as fixed kiosks and 2D desktop-based interfaces. Proving this hypothesis to be correct necessitates that the question of how manual interaction with virtual representations of artefacts efficiently facilitates engaging exploration and discussion of such virtual artefacts, for both remote and co-located collaborators, be answered.

To help frame the research, this chapter breaks down the four key themes whose relationship and interplay connect the key aspects shared by the research problem, its solution, and the research question that needs to be answered in order to show the hypothesis to be (or not to be) correct:

- Learning in Museums,
- Collaboration,
- Reality-Based Interaction
- Engagement.

2.1 Learning in Museums

Learning in museums is not a straightforward process, and can rely on many variables. Learning usually takes place in context, and is often an experiential process of discovery or construction. Learning can be based around physical objects and can be facilitated through the use of technology, although museum-exhibit technology that supports learning as a social or collaborative process has not always been well-realised in the past.

2.1.1 Learning in Context

There is a misguided idea in some circles that learning is about acquiring "new ideas, facts, or information", as opposed to understanding and consolidating information through the "slow, incremental growth of existing ideas and information" (Falk and Dierking, 1992). For many, learning is not just 'collecting information' but is both a 'process and an outcome' as proposed by Black (2005), who describes the process of "how we learn" and the outcome as "what we gain from learning".

Thinking about learning in this way, as being concerned with "knowledge, and the great leap from gathering knowledge to understanding it" (Black, 2005), is a product, according to Falk and Dierking (Falk and Dierking, 2000), of "hundreds of millions of years of survival-oriented evolution" and of the way people adapted, and continue to do so, in order "to intelligently navigate an ever changing social, cultural, and physical world". It is also a consequence of a natural need for humans, like all animals, to make sense of their surroundings and search for meaning in order to act in accordance with their environment (Falk and Dierking, 2000).

At the start of the learning process, when information is acquired, it tends to be arranged according to context. While prior knowledge, motivation and "a combination of emotional, physical and mental action" are some of the key ingredients of learning, acquired information requires "an appropriate context in which to express itself" (Falk and Dierking, 2000). Acquired information, stored in a learner's head as patterns and associations, would remain "dormant or meaningless" without the 'contextual clues' from the outside world with which we tie them together and turn that information into meaningful understanding (Falk and Dierking, 2000).

In keeping with this idea of learning not being an 'abstract' or 'isolated' but an "organic, integrated experience that happens in the real world", Falk and Dierking (2000) presented their *contextual model of learning*, an amalgamation of three key contextual components:

- Personal context, which involves:
    - Motivations and expectations,
    - Prior knowledge, interests and beliefs,
    - Choice and control.
- Sociocultural context, which involves:
    - Within-group sociocultural mediation,
    - Facilitated mediation by others.
- Physical context, which involves:
    - Advance organisers and orientation,
    - Design,
    - Reinforcing events and experiences outside the museum.

Falk and Dierking describe "the personal context as moving through time; as it travels, it is constantly shaped and reshaped as it experiences events within the physical context, all of which are mediated by and through the sociocultural context" (2000). They describe learning as being 'situated', in a physical context, and being 'bound' to the environment in which it takes place, only to offer something new to learners when "elements of an old context are reorganised in the new" (Falk and Dierking, 2000). The interplay between these three contextual elements is key to what and how people learn in a given situation.

The combination of the three contexts are involved in all museum visits, acting as "windows through which we can view the visitor's perspective" (Falk and Dierking, 1992). However, approaches to museum exhibitions often follow a *didactic* model, whereby the information is broken down into "small digestible pieces arranged in a logical order" for visitors to absorb "unquestioningly, in the order and manner intended" (Black, 2005). Curators using the didactic approach are aware that they possess certain knowledge, and seek to transfer that to visitors through organised and structured exhibitions (Black, 2005).

This is fine in the context of schools, or other sites for 'formal learning', but in museums the learning context is not the same (Hooper-Greenhill, 2007), following the less isolated and more organic approach described by Falk and Dierking's contextual model of learning. In this approach, visitors are seeking individual experiences that mean something to them, and that they can participate in directly, and so museums need to be responsive to different learning needs and levels of understanding if they are to appeal to a diverse visitor base (Black, 2005). In this scenario, something more organic and adaptable to the individual, rather than the didactic approach, is necessary.

All experiences are potential vehicles for learning, but that every experience results in learning is certainly not the case (Falk and Dierking, 1992). However, it is likely that when a museum experience contains "rich components of all three contexts", it will be memorable (Falk and Dierking, 1992) and could facilitate learning taking place, given that as Hooper-Greenhill (2007) describes museum learning is often "more open-ended, more individually directed, more unpredictable and more susceptible to multiple diverse responses".

2.1.2 Learning Theories

Quite opposite to education, which emphasises the teacher and what it is they are trying to teach, learning is an individual process, focused on the person who is gaining knowledge or expertise (Knowles et al., 2005). Knowles et al. (2005) describe two key theories of learning that are recurrent in the scientific study of learning:

- The elemental (reactive) world view:
    - The reactive and adaptive model, the metaphorical machine.
- The holistic (active) world view:
    - The active and adaptive model, the metaphorical organism.

Taking the reactive approach assumes learning to be incremental, and involves material being "broken down into small, discrete steps and arranged in the order appropriate for the items to be learned" (Hein, 1998). However, not everybody is agreed on the fact that learning can be boiled down to this kind of stimulus-response approach, and the counterargument that experiences are not just reactions to “a mass of separate details, but to a complex pattern of stimuli” (Knowles et al., 2005) led to the “active, developmental learning theories” that put the learner, rather than what is to be learned, in focus (Hein, 1998).

A good example of the two opposing approaches is described by Hein (1998), who provides the example of two history teachers – one transmits information “bit by bit, starting with the simplest facts” (reactive), while the other provides the students with material from which they can draw their own conclusions (active).

The active world view is far more in line with the kind of individual, context-aware experiences promoted by Falk and Dierking’s conceptual model of learning, while the reactive view fits better into the didactic exhibition approach. Even within the active world view, there are a number of different learning approaches that can be followed.

Experiential learning is the idea that, as opposed to being a one-off acquisition activity, knowledge and understanding come from the process of acquiring new information, reflecting on it, and then relating or applying it to existing personal life experiences (Black, 2005). It is essentially a learning cycle of doing something, learning from it, and applying that experience the next time we do a related activity (Black, 2005). Four key types of experience, described by Black (2005), appeal to four different types of learners:

- Concrete experience is about being directly involved in something and personally dealing with immediate situations:
    - These experiences appeal to divergers, who seek to discover ‘why’.
- Reflective observation is about understanding the meaning of ideas and situations, usually by observing and describing them:
    - These experiences appeal to assimilators, who are concerned with ‘what there is to know’.
- Abstract conceptualisation is about applying logic, ideas, and concepts, and involves thinking as opposed to feeling:

    - These experiences appeal to convergers, who are motivated by discovering ‘how’.
- Active experimentation is about the way activity influences people and changes situations, and involves practice as opposed to reflection:
    - These experiences appeal to accommodators, who want to know what will happen if they do or change something.

Discovery learning is a more active approach to experiential learning, whereby learners engage with “problem-solving, enquiry-based and ‘hands-on’ environments” (Black, 2005). This approach is said to encourage students to “ask questions and formulate their own tentative answers”, which in turn “supports active engagement and fosters curiosity” (Black, 2005). This allows for learners to use their intuition and think about the topic in question, which is a way of ‘personalising’ the learning experience (Black, 2005).

This type of learning is well-suited to learners who are “already interested in and possess a basic knowledge of a subject”, as they are going to have to be able to apply problem-solving strategies to what they are doing – if this basic structure is lacking, learners can “become confused about what they are meant to be doing, flounder and grow frustrated” (Black, 2005). However, discovery learning approaches can also be ‘highly motivating’ in the way that they allow for learners “to ‘do’, to experiment, to discover for themselves” (Black, 2005).

Finally, constructive learning is a similar approach to discovery learning, but with a greater emphasis placed on the learner being able to verify and ratify their ideas, based on existing knowledge. Learning in this approach is about constructing “new ideas or concepts” that are based on current and past knowledge (Black, 2005). From the curator’s point of view, presenting museum collections using the constructivist approach is about “providing visitors with opportunities to interact and to construct their own meanings” (Black, 2005), the importance of which will be returned to in *Section 2.2: Collaboration*.

2.1.3 Object-Based Learning

Encounters with real objects in a real space are an ideal opportunity to learn, providing a much more concrete experience and a truer sense of understanding than simply talking about something, which does not necessarily imply understanding (Hooper-Greenhill, 2007). Object-based learning is a recognised approach that draws heavily on the principles of active and experiential learning (Chatterjee, 2010), and so given the size of their collections and wealth of their expertise, giving visitors the opportunity to handle and discuss objects is a big opportunity for museums in terms of providing engaging learning experience (Black, 2005).

While the everyday objects around us and our personal effects may be very familiar, museum objects and their unfamiliarity can be intriguing and enticing – people are interested in discovering more about them and knowing how they work, and this encourages us to touch them (Pye, 2007). But underneath the intrigue, objects carry meaning, of which there are three main types (Hodder, 1994):

- Physical meaning: how the object is used, how it conveys information (which might be related to social characteristics, personal feelings, or religious beliefs), and the effect the object has on the world.
- Relational meaning: how the object fits into a wider 'code' or structure, and how its place within that structure affects its meaning.
- Content of meaning: how the object historically represents the changing of ideas and associations – the things that make its use 'non-arbitrary'.

A museum object's meaning is often a vehicle for histories, memories and cultures, which become 'encoded' in object-based museum experiences and "can be made meaningful in multiple ways" (Hooper-Greenhill, 2007). This makes museum objects "powerful sources of learning with both short and long-term impact" (Hooper-Greenhill, 2007). Museum research activities have often focused on "examining objects and mentally, or actually, comparing them with other possible similar objects" (Pye, 2007), drawing upon knowledge and experience to construct and piece together it's history.

This is now complemented by a growing interest in encouraging museum visitors, as well as staff and researchers, to learn through direct contact with objects (Pye, 2007). Museums recognise the evocative nature of physical things, and how they can transport people back in time, prompt their memories and encourage reliving and reminiscing about past experiences, allowing people to talk them through and make sense of object and experience alike (Pye, 2007).

2.1.4 Interactive Technology and Museum Learning

Museums make excellent learning environments because, despite the "widely varying interpretative skills, background knowledge, expectations and motivations to engage' (Otitoju and Harrison, 2008) that visitors arrive with, well presented and interactive exhibits provide "rich, multi-sensory experiences" that are powerful tools for 'sense-making', 'understanding', and 'meaningful learning' (Falk and Dierking, 1992). Interactive, in this sense, specifically refers to visitors being engaged in an "emotional, physical, or intellectual dialogue" (Otitoju and Harrison, 2008).

There are a number of interesting ways to facilitate interaction in museums. Directly influencing the content of an exhibition through direct participation or manipulation of physical elements is a popular approach to interaction, as is encouraging visitors to make personal interpretations by linking observations and various present stimuli to past experiences (Otitoju and Harrison, 2008).

However, the use of technology for facilitating interactive experiences has generally been quite constrained. Traditional computer setups with singular input devices (such as the mouse, monitor and keyboard paradigm) are very restrictive in terms of how much flexibility or co-participation they support, and even approaches that have experimented with more innovative interface designs, such as large screens and head-mounted displays, have often neglected how best to integrate such technologies into natural and already well-populated museum spaces (Hindmarsh et al., 2002).

Space in a museum is about much more than just housing exhibits in physical structures – it is where communication takes place upon encountering an exhibit, and as such, it is important that interactive elements deployed in museums allow for active participation in physically and socially engaging activities, as opposed to just individual consumption (Kortbek and Grønbæk, 2008). In order to facilitate this social engagement, visitors need to be able to actually work in tandem, rather than simply allowing for some degree of simultaneous use which is then passively observed by others (Hindmarsh et al., 2002).

In the past, museums have often struggled to provide these kinds of 'in tandem' opportunities to "collaborate at the exhibit-face" and to work together in making 'creatively engaging' contributions to the experience (Hindmarsh et al., 2002). One school of thought proposed by Snibbe and Raffle (2009) is the idea of socially immersive media. While their approach is based on their work with projected interactive graphics and gesture-based, as opposed to hands-on, tangible, input techniques, their ideas on social engagement are nonetheless very interesting. They propose that in order for media (in our case, interactive museum exhibits) to be socially engaging, they should be:

- Visceral (visual and physical), responsive (immediately, clearly, and predictably), and continuously variable (changing with 'infinite variability'),
- Socially scalable (designed to share with varying numbers of others), socially familiar (in keeping with existing social behaviours and comfort zones), and socially balanced (equal emphasis on the individual, other people, and the content itself).

Interactive technologies in museum spaces, particularly those geared towards collaborative experiences, should take these kinds of principles into consideration, in order to ensure that experiences with interactive technology are not only engaging (and thus facilitate learning) for the individual, but are socially engaging as well.

2.2 Collaboration

Collaboration is an important part of learning and can be both facilitated by interactive technology and based around interacting with objects. There is also evidence that collaboration is a successful approach to learning in museums, an area where mutual access is of key importance to the success of collaboration.

2.2.1 Learning Collaboratively

People are not just individuals, but are members of 'a larger group or society', and as such, learning is a group experience as much as an individual one – it's tied to the 'cultural and historical context in which [it] occurs', making it in many ways a form of 'distributed meaning-making' (Falk and Dierking, 2000). This means that learning is 'socially mediated', a process which is able to take place because of the fact that people talk to and watch each other, "incorporate other people's ideas in their own", and forge links during social contact (Falk and Dierking, 1992).

Learners, even in groups, are not all the same but exist as differing communities, each of which has its own different levels and 'boundaries' of knowledge and experience (Falk and Dierking, 2000). Within (and between) these communities, a process called scaffolding often takes place, where the more knowledgeable members of a group or community support others using "questions, cues, or other learning supports" (Falk and Dierking, 1992).

Roschelle and Teasley (1995) describe how collaboration can be thought of as "a coordinated, synchronous activity that is the result of a continued attempt to construct and maintain a shared conception of a problem". This problem-solving activity is supported by what they call the joint problem space (Roschelle and Teasley, 1995), an integration of:

- Goals,
- Descriptions of the current problem state,
- Awareness of available problem solving actions,

- Associations that relate goals, features of the current problem state and available actions'

When collaborators can all make sense of this problem space, a shared conception of problems is easier to construct and maintain. Within this conceptual problem-solving space, solutions are constructed and mediated through "shared language, situation and activity", and not simply as individual cognition (Roschelle and Teasley, 1995). Conversation is critical here in that it plays an important role in constructing and maintaining the problem space, and that having the shared conceptual problem space continually ensures that the conversation itself is meaningful (Roschelle and Teasley, 1995).

Of course, at the root of collaboration lies the idea of working together, and the climate in which collaboration takes place needs to have the same characteristics of being "safe, caring, accepting, trusting, respectful, and understanding" as the ones we create for ourselves as individuals (Knowles et al., 2005). Many theorists here highlight group preferences of "collaboration rather than competitiveness, encouragement of group loyalties, supportive interpersonal relations, and a norm of interactive participation" (Knowles et al., 2005). All of this supports what Knowles (2005) describes as the 'atmosphere of adultness', where mutuality and informality between learners at different levels is emphasised.

2.2.2 Collaboration in Museums

Museums recognise not only that museum visitors arrive "predominantly in groups", but that "social interaction through language" has a critical role to play in learning (Hein, 1998). However, although museums are often visited in groups, even solo visitors are generally aware of, and 'sensitive to', the behaviour of other visitors and groups of visitors around them (Heath and Lehn, 2010). The experience of engagement with a museum object or exhibit is often shaped by "our talk and interaction with others" (Heath and Lehn, 2010), taking learners beyond the predominantly individual experience and "[extending] their own knowledge and even their ability to learn" (Hein, 1998). This opportunity for engagement with collections on both the individual and group level is 'fundamental' to the service provided by museums (Black, 2005)

In bringing their own experiences, knowledge and learning styles to the table, visitors can help to inspire and engage each other in interactions with the 'rich resources' on offer (Hein, 1998), often by way of offering thoughts, reassuring each other, providing feedback, or simply wanting to talk to others about the experience (Haywood and Cairns, 2005). Groups of visitors in museums become communities of learners who participate in experiences together, "pursuing enquiries, making connections among various contexts, sharing interests with each other, and learning how to learn and how to assist and collaborate with others" (Falk and Dierking, 2000). Museum staff also have a part to play in these communities, being able to interpret ideas and influence the visitor experience in ways that make it meaningful for learners (Falk and Dierking, 2000).

These communities are better represented when they are included as active participants in exhibitions – as part of the presented history, in the "development of multiple perspectives within the exhibitions", etc. – and this helps to tackle the widely recognised problem of museums not relating to the communities they represent (Black, 2005). In order to ensure that communities are well represented, a "supportive environment for reflection" is needed, one where visitors can talk about their ideas, share multiple viewpoints and engage in dialogue with each other from various perspectives (Black, 2005). Through this kind of "social or collective endeavour", meaning making can be constructed by individuals or groups alike, with interpretations validated by a wide and supportive community of learners (Hooper-Greenhill, 2007).

2.2.3 Object-Centered Collaboration

Objects are mediators of culture, with museum objects providing "a focal point for acquiring subject specific knowledge" that helps learners to frame information and ideas in a physical context (Chatterjee, 2010). The underlying reality of a material object mediates culture by forcing learners to think about the "relationships between things, rather than simply in terms of the things themselves" (Tilley, 1994). Museum collections make use of objects in a variety of ways to "enhance and disseminate specific knowledge", making use of "practical, observational and drawing skills" to inspire learners and facilitate the understanding of the relationships to culture that make the object significant (Chatterjee, 2007).

Socially, objects acts as 'frames' that can transform, store or preserve information for use in social practice, a symbolic channel through which culture can be expressed (Tilley, 1994). Conversations are pivotal to this and are often stimulated by objects. Conversation and discussion is often based on, and generally begins with, previous ideas or experience of related objects – Falk and Dierking (1992) highlight the example of a family relating cats on display in a museum to their own experiences of cats in the home.

Once an association is made, objects can inspire further "discussion, group work, and lateral thinking" (Chatterjee, 2010), which as mentioned earlier in this chapter and in *Chapter 1: Introduction* are important learning tools. As discussion around the object progresses, this lateral thinking can lead to the posing of questions in an attempt to validate ideas and finding and constructing shared meaning, with simple questions (Trewinnard-Boyle and Tabassi, 2007) forming the basis of shared conceptions of meaning and significance:

- What am I?
- How old am I?
- What am I made of?
- Who would have made me and why?
- Who owned me or used me, and what for?
- What stories can I tell?

2.2.4 Mutual Access in Collaboration

Objects, be they physical artefacts, screens, documents, plans, diagrams or any other kind of information or media, are frequently made use of as a means of accomplishing and coordinating group activities (Hindmarsh et al., 2000). Communication and collaboration between groups of people are in fact highly dependent on the ability of group members limit ambiguity by "invok[ing] and refer[ing] to features of their immediate environment" (Hindmarsh et al., 2000). Generally, when people want to make a reference to something during collaboration, they can point in the direction of the object they are referring to, allowing co-participants to clearly see them "in relation to their surroundings" (Hindmarsh et al., 2000).

However, problems can occur when the positions and orientations of others are not clearly visible, as individuals can find it much more difficult to act accordingly with their collaborators when "they have little sense of how [their collaborators] are engaged in, or orienting to, the ongoing activity" (Hindmarsh et al., 2000). Clearly, collaboration relies heavily upon group members' "mundane abilities to develop and sustain mutually compatible, even reciprocal, perspectives" (Hindmarsh et al., 2000).

Objects can act as focus points, where shared collaborative activities, such as enquiry and problem-solving, provide a context in which that object can be understood (Hindmarsh and Heath, 2000). But again, subtle and mundane interactions between group members, such as glances, stares, and points, are important in establishing and deciphering a shared reference and spatial context in which to ground discussion (Hindmarsh and Heath, 2000). Common notions of objects and their features act as 'momentary hubs' for collaboration, acting as a coordination point for collaborative discussion and triggering an ongoing sequence of events and actions.

Clearly, if there are differences in the shared reference and spatial context that surrounds the object, then "subsequent [collaborative] tasks can be critically undermined", altering the course of the collaboration and potentially affecting the accuracy of the information being disseminated, or in the case of this research the meaning being constructed (Hindmarsh and Heath, 2000). Therefore, it is critical that collaborators can be sure they have a shared understanding of reference and are able to "discuss the same object and in the same way" (Hindmarsh and Heath, 2000).

The understanding of the spatial context of objects between collaborators is embodied in nature, typically involving actions such as talking, looking, and pointing (Hindmarsh and Heath, 2000). Whilst talking is possible remotely via the telephone or videoconferencing software, looking can be limited using such approaches, and pointing severely limited. While people do possess natural skills in managing such shortcomings, it is possible to provide shared features that collaborators can exploit, and so for remote collaboration in particular, "resources such as shared viewing of documents need to be supported" (Brown et al., 2003).

As well as shared viewing, voice, location and orientation are also critical in constructing shared spatial references and context for collaborating around objects, which is hindered by discrepancies of this nature (Brown et al., 2003). A technology approach geared towards the collaborative discussion of museum objects needs to take this need to exploit features that replicate mutual access for collaborators into consideration, allowing them to limit ambiguities and discrepancies and maintain a shared spatial reference and context.

2.3 Reality-Based Interactions

New interaction styles grounded in real-world concepts often revolve around manual interaction techniques, and can offer experiences that feel less removed and perhaps more faithful to that of interacting with physical objects. They offer a number of opportunities to leverage digital technologies to take advantage of representations of physical, real-world actions and processes.

2.3.1 Principles and Tradeoffs

Modern interaction styles make use of actions that "correspond to daily practices" from the real, non-digital world and allow users to interact directly with realistic interfaces (Jacob et al., 2008) in ways that WIMP (windows, icons, menus and pointers) interfaces simply do not. WIMP interfaces, not taking advantage of senses such as speech, hearing or touch, limit the brain's 'bandwidth information channel' to solely visual information, which, whilst being our most prominent information channel, is still best made use of by complementing it with other channels (van Dam, 1997).

People actually have a good understanding and a familiarity of their own bodies, which is independent of the environment they find themselves in. Jacob et al. (2008) illustrate how a person is generally aware of the position of their limbs, their range of motion, and how to make use of their senses to perceive the world about them. This helps us to build up a perception of naïve physics – a 'common-sense knowledge' of the physical world, taking into account concepts such as gravity, friction, velocity, density, and scale (Jacob et al., 2008).

As well as their own bodies, people also have a good spatial understanding of the objects and landscapes that make up their physical environment, making use of the many clues that are embedded in environments which help people to understand and orientate themselves spatially (Jacob et al., 2008). One such clue is the presence of others, which is something that people are generally acutely aware of, and is essential for communication and collaboration, be that verbal, non-verbal, or based around the exchange of objects or completion of a task (Jacob et al., 2008).

When interaction styles make good use of this real-world understanding, the 'gulf of execution', or gap between a user's goals and actions can be greatly reduced (Jacob et al., 2008). Of course, there is going to be some kind of balance required between real-world and digital elements, leading Jacob et al. (2008) to propose that reality is only given up in return for a selection of other desired qualities:

- Expressive power (users can perform a variety of tasks within the application domain),
- Efficiency (users can perform a task rapidly),
- Versatility (users can perform many tasks from different application domains),
- Ergonomics (users can perform a task without physical injury or fatigue),
- Accessibility (users with a variety of abilities can perform a task),
- Practicality (the system is practical to develop and produce).

Certain of these qualities offer additional benefits that basing an interface completely in reality would not provide, and so the idea of a balanced interface making use of a mixture of reality-based interaction themes complemented by digital-only, unrealistic functionality is the ideal outcome – of course, with the reality-based side being as large as possible and the digital-only component introduced only as necessary (Jacob et al., 2008).

2.3.2 Representations of Reality in Interaction

Representations of reality in interaction are varied and many. Virtual applications that make use of tangible interfaces allow users to perform actions such as grabbing, picking up, positioning, maneuvering and arranging of (usually virtual) objects, representative of the manipulation of objects in the everyday environment (Jacob et al., 2008).

One simple way to think of a tangible interaction is as a process of input and output (Fishkin, 2004). Essentially, what happens is:

1. An input event occurs (such as physical manipulation or gestures),
2. The input is sensed, and the state of some digital information is altered,
3. Feedback is provided (a change in the physical nature of the object).

With WIMP and graphical user interfaces (GUIs), the input and output devices are distinct and separate entities – controls (mouse, keyboard etc.) and displays (monitors, HMDs etc.) are separated. With tangible interfaces, the input and output space are as one, removing the distinction and joining them together as one single conceptual space (Ullmer and Ishii, 2000).

There are generally two ways of representing actions in this tangible process – physically and digitally (Ullmer and Ishii, 2000):

- Physical (concrete, embodied, tangible):
- Digital (observed, unembodied, intangible):

Physical representations are tightly coupled to underlying digital information, and embody actions that are representative of real-world control. These actions are perceptually coupled to the digital representations that they mediate, and once completed the resulting representation of the digital information is embodied in an updated way by the physical state of the system or the interface (Ullmer and Ishii, 2000). How closely linked the input and output focuses are is important here – ideally, users will perceive the system state to be 'inside' the object that they are manipulating, thus able to constantly see that the digital representation is embodied in the physical representation (Fishkin, 2004).

In short, we can think of physical representations as embodiment, ranging from distant, to environmental, to nearby, and to full – the smaller the distinction between the input space and the output space, the more complete the embodiment, and the smaller the ''cognitive distance'' between the input device and the results of the actions made using it (Fishkin, 2004).

In contrast, digital representations are about metaphor, the degree of analogy between the system effect and the corresponding real-world effects of similar actions (Fishkin, 2004). To make things easier, metaphor can be broken down into two key types – the metaphor of noun (corresponding to the shape or aesthetic qualities of the action), and the metaphor of verb (corresponding to the motion or the outcomes of the action) (Fishkin, 2004).

2.3.3 Reality-Based Collaboration

While desktop interfaces can be something of a bottleneck, limiting what is observable and support for face-to-face social interaction, hands-on interfaces and embodiments that make use of real-world concepts can make things much more visible and accessible for groups (Hornecker and Buur, 2006). In conjunction with the previously described ideas of representation and manipulation, Hornecker and Buur (2006) suggest two concepts that relate to the implications of reality-based interaction in collaborative contexts:

- Spatial interaction (the embedding of tangible interaction in real space and the way interaction occurs via movement through this space),
- Embodied facilitation (how the configuration of objects in space affects and directs group behaviour).

Spatial qualities are rooted in our understanding and perception of movement, therefore spatial relations between objects, people, and our own bodies greatly affect our perception of an environment (Hornecker and Buur, 2006). The key concepts associated with spatial interaction reflect this (Hornecker and Buur, 2006), being concerned with:

- How people and objects meet in a space, and whether that space is meaningful,
- How the space can be configured by moving people or objects, and the effect that has on meaning,
- Who can see and make reference to what's going on in the space.

Meanwhile, embodied facilitation is concerned with (Hornecker and Buur, 2006):

- Whether the environment uses constraints to encourage collaboration,
- Whether everybody has access and can contribute to what's going on,
- Whether representations reflect experience and skills and invite collaboration.

Shared visual feedback is very important and when visual effects and the actions that cause them are visible to everybody there are more opportunities for collaborators to reflect on the consequences of an action, which is important in learning contexts (Price et al., 2010). Also important is a shared representation of the input space, which can be constructed when the objects and interfaces used in collaboration are visible and accessible to everybody, allowing them not just to co-construct ideas but to be aware of each other's actions and resolve any emerging conflicts or discrepancies (Price et al., 2010).

When interfaces are inherently individual, collaboration can be limited, even in a group context. This is because people have a habit of focusing on the representations "linked to their own device", which whilst ensuring that each collaborator interacts with their interface, can leave them paying much less attention to the actions of their collaborators (Price et al., 2010). All the evidence points to the importance of collaborators working and constructing representations together in order to collectively build knowledge, something which Price et al. (2010) noted as part of their observation that children in a collaborative context will "[use]" the objects available collectively rather than taking possession of specific ones"

Of course, for all types of interfaces, the link between input and output has to be very clear, and in the collaborative scenario must be clear for everybody. For tangible approaches, the ambiguity of perceived couplings is critical, and when a fragmented coupling creates "difficulty in establishing the link between input actions and the system's output", there can be real problems conveying the intended understanding and meaning (Price et al., 2010). As already mentioned, observation and communication with collaborators are important for learning, and the location of representations – whether they are co-located or discrete – was found in the case of children to have “a direct impact on [their] foci of attention and awareness of others’ actions” (Price et al., 2010).

2.3.4 Opportunities for Reality-Based Interfaces

Tangible interfaces are great facilitators of meaning making, linking real-world actions to digital representations and information (Price et al., 2010). Three key interpretations of tangible interaction offer us a selection of ways to implement tangible principles into interactive experiences (Ullmer and Ishii, 2000):

- Spatial approach (configurations and interpretations of physical objects in space),
- Relational approach (“sequences, adjacencies or other logical relationships” between objects mapped to digital representations),
- Constructional approach (the assembly of modular interface elements).

Human interaction has in the past been largely overlooked by TUI theory and frameworks, which tend to take a structural approach to “mapping out an abstract design space” but without much focus on the human experience (Hornecker and Buur, 2006). This did start to change with the advent of embodied interaction, which incorporates the idea that “social action is embedded in settings” and how linking this to digital representations enables and facilitates the ‘social, cultural, and historical’ as well as just the physical construction of meaning (Hornecker and Buur, 2006).

Tangible interfaces offer great potential for “hands-on, physically engaging interaction”, which can be really important for learning communities in promoting experiential learning (Price et al., 2010). Desktop screens are often seen as a “window through which we reach into a digital world”, and tangible interfaces add an element of touch and physicality to that idea (Hornecker and Buur, 2006). Modern day tablets and mobile devices provide an opportunity here, being hand-held interaction devices with a unified input and output space, and capable of displaying very high-quality 3D graphics relative to the high standards required for realistic games and virtual reality applications (Hürst and Helder, 2011). Virtual reality environments tend to be first-person in nature, with the eyes, hands and display all linked in a realistic context, making them human-centric experiences (Hürst and Helder, 2011). When mobile devices are used as a physical window through which a virtual object (or environment) can be viewed, this is referred to as the 'eyeball' or 'camera' in the hand metaphor (Hürst and Helder, 2011), and puts the user's interaction with digital content directly in their hands.

Being able to efficiently interact with virtual objects and to manipulate them freely and naturally is an essential in virtual environments, but while 3D interactions are "well-established and researched in traditional desktop-based virtual reality worlds", research into how best to translate them to mobile devices and tablets is "still in its beginning", largely due to the small form factor of the devices and the noise issues that can affect sensor technologies (Hürst and Helder, 2011). Nevertheless, with the obvious hands-on qualities of such devices and their capacity to display high quality 3D content, they offer a real opportunity in the reality-based interaction space.

In terms of social actions, annotation has received limited attention on mobile devices. Research into mobile annotation for reading applications has questioned the suitability of touch interfaces for annotating (Pearson et al., 2012), but argue that the unconstrained, hand-held nature of the mobile form factor has great benefits for collaboration. In group reading scenarios, multiple paper documents are the preferred sharing method, as they can be passed around and read "wherever space is available" and without the constraints of traditional alternatives such as desktop computers (Pearson et al., 2012). However, the ability to share content simply by passing a tangible or mobile device around is of great benefit to group learners in the reading context (Pearson et al., 2012), and offers a close physical representation of passing a book or paper between co-located participants.

In the remotely located context, social annotations are an emerging solution for coordinating and associating spatial references within a group. Pearson et al. (2012) describe how the implementation of such annotations in commercial software still suffers from "limited support for multiple screens, shared mark-ups or group coordination within a document", but nevertheless we begin to see how a mobile device could offer a great platform for reality based sharing in both the co-located (physical representations of passing the interface around) and the remotely-located (digital representations in the form of annotations) contexts.

Simply overlaying annotations in the 2D context (reading applications, for example), is sufficient, but for interactive, moving content (3D or video, for example), a different kind of solution is required (Silva et al., 2012). When annotations are made on dynamic content, they need to be able to function in a constantly changing (usually in the spatial sense) context (Silva et al., 2012). How annotations deal with this change will have ramifications for the fluidity of the user interaction, potentially leading to a breakdown in the spatial understanding annotations are supposed to give, a misinterpretation of the information they should convey, or simply non-usage of the application (Silva et al., 2012).

However, if annotations can successfully coexist with, and adapt to, constantly changing, dynamic 3D content on mobile devices, there is a great opportunity to provide a spontaneous user experience (Silva et al., 2012), one which would allow learners to explore and manipulate 3D content using hands-on interactions and be able to construct shared understanding and spatial referencing in both co- and remotely located collaborative scenarios, by either passing mobile devices around or using 3D annotations to draw each other's attention to interesting areas and construct a shared spatial understanding.

2.4 Engagement

Engagement relates to a sense of involvement and immersion, and describes what happens when participation in an experience becomes enjoyable and leads to a state of flow. Theories of engagement share some interesting overlaps with learning theories, and technologies have been successful in realising engaging interactive experiences in museums.

2.4.1 Key Facets and Elements

Successful technologies are those which go beyond simply being usable and actually engage users (O'Brien and Toms, 2008). Engagement is a feeling of being involved, motivated, and in perceived control over interaction, something that's often related to ideas such as sensory appeal, feedback, and challenge (O'Brien and Toms, 2008). A common misconception is that engaging experiences are about losing the sense of physical reality, but this is not really the case – in fact, it's possible to engage with experiences without any real desirable outcomes or specific purpose (O'Brien and Toms, 2008).

Instead, engagement is more about striking a balance between a system and its user. This balance, when achieved, pushes the 'boundaries' of the user experience "from merely perfunctory to pleasurable and memorable" (O'Brien and Toms, 2008). Users engage with mediums that draw them in, 'surround' their activities, and stimulate their imagination (Benyon, 2010).

Benyon outlines that engaging experiences share five common traits:

1. Identity – this relates to a sense of authenticity. Generally, it is most noticeable when it breaks down. When something happens during engagement that reminds you that the experience isn't real, then its authenticity has been compromised.
2. Adaptivity – this relates to the ability to change and personalise aspects of an experience, such as difficulty, pace or movement. Contrary to making things 'easy', adaptivity is about making things "that can be experience at many levels of skill and enjoyment".

3. Narrative – this relates to the telling of a story, with convincing elements.
4. Immersion – this relates to a feeling of being involved with something, up to the point of being "taken over and transported somewhere else".
5. Flow – this relates to a sense of smooth movement or gradual change between states.

Looking at some of the described attributes of engagement, including challenge, sensory appeal, attention, feedback, interactivity, perceived control, awareness, motivation and so on, a correlation is evident between attributes of engagement and the "products of the user-system interaction" (O'Brien and Toms, 2008). From this, we can observe that while usable systems are not necessarily engaging, engaging systems "do appear to have an inherent baseline of usability" (O'Brien and Toms, 2008).

When a usable technology *is* engaging, meaningful learning can be facilitated, by involving potential learners in processes of "problem solving, reasoning, decision-making and evaluation" (Kearsley and Shneiderman, 1998). When learners view their learning environment and their interactions with others as being meaningful and engaging, they will be naturally much more motivated to learn (Kearsley and Shneiderman, 1998).

2.4.2 Overlaps with Learning Theory

Meaningfully engaging experiences have certain overlaps with existing learning theories. Kearsley and Shneiderman (1998) describe the process of relate-create-donate, implying that engaging learning activities:

- Occur in a group context:
    - The relate component – emphasizing team efforts that involve communicating, planning, management, and social skills, as well as the clarification and verbalization of problems and solutions.
- Are project based:

    - The create component – emphasizing the need for creative, purposeful, and context-specific activity, with focused and defined application of ideas and efforts.
- Have an outside (authentic) focus:
    - The donate component – emphasising useful contributions to the activities.

Social collaboration and team effort have been part of learning environments for centuries, since the days of the ancient teachers of China, Greece and Rome, all of who perceived learning "to be a process of mental inquiry, not passive reception of transmitted content" (Knowles et al., 2005). Many of their techniques for engaging learners in enquiry together are still in use today, including the case method, invented by the ancient Chinese and Hebrews, whereby a situation is described and a group of learners "explores its characteristics and possible resolutions" (Knowles et al., 2005). The Socratic dialogue, invented by the Greeks, is another example whereby a question or a dilemma is posed and members of a group "pool their thinking and experience to seek an answer or solution" (Knowles et al., 2005).

Theories of play have some correlation to the create component. Interfaces employ "physical activity that encourages learning and creativity" to mediate information, satisfying the "psychological and social needs" of engaged potential learners by way of competition and collaboration (O'Brien and Toms, 2008). Interaction, often described in learning theory as playful, is the communication between the user and the interface, the medium through which the experience is presented (O'Brien and Toms, 2008). When the interface stimulates the user's senses, information is more likely to be engaging and meaningful, and playful, creative interaction encouraged (O'Brien and Toms, 2008).

Finally, active participation is heavily linked to the donate component of engaging learning. Making contributions comes as a result and as a combination of: the curiosity that "underpins our desire to find out"; a sense of humour, which can encourage involvement and learning; shock or surprise; movement and the fascination it inspires; decision making and the comparison of different viewpoints; and evocation, which can bring an exhibition or a topic to life (Black, 2005). In short, taking part in and personalising experiences, with the aim of fascinating oneself and fascinating others, is what brings experiences alive and makes them engaging.

2.4.3 Engaging Technologies

When technologies are engaging, they draw the user into a state of flow – a state of sustained involvement and immersion (Peters et al., 2009) that can be achieved through striking the "ideal balance between level of ability and challenge" (Wyeth, 2008). Tangible technologies are successful in engaging users in a state of flow because they focus on "matching people's physical and cognitive abilities", so that the user feels that they are in control, whilst also offering "avenues for challenge and reward" that offer achievable goals and easily understood rules of interaction (Wyeth, 2008).

One way to think of engagement with interactive technologies is as a looping process, whereby the user's perception of cues (digital representations) motivate the said user to act on the interface (Peters et al., 2009) in accordance with their perception of control over it (physical representations) (Wyeth, 2008). Based on some kind of understanding (cognition) of the effect of their action and any potential change in the state of the system which might now cause different cues to be transmitted and perceived, the user's goals and motivations to act on the interface again – and as such, to remain engaged with it – may either change or remain the same (Peters et al., 2009).

Tangible interfaces, with their physical properties, provide an interesting case whereby the coupling of the physical object, the action or movement placed upon it and the digital information being represented will have an important role on cognition (Price et al., 2008). The potential to 'exploit' tangible representations are a well researched area, and it has been suggested that they offer an engaging experience, but the role these representations and the engagement they facilitate play in supporting learning is rarely touched upon (Price et al., 2008).

Designing engaging representations requires a number of issues to be taken into consideration. Location (the distance between the digital and physical elements of the system), dynamics (the flow of information and links between action, intention and feedback), and correspondence (the metaphors involved in the representations of tangible objects and interactions with them) are the three key elements that define representations in tangible interaction (Price et al., 2008).

Striking the right balance between the physical and the digital is important in providing the user with the perception of reality-based interaction, and will impact on how much control they feel over turning their intentions into actions (Wyeth, 2008). Knowing that well designed representations can engage users with tangible interfaces, and that there are key overlaps between engagement and learning theories, it could be proposed that a well-implemented hands-on interaction style with a good representation of real-world principles could facilitate engagement in learning contexts.

2.4.4 Engagement in Museums

Museums actively seek to engage their visitors, with the goal of provoking thought and stimulating interest "in a pleasurable way" (Black, 2005). In fact, the 'primary role' of museums is to use exhibits to "engage audiences directly with collections", gaining their attention, maintaining it, and encouraging them to reflect on it (Black, 2005). Engagement with interactive museum content, at least in the case of children, has been found to consist of a combination of participation, narration and the incorporation of the co-presence of others, an overlap between which is likely to result in a positive and engaging learning experience (Haywood and Cairns, 2005).

Museums want visitors to make their own interpretations of objects as a product of engagement, encouraging them to explore and participate with 'real things' for themselves in order to enhance their own understanding (Black, 2005). Personal relevance is an important element of this, engaging visitors emotionally and intellectually (Black, 2005) and encouraging playful and creative participation

(Haywood and Cairns, 2005), and so by making collections and ideas relevant to visitors' own experiences, museums are able to personalise the experience and encourage participation and engagement (Black, 2005).

Not everybody agrees that collaboration is such an essential ingredient in engagement, but a consideration of the co-presence of others does have a significant effect on the individual museum visitor (Haywood and Cairns, 2005), and interactivity, particularly discussion and problem-solving as described in previous sections, is seen in some circles as being very important in "enhancing interpretation and creating new forms of engagement" with museum content (Heath and Lehn, 2010).

Unfortunately, interactivity in the museum context tends to focus not so much on the interaction between people, but more on the individual's interaction with the interactive interface or system in question (Heath and Lehn, 2010). Adopting this view makes the assumption that activities are based on "plans and goals" and are "organised in terms of rules that determine patterns or sequences of conduct to allow those goals to be achieved" (Heath and Lehn, 2010).

However, focusing on the individual visitor means that the complex combinations of social and interactional circumstances, which are prominent between people in the space where the technology will be used, are left ignored (Heath and Lehn, 2010). Many of these circumstances "profoundly affect the visitor's encounter with and discovery of" the museum content, and play a critical role "in its ability to engage" (Heath and Lehn, 2010). This shows that there is a need to start thinking about interactive museum interfaces that are specifically geared towards collaborative engagement.

Despite the overlaps described in the previous sections, the link between learning and engagement remains unclear – in fact, it is reasonable to say that engaging experiences may not actually encourage users to learn at all, and certainly not all learning tools are particularly engaging (Haywood and Cairns, 2005). However, the majority of museum visits are motivated by an underlying desire to enhance understanding, just as audiences are aware when they have been in contact with and engaged with something special (Black, 2005) – a priceless artefact, for example. This leads to a sense of “personal enrichment and fulfilment”, and when museums present their collections in an “imaginative, interesting and enjoyable way”, learning goes beyond a disappointing, shallow presentation, and engagement goes beyond simply being entertained (Black, 2005).

Given the right opportunity for museum content to breathe (hands-on, manual interaction, active participation, and social engagement with strong representations that are relevant to visitors), meaningful, engaging learning can take place.

2.5 Related Work – A Summary and Justification

2.5.1 Previous Examples of Interactive Interfaces in Museums

Throughout the preceding four sections, a number of museum-based research projects have been mentioned and referenced (including (Otitoju and Harrison, 2008), (Kortbek and Grønbæk, 2008), (Hindmarsh et al., 2002) and (Heath and Lehn, 2010)) whose focus or scope are in line with the key themes of this thesis, particularly sociality in the museum experience and collaborative learning in museums. However, the last decade has seen many previous projects that have focused on systems designed to engage users with digital museum content, focusing to varying degrees on interaction techniques, navigation of large digital collections, and sociality and collaboration between users and visitors.

Many research projects have focused on the museum experience from the point of view of the user's navigation of and interaction with digital museum content, a number of which leverage the wealth of scanned and digitized museum materials that web technology has made available and offer visitors new ways – often in 3D – to access that information. Early research into augmented reality (AR) systems gave rise to various projects that experimented with the idea of rendering museum artefacts into a live video feed as virtual objects digitally 'registered' (fixed) to tracked real-world objects that the user can pick up and move around (Woods et al., 2004) (Liarokapis et al., 2004), something which was considered as an early direction for the research this thesis describes.

More recently, the focus of research seems to have shifted away from projects that focus on interaction with individual museum artefacts (although navigation through heritage sites still remains a key area) and more towards navigation through and interaction with large quantities of digitized museum content. One such example is the *mARChive* installation at Museum Victoria, Australia, which allowed visitors to navigate, using a tablet interface, through a digitized collection of around eighty-thousand digitized museum materials organized into eighteen categories, projected in stereoscopic 3D around the sides of a 360-degree cylindrical display (Kenderdine and Hart, 2014).

Previous research has also resulted in a number of systems designed to support the social and collaborative aspects of museum experiences. The *Sotto Voce* system developed by Xerox Parc is one early example of such work, an electronic guidebook allowing visitors to a heritage site to share audio with each other, "building stronger interactional ties between companions (encouraging more natural conversations) as well as increasing awareness of the [site] and its contents" (Aoki et al., 2002). Numerous projects have expanded on these ideas over recent years, introducing social and collaborative elements to museum experiences, by way of interactive elements such as visualizations that connect visitors to each other's reflections on museum content (Cosley et al's (2008) *ArtLinks*) or by way of designing interactive museum experiences around the idea of interweaving 'trajectories' that bring users together and encourage or even necessitate sociality and collaboration (Benford et al., 2009).

However, the existing system that is most similar to the system that this thesis describes is *3D Semantic Annotation (3DSA)*, a tool for exploring and annotating 3D, virtual representations of museum artefacts (Yu, 2010) (Hunter and Yu, 2010) (Yu and Hunter, 2011) (Yu et al., 2011). Similar to other, non-museum-specific systems such as *Lighthouse* (O'Neill et al., 2011), *3DSA* is a 3D browser application that allows the user to rotate the artefact around and, essentially, view it from all angles. Similar in its basic functionality to the system this thesis describes, the following subsection justifies the need for exploring this idea from a slightly different angle, outlining the convincing arguments for expanding on the previous systems developed as part of the ongoing exploration into interactive and collaborative museum experiences by creating a new prototype system specifically for the research problem described in *Chapter 1: Introduction*.

2.5.2 Justifying a New Prototype System

If, as described in the previous subsection, existing projects have already tackled some of the issues and themes raised in this chapter, why then is it viable or even justifiable to think about designing a new prototype system?

In *Chapter 1: Introduction*, the research context (collaborative discussion and exploration of museum artefacts), the research problem (limited access to artefacts due to physical or locational constraints), and the proposed solution to that problem (manual interaction and 3D annotation of virtual representations of museum artefacts using a tablet device) were introduced. By breaking down the key components of the proposed solution and comparing to what degree the existing systems described in the previous subsection fulfill these principles, it is clear to see that so far, existing systems do not provide all of the features that this research proposes as the solution to the research problem:

Table 1. A comparison of existing interactive and collaborative systems developed for museum contexts, and whether each system fulfills the key principles of the proposed system this thesis describes.

	Manual	**Interaction**	**Collabor.**	**3D Annotation**	**Virtual Artefacts**	**Tablet Device**
Sotto Voce	✗	✓	✓	✗	✗	✗
AR Approaches	✓	✓	✗	✗	✓	✗
ArtLinks	✗	✓	✓	✓	✓	✗
3DSA	✗	✓	✓	✓	✓	✗
mARChive	✗	✓	✓	✗	✓	✓
THIS RESEARCH	✓	✓	✓	✓	✓	✓

Table 1 clearly highlights that the existing systems described in this chapter do not deliver all of the properties that are considered to be important in the solution to the research problem. All of the existing systems offer an interactive experience of some kind, usually focusing on some kind of virtual representation of museum artefacts or materials. While many of the existing systems also encourage or facilitate some degree of sociality and collaboration, this is not always in the form of 3D annotation – the practical sharing of specific information, and those that do lack the manual interaction element that basing the experience around interaction with a tablet device provides.

The comparison offered in table 1 highlights that existing systems have not so far provided what this thesis hypothesizes that the proposed system does, and the rest of the preceding Chapter 2: Literature Review provides the theoretical basis that underpins that conclusion.

- The engaging and collaborative qualities of reality-based interaction have been described, as well as the contribution that interfaces with tangible and manual elements – such as tablet interfaces – have to play in that.
- The importance of collaboration – providing opportunities for enquiry, scaffolding and the collaborative construction of meaning – in engaging people in museum learning experiences has also been presented.
- The important roles that both direct participation and social, collaborative activity have to play in helping people to engage, both with activities and with the other people who may be involved in an activity, have been made clear.

Having provided evidence of these three conditions, it is with a high degree of confidence that the hypothesis is made that:

1. Manipulating a 3D, virtual representation of a museum artefact using a tablet can facilitate direct, manual and reality-based interactive properties that are in some way akin to those that are missed when we are unable to handle physical objects.
2. Marking interest points in 3D space on a virtual artefact introduces a social, collaborative element to the experience and supports a shared learning experience for both remote and co-located collaborators.
3. That this combination of features will result in a higher degree of user engagement than the desktop (mouse and keyboard)-based implementations of current systems such as *3DSA*, largely due to the

properties brought to the experience by manual interaction with the tablet interface.

Based on the strong links between engagement and learning theories presented in *Section 2.4: Engagement*, it is therefore anticipated that this increase in engagement is a potential facilitator of learning outcomes in museum contexts. Potential users could see real benefits from exploring (virtual) museum artefacts using the proposed system, which is specifically designed as a solution to the research problem of limits on access to artefacts for collaboration.

In summary, the expected increase in engagement that a combination of reality-based interaction principles and collaborative features can potentially facilitate justifies the expansion of previous work on the interactive exploration of virtual museum artefacts, particularly in the realm of 3D browser-based experiences, by taking such experiences away from the desktop and putting them in the hands, bringing to the experience the engaging, manual elements that are lost when access to physical artefacts is not possible.

Chapter 3: Research Methods

Hands-on, manual, tablet-based interaction has been proposed as a solution to the research problem of limited access to real-life museum artefacts for physical exploration and discussion, whether those limits be imposed by the fragility and condition of artefacts or by display concerns, such as the availability or effective use of space. The interplay between four key topics – 1) learning in museums, 2) collaboration, 3) reality-based interaction and 4) engagement – has also been explored, introducing some of the theories that suggest *why* an interactive system based on hands-on, manual, tablet-based interaction would be suitable as a solution to the research problem.

This chapter describes the methods employed in order to evaluate the effectiveness and suitability of hands-on, manual, tablet-based interfaces as a solution to the research problem, describing the research philosophy, strategy and design that have been used to gather the evidence needed to make interpretations and draw conclusions that:

- Support (or otherwise) the research hypothesis
  - That such an interface is engaging for the collaborative exploration and discussion of virtual objects and in the case of museum artefacts provides an experience closer to that of handling and viewing physical artefacts than alternative desktop-based methods,
- Provide answers to the research question:
  - How such an interface can efficiently engage users in the collaborative exploration and discussion of 3D, virtual representations of museum artefacts.

3.1 Research Philosophy

A hypothesis has been made that manual interaction and annotation with a tablet interface based on real-world principles would be engaging for the collaborative exploration and discussion of artefacts, and the research question posed of how such interaction can efficiently facilitate engagement – but neither the hypothesis made nor the research question to be answered have explicitly mentioned learning. With museums not actually being about teaching at all, but rather about engaging people in "educationally enjoyable experiences" such that they can go away and construct their own understanding (Basballe and Halskov, 2010), this thesis follows the philosophy of *not* striving to measure whether or not learning has taken place, but rather looking for evidence of the factors that contribute to engagement, which is here interpreted as an *indication* that learning *could* have taken place.

Learning in museums is a highly personalised experience, unique to the individual, that comes as a result of engaging visitors in enjoyable experiences from which they can construct their own understanding based on their own interests (Falk and Dierking, 2000). It is actually a very common misconception that visitors come to museums either to learn or to have fun, and in fact much more likely the case that visitors come to do *both*, seeking what could be described as a "learning oriented entertainment experience" (Falk and Dierking, 2000). Transformation and learning outcomes occur when this combination of personalised experiences and engagement results in memories, which can have long-lasting learning effects (Basballe and Halskov, 2010).

As described in *Chapter 2: Literature Review*, there are certain overlaps that exist between engagement and learning theories, and so the philosophy behind this thesis is that if the users of the prototype interactive system can communicate and are engaged effectively, then meanings and relationships will be revealed and the acquisition of knowledge, enhancement of understanding and process of learning can potentially have been facilitated (Black, 2005), a philosophy whose motivations for not explicitly measuring learning are shared with previous museum based studies. Haywood and Cairns (2005) also explored the relationships between engagement and learning as opposed to measuring learning itself, explaining that one of the key problems with measuring learning in the museum context is that it can actually interfere with "the participants' experience or reporting of engagement". For example, pre-testing might lead participants to alter their natural behaviour or their approach to using the exhibit, under the (correct) assumption that a post-test will follow (Haywood and Cairns, 2005).

3.2 Research Strategy

3.2.1 Design and Refinement of a Prototype System

While replicating the experience of physically handling an artefact is impossible, this thesis presents an alternative approach to making sense of museum artefacts through hands-on manipulation and collaborative discussion, based on 3D representations of their physical properties. As well as the loss of the tactile and physical understanding and sensation that comes from handling objects individually, it is also problematic for collaborators to convey gestural clues about the spatial relationships between themselves and the objects around them without mutual access to artefacts (Everitt et al., 2003).

The difficulty this causes for collaborators in attempting to maintain focus on museum artefacts is the challenge that this thesis sets out to solve (Oates, 2006), with one of the goals being the design of a prototype application and potential solution that is useful for a number of different museum user groups, including researchers, curators, educators, and visitors (both physical and online). Each of these groups has their own sets of motivations for engaging with artefacts - overseeing and caring for collections, organising educational programs, public service and community outreach, authenticating, evaluating and categorising artefacts, presenting information to the public, or receiving information from the museum institution (Bureau of Labor Statistics, 2012) (National Museum of Australia, n.d.) (Simon, 2008). The unifying thread between users in all of these museum groups is that they all have the desire to engage with artefacts – in experiences that through engagement are likely to facilitate learning outcomes – and that they all have opinions, ideas, or knowledge to share, drawing on everything from culture and personal experience to highly specialised training or knowledge.

New technologies breed new uses for computer-based systems, and raise "more questions about efficient and effective use" (Oates, 2006). Designing an engaging interactive system for hands-on exploration and collaborative discussion of (virtual) museum artefacts is a potentially exciting prospect for users both within and between each of these museum user groups, and the core research objectives of this thesis are to explore, as presented in the previous chapter, the hypothesis that such an interactive system is engaging and the question of how such a system is efficiently engaging for potential users from these museum user groups (Oates, 2006), in order to make separate interpretations about whether this engagement is enough to potentially facilitate learning. The design of new technologies per se is not really a part of these objectives, which are more about the re-interpretation of existing theories of hands-on interaction with tablet devices in order to provide an efficient and effective solution to the research problem of limitations on access to physical museum artefacts for handling and viewing.

It has been suggested that task environments have an outer boundary of what is visible to the person(s) carrying out the task, known as the 'horizon of observation' (Hutchins, 1995). Naturally, how an interactive system makes use of this boundary, particularly for collaboration, is going to have "consequences for the process of acquiring knowledge" (Hutchins, 1995). However, as introduced in *Subsection 1.2.2: Limits on Physical Access to Artefacts*, any of the museum user groups previously mentioned might find themselves in a situation where the horizon of observation around an artefact is too limited to be able explore or understand the object.

Objects themselves are often enclosed and cannot be seen or touched from all sides; if passed around between large groups (of museum visitors, for example), only smaller sub-groups of people will have good access to it at any given time; online visitors may only have access to still images via museum websites; and in remote-collaborative situations, even if one collaborator has access to the artefact, the rest of the collaborators will be limited to what is described to them by voice, shown to them as still images, or in the case of videoconferencing held up in front of a camera.

This thesis suggests looking at the problem in a new way (Oates, 2006). Manual interaction with tablet devices, supported by collaborative annotations in 3D, could help to expand this 'horizon of observation' in ways not possible with existing technologies, supporting real-time exploration of (virtual) museum artefacts and allowing (remote) collaborators to easily focus, communicate and discuss ideas and theories about artefacts in a 3D context. Based on the literature covered and the ideas described in *Chapter 2: Literature Review*, this thesis suggests the suitability to the research problem of a tablet-based interface based on the principles of – 1) hands-on, mobile, reality based interaction, 2) collaborative annotation, 3) engagement, and 4) learning:

- A tablet-based 3D browser based on real-world principles…
    - as categorised by aspects such as common sense knowledge, hands-on activities, a feeling of tangibility and of something concrete, an awareness of space and objects, and purposeful, context-specific activity,
- … that makes use of collaborative annotations for directing and organising discussion…
    - as categorised by aspects such as communication, communities of learners, social engagement, problem-solving activity, group coordination, and observation,
- … will provide an engaging experience with both the object and collaborator(s)…
    - as categorised by aspects such as experience, participation, engaging with others, objects and topics, and a balance between the real and the digital:
- … which is likely to lead to visible learning outcomes,
    - as categorised by aspects such as understanding, active adaptation and interpretation, concrete experiences, and interpretation in social contexts.

This mobile, tablet-based interactive system is a suitable solution for various collaborative scenarios, from passing one or more tablets around a large group of museum visitors to out-and-out remote collaboration by supporting real-time networked interaction. Putting the task 'in the hands' by way of the mobile context digitally widens this 'horizon of observation' or 'window' to (virtual) museum artefacts for different groups of people working across varied contexts of use. It is anticipated that such an interactive system will show the hypothesis that manual, hands-on interaction with tablet interfaces is engaging for the collaborative exploration and discussion of virtual objects to be correct, and that the application design presented in this thesis could inform subsequent research on certain trends or outcomes that might be pertinent to this problem or application space (Oates, 2006).

3.2.2 Study of the Prototype System in Context

In order to test the hypothesis that a tablet-based interface, by way of being hands-on and offering mobility, would be engaging for the collaborative exploration and discussion of virtual objects and closer to the experience of handling and viewing physical objects, a controlled experiment based around a comparison of interfaces and viewing methods was devised to allow for the study of users' "cognitive or interactive behaviour" (Cairns and Cox, 2008). The aim of the experiment was to make the experience of interacting with each of the two digital interface types (tablet-based and desktop-based) as equal as possible, engaging participants in the same tasks as each other and a physical object viewing scenario so that "observations [can] be made of how the application supports the museum [experience]" (Brown et al., 2003).

In this situation, equality and fairness in the task design should result in no differences between the viewing methods – the null hypothesis – and so the experiment aimed to prove the alternative hypothesis (Cairns and Cox, 2008) – that one viewing method (hands-on, mobile, tablet interface-based) is more engaging and closer to the experience of handling and viewing physical museum artefacts than the other. The study used a 'within-subject' approach, whereby “each participant performs under all conditions” (Cairns and Cox, 2008), repeating “a very similar procedure multiple times with different [viewing methods for collaborative exploration and discussion]” (Cairns and Cox, 2008).

The prediction, which is required for the results of an experiment to have any statistical significance, was that the tablet interface would be the most engaging, and so the point of the experiment was to prove it unlikely that none of the viewing methods were more engaging than any other, thus rendering the null hypothesis improbable (Cairns and Cox, 2008). Again, ensuring that the experiment was completely fair was vital, as despite the insight gleaned from *Chapter 2: Literature Review* suggesting the likelihood of a hands-on, mobile, tablet-based interface being more engaging, the possibility that people would prefer any of the viewing methods being compared should be allowed for (Cairns and Cox, 2008).

Dependent variables included measurements of factors such as usability, engagement, and different aspects of collaboration (which will be described in further detail in *Chapter 5: Experiment & Results*), with the intentionally varied independent variable being the viewing method used to collaboratively explore the different museum objects (Cairns and Cox, 2008). Three viewing methods were compared (described in greater detail in *Chapter 4: System Design* & *Chapter 5: Experiment & Results*): the desktop interface, the tablet interface, and real, physical object viewing. A secondary independent variable was the collaboration style used – whether the collaboration took place in a co-located context involving the sharing of interfaces, or a remote context with participants unable to see each other and connecting to each other over a network.

A third independent variable, agreed upon after discussion with staff at the QVMAG, was the choice of artefact that would be used – different artefacts are inaccessible for different reasons, such as being extremely delicate objects, extremely small objects, or objects with ‘moving parts’ that might suffer from excessive wear if they were allowed to function as part of the display (Pye, 2007). In order to limit possible biases caused by the evident (or not so evident) advantages of looking at one type of object over another, a selection of objects were agreed upon with the QVMAG for discussion as part of the study.

In experiments, the ideal scenario is usually to try and recruit "a representative sample of the user population" (Cairns and Cox, 2008). Due to the varied nature of museum visitors and workers, who can be from a range of different backgrounds and ages (a relatively equal representation of age ranges with perhaps a slightly smaller population of 16-24 year olds in the UK, although more recent surveys have shown that adult visitors are more likely to be over 35 (Black, 2005)), the study described in this thesis did not set any specific limits on the participants recruited, besides that they were adults.

The philosophy here was very much that if somebody was interested in participating in a museum study, they were also likely to be the kind of person who would be interested in visiting the museum itself, and so although user metrics were recorded for the possibility of later analysis if necessary, it seemed pointless to use any such metrics as limiting factors in the recruitment policy. Also key in deciding to keep the limits very broad in terms of recruitment was the idea that in experiments, any kind of limits placed on the sample "will bias how representative [that] sample is of the wider population", and that generally a study "will never get an ideal sample" (Cairns and Cox, 2008). These factors, coupled with a mindfulness of the serious organisational difficulties involved in recruiting participants to give up their time for a study of this nature, affected our decision to avoid putting limits on participant recruitment.

Ethical considerations, in line with the local policies at the University of Tasmania, were taken into account, to ensure that all participants were well informed and consenting, felt trusting that private and confidential data would be properly handled, and were not left feeling confused, unsure, or vulnerable by the experimental procedures (Cairns and Cox, 2008).

Space was another important consideration for the study, with the physical space used having to be suited to the activity. As the mobile nature of the tablet interface was seen as something that would be important to engagement, based on the idea that in exhibitions physical space represents "an opportunity to provide mental space [and] providing time for some reflection on what has gone before" (Black, 2005), it was important to ensure that even when the room was divided in the remote-collaboration scenario that users could feel free and mobile, and not constrained to the desk space.

Also important was that in the co-located scenario, users have sufficient space and use of that space to be able to "discuss each other's experiences and thoughts" – seating placed around circular tables or sitting in closed circles "encourages conversation" (Black, 2005), and so while in the interests of fairness it did not seem right to set different seating patterns for each of the collaboration scenarios, it was important to ensure that there was enough space that participants could decide how best to make use of it.

3.2.3 Analysis of In-Context Study Results

A varied mixture of data collection methods were used in conjunction with each other, to ensure that the results gathered from the in-context study would yield enough information to allow strong interpretations and conclusions to be made in support (or otherwise) of the research hypothesis and to allow for enough evidence to be gathered to suggest credible answers to the research question and core questions.

In order to make qualitative measurements of the 'qualities' of the application (how people used it, how they thought about it, and how they felt about it) (Cairns and Cox, 2008), a questionnaire was seen as being the best approach. Questionnaires are commonly associated with the survey method, being cost effective, easy to analyse, and good for collecting data from "large numbers of disparate users" (Cairns and Cox, 2008).

For this research, a more in-depth response was sought from participants than is usually associated with questionnaires. Although in-depth interviews or focus groups allow respondents greater freedom of expression (Cairns and Cox, 2008), the low likelihood of recruiting participants who would be willing to give up enough time to take part in the experiment and then take part in a lengthy interview or focus group afterwards made delivering a questionnaire as part of the experiment procedures the better option.

However, with careful planning there should be no doubt that a well-constructed questionnaire will deliver worthwhile information on the qualities of the interactive system being studied. Part of this is about making sure that the questionnaire itself is reliable (is consistent in what it measures) and valid (that it actually measures what it is supposed to) (Cairns and Cox, 2008). Piloting the questionnaire before the experiment proper is the best way to ensure its reliability and validity, but of course it is very important right from the start to make sure that the right questions are being asked – if the important issues pertinent to the hypothesis and the research questions are not considered in the design of the questionnaire, they won't be present in the analysis either (Cairns and Cox, 2008)

The questionnaire used in the study described in this thesis was written based on the information presented in *Chapter 2: Literature Review*, to ensure that all of the topics and facets that could be pertinent to the hypothesis and the research questions were measured. Haywood and Cairns (2005) describe how in a similar study, they probed for engagement by asking what past experiences participants were able to relate back to, and probed for collaboration by asking what the presence of others meant to participants. Both of these are aspects of the background literature presented in this thesis, and the phrasing of questions here has been approached in a similar way.

The idea for integrating the questionnaire into the procedures was to have participants use each viewing method to look at an artefact, and then to complete the appropriate section of the questionnaire afterwards based on their experience – an approach Haywood and Cairns (Haywood and Cairns, 2005) used with interviews. The experimental design of comparing different viewing methods should limit the "inherent tendency not to complain" which can be such a common problem in museum surveys, which normally leads to "very high [but not always accurate] satisfaction levels being reported" (Black, 2005) – participants actually have to think about the comparisons they're making.

In-depth interview and focus groups offer "a flexible and participatory method that contextualises users' perceptions and experiences" (Cairns and Cox, 2008) and so are ideal for collecting qualitative data on how people use an interactive system. Although time and organisational constraints meant that planning interviews and focus groups was not really an option, the view taken during this research has been that carefully worded open-ended questions in a questionnaire context can also provide "a better understanding of phenomena", giving participants "complete flexibility in their answers" (Lazar et al., 2010).

Open-ended questions still need to be carefully worded, so as to avoid responses that "do not really help researchers address their root question" or "do not provide enough information" (Lazar et al., 2010), as well as ensuring that they are not too subjective or reflective of the "researcher's own biases" (Cairns and Cox, 2008). However, they certainly provide more information than quantitative data, revealing things such as the challenges faced by users, their preferences in terms of features and functionality, or how they would like to see the software improved (Lazar et al., 2010).

Closed questions come in two types, both of which can be analysed statistically as quantitative data (Lazar et al., 2010). Ordered response questions refer to when a number of choices are given, presented in a logical order – Likert scales, where respondents are requested to choose one item between a lower and upper limit, are a good example of this (Lazar et al., 2010). Questions that solicit an unordered response, on the other hand, "allow for choices that do not have a logical order", usually allowing respondents to select more than one choice (Lazar et al., 2010).

The mixed methods questionnaire was also complemented by instrumenting, which is the practice of having the interactive system collect and measure data on its own usage, storing all of the significant user actions (choices, selections etc.) in a database or log file (Lazar et al., 2010). To be able to see these events organised according to time and action provides researchers with a "a complete history of which commands are used frequently, rarely, [or in] combination with other commands" (Lazar et al., 2010), and when combined with other data collection methods such as observations and questionnaires, can help the researcher to understand "not just what the user was doing, but why [they were] doing it" (Lazar et al., 2010).

Finally, video recording the in-context study's collaboration sessions was seen as being very important in supplementing the information gathered by the means described in the previous section with some human observations. Price et al. (2010) describe the advantages of being able to 'observe' how students engage in interaction, and how videos recordings made of sessions in their own studies "indicated a number of relationships between design, interaction and learning opportunities". This was important in answering the research question outlined in *Chapter 1: Introduction*, which is not just about whether or not hands-on, manual, tablet-based interfaces are engaging for collaborative explorations and discussion of virtual objects, but about *how* such a tablet-based interactive system would efficiently engage users in these kinds of experiences. For this research, it was decided that video recordings of sessions might highlight in context, visually and aurally, some of the things participants would report in the questionnaires, particularly phenomena such as the use of space, or interface sharing habits in the co-located scenario.

Through the combination of a carefully worded, mixed methods questionnaire, application instrumenting and video recordings, the in-context study (described in more detail in *Chapter 5: Experiment & Results*) was seen as being able to provide enough information to make in-depth, unbiased interpretations of what participants did, when they did it, how they did it, and why they did it using the various compared viewing methods for collaboratively exploring museum objects. From the resulting data, strong and confident interpretations could be produced in support (or otherwise) of the research hypothesis and in answer to the research question and core questions outlined in the introductory chapter of this thesis.

3.3 Research Design

3.3.1 Research Process Breakdown

The whole research process that this thesis describes can be thought of as a series of steps (Cairns and Cox, 2008):

1. A prediction is made (the alternative hypothesis) that hands-on, manual, tablet-based interaction is engaging for the collaborative exploration and discussion of virtual objects – in this case 3D representations of museum artefacts.
2. The null hypothesis, in contrast, is that it is no more engaging than alternative viewing methods, such as an equivalent desktop-based interface.
3. Data is fairly gathered by way of a mixed-methods questionnaire, system instrumenting, and video observations.
4. Statistical tests are used to determine how often the results would be likely to occur if the null hypothesis of no viewing methods being more or less engaging than another was true.
5. Based on the size of that likelihood, it can be decided whether or not those results are likely to have occurred by chance, or whether the viewing method used has played a part.
6. If the results are unlikely to have occurred by chance, it can be safely assumed that the hypothesis that hands-on, manual, tablet-based interaction is engaging for the collaborative exploration and discussion of virtual objects and in the case of museum artefacts more akin to the experience of handling and viewing physical artefacts, is probably true.

This process provides us with the (probable) answer to the 'gold standard' question, which in this case is whether one viewing method is more engaging than any of the others. This is the most important outcome, as it relates directly to the research question and the hypothesis that was made.

However, this gold standard finding is also supplemented by 'silver standard' findings, which despite not specifically being part of the hypothesis and therefore potentially being caused solely by chance, are nevertheless interesting purely by virtue of having occurred (Cairns and Cox, 2008). In the case of this research, this includes factors such as the collaboration scenario (remote or co-located), the artefact type, and the order in which artefacts or viewing methods are experienced. Of course, for both gold and silver standard findings, it is worth remembering that a statistical test "does not provide proof, it provides evidence" (Cairns and Cox, 2008).

3.3.2 Mixed-Methods Data Analysis

Subsection 3.2.3: Analysis of In-Context Study Results describes the three different measures that were used to gather data – a mixed-methods questionnaire, application instrumenting, and video recordings of the in-context study. These measures, which are described fully and in greatest detail in *Chapter 5: Experiment & Results*, provided both quantitative (closed questionnaire items and application instrumenting) and qualitative (open-ended questionnaire items and video recordings) data for analysis. Triangulating the qualitative and quantitative methods in this manner helps to ensure the validity of the data collected in the study, avoiding the limitations or biases of using either method by itself (Cairns and Cox, 2008), but necessitates the careful preparation and analysis of each measure to ensure that this validity is maintained across methods and data types.

Maintaining an equal, uniform likelihood of the probability of any of the possible outcomes of the study being recorded or reported is important in ensuring that the research has validity. A uniform likelihood is maintained in part by the design of the experimental procedures (outlined in detail in *Sub-subsection 5.1.2.2: Experiment Procedures*). For example, all participants have the chance to view each of the possible artefacts and to use each of the possible viewing methods, and the order in which this takes place is arranged according to a Latin-square design to ensure that artefacts or viewing methods are used in the first, second or third collaborations in a session in equal measure. Organising the procedures in this way ensures that there is no bias or favouritism caused by one particular artefact or viewing method always being used first or last, in theory maintaining an equal (uniform) likelihood of any viewing method or artefact being preferred over another.

The data collected itself and how it is analyzed also has a part to play in maintaining a uniform likelihood of any particular result or outcome taking place. Beginning with the analysis of the collected quantitative data, the aim is to explain variations in the results between the viewing methods being compared, and to decide whether they are caused simply by chance or by the interesting phenomena that have been specifically probed for (Cairns and Cox, 2008). Through statistical analysis, the probability that variations in the data are simply natural can be calculated, and if that probability is found to be significantly small, it can be safely assumed that the variation is intrinsically linked to the previously made hypothesis (Cairns and Cox, 2008) – in this case, that hands-on, manual, tablet-based interaction with virtual objects is engaging (compared to a desktop-based alternative).

Particularly in terms of the questionnaire items, the design of the quantitative measures themselves is very important in maintaining a uniform likelihood. The closed questionnaire items generally follow a Likert-scale format ranging from strongly agree to strongly disagree, with neutral in the centre, thereby allowing for a full range of response from participants. Some questions ask for viewing methods or artefact type to be rated in order of preference, but rather than just asking for the favourite ask for all three options to be rated in order (from 1 to 3), ensuring that as well as the favourite, the least favourite and the neutral are recorded.

As described in greater details in *Section 4.2: The Three Key Components of the System*, the questionnaire also incorporated two ten point scales – the System

Usability Scale (SUS) and a second version of it adapted to focus on engagement – to generate a single numerical value for both usability and engagement. Each of the twenty items in these two ten-item scales was in the Likert-scale format, with two extremes of agreement and a neutral point in the middle. Along with the previous two examples, this highlights how the quantitative aspects of the questionnaire provided participants with the opportunity to answer along the full spectrum of opinion, ensuring a uniform likelihood of any possible result or outcome from the usage of the prototype system being recorded by the quantitative measures.

Maintaining a uniform likelihood is equally important in the analysis of the qualitative measures. In theory, open-ended questionnaire items are geared towards the full spectrum of possible answers to begin with, offering participants complete freedom to report anything that they think or feel. The important thing with such methods is to ensure that they are interpreted correctly, and in order to do so in a way that maintains uniform likelihood and an equal probability of all possible outcomes being recorded, appropriate coding methods need to be adopted to ensure that the results observed from qualitative, open-ended questions are presented accurately (Lazar et al., 2010).

For this research, no existing annotation or coding methods were used to organise the qualitative, open-ended questionnaire items. Rather, the answers were collated and organised according to a process devised specifically for this project, and to ensure that the full range of outcomes and answers, both positive and negative, were given equal precedent. This process, also described in *Subsection 5.2.2: Qualitative (Open-Ended) Questionnaire Responses*, was as follows:

1. For each collaboration session, four tables were drawn up, one for each of the four key themes from the literature review – reality-based interaction, collaboration, engagement, and learning.

2. The table for each session contained two boxes – one for positive comments (in support of the research hypothesis) and one for more negative comments (contradictory to the research hypothesis).
3. Each open-ended answer from the questionnaires (two per session) was read, considered, and placed in the appropriate coding section (positive or negative, for one of the four identified coding categories)

This process allows each answer given to be considered, in terms of the full range of themes that comprise the research and regardless of whether it agrees with or contradicts the research hypothesis, to be included in the final analysis, thereby ensuring the uniform likelihood of every possible result or outcome being equally likely to be reported by participants and interpreted as such during analysis. The coding process was completed by merging the sixteen analyses together, placing the answers from corresponding sections together and merging them into one another where they are describing the same outcomes and qualities, so as to distil the information from the sixteen coded collaboration sessions into the single, concise collection of four themed qualitative analyses found in in *Subsection 5.2.2: Qualitative (Open-Ended) Questionnaire Responses*. This process was completed twice, to ensure that nothing was missed and that the same decisions in terms of merging similar answers together felt equally appropriate each time.

The mixed-methods approach to not just the collection but also the analysis of the data gathered during this research was crucial in providing the most complete picture of how collaborators used the prototype system, allowing for the triangulation of data and limiting any bias caused by the sole interpretation of either method by itself. Making use of mixed-methods was important for this research – participants' qualitative grading of certain features and phenomena, collected using closed questionnaire items and supported by selected information from the application instrumenting, made it obvious what the participants were doing during a session. But it was the supporting qualitative evidence, collected using open-ended questionnaire items and supported by selected comments made and observations noted in the video recordings, that shed light on *why* they might be doing those things.

The careful planning and integration of the measures in the mixed-methods questionnaire, supported by more general observations derived from application instrumenting and the video recordings, ensured that the full spectrum of possible answers, opinions or outcomes, regardless of theme or whether in support of the research hypothesis or not, could be recorded for analysis. Thus, a uniform likelihood or equal probability of any possible condition or outcome being reported or observed was maintained throughout the mixed-methods approach, ensuring that the data gathered has a good level of validity.

3.3.3 Potential Indicators of Learning Outcomes

While engagement was being measured and specifically probed for, deciding whether or not any learning could actually be facilitated by this was really a matter of interpretation, as explained earlier in this chapter. However, links to key learning and engagement concepts identified in *Chapter 2: Literature Review* could be identified during coding, and there are a couple of other things that helped to shed some light on whether or not learning could have been facilitated.

Basballe and Halskov (2010) describe the link between physical design (representation), interaction and content, and how this is 'parallel' to behaviour (how we act), cognition (what we think) and affection (how we feel). They also describe how engagement can be thought of as involving activities such as sense-making (human-object), conversation (human-human) and self-directed, playful exploration (Basballe and Halskov, 2010). Being able to pick out any of these elements of engagement in coding, as well as any of those described in *Chapter 2: Literature Review*, would offer a strong indication that learning could have been facilitated, based on the overlaps and links between engagement and learning theories.

Besides looking for signs of engagement, Hooper-Greenhill (2007) describes a set of museum specific *generic learning outcomes*, developed by the Museums, Libraries and Archives council in the UK in the early 2000s. Elements of the generic learning outcomes could also be identified during the coding of qualitative data and would provide a particularly strong suggestion that learning has, or could potentially have, taken place. These outcomes are:

1. Knowledge and understanding,
    - Learning facts or information, developing understanding, grasping meaning, showing connections or links, clarifying, making relationships, and offering assessments.
2. Skills: intellectual, practical, and professional,
    - Knowing how to do something, which comes as a result of the experience of doing something (divided into cognitive, intellectual, social, and physical dimensions).
3. Attitudes and values,
    - Developing attitudes and forming the values that inform decisions about the way people live.
4. Enjoyment, inspiration, and creativity,
    - A desire to repeat the experience, which may come from engaging in exploration and experimentation.
5. Activity, behaviour and progression.
    - The things that people do – observed or reported activities and behaviours, which usually come as a result of learning.

Chapter 4: System Design

A solid concept has now been formed of the proposed solution to the research problem – limits on access to physical museum artefacts for collaborative exploration and discussion. Based on the thesis' underlying background concepts of learning in museums, collaboration, reality-based interaction and engagement, a tablet-based 3D browser interface based on real-world principles and making use of collaborative annotations for directing and organising discussion. It's been hypothesised that such a solution will be engaging for collaboratively exploring and discussing virtual objects, and that in the case of virtual museum artefacts will lead to an experience which is more akin to that of viewing and handling physical objects than other, less-engaging interfaces.

Based on the philosophy that measuring learning outcomes is incredibly difficult, but that the overlaps between learning and engagement theories would suggest that if engagement was measured then it can be supposed that learning outcomes would also be facilitated, a strategy for evaluating the system proposed as a solution and gathering enough information to make interpretations based on the hypothesis and the research questions has been described. In this chapter, the system design of the proposed solution is outlined, breaking down the basic concepts that influenced and the key components that make up the system and then detailing its technical implementation, before summarising its applicability to the research problem and how it is expected that it will be engaging (as originally hypothesised) and how it will facilitate learning outcomes.

4.1 Basic Concepts

4.1.1 Complexity and Physicality of Interfaces

Research suggests that the actions generated by physical manipulation of tangible interfaces help to "draw up previous knowledge" and "generate important motoric representations to [support] representation" (Manches and

Price, 2011). Tangible interfaces are therefore able to 'computationally mediate' people's interactions with physical objects, by way of a balance between digital representations and the physical (embodied and persistent) representations that control them (Ullmer and Ishii, 2000).

When an interface is overly complex, it can be difficult for users to learn, even if it's individual parts are easy to learn one by one – it's the 'aggregate' of features that creates the complexity (van Dam, 1997). Price et al. (2008) describe how, rather than 'dividing' the user's attention between the input and the output space, complexity can be lowered, particularly for touch and sensing surfaces, when information is displayed directly on the surface itself, and that this is generally preferred by users. This is a huge advantage that mobile (and table-top) applications have when presenting real-world concepts, in that users can see the effects of their actions directly.

The prototype interactive system proposed as a solution to the research problem – which was named *RelicPad* – was designed with these ideas in mind, using physical interaction for the manipulation of the (virtual) artefact and the marking of interest points to support users' explorations and discussions of objects, just as physically handling an object helps to build context. As well as being suitable for user groups from a variety of the museum contexts outlined in *Subsection 3.2.2: Study of the Prototype System in Context*, the clear benefits of being able to physically manipulate the interface and see the effects of the interaction on the input space itself influenced the decision to use a mobile, tablet-based platform as the interface technology for the research. Essentially, *RelicPad* is therefore a mobile 3D browser, for the manual exploration and collaborative annotation of 3D virtual representations of museum artefacts.

4.1.2 Previous Examples of 3D Browser Annotation

Existing research shows how 3D browser annotation has matured over the past decade. Early examples such as *Redliner* (Jung et al., 1999) (Jung et al., 2002) used text annotations listed in separate windows, linked (via colour coding) to 3D spheres on the 3D object itself to provide referencing and annotation. Highly commented areas in the separate window with the text annotations were recognised as being areas of conflicting opinions (and therefore interest), but users of *Redliner* reported having trouble in relating the text comments back to the 3D spheres at times, and generally wanted a lot of the features that came in later projects.

Later projects really started to build on the idea of community knowledge construction, with *AnnoCryst* (Hunter et al., 2007) being a good example of this. This system allowed for the side-by-side comparison of multiple 3D objects, but importantly allowed for both synchronous and asynchronous annotation, with changes being mirrored for all users and sent to each other as messages to keep everybody in the loop. This allowed for wiki-style conversation threads to begin, with messages stored for sharing and re-use with users who are not logged on at the time of discussion, and shows how 3D annotation systems allow for "harnessing the collective knowledge of a community of group" in order to "facilitate more rapid understanding" (Hunter et al., 2007).

As well as creative and interactive uses of annotations for spatial referencing in remote collaboration, there are also examples of previous attempts to expand the 'horizon of observation' around 3D virtual content to include interaction not just with the 3D object in question but between users, and introducing ways for (remote) collaborators to communicate in real-time during the annotation session. The *Vannotea* (Schroeter et al., 2006) system was very similar in functionality to *Redliner* and *AnnoCryst*, but with the added functionality of synchronous chat and videoconference-based collaboration. Taking this one step further was *Lighthouse* (O'Neill et al., 2011), a remote-collaborative system for troubleshooting printer problems, which used synchronised 3D representations of printers visible to both the customer and the troubleshooter to support real-time remote collaboration and allow troubleshooters to manipulate a shared pointer to highlight problems with the printer for the customer.

Most recently, 3D annotation – in a 2D, desktop interface format – has been applied to the exploration of virtual museum content. The *3D Semantic*

Annotation System, or *3DSA* (Yu, 2010) (Hunter and Yu, 2010) (Yu and Hunter, 2011) (Yu et al., 2011), represents the overall maturity of 3D annotation systems in general – re-usable, sharable and exchangeable annotations, the ability to attach tags to specific points, regions and segments, multiple resolutions for each 3D representation, and semantic annotations based on 'ontology and folksonomy' (existing museum information used to relate annotations to each other and group them into categories). It also shows the clear potential of 3D museum content as a vehicle for 3D annotations and the remote-collaborative construction and sharing of community knowledge.

4.1.3 Bringing the Ideas Together

RelicPad aims to bring these ideas away from the desktop interface metaphor and into the 3D, mobile context, providing a hands-on, digital alternative to two key physical interactions – physically moving an object around in the hands, and pointing at different areas of objects. Taking into account the underlying aim of enabling users to share information about these 3D artefacts, *RelicPad* can be broken down into three fundamental elements that underpin the application:

1. Manipulation (rotation and scaling) of the virtual museum artefact in 3D.
2. Real-time marking of interest points in 3D.
3. An interactive conversation history.

4.2 The Three Key Components of the System

4.2.1 Manipulating the Virtual Artefact

Tangible interactions are impactive and "dependent on a physical point of contact", in that they require that an actual object (such as a switch) is acted upon in order to see the effect, which distinguishes them from gestures (for example, waving at a sensor) (Price et al., 2010). Interactions themselves can be described in terms of manipulation (the action style used, such as grabbing, pushing, pulling etc.) and movement (the direction, duration, flow, regularity, and so on) (Price et al., 2010).

Most useful interfaces will contain a mixture of real-world elements – the tangible interactions (physical representations) just discussed – and artificial functionality (digital representations) (Jacob et al., 2008), and there needs to be a careful balance between the two. For tangible interactions, Hornecker & Buur (2006) offer three concepts that come together to create a well-balanced tangible interaction:

- Haptic direct manipulation – can users feel the important physical elements?
- Lightweight interaction – does the interaction allow the user to advance in small steps, guided by feedback?
- Isomorph effects – are the relationships (representations) between actions and effects clear and easy to understand?

In ensuring that tangible interactions are balanced, and thinking about isomorph effects in particular, it is worth remembering that a common mistake made in designing tangible interactions is the belief that the GUI metaphor can be translated directly into a physical input context, which is usually not the case (Snibbe and Raffle, 2009). Physical objects should respond naturally to physical input, and it is a waste to "restrict the body [or obects] to act as a pointer that activates buttons and widgets" (Snibbe and Raffle, 2009). However, most of the interaction techniques developed for 'natural' manipulation of 3D content have been developed "for stationary computers", and are simply "not applicable" to mobile devices (Henrysson et al., 2007). This seems like a missed opportunity considering that the rapidly improved display capabilities of smartphones and tablets has made the delivery of rich, interactive 3D content very achievable.

Tablets have an advantage over mobile phones in that their bigger screen size lends itself to better visualisation and easier interaction tasks (Hürst and Helder, 2011). However, even with tablets, exploration of 3D content on mobile devices is at present fairly limited, especially in terms of what it offers to museum content. The University of Virginia Art Museum's (UVaM) *Interactive iPad Museum Catalog* (Idea.org, 2011) allows users to choose one of a number of preselected artifacts from the museum's collection to view as a high-quality 3D visualization, but interaction itself is limited to dragging the finger on a touchscreen to rotate around a single axis, and scaling.

Not having keyboards or physical controllers of their own, many mobile applications simply incorporate on-screen GUI elements for navigation, make use of the touch sensitive functionality of the screen of the device itself, or use the device's sensor data (such as the accelerometer, allowing for the 'tilting' of the device to manipulate virtual worlds (Hürst and Helder, 2011)) as ways of controlling interaction.

Explorations that have been made into manipulating 3D content on mobile devices have experimented with these kinds of 'tilting' concepts using either computer-vision techniques (Henrysson et al., 2007) or built-in sensors such as gyroscopes, compasses and accelerometers (Kratz et al., 2012), and have proven to be a promising alternative to more traditional 2D interaction or touch techniques for 3D content rotation tasks. However, sensors are not only prone to noise, but tilt-based interactions can be particularly problematic for users in applications where the orientation of the device is intrinsically tied to the viewpoint in the virtual world (Hürst and Helder, 2011), and so these kinds of techniques need to be deployed with careful consideration.

Regardless of whether touch or tilt techniques are being used, in order to feel natural the techniques used to manipulate virtual museum artefacts should be based "on the real world" (Jacob et al., 2007). When the user is already skilled at performing the actions that underpin the basic operation of the system, the "mental effort required" for that operation can be significantly reduced (Jacob et al., 2007), and so a strong representational metaphor of object handling, requiring minimal thought and giving users enough freedom and control to focus their attention on the physical nuances of the object rather than how to manipulate it, should be considered as part of the interaction technique.

In order to expand the 'horizon of observation' around virtual museum artefacts in ways that current applications do not, it is important to ground these digital interactions in reality-based movements that are more akin to handling physical objects. It is largely the 3D experience of handling physical objects – turning them over, looking inside them, viewing them from all angles – that prompts thoughts and understanding about them, and helps the handler to make sense of the object (Boyes and Cousens, 2012).

Finding an appropriate interaction metaphor that gives users freedom and control over the manipulation (rotation and scaling) of virtual museum artefacts is therefore very important. This research focused on exploring techniques that employ one of two interaction metaphors for manually manipulating 3D objects using a tablet as the interaction device – tilt, and touch (figure 1).

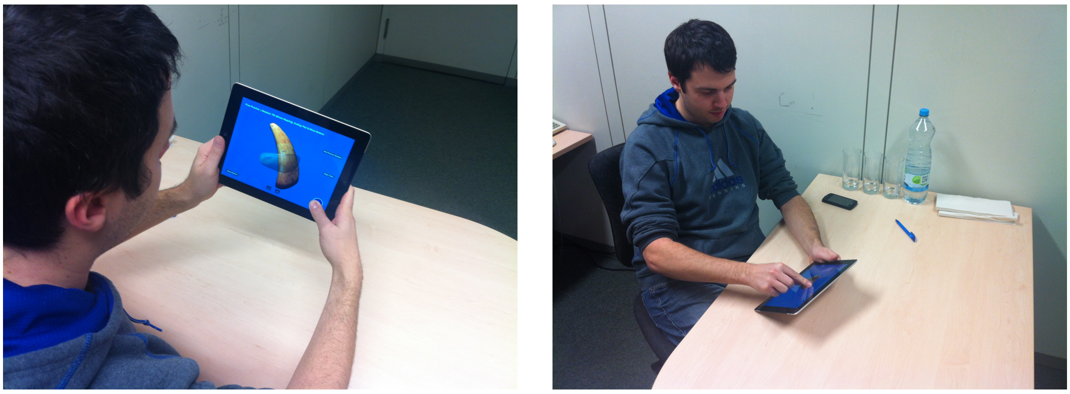

Figure 1. Tilt (left) and touch (right) interaction metaphors.

The tilt metaphor works by using the orientation of the device, given by the built-in sensors of the tablet (accelerometer and gyroscope), to calculate how the 3D content should be orientated, and represents the idea of using the hands simultaneously to grasp a physical object and rotating, twisting, or turning it around. Visually, it carries a strong physical representation of moving an actual object with both hands. In contrast, the 'touch' metaphor works by orientating the 3D content according to the position of the user's finger(s) on the device's screen, and represents something more akin to holding a physical object (in this case the tablet) in one hand, and using the other to rotate, twist or turn the object *within* that hand. Although more visually abstract than the tilt, this is certainly a more familiar and traditional tablet interaction technique.

Collaboration sessions were arranged in order to get a feel for the initial *RelicPad* prototype as a user experience, in which twenty-two participants, not selected based on any specific criteria, were invited to take part in eleven collaboration sessions and were encouraged to talk to each other, share ideas, and mark interest points in order to arrive at shared conclusions about what the virtual artefact (a nineteenth century piece of scrimshaw (scrollwork, engravings, and carvings done in bone or ivory (Wikipedia)) provided as a resource by the QVMAG) was, where it came from and the story behind it. During each session, each participant in a pair was given an iPad running a different version of the prototype. One participant was always using the tangible 'tilting' interaction method for rotating the virtual museum artefact, while the other participant was always using a more traditional 4-button 'directional pad' for rotating it.

The tilt rotation was rate-controlled (the virtual artefact rotates faster according to how far the tablet is tilted), with a rotation button or 'clutch' held to initiate and released to cease rotation. The four directional buttons were used to rotate the artefact up or down around the x-axis, or left and right around the y-axis. Neither participant knew that their collaborator was using a different technique to rotate the virtual museum artefact. The idea behind this was to evaluate whether or not there was any difference in how usable or engaging participants found *RelicPad* based on whether or not they used a physical, tangible rotation method, or a more traditional 2D interaction technique.

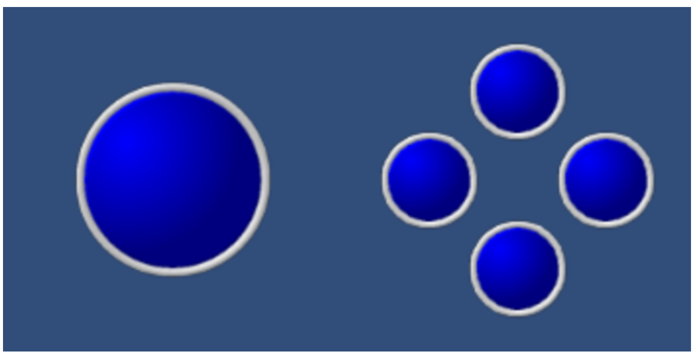

Figure 2. The ‘clutch’ used for the tilt rotation and the four rotation buttons compared as object manipulation methods in the early evaluation sessions.

Two ten-point scales were used to give numerical scores for the basic usability and the user engagement associated with each interface, based on the System Usability Scale (Brooke, 1996) – these scales will be described in greater detail in *Subsection 4.3.2: Interaction Design and Usability*. Separating the results of the first study according to which rotation technique was used, no significant statistical difference was found between the tilt and directional button techniques, and conclusions about which technique was more usable or affected the experience differently to the other could not be drawn. Two-tailed independent t-tests proved this to be the case for basic usability (t=-.981, df 15.6, P=.342), user engagement (t=-.612, df 20, P=.547), ease of rotation (t=-1.64, df 20, P=0.116) and overall impressions of rotation (t=-2.01, df 20, P=0.058).

However, ‘touch’ and ‘drag’ interaction techniques (well established interactions with tablet devices) and a direct (one-to-one) mapping of tilt to rotation (as opposed to rate-controlled) were both suggested as ways of improving the rotation technique. This was interpreted as an indication that while the rate-controlled tilt was not significantly worse than a more traditional 2D interaction, it was not significantly better either, meriting further exploration of interaction techniques and metaphors that might better represent the physical exploration associated with object handling.

In order to explore this further, a second study was devised in order to compare the efficiency of four rotation techniques for manipulation and exploration of a virtual museum artefact – two making use of the ‘tilt’ metaphor and two making use of the ‘touch’ metaphor. Efficiency in completing basic 3D manipulation tasks was here seen as being parallel to providing a good level of freedom and control over manipulating a 3D virtual artefact.

The two ‘tilt’ techniques were a rate-controlled tilt (where the angle at which the device is tilted defines the speed at which the virtual object rotates) and a direct-mapping tilt (where the virtual object's rotation follows the angle at which the device is tilted exactly). The two 'touch' rotation techniques were a 'virtual trackball' implementation (enclosing the virtual object in a sphere which is dragged with a single finger in order to rotate, described as a 'virtual sphere' in (Chen et al., 1988)) and a 'multi-touch' approach (dragging with a single finger to rotate the artefact on the x and y axes, and rotating two fingers clock-wise or counter-clockwise in order to rotate the artefact on the z axis).

Three techniques for scaling the virtual museum artefact were also compared – a 'plus and minus buttons' approach (holding one of two buttons to increase or decrease the scale of the artifact), a 'slider bar' approach (continuous dragging between the two end points on a slider bar widget to increase or decrease the scale), and a 'multi- touch' approach (increasing or decreasing the distance between two fingers, also known as 'pinching' and 'spreading', to increase or decrease the scale of the artefact)

Twelve participants were recruited to complete a set of 'object-matching' trials, using the different rotation and scaling techniques to match a virtual museum artefact (the scrimshaw piece from the first study) with a semi-transparent target orientation of the same artefact. The four rotation techniques were presented to participants in different orders according to a balanced Latin-square design (so as to minimise biases caused by practice or fatigue), and for each rotation technique there were eighteen trials – six with each of the three scaling techniques. Out of those six trials there were two simple, two medium and two complex rotation difficulties. Rotation difficulty was defined as being whether matching the virtual museum artefacts required rotation on one (simple), two (medium), or all three axes. This makes a total of seventy-two trials per participant.

For each trial, participants' speed (time taken to complete the trial), rotation error (difference between virtual and target artefacts in degrees) and scale error (difference in size of the virtual and target artefacts represented as vectors) were recorded. Participants were asked to think about each trial in terms of both speed and accuracy and move on to the next trial as soon as they were happy. However, to keep things moving and prevent the experiment from taking an unreasonable amount of time, participants were asked to move on to the next trial after around ninety seconds.

In between each rotation technique (every eighteen trials) participants were asked to answer some questions about that technique, and after all of the trials had been completed to answer questions looking back on all of the rotation and scaling techniques together. These questions asked participants to rate different aspects of the various techniques numerically, or to provide a few short sentences on the techniques.

The design of the experiment was based on a number of similar object-matching experiments from past research into techniques and technologies for 3D object manipulation, from early explorations with desktop-based VR systems (Chen et al., 1988) (Hinckley et al., 1997) (Poupyrev et al., 2000), to more recent approaches to manipulating 3D content with mobile devices (Henrysson et al., 2007) (Kratz et al., 2012) and touch displays (Martinet et al., 2010)

Table 2 shows how quickly and how accurately participants were able to complete the trials, on average, using each of the four rotation techniques – Rate-Controlled (RC) Tilt, Tilt with Direct Mapping (DM), the Virtual Trackball (VT) touch technique, and Multi-Touch. Touch techniques performed better than tilt techniques, being both quicker and more accurate to use:

Table 2. Speed and accuracy of the four compared rotation techniques.

Averages	Tilt (RC)	Tilt (DM)	Touch (VT)	Multi-Touch
Time Taken (seconds)	58.03	51.75	49.72	47.99
Rotation Error (degrees)	12.22	11.81	6.38	7.47

A comparison of how quickly and accurately trials could be completed, on average, using each of the scaling techniques is shown in table 3. Here, the touch technique performed better than its 2D counterparts, proving to be both the quickest and the most accurate technique:

Table 3. Speed and accuracy of the three compared scaling techniques.

Averages	+/- Buttons	Slider Bar	Multi-Touch
Time Taken (seconds)	56.08	50.91	48.62
Scaling Error (size difference)	7.03	6.63	4.65

Comparing all combinations of rotation and scaling techniques together supports this, with the combination of Multi-Touch rotation and Multi-Touch scaling resulting in the fastest average trial completion time at 41.61s, the smallest average scaling error (3.93), and the second-smallest average rotation error (6.10 degrees). The worst combination was Tilt (Rate-Controlled) rotation with Plus & Minus Buttons for scaling, which gave the slowest average task completion time (64.65), largest average rotation error (19.69), and largest average scaling error (8.66).

The questionnaires asked participants to rank the four rotation techniques in order from 1 (best) to 4 (worst) in relation to a number of different criteria, including: ease of rotation; perceived accuracy of rotation; perceived speed of trial completion; enjoyment; understanding of the movement of the artefact in 3D space; perceived control over the artefact; and favourite technique. On average, Multi-Touch recorded the lowest (best) average (between 1.42 and 1.75) for all of the criteria, while Tilt (Rate- Controlled) recorded the highest (worst) average (between 2.92 and 3.33) for all of the criteria. Participants were also asked to rank the three rotation techniques in order from 1 (best) to 3 (worst) in relation to the same criteria – Multi-Touch scaling also recorded the lowest (best) average (between 1.42 and 1.92) for all of the criteria.

Prior to the early evaluation, the tilt was seen as having a strong representational correspondence of moving an artefact with the hands (particularly visually), but the difference in rotation method used seemed to have little significance or impact on the usability of the application or what participants were able to make of the experience of interacting with the virtual museum artefact. The second study looked to explore alternative interaction metaphors for manipulating the virtual museum artefact, and to see what happened when scaling was introduced to supplement rotation.

The object matching trials, comparing various combinations of rotation and scaling techniques, showed that touch techniques performed significantly better and were more popular than tilt techniques, particularly 'multi-touch' techniques. Virtual objects could be rotated and scaled more quickly using touch techniques, and also with more accuracy – with no difference in display resolution that could influence this accuracy between the tilt and touch techniques, this suggests that manually fine-tuning to a target orientation is easier using touch techniques. Participants also reported enjoying using them more, having a better understanding of how the virtual object moves in 3D using them, and crucially having more control over the virtual museum artefact. This was interpreted as an indication that while the tilt metaphor carries a stronger visual representation of moving a physical object with the hands, the touch metaphor gives the user more control (figure 3).

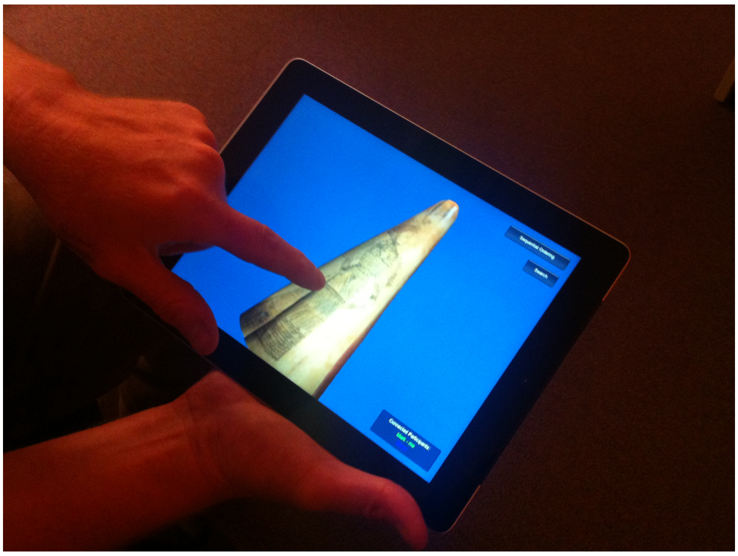

Figure 3. A user touching the screen of the tablet to rotate the virtual representation of the scrimshaw piece.

A number of factors may contribute to this – tablets have weight, and physically rotating them for long periods of time was tiring for some participants. The issue of viewpoint may also play a part here – with touch techniques the observation viewpoint is fixed while the hands manipulate the virtual objects (more akin to kind of viewing angles associated with physical object handling), while with the tilt it could be thought of as being the opposite, with the hands moving the observation viewpoint as opposed to the virtual object itself.

However, touch technologies have been around for decades in HCI research, and are now part of the everyday user's life, forming the backbone of countless smartphone and tablet interactions based on naïve 'physics' (Jacob et al., 2008). Clearly, touch techniques take advantage of interactions that are familiar to most users, leaving them free to focus on the content they are interacting with rather than the interaction technique itself. This thesis therefore takes the approach that by giving the user comfort and control, the touch metaphor better represents natural and relatively thoughtless manual interaction with the hands as a means of exploring the spatial properties of the 3D (virtual) artefact.

4.2.2 Marking Interest Points

As important as the manipulation of the (virtual) artefact was the question of which kinds of interactions support and help to organise discussion between collaborators, particularly remotely. Physical objects can play an important role in collaboration. As well as using them to "complete their own activities", collaborators often use objects to "coordinate [these activities] in real-time with the conduct of others" (Hindmarsh et al., 2000), and it has been suggested that collaborative activity "relies upon [collaborators'] mundane abilities to develop and sustain mutually compatible, even reciprocal, perspectives" of their environment and the objects within it (Hindmarsh et al., 2000).

Naturally, interaction with virtual museum artefacts needs to support similar processes of understanding and referencing between collaborators connected to each other over a network, who may well be connected remotely and unable to see each other. Common tools for collaboration and discussion (such as *Skype* or

Windows Live Messenger) allow users to share and exchange files, view each others' screens, send instant messages, and communicate in real-time using both voice and video. Existing research into systems that support remote collaboration have shown tags, metadata and annotations to be useful in constructing a mutual focus of attention for 2D data (e.g. text, images and video).

In museum informatics, the design of distributed systems for sharing information about artefacts and collections is a well-researched area in its own right, as various web (Goodman et al., 2010) and multi-media (Oomen et al., 2012) based approaches to managing museum data seek to encourage and facilitate the distribution of that data across as wide a museum community as possible. Visual media in such systems are generally 2D, and interactive content (beyond basic text, images and video) is limited. 2D interactions such as clicking images and following hyperlinks reflect this and there are few examples of these principles being used in 3D contexts, leaving these technologies with a very fixed horizon of observation that can only be pushed so far.

However, there is now such a wealth of available technologies for displaying and interacting with 3D content that interactive systems for remote collaboration could be making far better use of the visual channels available to them, particularly where the spatial referencing of 3D objects is concerned. When handling physical objects, people point to them to provide each other with a clear frame of reference and to clarify what portion, area or feature of the object is so interesting. Pointing is a clear visual gesture that draws attention to something that is deemed to be interesting.

Marking interest points with *RelicPad* supports discussion of virtual museum artefacts in the same way. Users are able to attach interest points to virtual museum artefacts that other users can then see for themselves in 3D space, in much the same way as people use pointing to guide others to what they want to see during discussions that focus on physical objects.

Annotations can be broadly classified according to their level of 'sociality' (whether the intended usage is by the individual annotator or by others) and their level of 'functionality' (intended uses, such as communication, organization and retrieval, or the communication of context), two dimensions which Ames and Naaman (2007) found crucial in understanding users' incentives for annotating photographs. They presented the following simple table (Table 4) for defining the incentives for annotation (Ames and Naaman, 2007), and it is interesting to think about some of the overlaps between these incentives and the collaborative elements of learning and engagement highlighted in *Chapter 2: Literature Review*:

Table 4. Ames & Naaman's (2007) definition of incentives for annotation.

	Self	**Social**
Organization	Search and retrieval	Public search and photo pools
Communication	Memory and context	Context and signalling

Marking interest points using *RelicPad* is achieved by tapping the screen on the area of the virtual museum artefact where the interest point is to be placed. As well as being a very familiar gesture to users of mobiles, tablets and touchscreens, the 'tap' gesture also resembles pointing in the physical and visual sense, making use of a single extended finger to "mimic [the] real world interaction" of pointing at something (Jacob et al., 2008). Tapping the virtual museum artefact brings up a box menu with a choice of three possible 'context' icons (see *Section 4.2.3: Conversation History* below) plus a fourth 'cancel' icon in case the user decides not to leave the point after all. Tapping one of these icons leaves an interest point with the selected context in the desired location.

Annotations are a common feature of collaborative technologies and efforts to increase interactivity have seen annotations transformed from being solely a means of "managing data and metadata" to becoming "critical" resources in "supporting communicative practice" (Fraser et al., 2006). The *Vannotea* system used annotations as 'metadata stores' to enable "the collaborative indexing, browsing, annotation and discussion of [in this case video] content between multiple groups at remote locations" (Schroeter et al., 2003), while the *Kinected Conference* sees annotations used to convey users' whereabouts in 3D, using video depth, audio cues and face-tracking algorithms to assign dynamic and interactive context tags to remote collaborators in a videoconference (DeVincenzi et al., 2011).

During the collaboration sessions that were arranged in order to get a feel for the initial *RelicPad* prototype as a user experience, observations were made and activity logs were kept that gave an indication of how interest points were used during collaboration. An average of twelve interest points were left during each of the eleven sessions. Participants on average would specifically refer to 48% of these interest points, whether that be to tell their collaborator that they had just left (or are about to leave) the interest point, to tell them exactly what part of the artefact it was being attached to, or to give them directions to help them find out where it is.

Participants on average asked their collaborator for clarification or an explanation of 13% of the interest points left, whether that was to ask where an interest point is, what it was supposed to be attached to, or whether they were looking at the correct one. Only once in all eleven collaboration sessions was a participant observed referring back to an interest point from earlier in the conversation, and this was only to clarify for their collaborator that an interest point left earlier had been placed there by mistake.

Referring back to Ames and Naaman's framework for annotation incentives, it could be argued that there is a sense of signaling each other (coordination and spatial referencing) and highlighting of context present in the way interest points were used. This shows that users made reference to interest points in order to limit ambiguity and confusion, and is very appropriate to the social, communicative nature of the collaboration sessions.

Based on some of the feedback received during these sessions, colour coordination was later added to the initial prototype, linking each connected collaborator to their interest points. Pearson et al. (2012) and Silva et al. (2012) describe incorporating colour-coordination in their own work, and how as well as being able to highlight, make notes, and have everything visible to everybody in real-time, in remote-collaboration "different members' [interest points] must be distinguishable".

A final addition to the original prototype, not strictly related to the marking of interest points but serving as an aid to them in limiting ambiguity and assisting in orientation, was a ghosting feature, whereby the user could click on the names of their co-collaborators and see a semi-transparent, colour-coded representation of exactly how their co-collaborators were manipulating their own 3D objects, in real-time (figure 4). The intention here was to support the use of interest points as a way of pointing out interesting areas by including a feature which would essentially allow each user to let the system point out for them exactly what their co-collaborator was looking at.

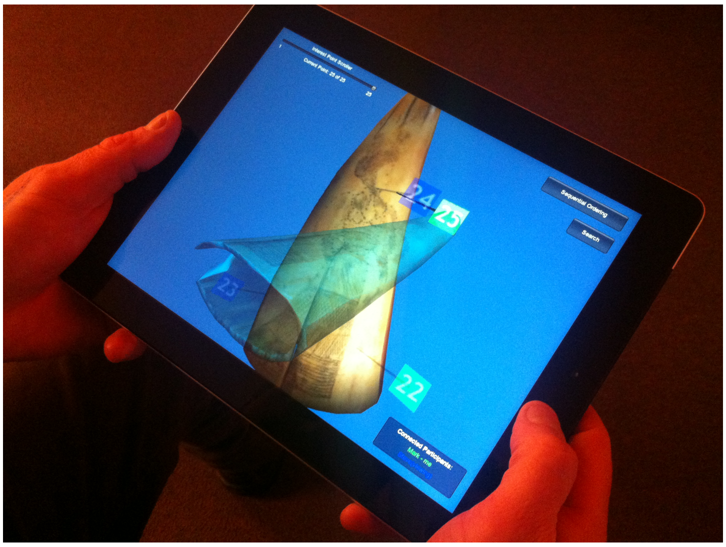

Figure 4. Viewing the colour co-ordinated ghost to work out how the collaborator might be looking at the virtual artefact differently.

4.2.3 Conversation History

As described in *Chapter 2: Literature Review*, people construct new ideas from prior knowledge, which is "the raw material that fuels learning" (Falk and Dierking, 2000). Learners are able to mentally organise and recollect information effectively, especially when it is shaped into a narrative format (Falk and Dierking, 2000), and use this to "bridge the gap" between themselves and new ideas – or in this case, museum artefacts (Black, 2005).

Interpretation is at it's most powerful when people are able to engage with the "human context" (Black, 2005), which often comes in the form of narration – "people relate to people", and to the accounts of events and the stories that they tell. People are fascinated by the idea of how people lived historically, and in touching something that was "last used hundreds or even thousands of years ago", an experience which carries a certain 'emotional impact' (Black, 2005). With this in mind, museums are acutely aware of the importance of narration and a linear structure in exhibits (Haywood and Cairns, 2005).

The interest points users leave during a RelicPad discussion come together to form an interactive 'conversation history', which acts as the narrative centered around the virtual artefact in question. An important classification tool for this conversation history is the context that can be used to define an interest point when it is being marked, something which Ames and Naaman (2007) consider as being of primary importance for annotations, alongside location. There are three context choices available, representing aesthetics (something about the way the (virtual) artefact looks that the user finds interesting), geometry (something about the shape of the (virtual) artefact that the user finds interesting), or meaning (something that the user feels provides clues about the cultural significance or idea behind the (virtual) artefact).

In addition to (optional) user provided keywords, the name of the user who left each interest point and the time at which it was left, the classification of context allows for a historical record of the actions made in discussions, conversations and collaborations to be kept, organised according to the interest points users have created. For collaborative use, this provides “a persistent record of interaction and collaboration” that can be easily referred back to (Stahl et al., 2006) and enables users to revisit earlier interest points and “remind [themselves] of the process by which they reached previous interim conclusions” (Fraser et al., 2006) – a linear, narrative account of the conversation unfolding around a given artefact.

RelicPad’s original approach to the ‘conversation history’ consisted of a scrollable menu in the top-right hand corner of the screen that stored all of the interest points in a discussion session (D in figure 5), adding the newest point at the top of the list each time they are added. This is a similar concept to the ‘look-at-this’ queue implemented into Pearson et al.’s (2012) collaborative reading application *BuddyBooks*, allowing users to ‘point out’ areas of a document to their collaborators and using menu entries as ‘placeholders’ that can be clicked through to enable quick and easy navigation through the document under discussion.

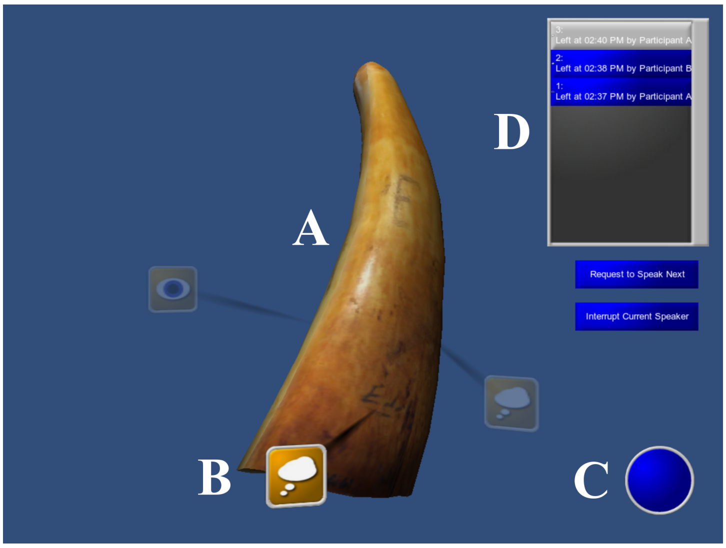

Figure 5. Key components of the initial *RelicPad* prototype: A) 3D artefact, B) interest point, C) ‘clutch’ for triggering tilt rotation, and D) interactive conversation history.

As well as an image representing the context assigned to each interest point, records of interest points in the conversation history also contained the keyword that the user left (if any), the name of the user that left the point, and the time at which it was left. This interactive but relatively traditional two-dimensional list left the conversation history in the periphery of the user's attention until it was needed – users could focus on their exploration and discussion of the artefact and on the physical interactions used to operate other *RelicPad* features, but could refer back to earlier points of discussion when they felt like it.

Many felt that the interest points themselves could have been more interactive – navigated to by touch, editable (renaming and deletion), more easily re-identifiable (either by keyword or by participant-based colour coding), and linked together to form a conversation thread. Working on the basis that combining the elements of interactivity from the conversation history into the interest points themselves may encourage collaborators to go beyond what they see of artefacts and to discuss further what those things might represent, giving spatial reference not only to areas of interest but to topics of interest as well, the revised version of the *RelicPad* system took a more interactive approach to the conversation history (figure 6).

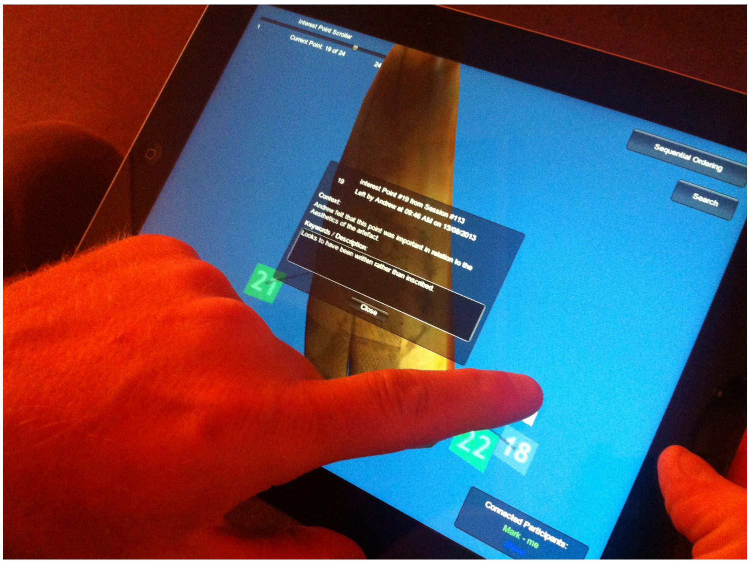

Figure 6. Exploring information after tapping a numbered interest point directly within the browser (as opposed to the previous menu-based approach).

This time, the information, keywords and context were linked not to a separate menu entry, but to the actual numbered interest point itself in 3D space, so as to connect the conversation history to the object not just linearly, but also spatially.

4.3 Creating the System

4.3.1 Developing the System

The implementation of the prototype system described in this thesis was designed for the Apple iPad tablet, which was chosen for both its convenience and accessibility, being not only readily available but also very familiar to the majority of potential users. In terms of software development, the application itself was written and developed using *Unity*, a "powerful rendering engine fully integrated with a complete set of intuitive tools and rapid workflows to create interactive 3D and 2D content" (Unity Technologies, 2014), rather than being written specifically for the iPad's native iOS operating system. The reasons for the decision to use *Unity* for the development of the system were two-fold:

- *Unity* offers an easy pipeline for the import, rendering and subsequent interactive programming of 3D content (in the case of this research, virtual representations of museum artefacts), which at the time that development of the system began was much more complicated in the iPad's native iOS.
- *Unity* facilitates exporting to a variety of formats. As well as meaning the developed application would not necessarily be tied solely to the iPad (but could potentially be exported to other tablet devices as well), this also made it very easy to export a desktop-based version of the application (for either MacOS or Windows) to use as the baseline desktop-interface version of the system for the later in-context evaluation (see *Chapter 5: Experiment & Results*).

4.3.2 The Technical Implementation of the System

The technical implementation of the system is relatively straightforward, revolving primarily around the three core features of the system as described theoretically in the previous sections – manipulation of the virtual artefact, marking of interest points, and interactive conversation history – which are linked together by a number of components and classes.

The whole application works using just two windows (referred to in *Unity* as *scenes*), the first of which is the LoginScene. Two important classes come into play here: the ArtefactPicker class, a simple selection for choosing which virtual artefact to explore, and the NetworkManager class. The NetworkManager class is the link between the application and the 'Master Server' functions provided by *Unity* for creating networked applications. The NetworkManager class searches for existing 'RelicPad_Sessions' giving the user the option to start a new session (by way of a StartServer function which registers a new host and updates the details of the session to the Master Server) or to join an existing session (a simple ConnectToServer function). The prototype system has been tested with four connected users successfully connected at the same time, and there is the potential for even more to successfully connect (although higher numbers of connected users would likely affect the speed at which the application can perform).

Whether a user is creating a new session as the server or joining an existing session as a client, the NetworkManager class stays active the entire time the application is running. The class is responsible for three important types of function, which constantly pass data about each user to and from the Master Server so that each connected user can see it. Five *update* functions (UpdatePlayerName, UpdatePlayerXY, UpdatePlayerRoll, UpdatePlayerScale, UpdateParticipantColor), four *get* functions (GetPlayerName, GetPlayerRotation, GetPlayerScale, GetParticipantColor) and four *fetch* functions (FetchPlayerName, FetchPlayerRotation, FetchPlayerScale, FetchParticipantColor) ensure that at any moment each connected user is transmitting their own position, scale, name and colour (for colour-coding of interest points) to the application, and can receive that information from any of the other connected users. Figure 7 shows how two iPads would send and receive information to and from both the Unity Master Server (via the NetworkManager class) and a MySQL database (via the

DatabaseCommunicator class as described later in this subsection) during a session:

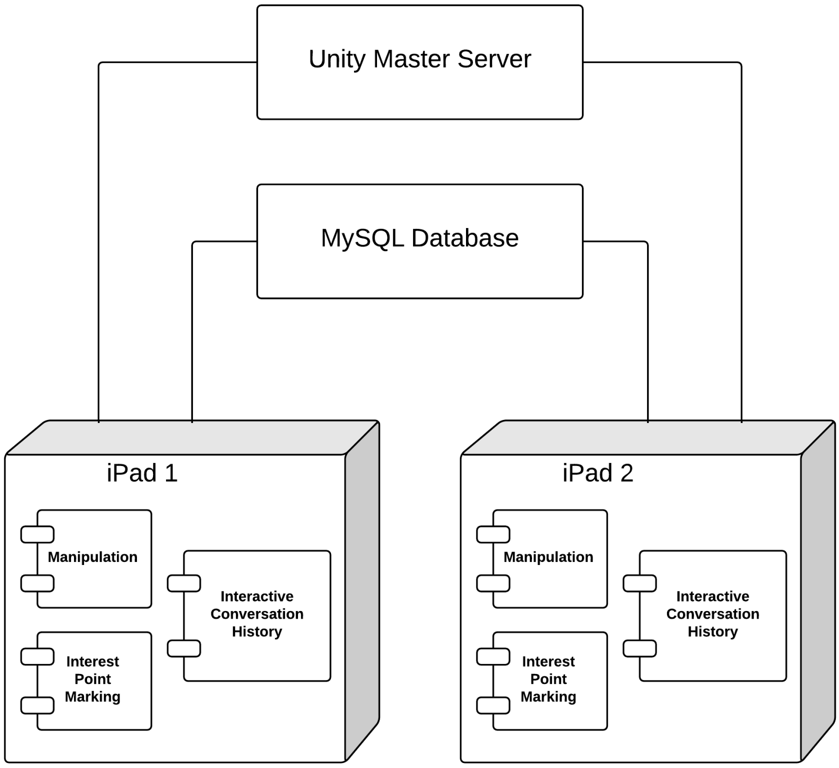

Figure 7. UML deployment diagram showing the connections between two connected iPads and the two online information sources – the Unity Master Server and the MySQL database.

After creating or joining a new session, the user is taken to the MainScene. This is the window shown in figures 3, 4 and 6, and where user interaction takes place. It is also the meeting point between the three key components of the system, which will now be described. The first of the three components is the manipulation of the virtual artefact, which is handled by an ArtefactManipulator class. This class is fairly straightforward, containing a constantly-running Update function which detects touches on the iPads screen by the user.

If the Update function detects just one touch, it first determines whether that touch occurred on the virtual artefact, and then rotates the artefact along its X and Y axes based on the position and movement of the touch (until such time as the touch ends). If two touches are detected, the Update function calculates a 'DeltaAngle' to determine whether the two fingers have been rotated around a center point, rotating the virtual artefact around its Z axis accordingly, or measures the distance between the two touches, increasing or decreasing the scale of the virtual artefact accordingly.

Besides moving the virtual artefact with the hands, the second major source of user input is the marking of interest points, the second of the systems three key features, which is handled by the IPMarking class. The user marks interest points by double tapping the virtual artefact at the point of interest, and an Update function waits for the double tap to happen. When it does, the IPSelection property becomes true, and the user is shown a box where they can enter a context and keywords for the interest point they are about to leave (similar to figure 6).

When they are ready to leave their interest point, the DrawInteractivePoint function is called, which adds a new interactive interest point object to the conversation history and to the database by way of the ConversationHistory and DatabaseCommunicator classes, which will be described imminently. Each new interest point that is marked is represented in technical terms by a PointOfInterest of the struct data type, and has a number of properties attached to it which describe both the information it contains (context, keyword, date and time) and it's physical properties (colour, location), both of which are important for the current session at the time that the interest point is recorded and for when it is recalled by future users in subsequent sessions.

The third key component of the system is the interactive conversation history, which is controlled by the ConversationHistory class. This class stores all of the interest points (created or loaded from the database) in the current session in a list, displaying them in the correct position and sequence around the virtual artefact based on their recorded positions and other properties such as their id numbers, the dates and the times at which they were recorded. An Update function listens for double taps from the user on any of the interest points, opening up a box for displaying information about a particular interest point when a user double taps it (figure 6). As well as opening up the box of information about a particular interest point, double tapping them also calls a ChangeInterestPoint function which makes the point in question the 'current' interest point.

The LoadInterestPoints function provides the link between the ConversationHistory class and the final class of note, the DatabaseCommunicator class, calling one of its major functions, GetInterestPoints. The DatabaseCommunicator class and its functions are the link between the application and the online MySQL database (independent from the Master Server which information about network connections and sessions is passed to and from by the NetworkManager class) where information about interest points in both current and previous sessions are stored, as well as 'actions' recorded as part of the application instrumenting described in *Section 3.2: Research Strategy*.

Key functions from the DatabaseCommunicator class include SendNewIP (which records details of a new interest point to the database), SendNewAction (which records details of an action made by the user to the database), and GetInterestPoints (which reads all the previous interest points about the current artefact NOT made during the previous session and loads them into the ConversationHistroy class as new PointOfInterest data structures). All of these functions essentially take data and variables from the application and push them to the SQL database by way of linked PHP scripts.

To summarise, the relationships between these components, classes and functions, which combine to create the foundational functionality of the prototype system, can be described by the following diagram (figure 8):

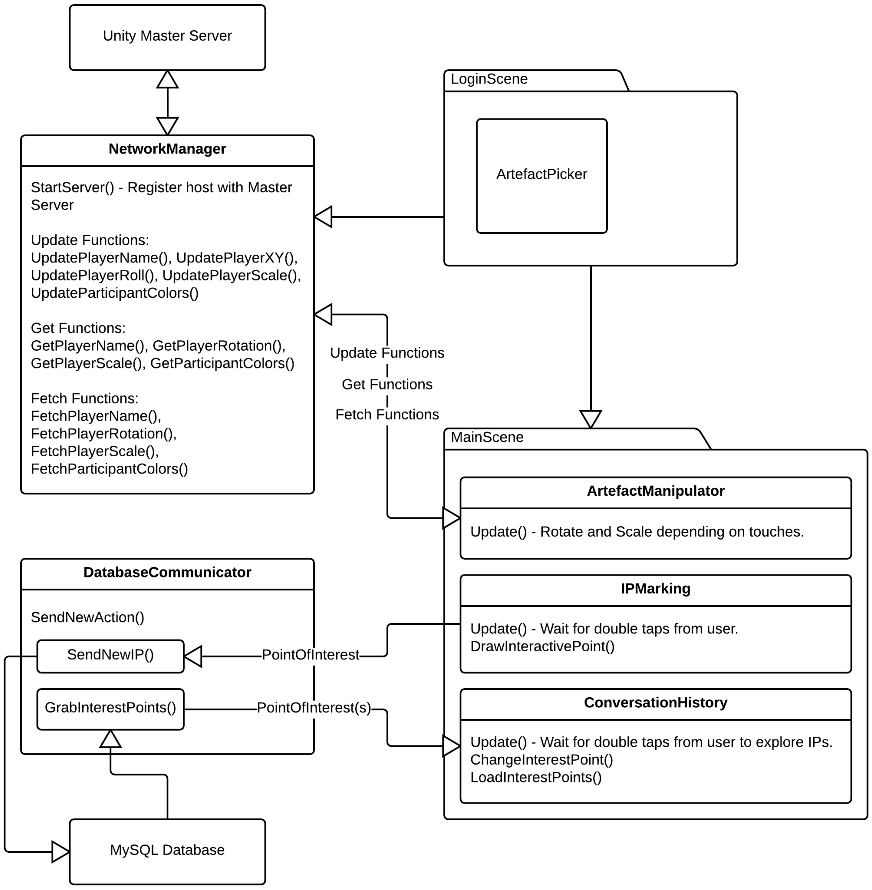

Figure 8. UML class diagram showing the relationships between scenes, functions, servers and databases that allow the three key components of the system to communicate with each other.

4.4 The System in Summary

4.4.1 Novelty and Representation

The three elements described in the previous section come together to provide representations of physical object handling, pointing and organising topics of discussion, giving users everything they need to be able to explore virtual museum artefacts in a hands-on manner and to discuss them in collaborative scenarios. Users can manipulate (rotate and scale) the virtual artefact using their hands to build up an understanding of it in 3D, can mark interest points to show each other where (and in what context) something interests them, and can refer to the interactive conversation history to remind themselves of how conclusions were made and revisit earlier topics of interest.

3D browser annotation in itself is not a novel concept: over the years research has seen applications that focus on the interoperability of 3D objects and tags, allow for the uploading and downloading of shared annotations over a network, semantic annotations that tap into existing ontologies and information folksonomies, and the ability to attach annotations to specific points or regions of 3D objects. The *3DSA* system described in *Section 4.1.2: Previous Examples of 3D Browser Annotation* is also an example of these kinds of ideas being applied in the museum space, to aid in the collaborative discussion of 3D museum objects.

However, even systems like *Lighthouse* and *3DSA* still use a mouse and keyboard (2D interfaces) as the input methods for interactions with 3D content. Alternatives to web browser-based exploration, particularly 3D, physical and tangible interaction techniques, have not received much exploration for this kind of experience, despite being ideally suited to exploring (virtual representations of) museum artefacts, whose 3D qualities are of vital importance to the messages and the histories they convey. Integrating collaboration, discussion and annotation with 3D object manipulation using a manual, mobile interface can expand the horizon of observation around virtual museum artefacts, and as hypothesised in the introductory chapter provide an engaging experience of exploration and discussion that facilitates meaningful learning outcomes.

Fishkin (2004) describes how tangible interactions can "embody different levels of metaphor", ranging from fully realised metaphors which are exactly equivalent to the corresponding real-life action to weaker metaphors, where the link between action and effect are not exactly as they would be in real-life. *RelicPad*'s interactions carry numerous different levels of metaphor, with some, of course, being more realised than others, but in general it is what Price et al. (2010) describe as a 'subject-centric' application, in that the emphasis is on the design of the interactions with the tablet interface, rather than the design of the tablet itself.

The eventual choice of touch over tilt metaphor described in *Subsection 4.2.1: Manipulating the Virtual Artefact* is a good example of this – tilting the tablet around is a more fully-realised metaphor of handling a physical object, but a weaker metaphor (touch, which is still manual and has some physicality but does not necessarily look as much like handling an object) was chosen as it seemed more natural to make use of an interaction style that was comfortable, familiar, and relatively thought-free for users.

Representations can be thought of in terms of their significance (how meaningful and long-lasting they are and the salience between physical and digital representations), their degree of externalisation (how successful interfaces are in providing focus and in mediating actions), and the perceived coupling between what the user does and what happens (Hornecker and Buur, 2006). Price et al. (2008) describe coupling in more detail, explaining that represented actions can be discrete (with the input and output spaces located separately), co-located (with the input and output spaces adjacent to each other), or embedded (with the effect occurring within the object/interface itself).

As an experience, externalisation is accounted for in the way that marking interest points and constructing a conversation history mediates the collaborators' thoughts and discussions, making sure that focal points are the same for all involved and providing a record of what has occurred in the current and in previous sessions. Representational significance, like learning, is something that is difficult to specifically test for or claim in this thesis, but as with the facilitation of learning, the approach taken is that if the experience, by way of being based on real-world concepts and collaborative, is engaging, then the effects of interactions are likely to be meaningful and long lasting.

The touch metaphor with RelicPad was seen as providing a strong coupling in terms of object manipulation, with the movement of the 3D artefact being responsive in real-time to the users touch, just as somebody exploring a real object by hand would expect it to move in a certain way according to their touch. The perceived coupling is made stronger by the fact that it's an embedded coupling – the user has to specifically touch the 3D artefact to move it (not just anywhere on the screen) and so the artefact only responds to actually being directly beneath the user's touch.

Similar to perceived coupling is the idea of causality, the association between objects and the action or effect they facilitate. This causality can be either simple (whereby the desired effect is direct and immediate), complex (whereby the representations and the effects of an action may change or develop in some way over time), or serendipitous (whereby actions are inadvertently or unexpectedly triggered) (Price et al., 2008). *RelicPad* makes use of simple causality for the most part – the movement of the virtual artefact is immediate and directly related to the user's touch – although in the case of marking interest points things are perhaps a little more complex, with the choice of context and writing of keywords taking place in between the action (tap) and the effect (realisation of the interest point) (figure 9).

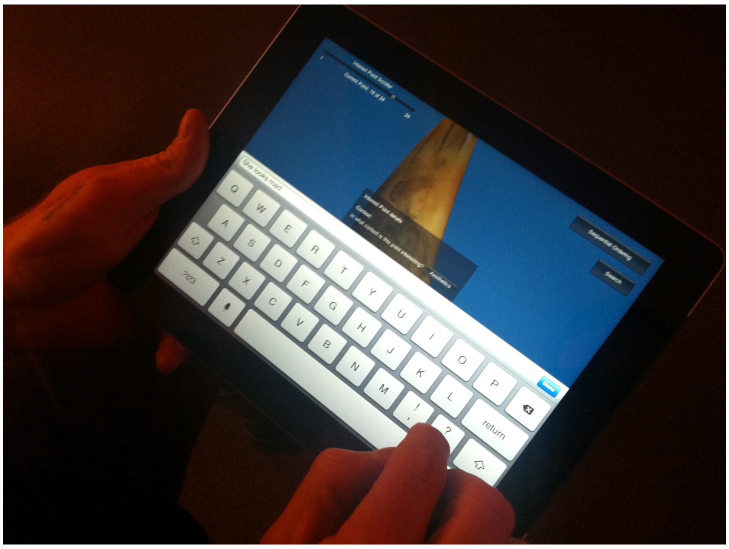

Figure 9. Writing additional keywords / information to accompany a newly left interest point.

A final aspect of representation that is interesting to think about is how physical representations, the actions themselves, can be interpreted. Physical representations can either be symbolic (leveraging few or no characteristics from the corresponding real-world action), literal (closely mapped to a real-world action) or representational (mapped to the learning domain metaphorically as opposed to literally or symbolically) (Price et al., 2008). Here, *RelicPad* carries a literal representational correspondence – the touch metaphor is probably not quite as symbolic as the tilt metaphor (it would be difficult in real-life to rotate a physical object using just the finger, for example), but it certainly more literal than using a mouse or keyboard (located discretely from the display device), which would constitute a symbolic correspondence in terms of physical interaction.

4.4.2 Interaction Design and Usability

In museums, "active (physical) media are very successful" and previous research has suggested that the hands-on approach "engage[s] many and all types of visitors for long interaction sessions" (Hornecker and Stifter, 2006). Coupled with the need to provide strong representations of handling objects, this suggests that, as originally hypothesised in *Chapter 1: Introduction*, the hands-on, tablet approach taken by this thesis could be more engaging, and thus better facilitate potential learning outcomes, than the traditional 2D mouse and keyboard approach to such applications.

However, equally important is that due to the "many competing objects, time pressures and voluntary usage" associated with museum experiences, "a low threshold for interaction is essential" whereby "the first ten seconds need to provide an incentive to continue" (Hornecker and Stifter, 2006). Clearly, that the application is usable is of the utmost importance, specifically when considering that, as described in *Subsection 2.4.1: Key Facets and Elements* (of engagement), engaging technologies do display an inherent baseline of usability.

Sharp et al. (2007) describe usability as being about "considering who is going to use an interactive system, how they are going to use it, and where they are going to use it", an amalgamation of five key factors:

1. Effectiveness – are the contents and functions appropriate and organised?
2. Efficiency – can users do things using the appropriate degree of effort?
3. Safety – is the system safe to use in context?
4. Utility – can the system do all the things the user needs it to do?
5. Learnability – can people learn and remember how to use the system?

During the initial prototype evaluation described earlier in this chapter, questionnaires were given to each individual user after the discussion was over. As mentioned in *Subsection 4.2.1: Manipulating the Virtual Artefact*, these consisted of two sets of ten questions based on the System Usability Scale (SUS), a widely accepted, "simple, ten-item scale giving a global view of subjective assessments of usability" (Brooke, 1996). The answers from the scale can then be used to generate a single number representing "a composite measure of the overall usability of the system being studied" (Brooke, 1996).

The first set of ten questions was identical to the original SUS scale, focusing on Sharp et al.'s five basic factors of usability (effectiveness, efficiency, safety, utility and learnability), with each pair of questions focusing on one of these five factors. For every pair of questions in the set of ten, the SUS seeks a positive followed by a negative response, which ensures that the respondent thinks about their answers, rather than answering positively (or negatively) out of routine or habit. The second ten questions were specifically written to follow the format of the SUS scale, but instead contained pairs of questions focusing on the five core components of user engagement as proposed by Benyon (2010) and outlined in *Subsection 2.4.1: Key Facets and Elements* (of engagement) – identity, adaptivity, narrative, immersion and flow.

The ten responses from the SUS can then be used to calculate a single number for usability, the mean score for which across all participants was 70.6. The second set of ten, based on the five core components of user engagement, were used to calculate a single number for engagement, the mean of which across all participants was 73.07. This gave a reliable indication that the initial *RelicPad* prototype was reasonably engaging in its early form, supported by a good degree of usability, and that the revised prototype going into the in-context study described in the next chapter would be evaluated from a solid starting point.

It is important that the interactions that the system makes use of are well designed, as this will obviously contribute greatly to how usable the interactions are. Interaction design generally revolves around four key principles (Benyon, 2010), which have some crossover with the key components of usability:

1. Helping people to access, remember, and learn:
   - This is largely about making things visible, so that they can see what can be done, what the available options are and what is happening (largely influenced by the consistency and familiarity of what is visible), and about making sure that things have good affordances that make it clear what they are and what they are for ("designing buttons that look like buttons"), something Norman (1990) refers to as "provid[ing] a good conceptual model".
2. Giving users a sense of control:
   - This is essentially a case of navigation (enabling users to move between different parts of the system and maintain their feeling of control over interactions) and feedback (making sure users are aware of the effects that their actions have had).
3. Safety and security:
   - This is about making sure that recovery is possible, and that users are able to correct themselves if they make mistakes or errors. Constraints are also needed to limit the number of allowed interactions, or warn users of (or ask them to confirm before making) potentially dangerous interactions.
4. Functionality that suits the user:

- This is about making sure that the application is flexible (that there are multiple ways of accomplishing tasks and that different levels or interest or skill are accommodated) and is convivial (polite and user-friendly, as opposed to being overly instructional or demanding in an aggressive sense).

These principles apply to the design of both physical and digital representations, but it is also important, in order to make the best use of the available interactions, to strike the right balance between the two types. Despite the cognitive benefits of well designed physical representations of interaction, an overreliance on physicality can actually be a hindrance to users in trying to make sense of the accompanying digital representations and engage with the actual content itself, as Otitoju and Harrison (2008) observed when they encountered that people interacting physically in museum spaces could often be so involved in, and focused on, discovering new interactive elements to explore, that the actual informational content of the exhibits themselves passed them by.

4.4.3 Facilitating Learning

Hein (1998) describes how there are four key types of learning experiences in museums:

1. Didactic experiences:
    - Sequential, hierarchal, arranged experiences, categorised by a clear beginning and end, an intended order, adherence to a curriculum, and specific learning objectives directed by the content itself (Hein, 1998).
2. Stimulus-response experiences:
    - Very similar to didactic experiences, but facilitated by focused influences that seek particular responses from museum learners (Hein, 1998).
3. Discovery experiences:
    - Explorative, interpretive experiences, that present information that asks questions and prompts visitors to find out for themselves, assess their own interpretations against the correct information, and engage

in activities such as contemplation and consideration of learning material (Hein, 1998).

4. Constructivist experiences:
    - Similar to discovery experiences, but without specific paths or a clear beginning or end, presenting a range of points of view, enabling participation in a range of different activities and providing some way for visitors to validate their conclusions (Hein, 1998)

Discovery experiences require an active learning situation that engages learners in challenging and cognitively stimulating activities, allowing them to “manipulate, explore and experiment” in order to learn (Hein, 1998). Where the use of interactive technologies is concerned, museum learners can be “overwhelmed with too much text and would prefer to find information next to exhibits (Hornecker and Stifter, 2006), making discovery experiences more suitable to engaging collaborative discussions than a didactic or stimulus response approach.

RelicPad, however, offers a more constructivist approach, simply presenting an environment (populated by a 3D virtual artefact) and waiting to see if the user can make any connections themselves – if they can find a ‘familiar reference’ (referring back to previous knowledge as described in *Section 2.1: Learning in Museums*, or communicating knowledge to their collaborator as described in *Section 2.2: Collaboration*), they will be able to engage with the content (Hein, 1998). Initial observations from the early collaboration sessions showed that people were able to use *RelicPad* to collaboratively construct knowledge, and using interest points to clarify, present, and validate points of view during discussion was a large part of this.

It was noted that participants were able to use interest points to give each other spatial references, that by the end of a discussion they had collaboratively constructed solid ideas of what the artefact (scrimshaw) was, and that they felt positive about being able to rotate the representation of the artefact in 3D, suggesting that *RelicPad* had and could facilitate the exploration and collaborative discussion of virtual museum artefacts. Touch interaction techniques were then found to provide a good representational model of being in control of the manipulation of a virtual museum artefact in 3D.

In the early evaluations, marking interest points proved to be the most popular and commonly used feature of *RelicPad*. Almost half of the interest points left were directly referred to by participants verbally, usually to explain what the interest point refers to as it is being left ("that there, it's a parasol"; "and you can see in this section here that it's lighter"; "down below there, that marking"; "it's broken, on your left side – I'll point it out for you"). This indicated that participants would use the interest points for the intended purpose, 'pointing out' interesting areas or features of the (virtual) artefact to help each other to maintain their spatial understanding of the topic of discussion, which as described in *Section 2.2.3: Object-Based Collaboration* is crucial for object-based collaboration.

Visitors to museums often "collaboratively explore or 'play with'" exhibits together (Hindmarsh et al., 2002), but this kind of exploration is severely constrained by didactic and stimulus-response approaches to the presentation of content, which is the approach still widely adopted by interactive museum experiences (Hindmarsh et al., 2002). A better option for encouraging participation and interaction between potential museum learners is to allow for experiences to be configured in different ways, providing "progressive opportunities to create and develop novel forms of interaction and participation" (Hindmarsh et al., 2002).

Allowing people to explore and talk freely about museum objects using *RelicPad* showed that allowing collaborators to configure the experience for themselves (through exploration and discussion of the artefact as opposed to digesting didactic information) facilitates collaborative exploration. The early evaluations showed that participants noticed and discussed most of the things that were identified prior to the experiment as providing the history, story and significance of the scrimshaw piece. This indicates that not only did participants enjoy exploring the artefact and marking interest points, but that being free to do so at their own (in accordance with their collaborator's) pace bore results, which is especially interesting given that to most participants it was not obvious from the start what the (virtual) artefact actually was.

It was through exploration, discussion and theorising with each other – configuring the experience in real-time as opposed to following didactic prompts – that participants were able to come to conclusions about what the (virtual) artefact was or was not. These results were interpreted as showing that using interest points to draw attention to notable features of a virtual museum artefact helps users to understand and clarify which areas are of particular interest, and that over the course of a collaborative discussion these interest points are used to drive conversations and exchange ideas and theories.

Comparing different interaction metaphors for the manipulation of virtual museum artefacts also suggested that established and familiar tablet interaction techniques such as multi-touch are efficient for controlling the manipulation of virtual museum artefacts, enabling users to understand the 3D experience of the (virtual) artefact comfortably and allowing them to focus on discussing the artefact rather than on the interaction technique being used to explore it. They also offer the user instant feedback based on simple causality – the virtual artefact moves directly and instantly according to the user's touch. This allows for 'a lightweight' and 'conversational' style of interaction whereby users can "express and test their ideas quickly" (Hornecker and Buur, 2006), and have hands-on, manual control over the (virtual) artefact as they look to make sense of it's 3D properties.

Collaborators are able to direct each other's attention to areas of interest on virtual museum artefacts, using a touch-tapping interaction that carries a literal representational correspondence akin to physical pointing to mark interest points on virtual artefacts in 3D. Participants in the collaboration sessions arranged as part of the early evaluations appeared to relish this ability to 'point' at the virtual artefact and being able to highlight areas of interest for each other.

In this sense, *RelicPad* is able to expand each participant's horizon of observation in relation to both the virtual museum artefact itself, and also to the focal points of each other's attention.

As well as being well received as a positive experience by many participants in the early evaluations, feedback showed that many of those participants saw the suitability of the application in museum contexts, specifically commenting that the application was good for remote collaboration and the spatial referencing of museum artefacts. This indicated that not only had *RelicPad* been used by participants to good effect, but that with the right touch interaction metaphor in place would offer a solution to the research problem and the scenarios highlighted in *Section 1.2: Research Problem* (such as the example remote-collaboration scenario provided by staff at the QVMAG) and as originally hypothesised provide an engaging, hands-on means of collaboratively exploring and discussing virtual museum artefacts, with that engagement being likely to facilitate meaningful learning outcomes.

Chapter 5: Experiment & Results

The prototype *RelicPad* system designed as a proposed solution to the research problem of limitations on access to museum artefacts for collaborative exploration and discussion has been outlined: a tablet-based 3D browser interface for exploring virtual representations of museum artefacts from all sides and angles, and with support for the marking of interest points on the virtual artefacts in 3D space and in real-time. It was earlier hypothesised that such a system will be an engaging way of collaboratively exploring and discussing virtual objects, and that in the case of virtual museum artefacts will lead to an experience which is more akin to that of viewing and handling physical objects than other, less-engaging interfaces.

This chapter describes how the philosophies and strategies outlined in *Chapter 3: Research Methods* have been put into use. Firstly, the in-context study designed to evaluate the system, according to the research questions posed in the introductory chapter and with a view to proving or disproving the original hypothesis, is described, including studies from related work that have influenced it and an outline of the proposed study procedures. The results gathered during the study are then presented, broken down and arranged according to the various data collection methods used to obtain them.

5.1 Experimental Design

5.1.1 Experimental Influences

As well as by the success of the early collaboration sessions conducted to give early impressions of the initial prototype (as described in *Chapter 4: System Design*), the in-context study of the system drew inspiration from similar experimental designs used to evaluate the 3D annotation systems described earlier in *Section 4.1.2: Previous Examples of 3D Browser Annotation*:

- *Redliner* (Jung et al., 1999, Jung et al., 2002) was evaluated with in-context usability evaluations, where an existing task and a sample task scenario are completed.
    - The evaluation consisted of an explanation of the procedures followed by the tasks, during which the investigators made observations of activity, followed by questionnaires.
    - Performance was compared with the completion of a physical version of the task, in order to evaluate the speed of task completion and the spatial understanding of participants.
- *Vannotea* (Schroeter et al., 2006) was also evaluated with in-context usability evaluations, with research groups invited to use the system to collaborate on their projects.
    - The evaluation was designed to test all aspects of the system and it's use, from logging on and successfully posting annotations to the robustness and performance of connections.
- *AnnoCryst* (Hunter et al., 2007) was also evaluated with a usability study.
    - Like *Vannotea*, the participants for the study were a research group invited to make use of the system in context.
- *3DSA* (Yu, 2010) (Hunter and Yu, 2010) (Yu and Hunter, 2011) (Yu et al., 2011) was again evaluated with a usability study, with 8 participants (a mix of museum staff and research students from technology and arts faculties) invited to use the system.
    - Like *Redliner*, the evaluations consisted of an explanation of the procedures followed by the tasks, with system output and questionnaires providing the materials to be evaluated.
    - *3DSA* was compared against existing systems – *Adobe Reader* for annotating points, and *ShapeAnnotator* for adding annotations to surface regions and segments – providing a baseline for comparison of functionality.
    - The performance of the system was also measured – characteristics such as download and upload speeds, and display efficiency across different browsers and platforms.

Based on the influence drawn from these previous evaluations of 3D annotation systems, the in-context study was designed to make use of as much information as possible to provide sufficient data of both quantitative and qualitative varieties, as initially described in *Section 3.2.2: Study of the Prototype System in Context*. Tracking system usage data and storing a log of user actions in a database provided quantitative data for statistical analysis (Hornecker and Stifter, 2006), while observations of collaboration sessions (Hornecker and Stifter, 2006) and mixed methods questionnaires, allowing users to subjectively compare the mobile, hands-on *RelicPad* experience with alternative viewing methods (Haywood and Cairns, 2005), provided qualitative data.

This information gathering was driven by an 'artificial' task, with study participants encouraged to use the system together to try and "achieve certain goals" (Brown et al., 2003) – in this case, to muse together about a (virtual) museum artefact. Using the mixed methods approach, the qualitative data collected could be used to "interpret patterns and highlight inaccuracies [or] blind spots" in the quantitative data, which could in in turn "create new issues to focus on in the qualitative" (Hornecker and Stifter, 2006). The complementary nature of the collected data types provided a wealth of information for, as described in *Section 3.2.3: Analysis of In-Context Study Results*, an in-depth analysis and interpretation of what, when, how, and why participants did things during the in-context study.

5.1.2 Experiment Outline

The experiment outline for the in-context study was essentially a larger-scale and more in-depth version of the earlier collaboration sessions with the initial *RelicPad* prototype described throughout *Section 4.2: The Three Key Components of the System*. For the in-context study, participants were invited to take part, in pairs, in collaboration sessions of approximately one hour in length. During the sessions, the paired participants were encouraged, as before, to talk to each other, share ideas, and (when using digital interfaces) mark interest points in order to arrive at shared conclusions about what the (virtual) artefact was. The sessions took place in a purpose-hired space at the QVMAG (figure 10).

Figure 10. One half (separated by a partition ready for a 'remote-located' session) of the purpose-hired space at the QVMAG.

As with the previous collaboration sessions from the initial evaluations, there were two key aspects based on which the system was measured:

- Dependent variables:
    - Usability (which can be thought of as just how 'reality-based' the system really is),
    - Engagement (which would be a good indicator of whether or not the experience of using the system is one that would facilitate or encourage learning).

However, the in-context study delved deeper than its earlier predecessor into the different conditions that might have had an effect on those measurements:

- Independent variables:
    - Collaboration type (co-located or remote-located).
    - Viewing method (whether the artefact is viewed as a physical object, digitally using a desktop browser, or digitally using the tablet browser).
    - Artefact type (delicate object, small object, or mechanical object).

5.1.2.1 Collaboration Types, Viewing Methods, and Artefact Types

During the collaboration sessions, each pair of participants was either remote-located (able to hear but not to see each other, and using the digital viewing methods to mark interest points and direct each other's attention) or co-located (seated together and sharing one interface between them) (figure 11). They were asked to discuss three artefacts using a different viewing method for each, so that by the end of an hour-long session, each pair had looked at all three artefacts, and had used each of the three possible methods of viewing an artefact.

Figure 11. A pair of participants share the tablet interface in a co-located session (left), while one from a pair of participants, separated from his collaborator by a partition as in figure 10, uses the tablet interface individually (right).

The three possible viewing methods for exploring the artefacts were:

- (Physical) Object Viewing:
    - Viewing the physical artefact in a glass case. This is the typical museum viewing experience, serving as a baseline for engagement against which the two digital viewing methods could be compared.
- Desktop Interface:
    - The *RelicPad* experience on a desktop computer – viewed on a fixed monitor and using a mouse and keyboard for interaction. Other than the interaction style and the fixed-monitor viewing paradigm, the *RelicPad* application itself was exactly the same, with identical options, features and control of the virtual artefact.
    - The desktop browser experience provided a comparison between the hands-on, mobile *RelicPad* experience and the way 3D

exploration and annotation of virtual museum artefacts is currently realised using systems such as *3DSA* (Yu, 2010) (Hunter and Yu, 2010) (Yu and Hunter, 2011) (Yu et al., 2011).

- Tablet Interface:
    - The true hands-on, mobile *RelicPad* experience, as described previously in *Chapter 4: System Design*, which as hypothesised in *Chapter 1: Introduction* was expected to be engaging and to provide an experience closer to (Physical) Object Viewing than 3D exploration and annotation using the Desktop Interface.

Figure 11. A participant using the desktop interface (left), and a participant using the tablet interface (right).

Figure 13. Two participants looking at an artefact in its glass display case during (Physical) Object Viewing.

Meanwhile, in collaboration with curators at the QVMAG, three different artefacts were chosen to serve as the content for the in-context study, based on characteristics that it was felt would benefit from the possibilities for 3D exploration that the digital viewing methods provided. The three artefacts were:

- Chinese Figurine – the *delicate* object:
    - The figurine was chosen for its delicate embroidered elements (the jacket of the character, for example), which would not be able to be touched during (Physical) Object Viewing.
- Insect (Raspy Cricket) – the *small* object:
    - The insect was chosen as an example of something very small, which without some sort of magnification could not be seen or easily appreciated in detail during (Physical) Object Viewing.
- Plate Camera – the *mechanical* object:
    - The camera was chosen as an example of something with complicated or moving mechanical parts, the function or relationships between which might not be obvious or apparent from the limited angles available during (Physical) Object Viewing.

Figure 14. The Chinese Figurine on display in the museum space in its glass case during the study (left) and virtually represented using *RelicPad* (right).

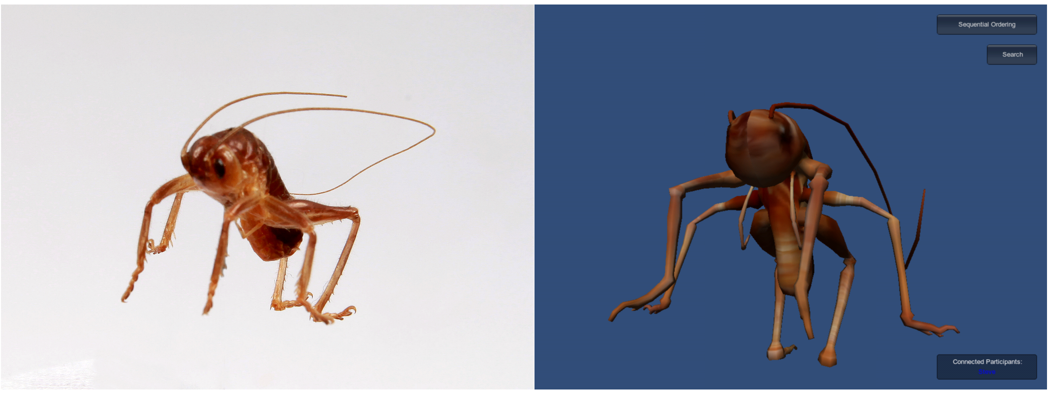

Figure 15. The Insect (Raspy Cricket) professionally photographed (left) and virtually represented using *RelicPad* (right).

Figure 16. The Plate Camera professionally photographed (left) and virtually represented using *RelicPad* (right).

Figure 17. How the Insect (left) and the Camera (right) looked on display in the museum space in their glass cases during the study.

5.1.2.2 Creating 3D Virtual Museum Artefacts

Any 3D models could potentially be loaded into *RelicPad* or a similarly designed system regardless of how it was created. Although many museums are now engaged in digitizing their collections and may have many artefacts already rendered as 3D models with incredibly high representational fidelity, the artefacts selected for this research at the QVMAG were not already digitized, and due to time, cost and access restraints the 3D scanning of the selected artefacts at short notice was not a viable option. Thus, the virtual museum artefacts used in the evaluation (as seen compared with their physical counterparts in figures 14, 15 and 16) were created specifically for this research, a process which was undertaken manually using *blender*, a "a free and open source 3D animation suite" (Blender).

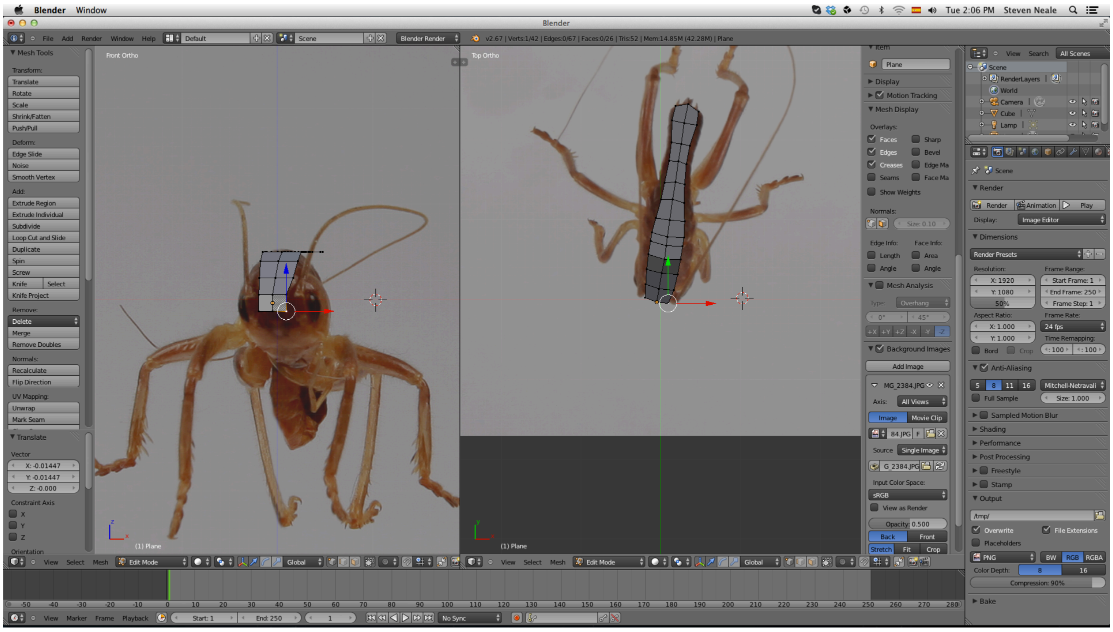

Figure 18. Images of the Insect (Raspy Cricket) being used for reference during the manual 3D modeling of it's virtual representation using *blender*.

Photographs were provided of each artefact from multiple sides and angles, which were used as background images in *blender's* viewports to provide a reference from which to work with. 3D models were then manually created using *blender* – following the reference images and drawing new vertices, edges and faces along the way to construct a 3D model from scratch (figure 18) – before the referenc images were then re-used to create a 'skin' or texture and mapped back onto the 3D model. This was more successful and produced better results in some cases than in others, with participants finding that the representational fidelity of the 3D, digital version of the Plate Camera was much more acceptable than the representational fidelity of the 3D, digital version of the Chinese Figurine, for example. The adverse effects of limited representational fidelity on engagement and the user experience are described in more detail in *Subsection 6.5.1: The Representational Fidelity of the Virtual Artefact*.

The final 3D, virtually represented artefacts differ therefore from their physical counterparts in that they have no weight, no size, and no texture. They are digital images projected to the user by way of, essentially, a flat screen, but in such a way that when manipulated using one of the two digital viewing methods (desktop or tablet-based interfaces) they can be seen from all sides and angles, giving the impression of movement in 3D. The physical artefacts, meanwhile, have all the properties of physical objects – weight, size, texture – but their movement is limited and restricted by their display conditions – in the case of this evaluation, a glass display case. They cannot be touched, they cannot be moved around with the hands to view different sides and angles. In the context of this evaluation, these are the key differences between the physically and digitally represented artefacts, differences best exemplified by figure 14.

5.1.2.2 Experiment Procedures

The procedures followed during the in-context study collaboration sessions were mapped out before the start of the study, to ensure that sessions ran smoothly and to limit the possibility of sessions overrunning, or confusion for either the participants or the investigator. The experimental procedure was as follows:

1) Welcome and introduction:
   a) Participants were welcomed into the space and seated – together at the same desk if co-located, and back-to-back at individual desks separated by a screen partition if remote-located.

   b) Participants were given an information sheet formally outlining the project, the study, and the people involved, and asked to read through it and sign a consent form if willing to continue.
   c) A short and informal verbal summary of the project and the in-context study procedures was then given to participants to put them at ease about what was expected of them.
2) First collaboration:
   a) The first of the three artefacts to be viewed and the first of the three viewing methods used to explore it were revealed to the participants.
   b) The participants were given a short outline of the basic characteristics of the artefact to provide them with some basic (limited) context and questions to give them a starting point for their discussion.
   c) Participants were given approximately ten minutes to talk to each other about the artefact using the viewing method, encouraged to discuss, contribute and share their thoughts, ideas and theories with each other.
   d) Approximately five minutes into the conversation (slightly later if the discussion was flowing and there was no lull in the conversation in which to instruct the participants, or slightly earlier if they had run out of ideas and things to say) the participants were asked to refer to the museum's supplied didactic information about the artefact, in order to answer some of their questions or to inspire further discussion.
      i) For (physical) object viewing, this involved referring to a card with the information displayed as bullet points. For the two digital (desktop and tablet) interfaces, this involved searching for interest points from 'previous sessions' (ready-made interest points created and stored for each artefact prior to start of the in-context study).
      ii) The interest points stored in the digital interfaces were identical to each of the bullet points on the cards used with the (physical) object viewing method, ensuring that the three sets of information were always identical regardless of viewing method.
      iii) Similarly, the didactic information (card bullet points and digital interest points) was always the same for each new pair of participants (newly marked interest points from each collaboration were not made

available as part of the conversation history for the next users to search for), ensuring that participants in later sessions of the study did not claim an unfair knowledge advantage from having more previous points to look at.

   e) The entire collaboration session was video-recorded for later analysis.

3) First question set:
   a) The participants were asked to complete a section of the questionnaire corresponding to the (first) viewing method that they had just been using during the collaboration. Questionnaires had been divided into four sections – one section specific to each of the three viewing methods, and an overall experience section at the end.
4) Second collaboration:
   a) The second collaboration followed exactly the same procedures as the first collaboration, but this time using the second of the three viewing methods to explore and discuss the second of the three artefacts to be viewed.
   b) Having already discovered during the first collaboration that didactic information is at some point introduced, it was possible that participants would choose to refer to this early, before the planned intervention (requesting that they look at the card or search the previous points). If the participants did want to see the didactic information early, this was allowed.
5) Second question set:
   a) The participants were asked to complete the section of the questionnaire corresponding to the (second) viewing method that they had just been using during the collaboration.
6) Third collaboration:
   a) The third collaboration followed exactly the same procedures as the first and second collaborations, but this time using the third and final of the three viewing methods to explore and discuss the third and final of the three artefacts to be viewed.
7) Third question set:

a) The participants were asked to complete the section of the questionnaire corresponding to the (third and final) viewing method that they had just been using during the collaboration.

8) Final (overall) question set:

a) The participants were asked to complete the final section of the questionnaire, a general and overall section that probed and compared the collaboration and user experiences as a whole.

Essentially, each pair of participants in a session would be either co-located or remote-located (fulfilling one of two possible conditions for collaboration type), and then during the session the remaining two independent variables, viewing method and artefact type, followed a 'within-subject' approach as described in *Section 3.2.2: Study of the Prototype System In-Context*, whereby each participant had the opportunity to use all three viewing methods and to explore all three artefacts in one way or another (fulfilling all three possible conditions for both viewing method and artefact type). The relationship between the three independent variables – collaboration type, viewing method, and artefact type – is therefore demonstrated by the following diagram (figure 19):

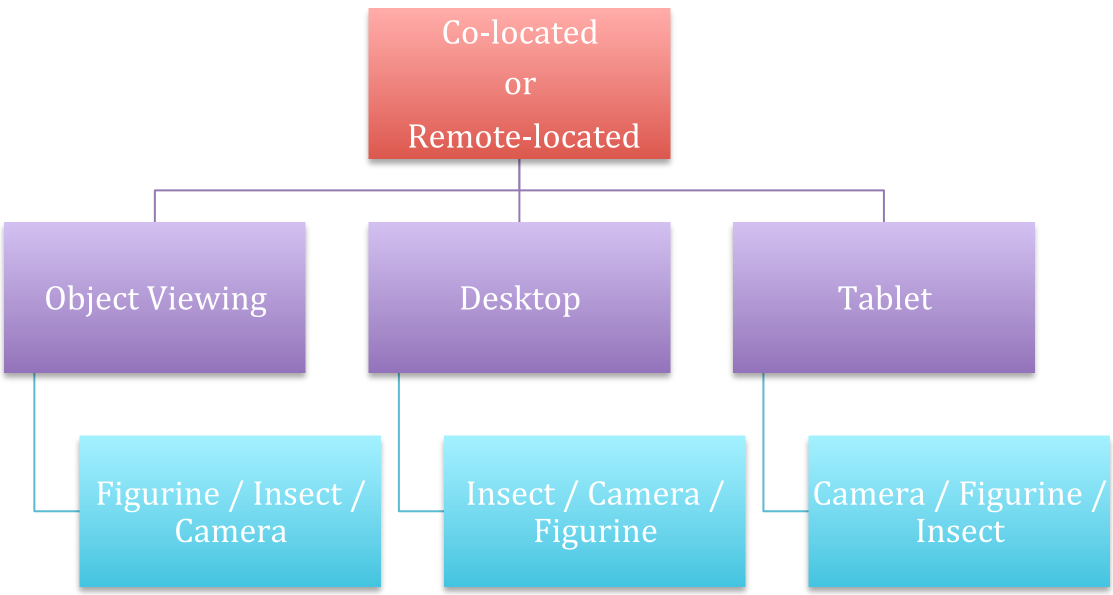

Figure 19. The relationship between the three independent variables that were tested in the in-context study.

5.1.2.3 Equality and Sequencing of Viewing Method Order

When designing experimental procedures, it was important to think about "minimising the effect of confounds" such as fatigue or practice having an effect on performance by "controlling the order in which we test the interfaces" (Cairns and Cox, 2008). For the in-context study, the viewing methods and the artefact types were interchanged to ensure that each combination of artefact and method used to do it was used (more or less) an equal number of times. The combination of three viewing methods ((Physical) Object Viewing, Desktop interface and Tablet interface) and three types of artefact (Chinese Figurine, Insect (Raspy Cricket) and Plate Camera) resulted in nine possible combinations:

Table 5. Possible combinations of viewing method and artefact type.

	Object Viewing (O)	**Desktop (D)**	**Tablet (T)**
Figurine (F)	OF	DF	TF
Insect (I)	OI	DI	TI
Camera (C)	OC	DC	TC

The perfect solution of having all possible sequences completed by every pair of participants was, of course, not practical at all – it would have required significantly more 3D modeling work in order to increase the number of artefacts used in the study to nine (three delicate objects, three small objects and three mechanical objects), and would also have meant that participants would use each of the three viewing methods three times each, surely leaving their later performances affected by experience and/or fatigue. With that in mind, a 'Latin-square' design was used to provide a "systematic approach to variation" (Cairns and Cox, 2008). The nine combinations of viewing methods and artefact types fit into a 3x3 Latin-square. Each row of the square represents one of the three unique orders that the study followed, ensuring that for every six participants (three pairs of collaborators), each of the three available viewing methods and artefact types had the chance to be presented to participants during the first, second and third collaborations of each session:

Table 6. A Latin-square arrangement of all possible viewing method and artefact type combinations.

1st Session (Participants 1 & 2)	OC	DF	TI
2nd Session (Participants 3 & 4)	DI	TC	OF
3rd Session (Participants 5 & 6)	TF	OI	DC

5.1.2.4 Experiment Participants

As described in *Section 3.2.2: Study of the Prototype System in Context*, there were no specific metrics used as limits in the participant recruitment policy, the philosophy being that the kinds of people interested in participating in a museum study were more than likely the same kinds of people who would be interested in visiting or working in the museum itself. Eighteen years old was introduced as a minimum age limit, in order to ensure that participants were from the 'student to professional' age range who could conceivably: a) visit a museum either for work or leisure; b) encounter a desktop interface during their work or study; or c) encounter a tablet interface during their work or study.

Participant recruitment was achieved primarily through advertising on mailing lists (two mailing lists at the QVMAG for volunteers and 'friends of the museum', plus various University of Tasmania campus and faculty mailing lists), posters placed around the University of Tasmania and in various locations in the city of Launceston (such as at the Tasmanian State Library and in shops and cafes), and from participants sending personal invitations or recommendations to friends and colleagues following their own participation in the study.

5.1.3 Data Collection

As described in *Section 3.2.3: Analysis of In-Context Study Results* and in *Section 5.1.1: Experimental Influences*, a mixture of quantitative and qualitative information was collected using three data gathering techniques: a mixed-methods questionnaire, application instrumenting (system output and data logs), and video observations.

5.1.3.1 Mixed-Methods Questionnaire

The mixed methods questionnaire was devised to deliver a mixture of both quantitative and qualitative information, in order to provide as much information as possible for making interpretations of the results later:

- Quantitative information was recorded using the two ten-point scales mentioned in Section *4.2: The Three Key Components of the System* – the SUS (System Usability Scale), and the additional ten questions adapted from it to provide a measure of engagement.
    - Their success in delivering results during the early collaboration sessions involving the initial prototype merited their subsequent use in the in-context study.
- Qualitative information was recorded using a mixture of open-ended and Likert-scale based questions, seeking both general and in-depth opinions on various aspects of the experience as it related to usability, collaboration and engagement.

5.1.3.1.1 Themes of Investigation for Questionnaires

As described in *Section 3.2.3: Analysis of In-Context Study Results*, it was important to ensure that to get the most leverage from the in-context study, all of the topics and elements that could be pertinent to the success (or otherwise) of the application were reflected in and measured by the mixed-methods questionnaire. With this in mind, the questions were written based on the information presented in *Chapter 2: Literature Review* and specifically targeted the four key elements described at the start of *Chapter 3: Research Methods* that bring this thesis together – 1) hands-on, mobile, reality based interaction, 2) collaboration, 3) engagement, and 4) learning.

Referring back to some of the key aspects of hands-on, mobile, reality-based interaction (Jacob et al., 2008) (Ullmer and Ishii, 2000) (Fishkin, 2004), some of the things the questionnaire needed to probe for included:

- Whether the participant had the necessary skills to manipulate the virtual artefact, whether the virtual artefact reacted and behaved as they expected it to, and how much the interaction style drew on pre-existing knowledge.
- The extent to which participants felt they had physical control over the manipulation of the virtual artefact, the effect (if any) that perceived differences between the input and output space might have contributed to aforementioned level of control, and whether they felt free and able to explore what they wanted to.
- How easy participants found it to collaborate with others, and whether or not they were aware of the interactions of other collaborators.
- How much mental effort was required to use the application, and how separated the interaction style felt from everyday, real-world actions.
- How strong a physical representation of object handling was felt, and whether or not a stronger physical representation of interacting with the object was missing or necessary.

Questions aimed at targeting these aspects of reality-based interaction therefore included:

21: How easy was it to rotate and scale the artefact in 3D?	Not very		Reasonably		Very
22: Did you feel like you had control over the artefact's movement?	No		Sometimes		Yes
23: Did the artefact behave as you expected it to during movement?	No		Sometimes		Yes

7: Did you find that the difference between the input and output space (hands and screen) between the tablet and desktop had an effect on the discussions? If so, why?

Closely related to reality-based interaction is the theme of object-handling in general (Hooper-Greenhill, 2007) (Hodder, 1994) (Pye, 2007), which required that the questionnaire set out to discover:

- To what extend participants felt like they were able to explore and experience the artefact, and whether or not this felt limited at all.

- Whether the participants were able to relate the artefact back to any previous knowledge, experience, or memory that they found to be useful during the discussion.
- Whether they felt they had discovered anything about the artefact's physical or cultural meaning.

Questions aimed at targeting these aspects of object handling therefore included:

24: How strong was the representation of handling a real object?					
	Not very		Reasonably		Very

26: Did you find that you able to relate back to any personal experiences or prior knowledge during your discussion of the artefact? If so, please provide an example.

6: Did you feel that a stronger representation of object handling was necessary in order to engage with the artefact? If so, what might have improved the representation?

Relating back to key aspects of collaboration (Falk and Dierking, 1992) (Roschelle and Teasley, 1995) (Knowles et al., 2005) (Hindmarsh et al., 2000) (Hindmarsh and Heath, 2000) (Kearsley and Shneiderman, 1998), the questionnaire had to ensure that it provided information about:

- Whether participants were able to work together and support each other, and maintain a good understanding of what each other was talking about.
- Whether participants felt able to actively contribute to the conversation and how meaningful they felt the conversation had been.
- The extent to which collaborating with others helped participants to clarify things about the artefact that they would not have been able to otherwise and whether they felt that the experience of exploring the artefact would have been more or less meaningful in an individual setting.
- Whether there were any moments in which there was ambiguity about which part of the artefact they were talking about.
- How confidently participants were able to draw each other's attention to what they wanted to talk about, or whether there was too much ambiguity about which aspects of the artefact were being discussed.

Questions aimed at targeting these aspects of collaboration therefore included:

25: Did being able to discuss the artefact help					
	No		Maybe		Yes

you to draw conclusions you might not have otherwise?

1: In all three cases, did you feel that you and your collaborator(s) had a good understanding of what each other was talking about? Were there any problems or ambiguities in trying to maintain a reference and understanding during discussion?

5: Did the digital interface used (desktop or tablet) alter the dynamics of collaborating as a group in any way? Was collaboration easier or more difficult with one interface or the other? Did either of the interfaces introduce (or remove) limits that affected successful discussion?

Finally, the questionnaires needed to explore how participants felt about some of the key aspects associated with engagement (Kearsley and Shneiderman, 1998) (Benyon, 2010) (O'Brien and Toms, 2008) , such as:

- How involved in the experience and in control of the interaction participants felt.
- To what extent participants felt stimulated by the artefact and by the conversation with their collaborators.
- Whether participants felt that interacting using either of the digital interfaces was worthwhile ways to explore the artefact.
- Whether participants felt motivated to learn about the artefact, or felt that they would be motivated to explore other artefacts using either of the digital interfaces.

Questions aimed at targeting these aspects of engagement therefore included:

27: Did you feel stimulated by the artefact and the experience in general?

No		Maybe		Yes

28: To what extent was this on a personal level, or as a result of collaboration?

Collab.		Both		Personal

Referring back to Falk and Dierking's (2000) (Falk and Dierking, 1992) *conceptual model of learning* as described in *Subsection 2.1.1: Learning in Context*, if the physical (corresponding to reality-based interaction), sociocultural (corresponding to collaboration), and personal (corresponding to engagement) contexts are present, the overall experience is likely to make sense to participants and to be long-remembered. As highlighted throughout *Chapter 2:*

Literature Review, sense making and a memorable experience are of great importance to learning, so positive answers to the questions presented in this section were seen as being a good indication that learning could be facilitated.

As described in *Section 3.1: Research Philosophy*, this research has avoided categorically stating or claiming that learning has taken place, but instead has aimed to show that learning could very likely have been facilitated. Referring back to aspects of learning highlighted in *Chapter 2: Literature Review*, it was therefore possible to carefully deconstruct the answers to the qualitative (and particularly the open-ended) questions and interpret that learning would have likely been facilitated if:

- There was a feeling of direct participation (involvement, a connection) with the artifact or the discussion (Black, 2005).
- There was a feeling of the experience being more active than passive (Knowles et al., 2005) (Hein, 1998).
- That through the discussion or exploration of the artefact, something new or interesting was discovered, or an idea about its history or significance was formed (Black, 2005).
- Prior knowledge had played a part in the process of discovery mentioned above (Black, 2005).

5.1.3.2 System Usage Data Logs (Instrumenting)

As described in *Subsection 3.2.3: Analysis of In-Context Study Results*, the mixed-methods questionnaire was accompanied by the collection of system usage data logs, also known as 'instrumenting' (Lazar et al., 2010). The idea behind the instrumenting was that the system logs would provide a record of what was done, when, and for how long during each collaboration session. This information could then be used to establish how different aspects of the system were used and what they were useful for. The system logs could also be used to try and establish links between system usage and the qualitative questionnaire responses.

5.1.3.3 Video Observations

Finally, as described in *Section 3.3: Research Design*, the mixed-methods questionnaire and the instrumenting were complemented by recorded video footage of each collaboration session, from which observations could be made. Video observations gave a visual and aural highlight to some of the things that were reported by participants using the questionnaires in context, and were particularly useful for studying interesting intrapersonal interactions between participants. These included: the use of pointing and gesturing while using the desktop and tablet interfaces; the use of shared (or individual) space; and interface sharing habits in the co-located scenario.

5.2 Analysing the results

5.2.1 Quantitative (Closed) Questionnaire Responses

The quantitative, closed-response questionnaire answers were organised into spreadsheets, from which averages could be calculated and various visual diagrams such as bar charts produced. Averages and diagrams provided a useful summary of key outcomes, from which statistical analyses could then be performed to "assess how useful" those visualised summaries really were, and begin to piece together "the whole story" (Cairns and Cox, 2008). Relating back to the scope of this thesis, averages and visual diagrams showed how reality-based, collaborative, and engaging sessions were, and then statistical analyses showed how big a part different collaboration types, viewing methods, and artefact types played in these results.

5.2.1.1 Usability and Engagement

Participants' answers to the ten-point SUS (System Usability Scale) and the additional ten questions adapted from it to provide a measure of engagement, both described in detail in Section *4.2: The Three Key Components of the System*, were used to generate single numbers corresponding to usability and engagement for each of the two digital viewing methods (desktop interface and tablet interface).

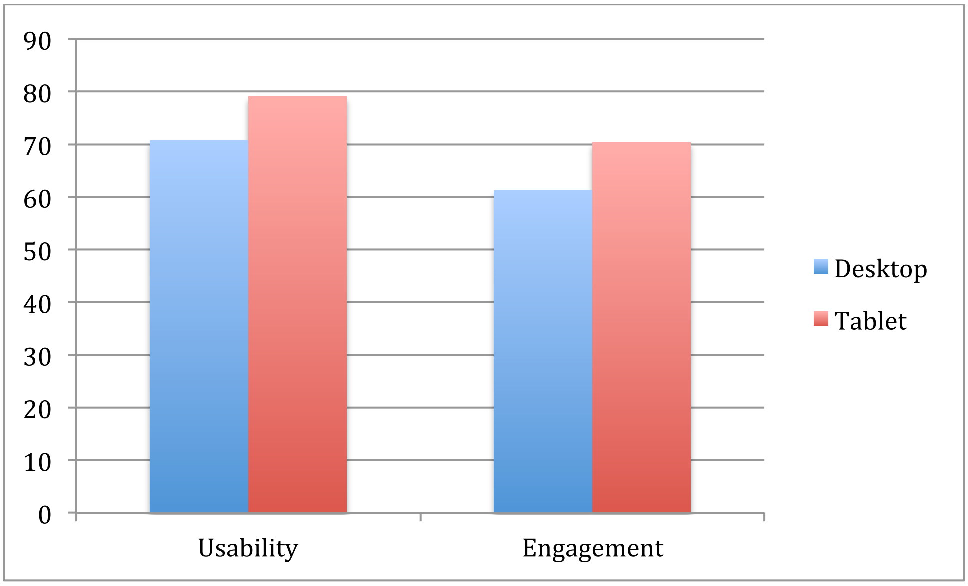

Figure 20. A chart showing the average scores for usability and engagement with the desktop and the tablet interfaces.

Two-tailed independent t-tests (used for comparing two groups (Cairns and Cox, 2008), in this case the two viewing methods: desktop interface and tablet interface) showed that the viewing method had a significant effect on usability (t= -2.15, df 61.98, P= 0.035) and on engagement (t= -2.56, df 61.58, P = 0.013). The tablet interface was more usable and also more engaging than the desktop interface. Two tailed independent t-tests also showed that collaboration type had a significant effect on engagement (t= 2.37, df 60.17, P= 0.21). The co-located experience was more engaging than the remote-located collaboration experience.

Table 7. The effects of viewing method and collaboration type on the averages for usability and engagement.

	Co-located		**Remote**		**Total**	
	Usability	**Engagement**	**Usability**	**Engagement**	**Usability**	**Engagement**
Desktop	73.6 (12.8)	67.5 (12.6)	67.8 (17.6)	54.8 (14.6)	70.7 (15.4)	61.2 (14.9)
Tablet	76.7 (15.8)	72.5 (13.4)	81.4 (15.7)	68.1 (14.0)	79.1 (15.7)	70.3 (13.7)

5.2.1.2 Reality-Based Aspects (Ease, Control, Behaviour and Representation)

Participants were asked to rate on a scale of 1 to 5 various aspects of the two digital interfaces relating to reality-based interaction, with 1 corresponding to a very negative and 5 corresponding to a very positive response to the question about that aspect of the interaction. The questions explored how easy it was to rotate and scale the artefact, how much control there was over the artefact, whether the virtual artefact behaved as expected, and whether or not there was a strong representation of object handling.

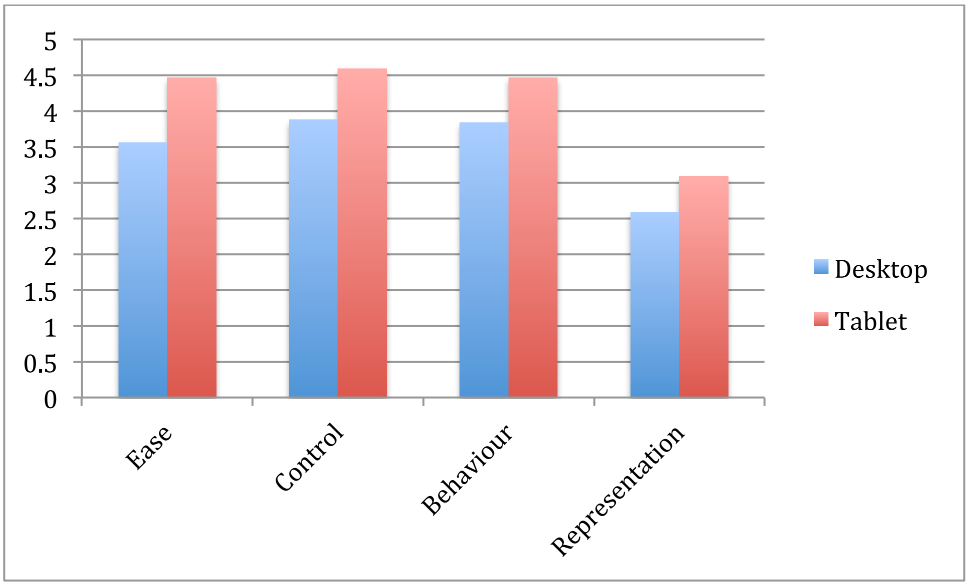

Figure 21. Bar chart showing the average scores for ease of movement, control of movement, expected behavior, and representational strength of object handling with the desktop and tablet interfaces..

Two-tailed independent t-tests showed that the viewing method had a significant effect on ease (tf= -3.47, df 57.09, P= 0.001), control (tf= -3.23, df 51.85, P= 0.002), and expectation (tf= -2.73, df 58.76, P= 0.008). With the tablet interface it was easier to rotate and scale the virtual artefact in 3D, participants felt like they had more control over the virtual artefact's movement, and the virtual artefact behaved more as the participants would have expected it to during movement than with the desktop interface.

Table 8. The effects of viewing method on ease of movement, control of movement, and expected behavior.

	Desktop	Tablet
Ease	3.56 (1.19)	4.47 (0.88)
Control	3.88 (1.07)	4.59 (0.67)
Behaviour	3.84 (1.02)	4.47 (0.80)

5.2.1.3 Did Discussing the Artefact Help with Drawing Conclusions?

Participants were asked to rate on a scale of 1 to 5 the extent to which they felt that being able to discuss the artefact with a collaborator helped them to draw conclusions about it that they might not have done otherwise, with 1 corresponding to discussion not helping them to draw conclusions at all and 5 corresponding to discussion being very important in helping them to draw conclusions.

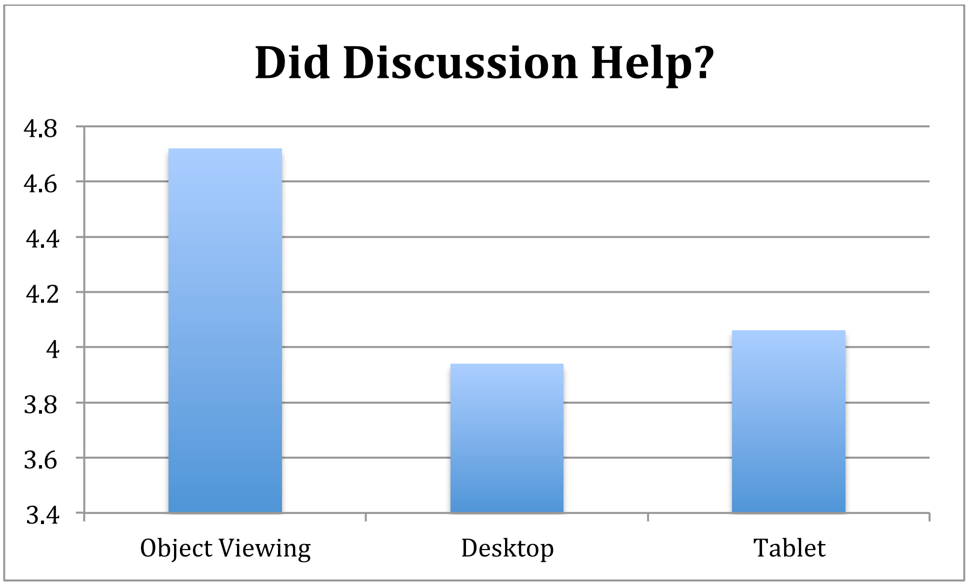

Figure 22. Bar chart showing how much being able to discuss the artefact helped participants to draw conclusions using each of the viewing methods.

An analysis of variance (ANOVA) (used for comparing three groups (Cairns and Cox, 2008), in this case the three viewing methods: object viewing, desktop interface and tablet interface) showed that the viewing method had a significant effect on how much the discussion helped participants to draw conclusions about artefacts ($F= 7.26$, df 2, 93, $P= 0.001$). Participants felt that the discussion with their collaborator helped them to draw conclusions that they might not otherwise have drawn to a much greater extent when viewing the physical object than with either of the two digital viewing methods.

Table 9. The effects of viewing method on how much being able to discuss the artefact helped participants to draw conclusions

	Object Viewing	**Desktop**	**Tablet**
Did Discussion Help?	4.72 (0.52)	3.94 (1.19)	4.06 (0.80)

5.2.1.4 Was the Experience Stimulating?

Participants were asked to rate on a scale of 1 to 5 whether or not they had felt stimulated by each collaboration session, with 1 corresponding to the session being a completely un-stimulating experience and 5 corresponding to the session being a very stimulating experience. Also rated on a scale of 1 to 5 was whether or not that stimulation (engagement) came a result of the collaboration, or an individual engagement of interest. 1 corresponded to collaboration, while 5 corresponded to a personal, individual sentiment.

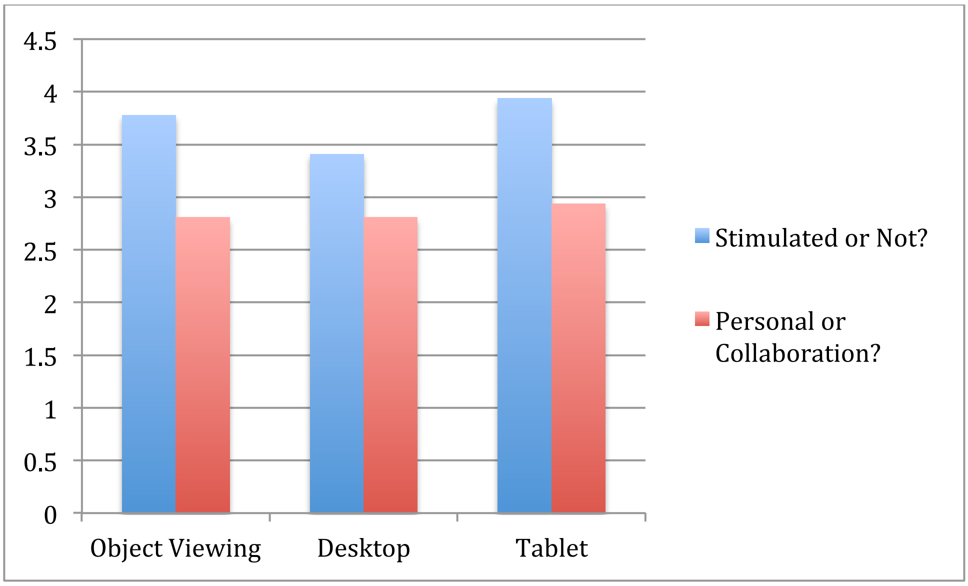

Figure 23. Bar chart showing how stimulating the experience was, and whether that was attributed to the collaboration or the individual, for each of the three viewing methods.

Two-tailed independent t-tests showed that the collaboration type had a significant effect on how stimulating the experience was (tf= 2.03, df 89.69, P= 0.045). Co-located discussions were shown to be slightly more stimulating experiences than remote-located discussions.

Table 10. The effects of collaboration type on how stimulating participants found the experience.

	Co-located	**Remote**
Stimulated or Not?	3.94 (0.98)	3.48 (1.22)

An ANOVA showed that the artefact being discussed also had a significant effect on how stimulating the experience was (F= 3.84, df 2, 93, P= 0.025). Of the artefacts used in the in-context study, the Insect (Raspy Cricket) was far less stimulating than either the Chinese Figurine or the Plate Camera.

Table 11. The effects of artefact type on how stimulating participants found the experience.

	Figurine	Insect	Camera
Stimulated or Not?	4.00	3.28	3.84

Asking participants whether their stimulation came as a result of the collaboration or an individual engagement of interest did not provide any useful information. The average response was 2.85 – very slightly in favour of stimulation being due to a personal, individual engagement of interest, but only 0.35 higher than the mid-point of 2.5, and so not greatly significant. None of the variables measured – viewing method, collaboration type, or artefact type – had any significant effect on this either.

5.2.1.5 Was Anything Learned About the Artefact?

Participants were asked to rate on a scale of 1 to 5 whether or not they had learned anything about the artefact during each collaboration session, with 1 corresponding to feeling that they had not learned anything and 5 corresponding to feeling that they had definitely learned something.

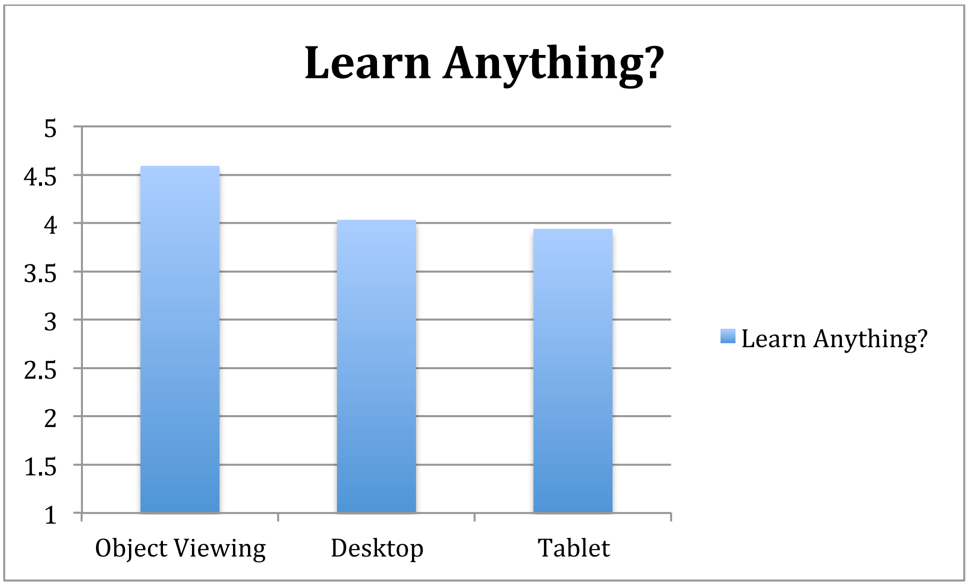

Figure 24. Bar chart showing whether or not participants felt like they had learnt something about an artefact for each of the viewing methods.

An ANOVA showed that the viewing method used in each session had a significant effect on whether participants felt that they had learned anything about the artefact they were collaboratively exploring (F= 3.52, df 2, 93, P= 0.034). Participants felt that they learned more about artefacts when they looked at the physical objects than looking at either of the digital versions.

Table 12. The effects of viewing method on whether participants felt like they had learnt something about the artefact.

	Object Viewing	**Desktop**	**Tablet**
Learn Anything?	4.59 (0.67)	4.03 (1.23)	3.94 (1.22)

5.2.1.6 With Which Viewing Method was Referencing Easiest?

Participants were asked to rate on a scale of 1 to 3 how easy it was to make spatial references using each of the three viewing methods (object viewing, desktop interface and tablet interface), with 1 being the method with which referencing was easiest and 3 being the method with which referencing was the most difficult.

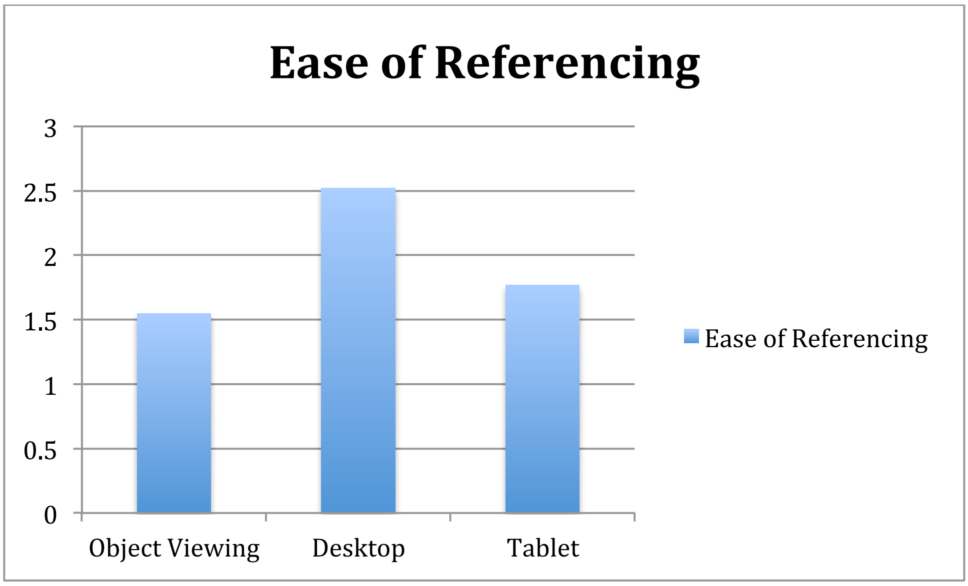

Figure 25. Bar chart showing how easy participants found it (1-easy, 3-difficult) to make spatial references using the three viewing methods.

An ANOVA showed that the viewing method had a significant effect on how easy it was to make spatial references during discussions (F= 13.71, df 2, 83, P<

0.001). It was far more difficult to make spatial references using the desktop interface, compared to the tablet interface with which referencing was almost as easy as with (physical) object viewing.

Table 13. The effects of viewing method on how easy participants found it (1-easy, 3-difficult) to make spatial references.

	Object Viewing	Desktop	Tablet
Ease of Referencing	1.55	2.52	1.77

5.2.1.7 How Useful Were the Collaboration-Specific Features?

The collaboration-specific features of the digital viewing methods (marking interest points, changing the current interest point, including information or keywords with interest points, the colour-coordination of interest points, and searching the history of previous interest points) were rated by participants on a scale of 1 to 5 for their usefulness, with 1 being of no use at all and 5 being extremely useful. All of the collaboration specific features scored above 2.5 on average, suggesting that all of the features were at the very least moderately useful to participants, with including information with interest points and searching the history of previous interest points being particularly useful features.

Table 14. The usefulness of the collaboration-specific features of the digital viewing methods.

	Marking	Changing	Including Information	Colour-Coordinating	Searching the History
Usefulness of Collaborative Elements	3.59	2.90	3.88	3.21	4.19

5.2.1.8 Favourite Viewing Method

Participants were asked to rate on a scale of 1 to 3 which of the three viewing methods (object viewing, desktop interface and tablet interface) they preferred, with 1 being their favourite viewing method and 3 being their least-favourite viewing method.

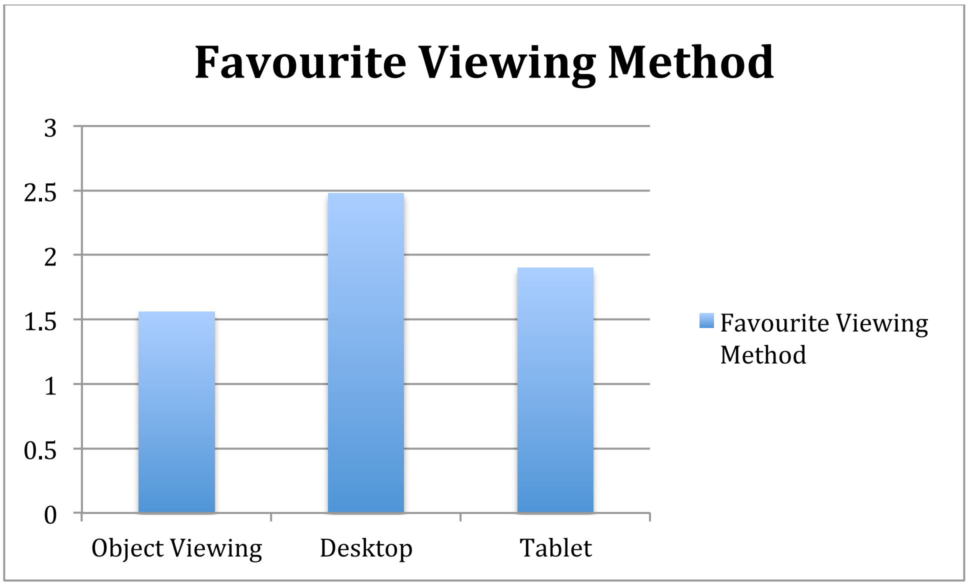

Figure 26. Bar chart showing participants' favourite (1-favourite, 3-least favourite) viewing methods.

An ANOVA showed that there was a significant difference in the participants' viewing method preferences (F= 12.83, df 2, 91 P< 0.001). The desktop interface was significantly less popular than the other two viewing methods, with physical object viewing being the preferred way of exploring museum artefacts.

Table 15. Participants' favourite viewing methods (1-favourite, 3-least favourite).

	Object Viewing	**Desktop**	**Tablet**
Favourite Viewing Method	1.56	2.48	1.90

5.2.1.9 Favourite Artefact

Participants were asked to rate on a scale of 1 to 3 which of the three artefacts (Chinese Figurine, Insect (Raspy Cricket) and Plate Camera) they preferred, with 1 being their favourite artefact and 3 being their least-favourite artefact.

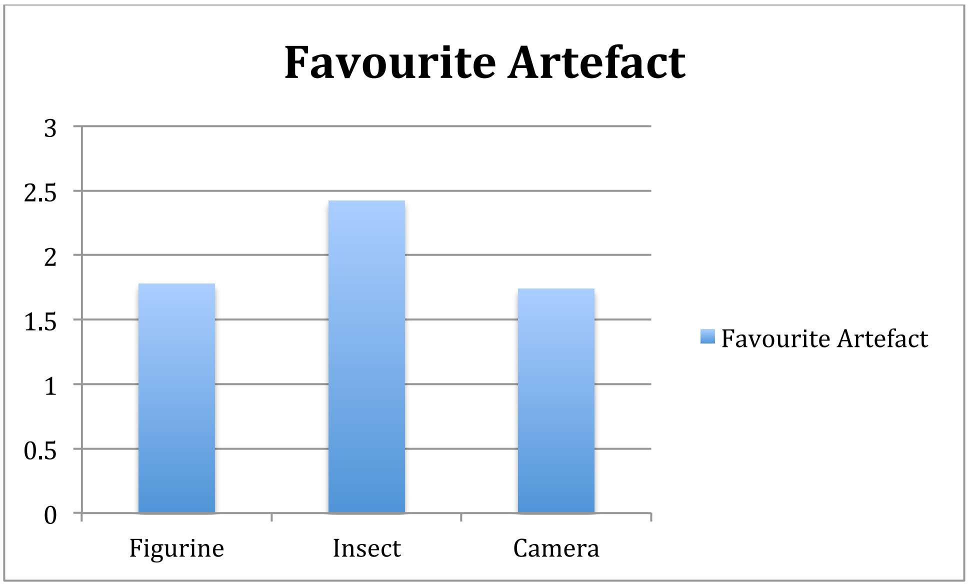

Figure 27. Bar chart showing participants' favourite (1-favourite, 3-least favourite) artefact types

An ANOVA showed that there was a significant difference in the participants' preferences towards one artefact over another (F= 7.74, df 2, 91, P= 0.001). The Insect (Raspy Cricket) was significantly less popular then the Chinese Figurine and the Plate Camera, both of which were much more favoured by the participants.

Table 16. Participants' favourite artefact types (1-favourite, 3-least favourite).

	Chinese Figurine	**Insect (Raspy Cricket)**	**Plate Camera**
Favourite Artefact	1.78	2.42	1.74

5.2.2 Qualitative (Open-Ended) Questionnaire Responses

The qualitative, open-ended questionnaire responses were coded according to the four key themes that have been prevalent throughout this thesis: reality-based interaction; collaboration; engagement; and learning. Lazar et al. (2010) describe how coding traditionally involves identifying "potential coding categories or items based on established theories or frameworks in the related literature", and the breakdown of this thesis' four key themes and the key concepts involved in each one at the start of *Chapter 3: Research Methods* provided the ideal set of items and categories to code the questionnaire responses according to.

With the coding categories in place, the responses for the questionnaires were read through and organised into the four key categories for each of the collaboration sessions that took place – sixteen coded sessions, each consisting of two questionnaires (one for each of the pair of participants from that session). Each questionnaire was read through twice, to ensure that the coding was reliable, and consistent (Lazar et al., 2010) – and of course that nothing important or interesting had been missed first time around. Once the coding of each session was complete, this information was then distilled into the four category summaries presented in this sub-section.

Obviously, there was a huge overlap between many of the items in all of the categories across the sixteen different collaboration sessions, and so distilling them down into an 'overall picture' of the information made sense. Going over the coded responses again and organising them together into one set of information for each category also allowed for a high degree of stability in the results, clarifying whether certain items of data should be rated in the same way (Lazar et al., 2010), strengthening items upon seeing them again and again, or revisiting and reconsidering items that were less convincing.

Each of the following four sub-subsections contains the coded information from the in-context study according the four key themes of the thesis: reality-based interaction; collaboration; engagement; and learning. Each category title is written in an orange box, with the items for that category above and below it. To ensure validity of the coding – "interpretations that account for all, or as much as possible, of the observed data", making it easier to defend as being valid (Lazar et al., 2010) - positive and negative items for each category were recorded. This allowed for all of the information, regardless of which theory or hypothesis it supports, to be included for the purpose of questioning and comparing the data (Lazar et al., 2010) and making valid interpretations later.

For each category, the positive items are above the orange title box in green, and the negative items are below it in red.

5.2.2.1 Thoughts on Reality Based Interaction

- Movement in 3D allowed for a complete visual of the artefact and enabled it to be fully studied from all sides and angles
- Being able to zoom in and out on different features was a really important part of this, making up for the fact that when viewing static objects it can be hard to get up close to them.
    - Being able to interact with artefacts in such a way gives users a sense of control.
    - The static object viewing experience, in contrast, is fixed and constrained, often with limited viewing angles and the inability to get up close.
- The hands-on experience and a sense of touch are really important in building up a physical picture of the artefact, and the tablet interface in particular offered this.
- Exploration with the tablet was worthwhile, and described as being:
    - Comfortable, easy, quick, direct, immediate, intuitive, realistic, authentic, believable, natural, and closer to a real-world experience (as originally hypothesised).
- The combined input and output spaces also gave the tablet interface a 'closer context' than the more separated desktop experience, and directly contributed to it being easier to use than the desktop – the relationship between touch and effect was direct, and so there was less distraction.
- It was also easier to pass the tablet around between collaborators in the co-located collaboration scenario, with the tablet interface providing a sense of mobility.
- The desktop, in contrast, was described as being:
    - Slow, static, clumsy, clunky, cumbersome, unnatural, difficult, a battle, counter-intuitive, and an interrupted, un-smooth experience requiring too much focus on the interaction technique

rather than the object.

- Familiarity with the desktop metaphor did make it easier for some users to get going with it straight away, with less instruction required.
- There were also some users who, perhaps less familiar with tablet technology, felt that balancing the tablet at the same time as using the touchscreen was an awkward process, or for some users the sensitivity of the screens themselves was an issue.
- Generally, while there are preferences (towards the tablet interface), users were able to match their skills to either of the digital interfaces – neither is 'unusable'.

Reality-Based Interaction

- A good understanding of relative scale is really important to making sense of the complete 3D picture of the artefact, and this is only really visible with the object viewing – the digital interfaces lack this reference.
- Even when viewing angles are limited (for (Physical) Object Viewing), there are usually enough to discover new things.
- Even with the hands-on exploration value of the digital interfaces, seeing the real object is still essential for building a true context.
- Many of the physical nuances of artefacts simply cannot be digitally represented – namely relative scale, a sense of perspective, weight, and intricate details such as texture.

5.2.2.2 Thoughts on Collaboration

- Collaborators generally had good dynamics with each other and a sense of being understood, with conversations being described as comfortable, reassuring, easy to maintain, precise, and without problems.
    - In the case of collaborators who had not met before, this tended to improve as they got to know each other, and in the case of people who did already know each other, it was felt that the digital tools 'facilitated' their existing communication dynamic.
- Collaborators also generally felt that they contributed knowledge to the

discussion.

- Collaborators would discuss, muse, deduce, figure out, theorise, piece together clues, bounce ideas off each other, and clarify questions about the artefacts in a team effort to construct knowledge.
    - This would revolve around various aspects of the artefact, including aesthetic elements, physical features, functionality, use, origin, history, and cultural meaning.
- Collaborators would share their pre-existing ideas, interests, experiences, theories, intrigue, points of view, and knowledge with each other.
    - This would be particularly useful when one collaborator had greater existing prior knowledge than the other, where the knowledgeable collaborator was able to give the other a sense of confidence as the conversation progressed.
    - Some users even felt that a lack of prior knowledge made them curious, and led to a better discussion.
- With both of the digital interfaces, many users felt that both being able to manipulate the artefact and being able to mark interest points on it made it easy to pinpoint and focus on different parts of the artefact.
    - The ease of using the interfaces also ensured that the collaborators could remain focused on the discussion.
- Annotations in particular were described as being great for drawing each other's attention to interesting features, with the colour coding for each participant a useful referencing feature for this.
- Other users simply felt that the artefacts themselves provided a great reference point to stimulate discussion, particularly when viewed in their physical form where making eye contact with the collaborator or simply pointing at something was easy.
- Many users felt that collaboration was easier on the tablet than with the mouse and keyboard, being more socially interactive and making it easier to verify and point things out for each other.
- In contrast, collaboration and referencing were described as confusing on the desktop interface.

• Some users did feel that the larger and fixed screen in the desktop interface made it easier to reference by pointing, and also that typing interest points was easier with the physical keyboard. • In the co-located scenario, referencing was mainly done using subtle eye and body movements and gestures, as opposed to pointing as such. Not having this takes time to get used to in the remotely located scenario.
Collaboration
• In some discussions, differences of opinion could make it difficult to arrive at shared conclusions and lead to uncertainty about the significance of contributions. • A difference in the level of interest and personal engagement with the artefact between collaborators also had adverse affects during some collaboration sessions. • When there was a lack of knowledge from either or both collaborators, collaboration was limited to guesswork and could become difficult and strained. • Not having enough previous information (museum-provided placards or previous history of interest points) to reflect on also made inspiring conversation difficult. • Some users felt that the marking of interest points was clunky and awkward, and that it could be difficult to map them to the desired location on the artefact. • It was also suggested that the artefact should have rotated according to the interest point being selected. • Some users felt that interest points were not so useful for non-experts who might be less confident about the knowledge they're leaving. • One user felt that a cursor helping to point out what the collaborator was looking at would have been useful. • In the remote-collaborative scenario, conversation sometimes took a back seat to personal exploration of the artefact and writing of interest points without discussing the reasoning behind them. • With the digital interfaces, boundaries also need to be clear, as if one

collaborator is more comfortable 'driving' or takes too much control over the manipulation it can be frustrating for the other.

5.2.2.3 Thoughts on Engagement

- A shared curiosity to discover the unknown is important in engaging more than one person in the collaboration:
  - The busier the discussion and the more theorising involved, the more engaged the collaborators feel – the exchange of ideas stimulates a wider view of the context.
  - When collaboration was petering out, searching through previous interest points could inspire and reignite interest for collaborators.
- Seeing the artefact in its true form is still the most satisfying and engaging experience – seeing the levels of detail and craftsmanship at their true fidelity can be 'awe-inspiring' and leaves the viewer feeling more connected and focused.
  - The visceral experience of seeing the object in the flesh provokes a reaction, and can make it seem like a puzzle, piecing together the various visual clues.
- Therefore with the digital interfaces, a good visual representation is really important to engagement. The fidelity of the object is orthogonal to maintaining an interest in it, and an aesthetically pleasing representation is more visceral and engaging.
  - The bigger screen size of the desktop was an advantage here, and a larger touch surface for the tablet experience was suggested.
- The digital interfaces offered an enjoyable and engaging level of interactivity, particularly the tablet where the more fluid, smooth, direct, quick, and natural interaction made it easy for collaborators to focus on the conversation.
  - In contrast, constantly looking up and down between the mouse, the keyboard, and the screen interrupted the viewing experience and the flow with the desktop interface.
- Regardless of the interface used, an enjoyment or a personal interest in

the topic or the style of the artefact in question remains the most important thing in fostering engagement with it.

  - Unfamiliar but highly detailed, aesthetic objects (the figurine, for example) inspire curiosity, surprise, and incite a lot of discussion, and are therefore much more engaging than those that do not require much theorising or pose so many questions (the insect, for example).

- This is especially prominent when the artefact touches and engages the viewer in the human, local or cultural context in some way, which leads to intrigue on a personal level:
  - For example, the change in technology and human use of it over time (the camera).
- A mechanical interest can also be very engaging (camera), trying to deduce how things might have worked by relating them to knowledge of similar mechanical processes.
- Being able to retrace and revisit prior knowledge and previously left interest points from other collaboration sessions was very engaging.
- Having to wait for the collaborator to finish writing and preparing an interest point before being able to see it did encourage listening to their ideas.

Engagement

- When the viewing angles are limited, the motivation to explore the artefact is limited, and viewers can be left feeling distant.
  - Some users thought the tablet caused a problem here, as their hands could cover up parts of the screen.
  - Others felt that the less fluid interaction style of the desktop interface left them feeling disconnected from the artefact.
  - The desktop was described as requiring the user to be 'too involved', to the extent that it was uncomfortable and interest was lost.
- There was a feeling that using the digital interfaces could distract attention away from the conversation, in that they do require a degree of

thought and attention to use them.

- With both of the digital interfaces, collaboration in the co-located scenario could feel constrained on the personal level, as only one collaborator could drive the viewing experience at a time.
- The level of detail of the 3D virtual representations of artefacts needs to be really high in order to maintain people's attention and interest. When this is lacking, the authenticity of the experience is compromised and everything feels too digital to the user, leaving them feeling detached.
    - Digital representations really need to be photorealistic to maintain the same kind of visceral attention as the physical artefact – this is a particular problem with natural objects (man-made ones tend to be easier to represent).
    - This is important for constructing knowledge based on how the object looks, and also especially important when the provided information relates directly to visual details (embroidery on the figurine).
    - This fidelity also needs to auto-adjust in tandem with zooming, to maintain the fidelity at all distances.
- Other digital viewing options would however be welcomed, such as X-ray or cross-section features.
- Additional multimedia informational material, such as diagrams, audio and video to accompany the 3D artefact, would also have been welcomed.
- The experience of leaving interest points could break the flow of interaction at times, with numerous steps or 'clicks' being needed to leave a point.
    - It could be quite difficult to clear fields that ended up overlapping each other after consecutive clicks or when wanting to correct something.
    - In the case of the tablet, when the virtual keyboard pops up and covers the artefact momentarily, this can also break the flow of the interaction.
    - Some interest points also did not appear to be on the right part of

the object, which is far from ideal.
    - Having to wait for a user to finish typing their interest point before continuing with the conversation could be cumbersome, and a temporary marker that showed where an interest point was going to be left while it was still being written was suggested.
    - This led to some users feeling that interest points were un-useful, and not being compelled to leave them.
- Audio annotation (voice input) was suggested as an alternative that might have helped here, especially seeing as the collaboration is already discussion based.
- Searching through the interest points using the slider bar could also break the flow of the interaction, and it was suggested that having interest points appear in view as the artefact was rotated might have been a better approach.

5.2.2.4 Thoughts on Learning

- In almost all collaboration sessions, at least one of the collaborators was able to relate the experience to some kind of previous knowledge or experience:
    - This included personal experiences, everyday life, childhood memories, travel memories, subject-specific (objects and processes) or general knowledge, local links, stories, times and places (the historical context), previous museum exhibits, and memories drawn from seeing video footage and photographs or reading books.
- This prior knowledge could be used to draw conclusions, agree on details, clarify ideas or eliminate certain theories.
    - Even when prior knowledge and experience was only limited, users still felt that they had enough to bring something to the discussion.
- Users felt that putting together knowledge and building shared conceptions of artefacts with their collaborator was crucial to their own

learning outcomes.

  - Drawing on and 'scaffolding' from the collaborator's prior knowledge and experience were key to this.

- In terms of interaction, being able to see artefacts from all sides and zoom in on smaller ones was crucial to learning, allowing the whole of the objects to be accessible for discovery and exploration.
- The interest points, and being able to scroll through them, was seen as being a useful way to explore and digest information, also allowing collaborators to direct discussions with minimal effort.
  - They allowed for information to be presented in a narrative-like structure, almost like a blog or a news feed.
- Interest points from previous users also shed light on information that had been missed by the collaborators during the discussion.
- When the representational fidelity is clear enough, it's easier to see how things would have worked (the camera, for example).

Learning

- There were some participants who did not have any previous knowledge or experience to draw upon, which made them hesitant to leave interest points.
  - In this scenario, it can be difficult for users to be able to construct new ideas.
  - Even when the user feels they have learned from the experience, they can be left feeling insecure about what they've contributed to the discussion.
- Prior knowledge is of course more or less limited depending on the object in question, and so cannot always be taken for granted.
- Additional contextual information (such as multimedia and videos) would have helped with learning.
  - This was certainly something that would have been very welcome with the physical object viewing, where supplementary information was more limited.
  - Having a descriptor before the session to get thoughts going from

the start does help.

- It would have been useful to be able to add extra comments to existing interest points, to further explore certain themes and thoughts.
- There was also an idea that when the interest points left were raising questions, a more instant form of feedback was required.
- In terms of assigning context, interest points and the future users who would view them would benefit from more options for context, perhaps mapped to different types of object.
- In terms of representational fidelity, when the level of detail was not high enough it was simply too difficult to make sense of certain aspects of the artefacts.
    - The lack of representational scale also limited the sense that could be made of the artefact, making it difficult to accurately ascertain a context of use (for the figurine), and leading to speculation as opposed to contribution.

5.2.3 System Usage Data Logs (Instrumenting)

System usage logs were recorded in an online database throughout the in-context study. This was a reasonably trivial step to take, as the digital interfaces were both already interacting with an online database in order to recall interest points from 'previous sessions' from the conversation history, which were stored online. As each of these interest points was stored in the database as a number of characteristics (session marked, artefact attached to, number, included text, chosen context, date and time left etc.), it was relatively simple to write new interest points left during the in-context study to a separate but similar table in the database, allowing participants' interest point marking habits to be examined later (Lazar et al., 2010).

From the system usage data logs, it was possible to construct a picture of the average number of interest points marked during a session, the average number of those interest points that included participant-entered information or keywords, the average time (in minutes) that the first interest point was marked, the average time (in minutes) that the final interest point was marked, and the average time (in minutes) that the history of interest points from previous sessions was searched (figure 28):

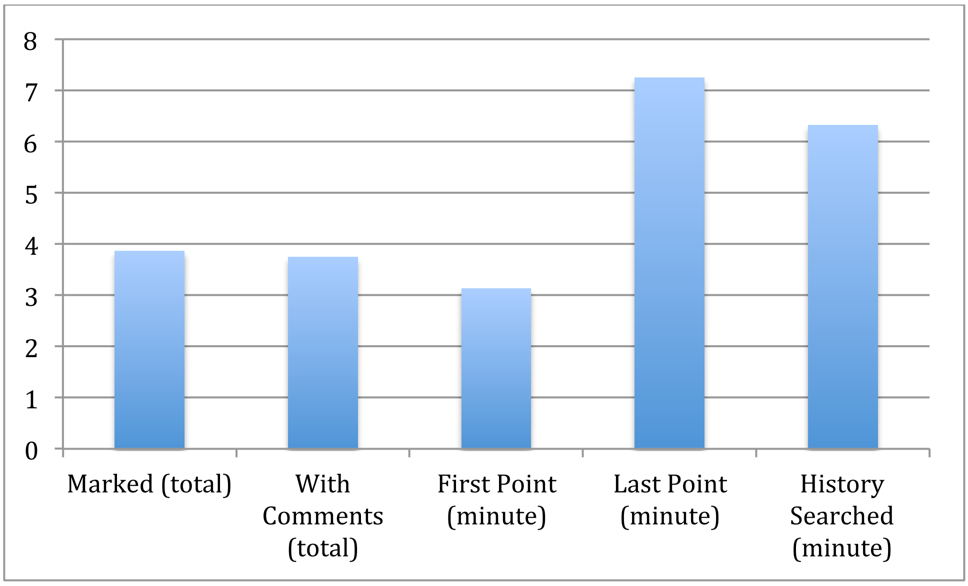

Figure 28. Bar chart showing the average number of interest points and interest points with comments, along with the average time in minutes that the first and last points were marked and that the history of previous points was searched.

Two-tailed independent t-tests showed that the collaboration type had a significant effect on both the number of interest points marked (tf= -2.14, df 24.41, P= 0.042) and on the time at which the last interest point was marked (tf= -3.69, df 15, P= 0.002). More interest points were marked on average in the remote-located sessions than in the co-located sessions, whilst the average time at which the last of the interest points was left was much later in remote-located sessions than in co-located sessions. This would suggest that users spend a longer amount of time marking more interest points in a remote-located session compared to a co-located session.

Table 17. The effect of collaboration type on the number of interest points marked and the time at which the last interest point is marked.

	Co-located	**Remote**
Number of Interest	2.64	5.07

Points Marked		
Last Interest Point Marked (Minute)	5.17	9.93

5.2.4 Video Observations

Video recordings allowed for the observation of intrapersonal interactions between participants, including pointing and gesturing, the use of shared (or individual) space, and sharing habits in the co-located scenario. The percentage of time that the tablet interface was either held in the hands or put down on a table to use is an example of something that it was possible to observe.

Table 18. The percentage of time participants spent with the tablet interface in their hands for different collaboration types.

	Co-located	Remote	Overall
Tablet held in the hands (% of time)	73.86	59.9	66.48

Sharing habits could also be observed. These included the percentages of time spent in control of the virtual artefact's manipulation (lower percentage for the participant in each pair who spent less time in control in contrast to upper percentage for the participant who spent more time in control). Also observed was the sum of times (across all of the co-located digital interface collaboration sessions) that participants offered to share control of the interface (tablet or mouse), asked to be able to take control of the interface, or more infrequently refused control of the interface.

Table 19. A summary of the sharing habits of co-located participants using the two digital interfaces.

	Desktop	Tablet
Lower Percentage of Control	17.19	27.44

Upper Percentage of Control	81.56	72.56
Offering to Share the Interface	12	10
Refusing Control of the Interface	1	1
Asking for Control of the Interface	7	3

Finally, physical and visual intrapersonal interactions were also observed in the video recordings, allowing for the average number of times participants made use of their ability to point at each other and to make gestures to each other during the various co-located sessions.

Table 20. The average number of times that co-located participants point or make gestures for each viewing method.

	Object Viewing	**Desktop**	**Tablet**
Pointing	4.25	3.27	3.23
Making Gestures	3.36	2.56	2.11

Chapter 6: Discussion

The in-context study designed to evaluate the prototype *RelicPad* system (the proposed solution to the research problem) has been presented and described, along with the results gathered during it. In some cases, the gathered results were supported by suggested interpretations as to what they could mean in the context of the research.

In this chapter, a more in-depth interpretation of the results is provided. These results are framed according to the four key themes that tie the proposed solution to the research problem (limited access to museum artefacts for collaborative exploration and discussion) and the research question (how a system such as *RelicPad* can help to efficiently facilitate engaging collaborative discussions of virtual museum artefacts) together:

- Reality-based interaction.
- Collaboration.
- Engagement.
- Learning.

6.1 What Makes a More (or Less) Reality-Based Interaction?

6.1.1 Usability, Control and Freedom of Exploration

The results of the in-context study gave strong indications that the hands-on, mobile approach of the tablet interface is much more reality-based than the traditional, desktop (mouse and keyboard) interaction approach used by current systems for manipulating 3D representations of museum artefacts.

One of the strongest of these indications was that the tablet was rated to be significantly more usable than the desktop in the results of the study, as evidenced by participants' responses to the System Usability Scale (SUS) used in the questionnaire. The participants' written responses support this finding.

There was a feeling that exploring virtual objects with the tablet was worthwhile, with interaction being described, as originally hypothesised, as being closer to real-world interactions such as handling physical objects: quick, direct and immediate; easy, natural and intuitive; realistic, authentic and believable.

As well as the positive score from the SUS, these written aspects show strong correlations to the five key aspects of usability (Sharp et al., 2007) outlined in *Subsection 4.3.2: Interaction Design and Usability*: effectiveness (realistic, authentic), efficiency (intuitive, direct), safety (easy), utility (quick, immediate), and learnability (natural, believable). This is in direct contrast to the interrupted, un-smooth experience of interaction using the desktop interface: static, slow and cumbersome; clumsy, clunky and counter-intuitive; unnatural, difficult and a battle to use.

Referring back to the descriptions of reality-based interaction in *Section 2.3: Reality-Based Interaction*, there are a number of ways in which it can be interpreted that the usability of the tablet interface contributed to it offering a more reality-based experience than its desktop counterpart:

- The tablet is learnable (it is more natural and believable than its desktop counterpart). This makes it more reality-based because it builds on users' pre-existing knowledge of the everyday, non-digital world.
- The tablet is efficient and has good utility (it is more intuitive, direct, quick and immediate than its desktop counterpart). This makes it more reality-based because it utilises actions that "correspond to daily practices" from the real, non-digital world and allows users to interact directly it.
- The tablet is effective (it is more realistic and authentic than its desktop counterpart). This makes it more reality based because it makes good use of the user's understanding of the real world, thus greatly reducing the 'gulf of execution' – the gap between a user's goals and actions.

The questionnaire also probed aspects of the realism of the interaction technique itself. Results showed that with the tablet interface it was significantly easier to rotate and scale the virtual artefact in 3D than with the desktop interface, participants had more control over the artefact's movement than with the desktop interface, and the virtual artefact behaved and responded closer to the way in which participants would have expected a physical artefact to respond to manual handling than with the desktop interface. This shows that the tablet interface offers a more realistic experience, being easier, more controlled, and triggering a more natural behavior or response than the corresponding action using a desktop interface.

Written answers from participants demonstrate how important it is that interaction techniques, particularly for exploring (virtual) museum artefacts, are grounded in reality, with participants describing how the movement of the artefact in 3D allows for a more complete visual and the ability to study it from all sides and angles. Being able to zoom in on and away from different features was an important part of this, and combined with viewing from all sides and angles offers a freedom of exploration that visitors do not normally experience in traditional, static museum object viewing experiences, where it can be difficult at times to get up close to the artefact in question.

The fact that the tablet interface is more usable than the desktop interface shows that it has more of the characteristics that are associated with real-world interactions – the tablet is learnable (natural and believable), building on the user's pre-existing knowledge of the physical world; the tablet is efficient and has good utility (intuitive, direct, quick and immediate), corresponding to well-used actions from the real-world; and the tablet is effective (realistic and authentic) making good use of the user's understanding of how physical objects move.

This makes it easier to interact freely, with a virtual museum object that behaves as the participant would expect a real object to behave, with the tablet interface than with the desktop, giving the user a sense of control over multi-sided and multi-angled exploration of virtual artefacts. This shows the hands-on, mobile (tablet) approach to be a more realistic experience than it's fixed, desktop counterpart, and as correctly hypothesised in *Chapter 1: Introduction*, one that is closer to that of physically handling a real artefact.

6.1.2 Input and Output Space, and the Closeness of Context

Statistically, no real differences were found in the strength of the representation of object handling between the desktop and the tablet interfaces, but the participants' subjective, written responses did suggest a difference of opinion in this respect.

Participants described how the combination of input and output space with the tablet interface resulted in a 'closer context' than the more separated experience of its desktop counterpart. This relationship between the touch and the effect – which as described in the previous sub-section was direct, quick, intuitive and immediate – meant that there was less distraction when using the tablet interface than when using the desktop interface, and directly contributed to the tablet interface being more usable. In contrast, participants felt that using the desktop interface required too much focus on the interaction technique, which detracted from their ability to fully engage with the object itself.

The static experience of physical object viewing was described as being 'fixed and constrained', with limited viewing angles and an inability to 'get up close'. Many participants felt that the hands-on experience and sense of touch that are lacking in some physical object viewing experiences are crucial in building up a physical picture of artefacts, and that the freedom of exploration made possible by the tablet interface provided this. Having freedom and control over the manipulation of the virtual artefact and being able to view it from all sides draws visitors in, engages their senses, and "compels them to investigate the topic at hand" (Falk and Dierking, 2000) in a way that is sometimes made difficult by the limited viewing angles associated with physical object viewing.

Input and output space clearly play an important role in building up a contextual association between action upon the tablet and the perceived reaction of the (virtual) museum artefact, which almost certainly directly contributes to the usability of the tablet interface and allows the user to manipulate the artefact quickly, directly and with minimal outside interference or distraction. Coupled with the freedom and relatively unlimited control of the (virtual) artefact that digital manipulation offers, the simple fact that with the tablet interface the action and the response both take place in the hands is important in making the interaction feel more natural and in compelling and engaging participants, supporting the initial hypothesis that manual interactions based on real-world principles are an engaging way to collaboratively explore (virtual) objects.

"Having it in your hand, it's a lot easier to control, and easier to explore"

6.2 How is Collaboration Best Facilitated?

6.2.1 Establishing Mutual Focus and Frame of Reference

Questionnaires showed that participants found it much more difficult to make spatial references using the desktop interface than with the tablet interface, which was almost as easy to make references with as during physical object viewing. This is most likely linked to the 'closeness of context' described in *Subsection 6.1.2, Input and Output Space, and the Closeness of Context*, and the connection between the freedom (or otherwise) associated with the interaction space and the focus of collaborators' actions, effects and attention.

Studies of collaborative group reading have shown the sharing of multiple paper documents to be popular because of the freedom that paper allows for users to sit wherever they choose and "interact with each other without being constrained by bulky technology" (Pearson et al., 2012). Similarly, the feelings of many of the participants in the in-context study were that collaboration was easier with the tablet interface than with the 'confusing' desktop interface, being more socially interactive and making it easier to verify and point things out (make references) for each other.

It's been noted in museums that terminals and other fixed interactive installations (such as the desktop interface with its 'mouse, keyboard and monitor on a desk' paradigm) are usually visited by less people simultaneously than "hands-on installations" with a manual element, which were more often surrounded by groups of people interacting in parallel (Hornecker and Buur, 2006). In this situation, although everybody manually experimenting with the interface itself is not an option, those participants in a group who are not in active control of the interface are still able to observe and direct their peers, which offers them "more opportunity for reflection" (Price et al., 2010) and for profiting themselves as a result of the 'scaffolding' effect (Hornecker and Buur, 2006).

While this is of course the case with both the tablet and desktop interfaces in the in-context study – one collaborator is usually watching the other one holding the tablet or operating the mouse – it is likely that where the observer sees their collaborator's interactions taking place is important in building up a frame of reference and a mutual spatial understanding of the (virtual) artefact. Price et al. (2010) noted how, in their own studies of groups of children collaborating using different types of tangible interfaces, to be able to draw conclusions from the (usually visual) effects of interactions on some kind of display device, users generally "also needed to know what was happening to the [interface] itself".

Studies suggest that multiple interactive objects, where many collaborators each have their own interface with which to perform actions, enable users to move freely around an interaction space, with their movement and orientation within that space affecting digital representations (Price et al., 2010). However, these experiences generally involve a discrete location design – the display is likely to be separated from the individual objects and interfaces – which can result in the link between each participants' actions and their effects being less clear, particularly when interacting simultaneously (Price et al., 2010). Corresponding studies with large touchscreen applications for collaboration have shown that due to everybody being focused on the same display and with the input and output spaces being coupled on the surface of that display, "all actions and consequent digital effects [are] visible to the whole group" (Price et al., 2010).

Clearly, there is an important connection between the frame of reference within an interaction space and the focus of action, effect, and attention. The size of screens and visual displays (where the effects of actions are likely to be seen) will affect how users can and will position themselves within a space – with larger displays, users can be separated and have far more individual freedom within an interaction space (Price et al., 2010), providing that they still have a way of making interactions through some kind of portable or individual interface.

Some of the in-context study participants did feel that the larger (and fixed) screen of the desktop interface made it easier to understand spatial references during collaboration as a result of it being easier with the larger screen space to physically point something out. However, the desktop interface suffers from the input and output spaces being discrete – the collaborators' attention is on the screen, while the actual interaction takes place using the mouse and keyboard positioned away from the screen.

With the tablet interface, while the screen size is smaller, the input and output space are coupled, and so for both collaborators the focus of attention is constantly on the same space, regardless of who is in control. Not only does the collaborator in control of the experience benefit from the closeness of context in the personal sense, enabling them to see the immediate effects of their actions, but the collaborator observing the interactions can see exactly what their collaborator is doing and what effect that action is producing on the (virtual) artefact without having to adjust their focus. This enables both collaborators to build up a frame of reference and spatial understanding as the (virtual) artefact is manipulated. This is likely to be the primary reason for participants reporting that spatial referencing was easier using the tablet interface, despite the desktop interface probably offering the users more space within which to physically point at the (virtual) artefact.

6.2.2 Using Interest Points to Drive Conversations and Focus Attention

The questionnaires showed that all of the collaborative features that the two digital interfaces provided were positively received and thought to be at least moderately useful, all scoring above 2.5 on a scale of 1 to 5, with 5 being extremely useful. Deemed to be particularly useful were the ability to mark interest points, to include information with those interest points, and being able to search through the history of previously left interest points.

Most participants felt that with both the tablet and the digital interfaces, being able mark interest points on the (virtual) artefact whilst manipulating it made it easy for them to pinpoint and to focus on different parts of the artefact. They were able to use the interest points to draw each other's attention to the artefact's interesting features, and in the remote-collaborative scenario the colour coding of interest points for each participant helped with this.

"If you look to the bottom there, your comment has peaked my interest..."
"There's a bit that I've just marked there, I think that's where the film or the plate gets developed"

This was augmented by the usability of the digital interfaces (particularly the tablet interface) which, by making the manipulation of the artefact thoughtless, allowed participants to focus on their discussion and their collaboration, driven as that was by the interest points.

Roschelle and Teasley (1995) describe a process of 'narration' during collaboration, where there can be a number of possible intentions when a collaborator makes an action and it's not always clear what that intention is. Narration in collaborative activity is about providing a "context for the production of action and gesture" (Roschelle and Teasley, 1995) so that an understanding of actions can be maintained without the need for verbal explanation. For the collaborative exploration of (virtual) museum artefacts, interest points (marking them, including information with them and searching through previous ones) offer this 'narration', a clear indication of each collaborator's interest and intent, a way of maintaining understanding and focus, and a vehicle for driving collaborative discussions.

6.2.3 Spatial Referencing Using Interest Points During Remote Collaborations

Of course, when the collaborators could not see each other, and the shared focus of attention described in *Subsection 6.2.1: Establishing a Mutual Focus and Frame of Reference* could not come from a mutual view of co-located input and output spaces, the onus falls more heavily on interest points not just to offer a narration of intent, but also to add the spatial frame of reference to the proceedings.

In the co-located scenario, spatial referencing can be achieved by pointing during physical object viewing (and even to some extent when using the digital interfaces), and as described *in Subsection 6.2.1: Establishing a Mutual Focus and Frame of Reference*, there is a natural focusing and framing of reference that comes from the coupling of the input and output spaces when using the tablet interface. Instrumenting during the in-context study showed that more interest points were marked on average in the remote-located sessions than in the co-located sessions, which suggests that when the participants could not establish a mutual focus through seeing their collaborator or how their collaborator interacted with the (virtual) artefact, they relied upon the marking (and positioning) of interest points to attach a spatial context to each other's actions.

"I think it takes a photographic plate." /
"Where does the plate go, are you marking it?" /
"Yeah, I was." /
"Oh yeah, I can see it."

Also discovered through instrumenting was that the average time at which the last of the interest points was left was much later in the remote-located sessions than in the co-located sessions. This would suggest that users not only mark more interest points, but also spend a longer amount of time doing so when remote-located. This could be interpreted as being because, as previously mentioned, interest points become necessary in the remote context for spatial referencing – perhaps even after interest points cease to be useful for purely information sharing purposes, remotely located collaborators continue to use them for spatial referencing.

6.2.4 Sharing Control of the Interface in the Co-Located Scenario

Video observations were an opportunity to study the amount of time each individual in a collaborating pair spent in control of the interaction while their collaborator observed during the co-located sessions. For both the tablet and desktop interfaces, it was possible to estimate the average percentage of time that the dominant collaborators spent in control of the interaction, as well as the average percentage of time that the less dominant collaborators spent in control.

The difference between the average upper (dominant collaborator) and lower (less dominant collaborator) control percentages was greater with the desktop interface than with the tablet interface, suggesting that the division of time spent in control of the interaction was more equal when collaborating using the tablet interface than with the desktop. There are a number of possible explanations for this – participants may have felt more comfortable, more willing, or simply more aware of the need to share the interface. This would likely have been influenced by the mobility of the tablet interface's form factor – it is light and unconstrained, which without the fixed constraints of the desktop interface, makes passing it around between collaborators a much easier process.

A good sharing dynamic has a number of advantages for collaborative exploration. When users can see each other manipulating an object or an interface, seeing both their collaborator's actions and the resulting effects, those users who are not in control are able to reflect on and talk about the links between those actions and effects, facilitating a strong sense of "learner-to-learner" interaction despite only one collaborator being in control (Price et al., 2010). However, the layout or arrangement of interfaces can also encourage simultaneous actions from multiple users, for the user in control to ask their collaborator[s] for help, or for the user in control to "pass [their collaborator[s]]" a specific object so that they can use it themselves (Price et al., 2010).

Hornecker and Buur (2006) describe 'embodied constraints', whereby the size and arrangement of an interactive interface encourages or facilitates certain types of collaborative or shared input. For example, larger interfaces (such as the *SmartBoard* and *CLAVIER* prototypes which they describe) can encourage group activity by allowing only a small range of outputs and effects for the individual user that become more complex when produced in tandem with collaborators, therefore necessitating that users share and coordinate control with each other in order to make full use of the interface (Hornecker and Buur, 2006).

Both the desktop and tablet interfaces used in the in-context study are comparatively small, and so it is difficult to strictly impose or necessitate that collaborators share the interface with each other. Some participants felt that collaboration was constrained by the fact that only one participant could 'drive' the experience at a time, and there was a feeling among some that clear boundaries were needed to ensure that the collaborator *not* in control was not frustrated by their lack of hands-on exposure to the interface.

However, the difference in the upper and lower percentages suggests that this was far less of a problem with the tablet interface than with the desktop interface. Whilst there was still an imbalance on average, with one collaborator usually having more control than the other, the mobility of the tablet did appear to make it more likely to be passed around, and so this imbalance was not as large as with the desktop interface collaborations.

Additionally, the close coupling of the input and output spaces and mutual focus of attention with the tablet interface meant that during many of the sessions, the collaborator without control of the interface was equally active in the discussion. They would often appear to observe, direct, guide and suggest movements to their 'in control' collaborator (Price et al., 2010), and thus were firmly involved in the exploration of the (virtual) artefact from the perspective of collaborative enquiry, if not from the perspective of physical manipulation.

6.2.5 Encouraging Enquiry and Collaborative Thinking

Perhaps most importantly in terms of collaboration, participants in the in-context study generally felt that they had a good dynamic with each other during the collaboration sessions. Questionnaire responses revealed that participants felt that they understood each other more often than not, with conversations being described as being comfortable, easy to maintain, precise, reassuring and without problems.

That conversations were described as 'reassuring' is particularly interesting when considering that where the pairs of participants had not met each other before participating in the study, it was reported that the collaboration dynamic improved as the conversation went on and the pairs got to know each other. In the case of pairs who did already know each other before participating, it was felt that the digital tools 'facilitated' their existing communication dynamic.

Collaborations would typically involve the participants discussing, musing, deducing, figuring things out, piecing clues together, bouncing ideas off each other and clarifying questions about the (virtual) artefact as part of a collaborative, team effort to construct knowledge. These are all important characteristics of collaborative learning and engagement in a group context (as outlined in *Section 2.2: Collaboration* and *Section 2.4: Engagement* in *Chapter 2: Literature Review*), and as described in *Subsection 2.2.3: Object-Centred Collaboration* often revolved around various aspects of the (virtual) artefact itself. Characteristics of the artefact that provided the focus of collaborative enquiry during the in-context study included aesthetic elements, physical features, the use or functionality of the artefact, and its origins, history and cultural meaning.

"Do you think it folds flat?"
"Yeah, there's rails on the side."

"Do you think that bit at the back is like a viewfinder?"

"It's got a carry-strap on the top."

For many collaborators, the sharing of pre-existing ideas, interests, experiences, theories, intrigue, points of view and knowledge with each other was most useful when one collaborator had more existing prior knowledge about the (virtual) artefact than the other. The more knowledgeable participant tended to 'take the lead' and give instructions to their less knowledgeable collaborator, asking them explicit questions and directing their actions to try and bring them into the discussion and in order to construct knowledge and achieve their own (and the group's) goals of understanding the (virtual) artefact (Price et al., 2010).

In this situation, the input from the more knowledgeable of the collaborators allows their less knowledgeable partner to build up their confidence as the conversation progresses. Rather than feeling intimidated by this, some of the less knowledgeable participants felt that a lack of prior knowledge added a dimension of curiosity to the proceedings and actually made for a better discussion, and sometimes it was actually the less knowledgeable collaborator who took the lead in order to squeeze knowledge from their partner.

Just as the interface itself has the potential to encourage communication, it also has the potential to facilitate and to encourage collaborative thinking. When interfaces contain a performance aspect, where interactions are 'externalised' such that they draw people's attention and make them feel part of the 'content' of the interaction, groups can benefit from shared understanding and awareness, which helps groups of collaborators to think and communicate (Hornecker and Buur, 2006). This links back quite strongly to the idea of the mutual frame of reference (described in Subsection *6.2.1: Establishing Mutual Focus and Frame of Reference*) that is so important for collaborators in building up a shared spatial understanding.

This also highlights – and perhaps even explains – the positive effect that the ease of maintaining that mutual frame of reference with the tablet interface provides during collaboration. When groups are given the tools to alter images and experiences (in this case the viewing angle and scale of the (virtual) artefact), the interest and interaction of group members can be better sustained as a result of the numerous ways that the content can potentially be reconfigured (Hindmarsh et al., 2002). Another way to interpret this is as a collaborative process of problem and reward – the participants are initially faced with a problem (that they do not know enough about the (virtual) artefact), and by manipulating the learning situation (exploring the (virtual) artefact) they are rewarded by being able to construct new knowledge and/or ideas together, which maintains their interest and attention (Knowles et al., 2005).

Of course, while being able to manipulate the (virtual) artefact allows collaborators to reconfigure and reinterpret spatial references together in order to mutually explore, deduce and observe, it's through discussion and "verbally stated questions of the 'problem-solving' variety" (Knowles et al., 2005) that collaborators start to understand each other's ideas, clarify each other's questions, and construct knowledge. Participants in the in-context study generally reported feeling that by the end of a session of collaborative exploration, they had succeeded in contributing at least some of their own knowledge or ideas to the discussion. Interestingly, however, participants felt that the discussion with their collaborator helped them to draw conclusions that they might not otherwise have drawn about the artefact to a much greater extent during physical object viewing than with either of the two digital interfaces.

One explanation for this could simply be that the physical object viewing was more likely to be a purely natural viewing experience without any outside interferences. For example, some participants felt that with the digital interfaces, marking interest points was not particularly useful for non-experts, who were potentially far less confident about the contributions they are making. It was also noted that with the digital interfaces in particular, a lot of pressure was placed on the information provided in the history of previous interest points to maintain interest in the discussion – when there was not enough pre-provided information to reflect on, inspiring conversation became more difficult. These kinds of outside factors, leaving interest points and referring back to additional information, perhaps took away from or interfered with the purer 'look and discuss' experience of physical object viewing.

Some collaborators also felt that differences of opinion made it difficult to arrive at shared conclusions, and even led some collaborators to feel uncertain about the significance of their own contributions. For some participants this brought difficulty to the collaboration, which could end up feeling strained and limited to guesswork. However, it was also argued that even when the collaborators do not arrive at the same conclusions, they are able to "supplement [each] other's recollection", which "enriches the process of meaning-making" (Otitoju and Harrison, 2008).

6.3 What Makes a More (or Less) Engaging Experience?

6.3.1 Being in Control Without Needing Too Much Attention

In-context study participants' responses to the adaptation of the System Usability Scale (SUS) used to provide a measure for engagement showed that the tablet interface was significantly more engaging than the desktop interface, supporting the initial hypothesis from *Chapter 1: Introduction*. This finding would appear to have a lot to do with the fact that, as outlined in Subsection *6.1.1: Usability, Control and Freedom of Exploration*, the tablet interface was significantly more usable (and thus significantly more realistic) than its desktop counterpart.

Although some participants felt that in requiring some degree of thought and attention to use them the two digital interfaces could potentially distract attention away from the discussion itself, most participants reported that as far as exploring the (virtual) artefact goes, the digital interfaces offered an enjoyable and engaging sense of interactivity. This was particularly the case for the tablet interface, with which the fluidity, directness, smoothness and speed of the interaction created a natural feel, and made it easier for collaborators to focus on the conversation without having to give too much of their attention to the interaction technique being used.

In contrast, participants described how constantly having to look up and down to shift the focus of attention between the mouse, the keyboard and the screen was a constant interruption to the smoothness and the flow of the experience when using the desktop interface. The coupling of the input and output spaces has already been described in this chapter in terms of the realism of the interaction technique (*Subsection 6.1.2: Input and Output Space, and the Closeness of Context*) and in ensuring that collaborators have a shared understanding of spatial references (*Subsection 6.2.1: Establishing Mutual Focus and Frame of Reference*), and these descriptions of the interrupted experience of using the desktop interface show that the coupling of input and output space and closeness of context is just as important for engagement as well.

Somewhat related to this is the percentage of time that participants spent holding the tablet interface in their hands during collaboration sessions. Video observations showed that in most of the co-located sessions, the tablet was held in the hands, and as previously mentioned this has numerous advantages – the coupling of input and output space and the effect of this on realism and spatial referencing, the ease of passing the tablet between collaborators, and so on. However, during the remote-located collaboration sessions, it was more common to see individuals resting the tablet on the table rather than holding it in their hands.

In the questionnaires, it was reported by some users that balancing the tablet at the same time as using the touchscreen could be an 'awkward' process. Clearly, this shows that while the co-located scenario necessitates that the tablet needs to be angled so that both collaborators are able to view the input and output space (the touchscreen), which is best achieved using the hands, during the remote-located sessions angling the tablet using the hands is just another distraction from the real business of exploring the artefact, and so users are more likely to let it rest on a desk or a table and focus solely on their interactions with it.

This essentially means that the more comfortable, at ease and in control the user feels, the less barriers there are between themselves and the (virtual) artefact that they are supposed to be engaging with. Children have been shown to relate their enjoyment of, and participation in, a museum exhibit to “the power that it made them possess” (Haywood and Cairns, 2005), but what is referred to here is not so much about the ability to perform a huge array of functions, but more simply about being able to “directly interact with the exhibit” (Haywood and Cairns, 2005). Being able to interact freely and with an appropriate degree of control, without having to focus extra attention on unnecessary processes, gives users every opportunity to engage with, in this case, the (virtual) artefact.

Orthogonal to being in control of interaction is being able to make sense of and understand the effects of it. Once again, the coupled input and output space of the tablet interface, whereby the user touches the tablet’s screen to alter the display of the (virtual) artefact on it, is crucial. This “presentation of feedback” shows the user the exact response of the (virtual) artefact to their actions directly and immediately, making them feel “in charge of the interaction”, maintaining their attention and interest, and thus being more likely to lead to “period[s] of sustained engagement” (O'Brien and Toms, 2008).

6.3.2 Exploring Shared Curiosity in Busy Collaborative Discussions

Participant’s open-ended questionnaire responses revealed that having a shared, mutual curiosity to figure out the unknown and learn about the (virtual) artefact is vital in engaging more than one person in the collaboration – if only one of the participants is interested, the collaborative element of the discussion really suffers. Generally, the busier the discussion and the more theorising involved, the more engaged the collaborators feel, with the exchange of ideas between them stimulating a wider shared view of the context.

Instrumenting showed that more interest points were marked on average during the remote-located sessions than in the co-located sessions, whilst the average time at which the interest points was left was much later in the remote-located sessions than in the co-located sessions. This suggests that users spend a longer amount of time marking more interest points in a remote-located session compared to a co-located session, and it could be interpreted that this represents a 'busier', and therefore more engaging, collaborative discussion.

However, the in-context study participants' responses did show that co-located discussions were slightly more engaging and stimulating experiences than remote-located discussions. Just as the switching of focus between the mouse, keyboard and display interrupted participants' attention and made it difficult to engage with the desktop interface (see *Subsection 6.3.1: Being in Control Without Needing Too Much Attention*), the experience of leaving interest points was reported to 'break the flow' of the interaction at times, with too many steps or 'clicks' being needed to leave a point. Considering that more points are left during a typical remote-located discussion, this could be a key factor in that they were less engaging for collaborators.

"It's interesting, when you're reading stuff and typing stuff, you don't collaborate."

Some of the steps that caused participants difficulty were generally down to text-entry-related usability issues: text fields could end up overlapping each other after consecutive clicks; it was difficult to clear text fields when wanting to correct something; and on the tablet, when the virtual keyboard pops up and covers the artefact momentarily, the flow of the interaction is broken. Another complaint about the interest points was that, even after being successfully marked, they sometimes did not appear to be attached to the intended part of the (virtual) artefact.

A more collaboration specific problem that interest points caused was that waiting for another user to finish typing their point before continuing with a conversation was 'cumbersome', and it was suggested that this could be avoided by incorporating a temporary marker of some sort that could highlight where a user was going to leave a point while it was still being written and created. This, coupled with the issues highlighted in the previous paragraph, led to some users describing interest points as 'un-useful', and not being sufficiently compelled to leave them – although searching through the history of previous interest points was, in comparison, considered to be extremely useful for inspiring and reigniting collaborators' interest when a conversation had begun to dry up.

The issues raised with interest points described above were, of course, applicable in both the co-located and the remote-located scenarios. They could cause participants to lose their focus, divert their attention, and hinder them from fully engaging with the (virtual) artefact and in the collaboration. Busy discussions and shared curiosity are vitally important for an engaging collaboration, and in the remote-located scenario more of this discussion is facilitated by the marking of interest points.

It can therefore be interpreted that with more interest points being marked, there are more opportunities for these breaks and interruptions to engagement to occur, thus making the remote-located discussions slightly less stimulating and engaging than their co-located counterparts. For remote-located interfaces, it is therefore crucial that busy collaborative discussions driven by shared curiosity are given a chance to flow, and that referencing or communication measures such as the marking of interest points do not interrupt users or lessen their engagement.

6.3.3 Being Motivated to Explore and Free From Restrictions

The questionnaires probed for the popularity of the three viewing methods, and results showed that the desktop interface was significantly less popular than the other two viewing methods, with physical object viewing being the preferred way of exploring museum artefacts. This was due to the fact that for many participants, even with the hands-on exploration value that the digital interfaces provided, seeing the physical artefact itself was still essential for building a true context. It was described as both satisfying and engaging to see artefacts in their true form, with the levels of detail and craftsmanship (in the case of man-made objects) being 'awe-inspiring' at their true fidelity.

This visceral experience of seeing an artefact in the flesh leaves the viewer feeling more connected and more focused on it, and is largely down to the "cultural value it is given" as opposed to any technology that may have been used "to give it form or content" (Pearce, 1994). Seeing artefacts in their true form provokes a reaction and can make the discussion of them seem like a puzzle where the various visual clues associated with it have to be pieced together, engaging "those who might not normally be interested" by giving them a sense of "privileged access" (Mastoris, n.d.).

However, while simply seeing an artefact in its true form can be satisfying and engaging, it's still essentially a "passive" object, and so some kind of information and focus is still needed in order to challenge "the preconceptions people bring with them" and facilitate discovery and learning (Pye, 2007) – as Hein (1998) states, "people need to connect to what is familiar [such as an object], but learning, by definition, goes beyond the known". While a physical artefact may be able to engage an individual and be viscerally satisfying, there still needs to be some kind of challenging of ideas and focusing of attention in order to take that from a pleasurable experience to one where learning can occur.

The user experience can be designed to do just that, exploiting "emotional and cognitive values" (visceral engagement with the artefact) through interactions that "suggest context" (reality-based digital interactions) in order to facilitate a more "direct engagement" (Price et al., 2010) – one in which discovery and learning are facilitated. In other words, if "the right degree of intellectual challenge" is offered (pre-provided information, collaborative discussion, mutual focus of attention) while still maintaining "sufficient orientation" to be able to "recognise the challenge" (reality-based interaction, shared frame of reference), then the learner is likely to 'accept' the challenge, and find themselves motivated to engage in a more active process of collaborative discussion and discovery.

For the exploration of artefacts in particular, one of the biggest threats to that motivation to engage is when there are limited viewing angles, which can leave the viewer feeling 'distant' and detached from the artefact.

"I'd love to have a close-up view for a look at its face."

While it would be natural to assume that this is less of a problem for the digital interfaces, as they allow users to explore artefacts from all sides, participants did in fact describe some issues that limited their motivation to explore the (virtual) artefacts using the digital interfaces. With the tablet interface, for example, a few participants felt that their view of the artefact was obscured, and thus their motivation to engage with it affected, by their hands covering up parts of the image as they tried to interact with the touchscreen.

With the desktop interface, motivation to engage with the (virtual) artefact suffered more generally from the kinds of usability issues brought to light in *Subsection 6.1.1: Usability, Control, and Freedom of Exploration*. Some participants felt that that the less fluid interaction style of the desktop interface left them feeling 'disconnected' from the artefact, requiring them to be 'too involved' in the interaction technique to the extent that the interaction was uncomfortable and interest in the (virtual) artefact was lost. This supports existing theories that there is an "inverse relationship between users' level of interaction with [an interface] and the depth of [their] interpretations" (Otitoju and Harrison, 2008), with interfaces that require too much involvement detracting from the user's attention and motivation to engage with the content, in this case the (virtual) artefact.

Clearly, the visceral experience of seeing an object in the flesh provides a strong motivation to engage with it and to find out more, and when this is coupled with an activity with elements of challenge or that focuses attention, such as a collaborative exploration and discussion, this engagement and interest can become an active process of discovery and learning. When exploration is restricted by limits and boundaries, the motivation to engage is adversely affected, and so ideally the visceral experience will facilitate exploration from all sides and multiple angles, something which reality-based digital interactions such as those offered by the tablet interface provide. However, these need to be as natural and as seamless as possible, because any unnecessary complexities or interruptions in the interaction style will also affect the motivation to engage with the (virtual) artefact.

It is also worth noting that for the experiences provided by the digital interfaces to be truly engaging in their own right, a good visual representation of the virtual artefact is vitally important. The fidelity of the 3D representation is orthogonal to engagement and maintaining the user's interest in it, and as described in this section, seeing an artefact in the flesh provokes strong reactions and helps users to connect to the artefact. For the digital exploration of virtual museum artefacts, the 3D representation must be accurate and aesthetically pleasing in order to ensure that it is sufficiently visceral and engaging. This will be described further in *Section 6.5: Considerations for Future Improvement*.

6.3.4 Excitement About and Engagement with the Artefact Itself

Of course, in the museum context (and probably in most learning scenarios), it is important to remember that any attempts to foster control, shared curiosity and motivation are fairly meaningless if collaborators cannot engage with the (virtual) artefact itself from a personal perspective. Participants described how, regardless of the interface used to examine a particular artefact, an enjoyment or personal interest in the topic or the style of the artefact being explored remains the most important factor in whether or not they can engage with it.

Questionnaire responses showed that in the case of the in-context study, the Insect (Raspy Cricket) was significantly less popular than the Chinese Figurine or the Plate Camera (both of which were much more favored by the participants), as well as also being far less stimulating than the other two. Of course, collaborators' preferences for one type of artefact over another are going to be highly subjective, and so even if for the sake of argument there were nine out of ten participants who disliked the insect, it is quite possible that there would still be a participant who found it, for whatever number of possible personal reasons, incredibly interesting and engaging (*"Someone knows their crickets!"*). Participants described how when they were paired up with a collaborator who had a different level of interest and personal engagement with the artefact than themselves, adverse effects on the collaboration could occur.

Some of the reasons that people gave for their interests in the artefacts used during the in-context study shed some light on why the Plate Camera and the Chinese Figurine may have proven to be more popular than the Insect. A mechanical interest, whereby people can become interested in trying to deduce how things might have worked by relating them to knowledge of similar mechanical processes, can be very engaging, and this would have been something that people could find interesting about the Plate Camera.

"I can't see a button there to upload your pictures to Instagram…"
"Yeah, I don't think it's very 'instant'!"

Unfamiliar objects are also able to inspire curiosity, surprise, and instigate busy discussions, particularly when they are highly detailed and have strong aesthetic qualities. This helps make artefacts like the Chinese Figurine much more engaging than objects that perhaps do not pose as many questions or facilitate as much theorising, such as the Insect.

These factors are most prominent when the artefact touches and engages the viewer on a personal level, either through the human, local, or cultural contexts. This leads to intrigue and engagement on the personal level, which is then filtered into the collaboration as well. The Plate Camera offers a good example of this, with many participants describing how their own knowledge of using cameras in a modern context meant they could connect on a personal level with the way that camera technology has advanced over time, and how human uses of such technology would have been affected by such changes.

It is therefore vital that for the experience of collaborative exploration and discussion of (virtual) artefacts to be truly engaging, the artefact itself needs to be something that each user can relate to and engage with on some kind of personal level, with that personal engagement then fostered and focused by offering control over interactions, encouraging shared curiosity, and maintaining motivations to explore without unnecessary interruptions or restrictions.

6.4 How are Learning Experiences Facilitated?

6.4.1 Making Sense of Artefacts Through Real-World Principles

Participants in the in-context study described how important it was to be able to see artefacts from all sides, and to be able to zoom in on smaller ones (such as the Insect), using the digital interfaces. Having the whole of an object accessible for discovery and exploration without limits was thought to be 'crucial' to learning, and when the representational quality was clear enough, this accessibility made it easy to see how artefacts such as the Plate Camera would have worked.

This can be interpreted as being related to the way people traditionally interact with objects when examining them by hand – objects can be twisted and turned in the hands to be viewed from all angles, and can be brought closer to the face to get a better view of harder-to-see details. When trying to offer a digital alternative to the physical exploration of artefacts, this freedom and accessibility that is associated with physical object handling is expected by the user, and needs to be accomodated. The digital interfaces compared in the in-context study allow this freedom of exploration, in particular the tablet interface which with it's direct, immediate interaction style and close coupling of input and output space (see *Subsection 6.1.1: Usability, Control, and Freedom of Exploration*) makes use of users' "pre-existing real world knowledge and skills" to reduce the mental effort needed to interact with the (virtual) artefact (Jacob et al., 2008).

"This is where the pad [tablet] would be useful, to turn it upside down and have a look."

Existing research has shown that this reduction in required mental effort can improve performance and, crucially, speed up learning, particularly in "situations involving information overload, time pressure, or stress" (Jacob et al., 2008). It has also been suggested that physical, reality-based activities and interactions are often augmented by 'fantasy', with children having been observed to use their imagination to make sense of their interactions and relate them to real life (Haywood and Cairns, 2005). The realism of the interaction empowers users, giving them the opportunity to make sense of what they are doing through their imagination, and the combination of these two concepts helps to "reinforce the feeling of engagement" (Haywood and Cairns, 2005).

It seems reasonable to conclude that the more grounded in reality digital interactions are, the easier users would find it to apply their imagination to the interaction and make sense of it (in theory leading to learning outcomes), and that this would make the tablet interface in particular very useful in making sense of and learning about the (virtual) artefact being explored. However, questionnaire responses from the in-context study showed that participants felt that they learned more about the artefacts by looking at the physical objects than by looking at either of the digital versions.

One reason for the preference towards physical object viewing was simply that for some participants, the artefacts themselves provided the best reference point to stimulate collaborative discussion, largely due to the fact that making eye contact with the collaborator or simply pointing at something was easier. Clearly, the collaboration dynamic had an influence on participants' ability to make sense of the artefacts (as will be described shortly in *Subsection 6.4.2: Referring To and Sharing Existing Knowledge*), and participants did also describe how even when viewing angles are limited, for example by the artefacts' fixed positions in glass display cases, there are usually enough visible features to discover new things.

However, the qualitative responses that participants offered shed some light on why, specifically, the digital interfaces might not have had quite the same effect in engaging the imagination and facilitating learning and sense-making as physical object viewing had. One of the major concerns about the digital interfaces was that there was no sense of relative scale (i.e. how big the artefact is in centimeters or inches), which was only really visible from viewing the object in the flesh. Without this reference, it was always more difficult than it should have been for participants to make sense of the complete 3D picture of the artefact. Relative scale was one of a number of the 'physical nuances' of objects that participants found it difficult to make sense of from the digital representation alone, with others including a sense of perspective, the weight of the object, and intricate details such as textures (and embroidery in the case of the Chinese Figurine).

It seems clear that the more reality-based digital interactions are, the more opportunities collaborators have to make sense of the (virtual) artefact being explored, as they can use their imagination to make sense of the interaction technique in the context of the (virtual) artefact, thus learning more about it. However, in order to take advantage of the imagination and make the best sense of the interaction technique, the 3D representation of the artefact needs to provide an accurate depiction of the physical nuances of the artefact in its own right, a necessity which although difficult to get right due to the many nuances of physical objects, can hinder imagination, sense-making and learning, if missing.

6.4.2 Referring To and Sharing Existing Knowledge

In-context study participants reported that in almost all collaboration sessions, at least one of the pair of collaborators was able to relate the experience back to some kind of previous knowledge or experience. This breadth of the experiences that participants were able to relate back to was large, including: personal experiences; moments from everyday life; childhood memories; recollections of travel; subject-specific knowledge, such as of objects or processes; general knowledge; local links and stories; times and places (the historical context); previous museum exhibits and visits; and memories of previous learning that has taken place from seeing video footage, photographs, or from reading books.

This prior knowledge could be used to draw conclusions, agree on details, clarify ideas, or eliminate certain theories, and participants also reported that even when prior knowledge and experience was only quite limited, they still generally felt that they had enough to bring something to discussion. This allowed collaborators to put their knowledge together and build towards shared conceptions of artefacts, a process of drawing on and 'scaffolding' from each other's prior knowledge and experiences that they felt was key and crucial to their own learning outcomes.

"You've absolutely peaked my interest and certainly provided information, in a way that the computer hadn't… but that again is being able to bring prior knowledge to the objects."
"Which is why we seek out guides and tours where people tell us stories of objects and of places and experiences."

Existing research has shown that collaborative exploration helps learners to arrive at shared conclusions about problems and concepts, often "[beginning] with different, although not entirely incompatible ideas" that converge into shared ideas over time (Roschelle and Teasley, 1995). Groups of collaborating children in museum spaces have exhibited that "the mere presence of others" is reassuring in itself, in that it offers them feedback – this is rooted in a natural desire to talk to others about the experience, which can sometimes be even more important to arriving at shared conclusions than the feedback provided by the exhibit itself (Haywood and Cairns, 2005).

In *Subsection 6.2.2: Using Interest Points to Drive Conversations and Focus Attention* the role of interest points in helping to bring focus to the narrative of the conversation was highlighted, and in *Section 2.4: Engagement* narrative was identified as a key component of engagement. However, it is often the case that the narratives people create for themselves and each other "do not necessarily match with the narrative intended by the exhibit" (Haywood and Cairns, 2005), and the continual process of making sense of the exhibit (or artefact) is how collaborators "fill in the gaps" (Haywood and Cairns, 2005). The prior knowledge or experience that collaborators bring with them to a discussion and share with each other helps them to shape and construct a shared 'narrative' and conception of the exhibit or artefact.

Bringing prior knowledge and experience to the fore was not always easy for participants, with some describing that when they felt that they did not have (or know) enough to draw upon, it made them hesitant to make too many comments or leave interest points. When this happened, it was sometimes difficult for collaborators to be able to construct new ideas, and even if a collaborator felt that they had learned something from the discussion, they could sometimes be left feeling insecure about what they themselves had contributed to it. Participants also described that prior knowledge in particular can be more or less limited depending on the topic (or in this case artefact) in question, and so it should never be taken for granted that collaborators will actually have enough of a base-knowledge to be able to contribute confidently from the outset.

However, interest points (and in particular the history of previous points) helped to account for this, and provide an additional 'prior experience' of their own that collaborators could refer to. Being able to scroll through the interest points was described as being a useful way of exploring and digesting information, allowing collaborators to direct the discussion with minimal effort. The interest points reminded some participants of a blog or a news feed (something that was alluded to when describing the *AnnoCryst* system in *Subsection 4.1.2: Previous Examples of 3D Browser Annotation*), presenting information in a narrative-like structure, which was particularly useful for shedding light on information that the collaborators had not picked up on themselves during sessions. Being able to retrace and revisit prior knowledge and interest points left from previous sessions, besides being described as a very engaging feature, helped with the convergence of ideas and theories during moments when collaborators may have struggled to force a convergence of ideas using their own previous knowledge and experience.

Being able to refer back to prior knowledge, which collaborators can bring and draw from a wealth of memories and previous experiences, is clearly an important tool for collaborative discussion. This process of the sharing and narration of ideas sees collaborators go from different thoughts and theories that can sometimes be in stark contrast to each other, to a convergence of ideas and a shared conception of the learned concept – in this case, the story of a (virtual) artefact. Through the appropriate use of digital impetus, such as the interest points used in this research, this narration can be further focused, helping collaborators to draw not only on their own but on the prior knowledge and experiences of connected users past and present, focusing and facilitating the convergence of ideas and (hopefully) shared learning outcomes.

6.5 Considerations for Future Improvement

6.5.1 The Representational Fidelity of the Virtual Artefact

One of the critical concerns that was constantly raised by participants over the course of the in-context study was the level of the virtual artefact's representational fidelity, which needs to be at an extremely high level in order to maintain collaborators' attention and interest. When this fidelity is lacking, the authenticity of the experience is compromised and things feel too 'digital', which interrupts engagement and leaves users feeling detached.

To ensure that this does not happen, 3D virtual representations of museum artefacts for digital exploration should really be photorealistic in order to maintain the same level of visceral engagement as a physical artefact. Unfortunately, participants felt that the representational fidelity of the 3D representations used in the in-context study fell below what is required to truly maintain engagement, and that because of this, it was sometimes difficult to make sense of certain aspects of the artefact.

Being able to see the (virtual) artefacts at a high level of detail is important for constructing knowledge based on how the object looks, and especially so for those artefacts where the provided information is directly related to visual details, such as the embroidery on the Chinese Figurine. This was a particular problem with natural objects, and participants also had trouble adjusting to the level of representational fidelity of the Insect (Raspy Cricket) at times. There were not nearly as many fidelity-related problems with the Plate Camera, with participants noting that man-made objects seem to be easier to digitally represent, but for most cases there appears to be a need to improve the digital fidelity of 3D representations of museum artefacts in order to ensure authenticity and sustained engagement.

The issue of scale also ties in with representational fidelity, and participants suggested that for zooming in and out of artefacts, the fidelity needed to auto-adjust in tandem with the changing viewpoints – fidelity has to be maintained throughout all the possible viewing distances, as a drop in the level of detail as the user zooms in on an artefact also affects the authenticity of the experience. As important as the representational fidelity of detail is, the issue of representational scale for virtual artefacts, and the lack of this, caused numerous problems for in-context study participants.

> *"I think we probably assumed a size, whereas with this one it's difficult because we don't have a reference point."*

Not being able to understand what would have been the physical scale of a virtually-represented artefact made it difficult to accurately understand a (virtual) artefact's context of use (for the Chinese Figurine in particular), which led many collaborators to feel that they were merely speculating as opposed to contributing.

6.5.2 The Smoother Integration of Interest Points

In Subsection *6.3.2 Exploring Shared Curiosity in Busy Collaborative Discussions* the ways that marking interest points could interrupt engagement were described, and so in order to avoid this, a smoother integration of interest points into the digital experiences is required in the future. Some users described the marking of interest points as clunky and awkward, and reported that it could sometimes be difficult to map them to the desired location on the artefact, which could create a highly undesirable barrier to engagement with the (virtual) artefact. Some participants also suggested that the awkwardness of leaving interest points and the problems this presented for engagement may have been avoided if marking interest points, and more specifically leaving comments on interest points, was audio-based and facilitated using speech input, particularly as the collaborations were discussion-based to begin with.

Some of the reported 'clunkiness' of the interest points appeared to be down to perspective – while the intention was always that interest points would act as a way of helping users to focus their attention on different parts of the (virtual) artefact, it would appear that some participants had trouble focusing on the interest points themselves to begin with. Participants described how it would have been much better if the virtual artefact had rotated to the front as interest points were being selected, particularly when searching through the points using the slider bar, which without the coupled rotation of the virtual artefact could break the flow of the interaction.

The actual marking of interest points was also highlighted as an area for future improvement, and something that could be expanded upon in future systems. One of the most commonly suggested improvements regarding interest points was that it would have been useful to be able to add extra comments to existing ones, in order to further explore certain themes and thoughts. If these comments could also be 'liked' and 'favourited', contributors are then provided with information and feedback on the popularity and attention being given to points they've made (Ames and Naaman, 2007). This kind of feature has been described, for users of photo-sharing service Flickr, as being important in satisfying personal motivations for tagging and commenting on photos (Ames and Naaman, 2007).

Considering why people choose to annotate something is also an interesting concern for future implementations of interest points. Ames and Naaman (Ames and Naaman, 2007) describe that most participants "only considered one or two motivations for adding tags [making annotations]", without giving much thought to other possible benefits. They found that "organisation for oneself" and "personal search and retrieval" were commonly considered by Flickr users in tagging photos, but that tagging for communication or for personal memory were not generally considered as benefits in the motivation to tag [annotate] things (Ames and Naaman, 2007).

This is probably well reflected in some of the observations of the use of interest points highlighted in this chapter. As described in *Subsection 6.2.2: Using Interest Points to Drive Conversations and Focus Attention*, interest points were considered to be a useful tool in directing conversations and focusing attention – the element of organization mentioned above. But, as described in *Subsection 6.4.2 Referring To and Sharing Existing Knowledge*, participants were far more reserved in using interest points when they were not completely confident in their knowledge of the (virtual) artefact, and were reluctant to communicate their ideas for fear of making some kind of mistake.

"I'd make my own comments elsewhere and then check them before adding them."

In this sense, the 'communication' aspect of the interest points seemed to have been missed, with participants not really understanding or believing in the benefits of sharing their ideas and contributions, whether they be the correct 'facts' or not, with a wider community of learners. Some participants highlighted this, suggesting that when the interest points they had left raised questions, a more instant form of feedback answering those questions had been expected (*"Are you going to tell us anything about this?"*). In future implementations, users need to be made more aware of the fact that rather than being an instant 'question/response' dynamic, the idea of sharing thoughts and ideas using interest points is more about giving other users and later collaborators food for thought, thus contributing and raising questions as part of an ongoing, wider-scale discussion.

It was suggested that more options for assigning context to interest points, mapped to different types of artefact, might have encouraged participants to leave more of them, and contribute more frequently or more confidently to the discussion. Ames and Naaman (2007) describe the importance of context-specific tags in the motivation to annotate and comment, with seemingly simple tag-types such as 'place-name' for photos being important for retrieval (organisation), communicating location to others (community communication), and for reminding the user where the picture was taken at a later date (personal communication). In the in-context study, additional context options might well have given participants more confidence that any knowledge they might be leaving, however small, had some relevance – with the current three choices for context, participants may not have felt that their contributions or ideas were specifically related to the aesthetics, geometry or meaning of the artefact, or have been able to see how their contribution might fit into those three categories.

Throughout the previous sections of this chapter, the importance of usability in realistic, natural and thus engaging exploration of the (virtual) artefact has been highlighted, and interpreted as a key factor in showing the hands-on, mobile approach of the tablet interface to be more suited to the task than its existing desktop alternative. It has also been highlighted that unless users feel comfortable not only with their contributions to a discussion but with the context in which they are making them, they will be far less motivated to leave interest points for others to view. It is therefore important to ensure that a clumsy, complicated implementation of interest points and digital annotation aids, or one in which users cannot see the relevance of leaving interest points, does not undo this good work and make for a frustrating or unengaging experience regardless of the naturalness of the actual (virtual) artefact-level interaction technique or the potential benefits of sharing their ideas.

6.5.3 Additional Content and Viewing Options

Finally, for many of the in-context study participants, the (virtual) artefact alone was simply not enough to explore, and some kind of additional content or experience was expected, particularly from the digital sessions. For many participants, although being given some hints in the form of a descriptor before each collaboration session helped to get them started and inspire some thoughts about the (virtual) artefact from the outset, it was felt that additional contextual information presented using video or multimedia would have helped with learning. This was particularly the case for the physical object viewing, where participants described the supplementary information as being 'more limited'.

This is an interesting comment, because the supplementary information provided during the physical object viewing was actually the same as with the digital viewing methods – all of the previous interest points that participants could search through using the digital tools (besides the ones they left themselves) were provided as bullet points on the didactic card accompanying the physical artefacts. This suggests that either the participants really felt that their own interest points added some contextual information to the proceedings, or that when the didactic information was presented to them in a more interactive, digital format (when using the desktop or tablet interfaces), this somehow made it seem like there was actually more information being provided.

"You need a Wikipedia button in the corner there."

Besides as an accompaniment for the physical object viewing, a number of participants also felt that something extra to expand the virtual artefact viewing experience would have been welcomed. Some of the possible additional informational multimedia material that participants would have been interested in seeing included diagrams, audio content, or video to accompany the 3D representation of the artefact, as well as additional options for viewing the 3D representation itself, such as x-ray or cross-section functionality to explore the inner workings or materiality of (virtual) artefacts.

With the digital interfaces, the opportunity to supplement the reality-based exploration of a virtually represented artefact with additional digital and multimedia information is there. If, as described in *Subsection 2.3.1 Principles and Tradeoffs*, a balanced mixture can be found between reality-based digital interaction techniques (exploration of and interaction with the virtual artefact) and the non-realistic digital functionality (exploration of additional multimedia), this creates a multitude of potentially powerful and engaging options for digital exploration, collaboration and learning experiences.

Chapter 7: Conclusions

Over the last two chapters, the in-context study and the results it produced were described, and these results were then interpreted in the contexts of reality-based interaction, collaboration, engagement and learning. In this chapter, conclusions are drawn based on these interpretations, and how they and the results that they were based on relate to the hypothesis, the research question and core questions, as well as to the various theories and frameworks described throughout the thesis and that influenced the design of the proposed interactive system that was evaluated. In particular, these conclusions are framed around the research hypothesis, which by providing evidence that the tablet-based *RelicPad* interface was engaging, and by way of being more natural and realistic was closer to the experience of physically viewing and handling objects than its desktop counterpart, has been proven to be correct.

7.1 Revisiting the Research Question and Hypothesis

7.1.1 Answering the Research Question

In *Chapter 1: Introduction*, the research question was posed:

> *"How can manual interaction with 3D, virtual representations of museum artefacts and interest points using a mobile device help to efficiently facilitate engaging discussions of (virtual) museum artefacts for remote or co-located collaborators?"*

The answer to this question, based on the results described in *Chapter 5: Experiment & Results* and the interpretations made of them in *Chapter 6: Discussion*, is:

> *"Manual interaction with 3D, virtual representations of museum artefacts and interest points using a mobile device efficiently facilitates engaging discussions of (virtual) museum artefacts for remote and co-*

located collaborators by being more usable than alternative interaction techniques, having a tight coupling of input and output space, and by allowing for the marking of interest points in 3D space."

As discussed in the previous chapter, manipulating 3D objects manually using the tablet interface with its hands-on, mobile properties was both more usable and more engaging than manipulating the same objects using a desktop (mouse and keyboard)-based interface for interaction. This is mainly the result of two key characteristics of the tablet interface:

- Being more *usable*, the tablet interface feels more *natural*, intuitive, and comfortable to use, giving users a stronger sense of *control* over a more believable, *realistic*, and authentic experience.
    - This freedom and control allows users to explore (virtual) artefacts in a way that does not require excessive attention or concentration on techniques and processes, motivating them to fully engage with the content (the virtual artefact itself) without distractions.
- Having a close coupling of input and output space, the tablet interface carries a 'closeness of context' whereby the action (user's touch) takes place in exactly the same place as the response (movement of the virtual artefact) on the tablet's touchscreen, in full view of all collaborators.
    - For the individual, this tight coupling limits the potential distraction that more complicated or discrete interaction techniques can cause, and focuses the attention of the user on their actions and an immediate, direct response.
    - For (co-located) collaboration, the tight coupling helps collaborators to build up a mutual understanding of the actions of group members by focusing everybody's attention on the same input and output space.
    - The direct presentation of feedback – the immediate movement of the (virtual) artefact according to the user's touch – fosters a sense of being in control of the interaction, which helps to maintain

users' (and their collaborators') interest and motivation and leads to periods of sustained engagement.

Although they could be used with the desktop interface as well, the efficiency of the hands-on, mobile *RelicPad* experience in facilitating engaging collaborative discussions was supported by:

- Interest points, which provided a means of driving conversations in the visual sense, and enabling collaborators to pinpoint, focus on, and draw each other's attention to interesting parts of the artefact.
  - During collaboration, interest points allowed users to create a 'narrative' of their interests and intentions, helping to maintain an understanding of and a focus on the collaboration.
  - For remote collaborations, when the participants could not establish a mutual focus of attention or make spatial references by observing each other's actions upon the tablet, the marking (and positioning) of interest points was relied upon to provide a spatial context for each other's actions and intentions.

In summary, *RelicPad* (the proposed solution to the research problem) has answered the research question posed in *Chapter 1: Introduction* by showing that manual interaction with 3D, virtual representations of museum artefact and interest points using a mobile device efficiently facilitates engaging discussions of (virtual) museum artefacts for remote and co-located collaborators through a combination of 1) usability and control that makes the experience feel more realistic, 2) tight coupling of input and output space that limits distraction and focuses attention, and 3) interest points for maintaining a 'narrative' of interests and intentions and making collaborative spatial references.

7.1.2 Was the Research Hypothesis Correct?

In *Chapter 1: Introduction*, a prediction was made about the eventual outcome of the research. The hypothesis was that:

> *"Manual interaction and annotation with a tablet device, based on real-world principles, is an engaging way of exploring and collaboratively discussing 3D, virtual representations of objects. In the case of oft-inaccessible (virtual) museum artefacts, such interaction techniques offer an experience much more akin to handling physical artefacts than that of the less-engaging digital techniques that are currently used."*

The results described in *Chapter 5: Experiment & Results* and interpreted in *Chapter 6: Discussion* support this hypothesis, and show it to have been correct. The tablet-based interface outperformed and outscored its desktop-based equivalent in almost every measured aspect of the in-context study, including:

- The tablet being more engaging than the desktop,
- The tablet being a more reality-based experience than the desktop, based on:
  - The tablet being more usable than the desktop,
  - It being easier to rotate and scale the virtual artefact in 3D with the tablet than with the desktop.,
  - Participants feeling like they had more control over the virtual artefact's movement with the tablet than with the desktop,
  - The virtual artefact behaving more as the participants would have expected it to when moved using the tablet than with the desktop,
- It being easier to make spatial references with the tablet than with the desktop,
- The tablet being preferred as a viewing method to the desktop.

As expected, physical object viewing was the method with which participants found it easiest to make spatial references for their collaborator, as well as being the preferred viewing method of the three overall – as described in *Subsection 6.3.3: Being Motivated to Explore and Free From Restrictions*, viewing a physical, 'flesh and blood' artefact is still the most satisfying and engaging way to experience museum content, and necessary for building a true understanding of context. As a digital alternative, however, the experience of using the tablet-based *RelicPad* interface is shown to be more engaging than its desktop-based equivalent, and by virtue of being more reality-based and easier to make spatial references with is also shown to be more akin to the physical object viewing (and handling) experience. This shows the research hypothesis to have been correct, and that manual, hands-on exploration of virtual representations of museum objects on a mobile device can potentially offer a viable digital alternative to physical object handling for the collaborative discussion of (virtual) museum artefacts.

7.2 Exploring the Three Core Research Questions

Being able to answer the research question involved the exploration of the three 'core questions' outline in *Chapter 1: Introduction*, which broke the overall research question down into its constituent parts. Reviewing these three questions in the context of the results from *Chapter 5: Experiment & Results* and the interpretations of them *Chapter 6: Discussion* demonstrate in more detail how the answer to the research question was arrived at, and therefore how the hypothesis was shown to be correct.

7.2.1 First Core Question - The Benefits of Manual Interaction

The first of the three core questions was:

1. What are the benefits of manual interaction with a mobile device for the rotation, scaling, and marking of interest points on (virtual) artefacts?

The key benefits of manual interaction with a mobile device for the described manipulation processes (presented in *Section 7.1: Answering the Research Question*) were a) usability and b) the tight coupling of input and output space, the combination of which made interaction with the tablet interface feel natural, intuitive, and realistic. The tight coupling of the input and output space in particular also give a feeling of directness and immediacy to interaction, with the response (the movement of the virtual artefact) taking place at the exact moment and based on the exact position of the action made (the user's touch).

This not only adds to the realism of the interaction technique (physical handling is of course also direct and immediate), but also makes it easier for users to maintain an understanding of and their focus on the (virtual) artefact, based on the way it responds and behaves naturally when interactions are made. These benefits of manual interaction – usability, naturalness and realism as a result of tightly coupled input and output spaces – directly contribute to the experience of exploring (virtual) artefacts using the tablet interface being more engaging than with the desktop interface, and that experience therefore being more akin to physical object viewing and handling, as was correctly hypothesised in *Chapter 1: Introduction*.

There are also some collaboration-specific benefits to manual interaction with a mobile device. All of the benefits mentioned in the previous paragraph are just as applicable to individual users as they are to groups, but for collaborators in the in-context study the tablet-based *RelicPad* interface appeared to be passed around and shared much more openly. This is possibly influenced by the fact that tablets are relatively light and unconstrained, but may simply have been that because the tablet was more of a hands-on experience, participants may have felt more comfortable, more willing, or simply more aware of the need to share it.

Additionally, regardless of who was in control of the interface at a given moment, it appeared that an additional collaboration-specific benefit of manual interaction with a mobile interface is that due to the close coupling of input and output spaces, the collaborator *without* control often appeared to be equally active in discussions, observing, directing, guiding and suggesting things to the collaborator *with* control. It would appear that because the closeness of context allows all users to see and understand each other's actions on the tablet and the subsequent reactions of the virtual artefact, participation becomes easier for the collaborator *without* control, who can still be firmly involved in the experience by way of collaborative enquiry side, even when not necessarily by way of physical manipulation.

7.2.2 Second Core Question – Communicating Using Interest Points

The second of the three core questions was:

2. How efficiently can precise and focused information about (virtual) artefacts be communicated using interest points?

As mentioned in *Section 7.1: Answering the Research Question*, interest points are efficient in communicating precise and focused information because they allow collaborators to drive conversations, enabling them to pinpoint, focus on, and draw each other's attention to interesting parts of the (virtual) artefact. The use of interest points (as well as being able to search through previously-left ones) allowed collaborators to construct a 'narrative' history of their interests and intentions that was important in the maintenance of understanding and focus, and for remote collaborations in particular, interest points were vital in augmenting this narrative with a spatial context when this could not be achieved by watching collaborators or their actions.

While interest points' basic goals of focusing attention, driving conversations and providing additional (or supplementary) spatial context were met, the interpretations of results made in *Chapter 6: Discussion* did provide a number of examples of how future implementations of interest points could be expanded to make them more efficient, as well as more useful in the eyes of collaborators. As described in *Subsection 6.5.2: The Smoother Integration of Interest Points*, the process of leaving interest points was considered clunky and awkward by some users, who felt there were too many steps or 'clicks' involved and that marking points using speech instead of text input would have been better, and also that navigating through the history of interest points would have been made much easier if the virtual artefact had rotated automatically according to the currently selected interest point.

It was also highlighted that interest points would have been much more efficient in communicating precise and focused information if extra comments had been able to be added to existing ones to allow for further exploration of interesting topics, possibly supplemented by functionality to 'like' and 'favourite' interest points to provide feedback on the popularity and attention that points relating to specific areas or topics might be accruing.

Additional options for assigning context to interest points would also have made them more efficient – as it stood, some participants in the in-context study felt reserved about creating interest points unless they were absolutely sure that they were sharing a fact and were reluctant to share speculation or opinions, despite the idea of the points partly being to raise questions and to instigate discussion as part of enquiry – not necessarily the reporting of facts. More context options might have encouraged collaborators to think about their opinions in a different way, and even have encouraged them to share ideas they were less confident about because of their uncertainly about the suitability of their associations with the three context options the *RelicPad* prototype used.

7.2.3 Third Core Question – Facilitating Engagement

The third of the three core questions was:

3. How does the combination of manual exploration and marking of interest points facilitate engagement with (virtual) artefacts?

As described in *Section 6.3: What Makes a More (or Less) Engaging Experience*, engagement with (virtual) artefacts is largely dependent on:

- Being in control without needing too much attention,
- Exploring shared curiosity in busy collaborative discussions,
- Being motivated to explore and free from restrictions, and
- Excitement about and engagement with the artefact itself.

In terms of being in control without the need for too much attention, it is precisely the benefits of manual interaction with a mobile device described in response to the first core question that fulfill this criteria of engagement – the usability and associated realism of the experience, and the closeness of context that comes from the tight coupling of input and output space. The usability – fluidity, directness, smoothness and speed of the interaction – creates a natural sense of realism that makes it easy for collaborators to focus on the conversation as opposed to having to concentrate on the interaction technique. As a result of this, the user feels comfortable and in control, and there are fewer barriers between themselves and the (virtual) artefact they are meaning to engage with. The coupling of the input space is crucial to this, and instant changes in the display of the (virtual) artefact according to the user's touches on the tablet's screen give the user a sense of control and understanding of their actions.

A shared curiosity to figure out the unknown and explore the (virtual) artefact as part of a busy discussion is important in engaging multiple people in collaboration. Generally, the busier the discussion and the more theorising involved, the more engaged the collaborators are, although this can be problematic if the collaborators have very different levels of interest in a particular (virtual) artefact. As discussed in relation to the second core question, the potential for interest points to help communicate information about (virtual) artefacts allows collaborators to drive discussions and maintain a spatial understanding of actions, interest and intent, which in turn helps to maintain their interest and engagement.

However, as described in *Subsection 6.3.2: Exploring Shared Curiosity in Busy Collaborative Discussions*, usability issues can sometimes 'break the flow' of the experience of marking interest points. In order to ensure that collaborators can remain focused, attentive and engaged with the (virtual) artefact and in the collaboration, interest points must be usable and be fluidly integrated into the interaction process to ensure that they do not disrupt or detract from collaborative discussions.

Finally, being motivated to explore – and to do so free of restrictions – is crucial to engagement. Motivation can be facilitated by intellectual challenge, which in the case of *RelicPad* comes from a combination of a) the collaborative discussion and sharing of (sometimes pre-provided) information using interest points, and b) the tight coupling of input and output space associated with manual, tablet-based interaction that facilitates a mutual focus of attention. Both the sharing of information / collaborative discussion driven by interest points and the mutual focus of attention that the close coupling of input and output spaces provide are closely tied to the collaborative side of the experience, which is where the intellectual challenge stems from – understanding both the (virtual) artefact and also the collaborator's experience of it.

In order for collaborators to recognise this challenge, they need to be able to sufficiently orientate themselves and navigate within the experience. This comes from the more physical and exploratory (as opposed to the collaborative) aspects of the experience, a combination of the shared frame of reference (the close coupling of input and output space) and reality-based interaction (the naturalness and intuitiveness that comes from good usability and representation of manual interaction). When this physical side of the experience complements the collaborative aspect, then the user is likely to accept the intellectual challenge and engage in active, collaborative discussion and discovery.

Of course, there are restrictions to the motivation to engage and to explore artefacts. One of the most severe detriments to motivation and engagement is limited viewing angles, which leaves the viewer of an artefact feeling detached and distant, and so manual, hands-on interaction with the 3D, virtual artefact can potentially facilitate motivation and promote engagement by opening up all the possible viewing angles and sides of the (virtual) artefact for exploration. However, this of course necessitates that the 3D digital representation of the artefact be incredibly accurate and detailed, with the representational fidelity of the virtual artefact being orthogonal to engagement and the maintenance of interest and motivation. As described in *Subsection 6.5.1: The Representational Fidelity of the Virtual Artefact*, this is one area where problems occurred during evaluations of *RelicPad* in the in-context study.

By a) putting users in control without demanding too much of their attention, b) supporting the exploration of shared curiosity in busy collaborative discussions, and c) helping to keep users motivated and free from restrictions, the in-context evaluation of RelicPad has shown that, as this thesis hypothesised, tablet-based interfaces are an ideal and *engaging* facilitator of manual interaction and annotation of virtual objects. However, it is important to remember that, as described in *Subsection 6.3.4: Excitement About and Engagement with the Artefact Itself*, all of the elements, theories and factors described in this subsection are to a large extend redundant if the collaborators do not have some kind of personal interest or connection to the virtual object (in this case museum artefact) itself. Without this connection or interest, any kind motivation to engage will always be extremely difficult to facilitate.

7.2.4 The Three Core Questions in Summary

To summarise, the answers to the three core questions outlined in Chapter 1: Introduction can be answered as follows:

1. The benefits of manual interaction with a mobile device for the rotation, scaling, and marking of interest points on (virtual) artefacts are:
    a. Interaction feels more natural, intuitive, and realistic, because of the usability of tablet devices and their tight coupling of input and output space.
    b. Mobile devices such as tablets can be easily passed around between multiple collaborators to share control of the experience.
    c. The tight coupling of input and output space means that all collaborators, whether they are controlling or observing the experience, have a mutual focus on and understanding of the interaction space.
2. Interest points are reasonably efficient in communicating precise and focused information about a (virtual) artefact because:
    a. Collaborators can use them to drive discussions, pinpointing, focusing and drawing each other's attention to interesting features.
    b. They can be used to provide a 'narrative' of intention, interest and actions in a spatial context, particularly useful for remote-collaboration when this is not possible by way of gesturing or establishing a mutual focus of attention.
3. Ways that the combination of manual exploration and marking of interest points facilitate engagement with (virtual) artefacts include:

a. The usability and closeness of context of the tablet interface – the naturalness and 'realism' of interactions – leave users feeling in control and thus engaged with the (virtual) artefact.
b. Using interest points to make spatial references and to drive collaborative discussions helps to maintain a) collaborators' interest in the topic, b) the flow of information being shared, and c) collaborators' engagement with the (virtual) artefact.
c. The naturalness and realism of manual interaction with the tablet interface makes it easy for collaborators to orientate themselves in order to take on the intellectual challenge of collaborative discussion, which motivates them to actively participate in the experience and to engage with the (virtual) artefact.

In highlighting and breaking down these three core questions, the interplay between the three becomes clear. It is through this interplay that the tablet interface is shown to be usable, to have a tight coupling of input and output space that is crucial to realism, collaboration and engagement, and to allow users to direct their collaborative discussions by marking interest points in 3D space. From this, the answer to the research question was arrived at – that manual interaction with 3D, virtual representations of museum artefacts and interest points using a mobile device facilitates engaging discussions of (virtual) museum artefacts for remote and co-located collaborators – and the thesis has been able to support the original hypothesis that such interaction (hereby realised using the tablet-based *RelicPad* interface) is an engaging way of exploring and collaboratively discussing 3D, virtual representations of (in this case museum) objects, offering an experience much more akin to handling physical artefacts than that of the less-engaging digital techniques that are currently used

7.3 Why the Proposed Solution Works

In the preceding two sections, it has been documented how the tablet interface's usability and closeness of context for interacting with 3D content give users a sense of control, and also make it easy for them to orientate and motivate themselves to actively participate in intellectually challenging collaborative discussions. Coupled with the use of interest points, which can be used to direct, focus attention, and provide a 'narrative' of collaboration in a 3D context, this makes manual interaction with tablet interfaces an efficient way to facilitate engaging collaborative exploration and discussion of virtual museum artefacts, in situations where handling physical artefacts or sharing mutual access with a (possible remote located) collaborator is not possible.

By referring back to some of the key concepts and frameworks described in the earlier chapters of the thesis, a clearer understanding can be reached of how and why these features made *RelicPad*, the hands-on, tablet-based virtual artefact exploration application proposed as solution to the research problem in *Chapter 1: Introduction*, successful in addressing the research problem, and also of how the original hypothesis, that it offers an engaging way to collaboratively explore and discuss virtual objects in a manner that is more akin to the experience of handling physical artefacts, was proven to be correct.

7.3.1 Balanced, Fully Embodied and Collaborative Interactions Based on Real-World Concepts

In *Subsection 1.3.2: A System Designed to Support Reality-Based Interaction Principles* the key elements of Jacob et al.'s (2008) reality-based interaction framework were introduced – naïve physics, body awareness and skills, environment awareness and skills, and social awareness and skills. All four of these elements are present to varying extents in *RelicPad*:

- The usability and close coupling of input and output space that make interaction feel natural and realistic take advantage of the fact that users *expect* the virtual artefact to move in a certain way when they touch it (naïve physics).
- The close coupling of the input and output space in particular takes advantage of the fact that users know what to expect when they interact with things using their hands whilst focusing their line of sight there, something that is inherently familiar from handling real, non-digital objects (body awareness).

- Being a mobile device, users are free and able to move the tablet around as they see fit, using it whilst sitting in a chair or with it resting on a desk (environmental awareness), and when co-located with another collaborator are more likely to share the tablet with others freely, easily and naturally (social awareness).

Making use of these principles reduces the 'gulf of execution' between the user's actions and their goals – in this case engaging with both the virtual artefact and their collaborator (Jacob et al., 2008). This is augmented by the introduction of a non-realistic feature – the ability to create and explore interest points. This is not necessarily realistic, but enables remote collaborators in particular to make the spatial references that they would not otherwise be able to, and so a compromise is struck between the more reality-based features and this digital-only functionality in order to ensure that a variety of tasks appropriate to collaborative exploration and discussion can be performed (Jacob et al., 2008).

In *Subsection 2.3.2: Representations of Reality in Interaction*, two types of representations were introduced – physical (concrete, embodied, tangible) and digital (observed, unembodied, intangible) (Ullmer and Ishii, 2000). Physical representations are coupled to digital information, and can be classified according to the closeness of the link between input and output space – this is also known as embodiment, ranging from distant, to environmental, to nearby, to full, and the smaller the distinction between the input and output spaces, the smaller the 'cognitive distance' (similar to Jacob et al.'s 'gulf of execution') between an input device and the results of actions made using it (Fishkin, 2004). With tablet devices, the direct and immediate physical coupling between the input and output spaces (the touchscreen) makes for a very small cognitive distance – *RelicPad* users, for example, have no problem understanding how their actions affect the virtual artefact when they touch the tablet's screen, thanks to the full embodiment of its physical representations.

In *Subsection 4.2.1: Manipulating the Virtual Artefact*, Hornecker & Buur's (2006) three elements that define a well-balanced tangible interaction were introduced

– haptic direct manipulation (whether users can feel the important physical elements), lightweight interaction (allowing the user to advance in small steps, guided by feedback), and isomorph effects (the relationships between actions and effects and how easy they are to understand). All three of these elements are covered by *RelicPad*, showing that using the tablet is a balanced way to tangibly interact with and explore the virtual artefact:

- Users can feel the touchscreen under their fingers – they know that they are interacting with something as they make actions upon it. While this may not be haptic as such (although the touchscreen is felt underneath the fingers, it is not necessarily transmitting any kind of haptic sensation back to the user in response), it is certainly a more tactile approach than viewing objects behind, for example, a glass display case. The hands are to an extent made use of, and the fact that the virtual artefact moves immediately in response to the actions made with the hands facilitates direct manipulation.
- The immediacy and directness of the interaction and its response means that users can manipulate the virtual artefact in large movements or small steps, with the virtual artefact moving and stopping accordingly. *RelicPad* users can therefore make use of lightweight interaction principles, exploring and manipulating the virtual artefact at their own pace.
- The close coupling of the input and output spaces with tablet interfaces – a 'fully embodied' physical representation – makes it easy for *RelicPad* users to understand the relationship between their actions and the subsequent effects. Therefore, *RelicPad* takes advantage of isomorph effects.

In *Subsection 2.3.3: Reality-Based Interaction*, Hornecker & Buur (2006) also describe reality-based interactions in collaborative contexts, in terms of spatial interaction (how objects and people meet in meaningful spaces; how that space is configured by movement within it; who can see or reference what happens in a space) and embodied facilitation (whether environmental constraints encourage collaboration; whether everybody has access and can contribute; whether representations reflect skills and experience and invite collaboration).

In terms of spatial interaction, the tight coupling of input and output space with the tablet interface allows for everybody within a given space to see and understand the relationships between actions and effects, meaning that *RelicPad* users are able to maintain a mutual focus of attention and understanding of their collaborators' actions even when they are *not* in control of the interface. The importance of this in learning contexts, where mutual visibility, access and feedback creates opportunities for collaborators to reflect on the consequences of actions, co-construct knowledge and resolve emerging conflicts or discrepancies, was also highlighted by Price et al. (2010).

Meanwhile, in terms of embodied facilitation, the physical representations *RelicPad* employs (interacting with the touchscreen interface to manipulate the virtual artefact) reflect basic manual skills and movements and thus invite participation and collaboration, while even in the remote collaborative scenario, the introduction of interest points into the experience enables everybody, regardless of location, to be able to access information and contribute to the collaboration.

7.3.2 Social Mediation and Engagement Through Supportive Enquiry, Discussion and Problem Solving

In *Subsection 2.2.1: Learning Collaboratively*, the idea of 'socially mediated' learning was described, which takes place as people watch, observe and make sense of each other's actions and ideas in order to make links through social contact (Falk and Dierking, 1992). This is facilitated by collaborators' ability to maintain an understanding of the 'problem space' through conversation, in order to ensure that through this shared understanding, the discussion remains meaningful (Roschelle and Teasley, 1995).

Objects are often the focal point of socially mediated learning and of the 'problem space', with activities such as enquiry and problem solving providing a context from which an object, in this case a (virtual) museum artefact, can be understood (Hindmarsh and Heath, 2000). As described in *Subsection 2.2.4:*

Mutual Access in Collaboration, this relies on subtle, mundane interactions and gestures between collaborators, which are used to establish a mutual frame of reference and spatial context that ensures that collaborators can "discuss the same object and in the same way" (Hindmarsh and Heath, 2000).

During the in-context study, participants discussed and shared their ideas to maintain a mutual understanding of the virtual artefact, which in their case constituted the problem space. With the tablet interface, the tight coupling of input and output space allowed both collaborators to clearly see each other's interactions with the virtual artefact, and in the remote collaborative scenario interest points were used to point out interesting features and to replicate mutual access for collaborators, limiting ambiguities and discrepancies and maintaining a shared spatial reference and context when observing each other's actions was not possible.

Much of the problem solving and enquiry around (virtual) artefacts stemmed from a process of lateral thinking, where questions were posed and ideas validated via simple questions that were posed to form shared conceptions of the meaning and significance of the (virtual) artefact: what it is; how old it is; what it's made of; who made it and why; who used it and what for; and what stories it can tell (Trewinnard-Boyle and Tabassi, 2007). In-context study participants would discuss, muse, piece clues together, figure things out, bounce ideas off each other, and clarify questions using this process of lateral thinking, as part of a collaborative, team effort to make sense of the (virtual) artefact.

This process of lateral thinking also plays a part in 'scaffolding', the process of more knowledgeable group or community members supporting others through "questions, clues, or other learning supports" (Falk and Dierking, 1992) that allow groups and communities with different levels and boundaries of knowledge and experience to collaborate efficiently (Falk and Dierking, 2000). The reassuring effects of scaffolding are rooted in people's natural desire to talk about experiences, and through this process of feedback and scaffolding from each other, collaborators are generally able to go over the course of a discussion from having very different ideas (often in stark contrast to each other) to a convergence of ideas and a shared conception and understanding of, in this case, the (virtual) artefact.

RelicPad clearly facilitated scaffolding during the in-context study, where the sharing of ideas, experiences, theories, and knowledge was considered to be most useful when one participator had more knowledge about something than the other. This generally resulted in the more knowledgeable collaborator 'taking the lead' and posing questions to help and encourage their partner as the conversation progressed, but there were also times that less knowledgeable participants felt that their lack of knowledge was actually useful for them, giving them an added sense of curiosity and ending up with them as the less knowledgeable participants taking the lead in order to 'squeeze' information from their more knowledgeable partner.

This kind of collaborative discussion is best facilitated by what Knowles (2005) describes as the 'atmosphere of adultness', an informal dynamic whereby collaboration is emphasised over competitiveness, and supportive interpersonal collaborations are encouraged within a group. In-context study participants reported having a good collaboration dynamic, both in cases where a participant did or did not already know their collaborator beforehand, with collaborators feeling that they understood each other more often than not and describing collaborations as being comfortable, easy to maintain, reassuring, and without problems. This suggests that participants found that there was an atmosphere of 'adultness' and supportive collaboration during the in-context study.

Finally, *Subsection 2.1.4: Interactive Technology and Museum Learning* describes how in order for media to be socially engaging, they should be:

- Visceral (visual and physical),
- Responsive (immediate, clear and predictable),
- Continuously variable (changing with 'infinite variability'),
- Socially scalable (shareable with varying numbers of users), and

- Socially balanced (equal emphasis on the individual, the content, and potential collaborators).

RelicPad fulfills these criteria for social engagement, being:

- Visceral in it's 3D representation of museum artefacts and the manual, hands-on techniques used to manipulate it using the tablet interface,
- Responsive in the immediacy, directness and intuitiveness of its interaction style, made possible by the tight coupling of the tablet interface's input output spaces ensuring that actions and their responses both take place in the hands,
- Continuously variable, with users constantly able to manipulate and explore the virtual artefact from all sides and angles,
- Socially scalable, with as many collaborators as are willing able to either a) pass around and share a single tablet device or b) connect themselves to a (possibly remote located) collaborator using their own tablet device
- Socially balanced, with a simple manipulation, display, and collaboration dynamic making the virtual artefact clear and easy to understand both for the individual manipulating it and for any number of potential collaborators involved.

7.3.3 Control, Understanding, and Contribution – Motivations to Engage in Collaborative Activities

In *Subsection 2.4.1: Key Facets and Elements* (of engagement), Benyon's (2010) five common traits of engaging experiences were described:

- Identity (the authenticity of an experience),
- Adaptivity (the ability to change and personalise aspects of an experience),
- Narrative (the telling of a 'story'),
- Immersion (the feeling of being involved with something), and
- Flow (the smooth movement or gradual change between states).

As described in *Subsection 4.3.2: Interaction Design and Usability*, these five traits were adapted and included in the mixed methods questionnaire used in the in-context study as a set of ten Likert scale questions (two questions focused on each of the five traits of engagement) in order to produce a single number as output to measure the presence of these five key traits of engagement, for each of the digital interfaces being compared. Results showed that the tablet interface was, based on this number, significantly more engaging than the desktop interface, which suggests that *RelicPad* exhibits these five common traits of engagement to a greater degree than equivalent, desktop-based systems for the exploration of (virtual) museum artefacts and supports the original hypothesis that hands-on, tablet-based interfaces are an engaging way to collaboratively explore and discuss virtual objects.

Referring again to *Subsection 2.4.1: Key Facets and Elements* (of engagement), engagement is described as a feeling of being involved, motivated and in perceived control over interactions, facilitated by sensory appeal, feedback, and challenge (O'Brien and Toms, 2008). The success of the tablet in motivating users to explore and providing them with control over the manipulation of virtual artefacts has already been mentioned throughout this chapter and sections of *Chapter 6: Discussion*, largely attributed to the tablet's usability and to it's tight coupling of input and output spaces. The feedback and understanding that comes from seeing the immediate and direct effects of interaction with the (virtual) artefact on the touchscreen help to hold users' interest in it, maintain their spatial understanding of it, and keep them motivated to engage with it.

A more complicated framework for engagement was outlined in *Section 3.3: Research Design*, describing the link between physical design (representation), interaction, and content, and how this is parallel to behavior (how we act), cognition (what we think), and affection (what we feel) (Basballe and Halskov, 2010). In terms of *RelicPad*, the tight coupling of input and output space (full embodiment), gives the user control over interaction with immediately responsive content (the virtual artefact). This results in a natural, intuitive approach to manipulating the virtual artefact further (reality-based interaction), a better understanding of its physical properties (a possible learning outcome), and the motivation to explore the virtual artefact further (engagement) – as originally hypothesised, not only engaging, but also a realistic experience, more akin to that of handling physical objects than alternatives such as the desktop interface. So, to summarise *RelicPad* according to this particular theory:

Full Embodiment + Control + Immediate Response

=

Realism + Engagement + (Possible) Learning Outcome

This correlates well with Basballe and Halskov's (2010) theory of engagement as a process that involves activities such as sense-making (the human-object connection, exemplified by interacting with the virtual artefact and the cognition that this provides) and self-directed, playful exploration (exemplified by the subsequent motivation to continues exploring the virtual artefact), which when augmented by conversation (the human-human connection, as exemplified by busy collaborative discussions driven by interest points for communication and spatial referencing) makes for an engaging experience.

The 'relate-create-donate' framework described in *Subsection 2.4.2: Overlaps with Learning Theory* highlights again the importance of collaboration and contribution in engagement, implying that engaging learning activities:

- Occur in a group context:
    - The relate component – emphasising team efforts, social skills, and the clarification and verbalisation of problems and solutions.
- Are project based:
    - The create component – emphasising creative, purposeful, and context-specific activity, with focused and defined application of ideas and efforts.
- Have an authentic, outside focus:
    - The donate component – emphasising useful contributions to the activities.

RelicPad fits into this framework as well, with the group context exemplified by the way it encourages collaborators to share their ideas in order to clarify and validate their ideas to arrive at converged, shared conclusions about the (virtual) artefact (the relate component). This gives them opportunities to focus their ideas and their efforts in the context of discovering what the (virtual) artefact is (the create component), and encourages them to share their thoughts and opinions with their collaborators and, using interest points, with the wider community of museum learners (the donate component), showing once again that *RelicPad* is a useful and efficient application for fostering and facilitating engagement in collaborative learning activities.

7.4 Has Learning Been Facilitated?

In *Section 3.1: Research Philosophy*, the decision not to try to specifically measure whether learning had taken place was described. It was decided that, due to a number of inherent problems and discrepancies with the 'measurement' of learning, a safer approach would be to measure engagement. The original hypothesis was that hands-on, tablet-based interfaces are an engaging way to collaboratively explore and discuss virtual objects, which has been reported, discussed, and shown to be correct throughout this and the preceding two chapters. As described in *Subsection 2.4.2: Overlaps with Learning Theory*, the close links between engagement and learning theories suggest that learning outcomes can occur when users are engaged, and this section describes the evidence and interpretations that support their facilitation in the context of this research.

In *Subsection 2.1.1: Learning in Context*, the contextual model of learning was described, an amalgamation of the personal (motivations and expectations; prior knowledge and interests; choice and control), the sociocultural (within-group sociocultural mediation), and the physical contexts (orientation, design, and reinforcing events and experiences) (Falk and Dierking, 2000). The personal context is described as 'moving through time', constantly shaped by experiences within the physical context, and 'mediated by and through the sociocultural context' (Falk and Dierking, 2000).

Referring back to *Section 7.2: Exploring the Three Core Research Questions*, there is a clear connection between the contextual model of learning and the third core question – the ways in which the combination of manual exploration and marking of interest points facilitates engagement with (virtual) artefacts. This shows that *RelicPad*'s combination of reality-based and collaborative features make it efficient in facilitating learning in context:

- The naturalness and realism of manual interaction with the tablet interface, which makes it easy for collaborators to orientate themselves, participate in the experience, and to engage with the (virtual) artefact, relates to the personal context, putting the user in a situation that feels familiar and comfortable so that they can draw on existing knowledge and experience.
- The usability and closeness of context of the tablet interface, which make the interaction feel natural and realistic, relate to the physical context, helping to shape the user's motivations in the personal context.
- Using interest points to make spatial references, drive collaborative discussions, and maintain interest and engagement relates to the sociocultural context, which mediates the learning experience and allows it to be shared with others.

As for the type of learning experience facilitated by collaborative exploration and discussion of virtual museum artefacts using tablet devices or application such as *RelicPad*, two key theories of learning were introduced in *Subsection 2.1.2: Learning Theories* – the elemental (reactive) theory, an example of which would be transmitting information in discrete chunks starting with the simplest facts, and the holistic (active) theory, an example of which would be providing learners with material from which they can then draw their own conclusions (Knowles et al., 2005) (Hein, 1998).

The holistic, active learning theory is related to the idea of experiential learning, where it is argued that knowledge and understanding come about as a result of acquiring and reflecting on information, and then relating it and applying it to existing experiences (Black, 2005). Discovery learning is an even more active approach to experiential learning, which engages learners in enquiry and problem-solving in hands-on environments – this enables learners to ask questions and formulate answers, which engages them, fosters curiosity, and encourages them to use their intuition to think about the topic in question, adding a personal touch to the learning experience (Black, 2005). Discovery learning is well suited to learners who already have an interest or basic knowledge of a subject, and is ideal for the various museum groups outlined in *Subsection 3.2.1 Design and Refinement of a Prototype System*, who would already have either an interest or a basic knowledge of the (virtual) artefact (or similar artefacts) that they were collaboratively discussing (Black, 2005).

Exploring and manipulating virtual artefacts using *RelicPad* is an active, experiential experience of discovery, with users' hands-on manipulation of the virtual artefact using the tablet device answering their questions about its physical properties, engaging them with it, and encouraging them explore their curiosity and to think about what the (virtual) artefact is and what it means. The collaborative aspect of *RelicPad*, however, places a greater emphasis not just on discovery, but also on the verification and ratification of ideas (Black, 2005). This is synonymous with a constructive learning approach, where users are provided with the opportunity to "construct their own meanings" through interaction not only with the virtual artefact but also with interest points and with each other, a convergence of "new ideas of concepts" based on both current and past knowledge (Black, 2005).

As described in the preceding paragraphs of this subsection, *RelicPad* and similar hands-on, manual, tablet-based systems for collaboratively exploring virtual representations of museum artefacts not only to engage users, as originally hypothesised in *Chapter 1: Introduction*, but they also facilitate learning experiences. They offer a discovery learning experience for the individual and a constructive learning experiences for collaborators, whilst also balancing the physical, sociocultural and personal aspects of the experience to allow for learning to place in context. But how successful was this during the in-context study, and were there any suggestions of learning outcomes as a result of participation in the study and collaborative interaction with the system?

In *Section 3.3: Research Design* a set of generic learning outcomes were outlined, developed by the Museums, Libraries and Archives council in the UK in the early 2000s with the specific intention of monitoring learning outcomes from museum experiences (Hooper-Greenhill, 2007). Whilst the immediacy of the in-context study and the lack of a post-test make it difficult to discern how the experience and anything learned from it might have caused changes or progression in the way participants act or behave, the results of the study and their interpretations certainly suggest that learning outcomes were present in terms of knowledge and understanding, skills, attitudes and values, and enjoyment, inspiration and creativity:

- Knowledge and understanding:
    - Clearly evidenced by the way collaborators discussed, mused, pieced clues together, figured things out, bounced ideas off each other, and clarified questions, engaging in lateral thinking with each other as part of a collaborative, team effort to make sense of the (virtual) artefact. This was often augmented by a process of 'scaffolding', whereby more knowledgeable users supported their collaborators to ensure that differences in knowledge boundaries within and between learning communities did not hinder collaborative convergence of ideas into shared knowledge and understanding.
- Skills: intellectual, practical, and professional:
    - The tablet interface, with its direct, immediate interaction style and close coupling of input and output spaces, leveraged users' "pre-existing real world knowledge and skills" to reduce the mental effort needed to interact with the (virtual) artefact, and

enabled them to freely explore it with a comfortable degree of control.

- Attitudes and values:
    - Participants' identification with the (virtual) artefacts themselves provided evidence of how the experience affected their attitudes and values (possibly leading to learning outcomes), whether that was due to a mechanical interest in deducing how something works, curiosity inspired by the (virtual) artefact's unfamiliarity, or as a result of the artefact touching and engaging the viewer on a personal level, leading to intrigue and engagement.
- Enjoyment, inspiration and creativity:
    - The physicality and realism of the interaction technique empowered users, giving them the opportunity to make sense of what they are doing through their imagination, and the combination of these two concepts helped to motivate participants, inspire them, maintain their interest, and "reinforce [their] feeling of engagement".

Finally, as described in *Subsection 5.1.3.1.1: Themes of Investigation for Questionnaires*, learning outcomes were also suggested by the fact that:

- There was a feeling of direct participation with the artifact or in the discussion (Black, 2005):
    - This was certainly the case, with the experience being both realistic, direct, and focused thanks to the usability of the tablet and its tight coupling of input and output space, and busy discussions with plenty of theorizing involved being described as highly engaging.
- There was a feeling of the experience being more active than passive (Knowles et al., 2005) (Hein, 1998):
    - There is no doubt that the experience was active, facilitating (as described just a few paragraphs ago) a combination of discovery learning for the individual exploring the (virtual) artefact and constructive learning for the group of users collaboratively

discussing it, both examples of active, experiential learning theories.

- Through the discussion or exploration of the artefact, something new or interesting was discovered, or an idea about its history or significance was formed (Black, 2005):
    - Almost all participants felt that they had a) learned something about the (virtual) artefact, and b) contributed something to the discussion.
- That prior knowledge played a part in the process of discovery mentioned above (Black, 2005):
    - This is clearly evidenced by the importance of scaffolding in the collaboration dynamic, whereby collaborators with slightly more prior knowledge were compelled to pose questions and encourage lateral thinking from their collaborator, or conversely whereby collaborators with slightly less knowledge were compelled to drive discussions in order to 'squeeze' knowledge from their collaborator.

7.5 In Summary – The Contribution to the Research Problem

Over the past four sections of this concluding chapter, hands-on, manual interaction with tablet interfaces has been shown to efficiently facilitate engaging exploration and discussion of 3D virtual representations of museums artefacts, for both remote and co-located collaborators. The combination of reality-based interaction (facilitating discovery learning experiences) and collaborative features (facilitating constructive learning experiences) makes these kinds of interfaces, as originally hypothesised, ideal for engaging users in collaborative learning activity, as highlighted by visible effects of the in-context study that suggest the possibility of there having been learning outcomes.

This closing section, of both this chapter and this thesis, describes the contribution of the research and *RelicPad*, the proposed solution it describes and evaluates, to the research problem outlined in *Section 1.2: Research Problem –*

the inaccessibility of museum artefacts for collaborative exploration and discussion in both co-located and remote scenarios, where handling and maintaining mutual access and reference of the physical artefacts themselves is, for whatever reason, not possible.

7.5.1 Engaging Communities as Equal Contributors in Stimulating Learning Experiences

Research and learning activities are, as described in *Subsection 2.1.3: Object-Based Learning*, often focused on examining artefacts and drawing upon previous knowledge and experience to compare them with similar objects, piece together their history, and construct knowledge about them (Pye, 2007). This kind of experience, which is “not only ‘hands-on’ but also ‘minds-on’”, is more stimulating than a routine viewing experience, and as such is more likely to lead to learning outcomes (Hein, 1998). The process of manually exploring virtual artefacts using tablet-based interfaces such as *RelicPad* constitutes the hands-on part, with collaborative discussion being the minds-on aspect that takes it from a routine experience to a stimulating and engaging one with possible learning outcomes.

As described in *Subsection 2.1.4: Interactive Technology and Museum Learning*, encouraging people to make interpretations by linking observations and stimuli to past experiences and influencing the content of an experience through direct participation and manipulation of physical elements are both popular approaches to interaction (Otitoju and Harrison, 2008). Museum experiences are reflecting this on an increasing scale, moving towards being “environments” in which visitors interact and participate with art, history, nature, or science” as opposed to simply places where these thing are visually displayed (Falk and Dierking, 2000). As the in-context study showed, regardless of whether the tablet interface or the desktop interface was used to explore the virtual artefact, participants felt that they were usually able to match their skills to digital interfaces. This shows that people are (usually) able to quickly and easily adapt to the presence of technology and digital interaction in the museum experience, and as virtual museum experiences and collections becoming more prominent, this ability to adapt to digital interaction is likely to be increasingly important (Falk and Dierking, 2000).

While the use of technology for facilitating interactive museum experiences has generally been quite constrained in its approach, the rapid development of technologies and the possibilities they provide for new types of digital interaction led Pye (2007) to predict that they could play an important part in "reaching otherwise inaccessible parts" of artefacts that cannot be handled, "enhancing the experience" of investigating and exploring them. This thesis has shown that hands-on, manual exploration of virtual museum artefact using a tablet interface such as *RelicPad* opens up these inaccessible qualities of artefacts for digital exploration and investigation, and that when the interaction techniques used to explore the virtual artefact are grounded in reality-based principles, the experience is usable and easy for potential users to adapt to.

While the results of the in-context study are positive and encouraging in this respect, it is important to acknowledge that the nature and constraints of the study's procedures merit a moment to reflect on how such an experience would translate into a real-world museum setting. Collaboration sessions during the in-context study were contained and controlled, typically lasting around ten minutes per artefact – the focus on one object is prolonged and is more intense by default, in contrast to the typical museum visitor experience where focus on a particular object, and the threshold for engaging with it (Hornecker and Stifter, 2006), are generally much lower – sometimes as little as a few seconds. This is likely to have resulted in in-context study participants engaging with the artefacts they viewed to a higher degree than they might normally do when visiting a museum. This does not necessarily mean that the results are invalid, or that such an experience – more prolonged, intense, and focused engagement – has no place in the everyday museum. Rather, it reminds designers and researchers alike that care must be taken to implement such an experience in a way that such an engagement can be naturally facilitated, and does not seem out of place or context amid the pressures on time and attention that occur during a typical museum visit.

Of course, as highlighted in *Section 7.4: Has Learning Been Facilitated?*, the exploratory, discovery learning side of the *RelicPad* experience is augmented and complemented by the collaborative, constructive learning side of the experience. *Subsection 2.2.2: Collaboration in Museums* described how "a supportive environment for reflection" is needed to represent learning communities, giving collaborators the opportunity to talk about their ideas, share multiple viewpoints, and engage in dialogue with each other from various perspectives (Black, 2005). Meaning making then occurs and interpretations are validated through the "social or collective endeavour" of a wide and supportive community of learners (Hooper-Greenhill, 2007). Collaborative discussion and sharing of ideas, both verbally and by way of interest points, allows groups of *RelicPad* users collaborating together to engage in this kind of collective endeavor, working together to share thoughts and viewpoints and construct new knowledge and ideas through enquiry, problem solving, and busy, engaging collaborative dialogue.

This kind of constructive learning through collaborative discussion not only facilitates efficient communication between those with existing knowledge or interests in exploring artefacts, but also has a role in audience development for museums, particularly in reaching out to new and previously under-represented audiences (Black, 2005). As described in *Subsection 1.3.1: A System Designed to Support (Remote) Collaborative Exploration*, many museum collections and artefacts continue to be of great cultural significance to the colonial groups, indigenous peoples, or communities from which they came, who are increasingly eager to have access to such artefacts and collections in order to reminisce, revisit cultural roots, and explore traditions and practices from their past.

The possibilities that *RelicPad* and similar systems have in opening up these collections to be revisited by these communities (collaboratively and regardless of the locations of group members and physical artefacts, or even limits imposed by the fragilities or condition of the artefacts) would make them incredibly useful not only in allowing community members themselves to get directly involved with (virtual) artefacts from the collections concerned, but also in helping museums to establish an active presence in these communities (Black, 2005). The collaborative, constructive side of the *RelicPad* experience and the possibilities it provides to share information during exploration, even in remote located discussions, make it an ideal platform for museums aiming to share expertise, build sensitive working relationships, and recognise communities (filled as they are with potential learners) as equal participants in museum learning experiences (Black, 2005).

Much of the value of encouraging the direct involvement of varied communities of learners comes from the fact that people generally exhibit a variety of personal contexts, based on their "interest, prior knowledge, expertise, skill level, motivation, capacity for independent thought and even emotion" (Black, 2005). Rather than arriving as "blank slates", potential users from the museum groups outlined in *Subsection 3.2.1 Design and Refinement of a Prototype System* bring those personal contexts with them, the elements of which combine in different ways to affect "not only [how] they interact with educational experiences but also what meaning, if any, they make of such experiences" (Falk and Dierking, 2000). The in-context study showed how participants were able to use these elements of their personal context to contribute ideas and viewpoints during collaborative discussions, and the important role this played in making sense of the (virtual) artefact and in subsequent learning outcomes.

Again, the results of the in-context study do show the important role that this prior knowledge played in participants' experiences of using *RelicPad*. Along with personal interest in particular objects (some more so than others), it is possible that the level of prior interest would have affected participants' levels of engagement in some way. It would be interesting to see in future research whether the results would have been different had the participant sample contained more people with specific interests in, for example, the Insect (Raspy Cricket), which throughout the collaboration sessions that took place during the in-context study drew less engagement and interest than either of the other two artefacts. In future studies it might be interesting to target participants with (or without) specific interests or knowledge of given types of artefact, to see how this might affect the observed results and how this might inform the design of future systems.

Encouraging contributions and participations based on elements of the personal context not only leads to immediate engagement for *RelicPad* users with the (virtual) artefact and with their collaborator in a particular discussion, but also with the wider community of museum staff, learners, visitors, and researchers. People do not like "being talked down to" and will "avoid situations whey they are made to feel inadequate or stupid as a result of a lack of prior knowledge" (Black, 2005), and so as well as making sure that potential users and communities feel like equal participants in learning experiences, it is also important to make sure that they feel that their participation is meaningful.

By contributing not just to the immediate collaborative discussion but also to the interactive history of interest points that gets build up over time and distance, *RelicPad* users are encouraged to be confident, active, and equal participants in the immediate, historical and ongoing museum learning experience – in this case, the collaborative exploration of (virtual) museum artefacts.

7.5.2 Specific Persons and Social Scalability - Participant Recruitment Issues for Future Studies

As described in the previous subsection, potential users of a *RelicPad*-style system can come from any number of the possible museum groups outlined in *Subsection 3.2.1 Design and Refinement of a Prototype System*, including museum visitors, digital (online) visitors, museum staff, teachers, or researchers, as well as from the communities themselves that certain artefacts might be representative of. Enabling these communities and user groups to contribute to the learning experience together as equal participants is important for museums, and a key benefit of using tablet-based interfaces such as *RelicPad* to collaboratively explore and discuss 3D, virtual representations of artefacts.

However, the interesting complexities that this would present, in terms of how interaction, collaboration, and even learning outcomes might have been affected based on the interpersonal relationships between and even within different communities and groups during discussions, were not really explored as part of this research. As described in *Subsection 3.2.2: Study of the Prototype System in Context*, participant recruitment was very broad, largely down to a) the philosophy that if somebody was interested in a museum study, they were very likely the kind of person who would be interested in engaging with museum artefacts anyway, and b) the serious organisational difficulties involved in recruiting participants to give up their time for the study of this nature.

Even a) without many limits on who could take part in the study, b) targeting large numbers of staff and students via various faculties of the University of Tasmania and friends and associates of the QVMAG, and c) trying to recruit participants using flyers in public places such as the Tasmanian state library and various shops and cafes, reaching the eventual participant total of thirty-six for the in-context study was a huge challenge. To put that in perspective, that is only four participants more than the envisaged lower limit for participant numbers, based on the equal comparison of viewing methods using a within-subject experimental design and the numbers needed for a meaningful statistical analysis based on that, which was thirty-two.

While the varied and non-specific backgrounds of the thirty-six participants and the good results gleaned from the in-context study suggest that *RelicPad* is useful for a variety of people regardless of their role or background, it would have been interesting to explore the possible effects that interpersonal relationships between the museum (or artefact) specific groups or communities may have had on collaboration, had it been possible to target them.

As described in *Subsection 2.1.4: Interactive Technology and Museum Learning*, facilitating social engagement necessitates that users of the system are able to work not just simultaneously (with others passively observing) but in tandem (Hindmarsh et al., 2002). Social scalability, the difficulty of supporting multiple users rather than simply two or three, plays a big part in this (Hindmarsh et al., 2002), as defined in Snibbe and Raffle's (2009) description of engagement with socially immersive media. It can even sometimes be the case that certain aspects of an experience are "more readily noticeable when there are more people [involved]", as HIndmarsh et al. (2002) found to be the case during observations of how museum visitors experienced their *Ghost Ship* exhibition. They also describe the importance of designing for reverse scalability in order to properly encourage collaboration – "designing to accommodate smaller as well as larger numbers of users" (Hindmarsh et al., 2002).

The original intention had been to organise participants in the in-context study into groups of either two or four, in order to observe any differences in the collaborative exploration and discussion of virtual artefacts that may or may not have arisen as a result of being in a smaller or larger group, particularly in terms of interpersonal relationships – who would take the lead in discussions, whether some participants would choose to remain in the periphery and participate less, and so on. However, as described a few paragraphs ago, reaching just thirty-six participants for the in-context study was a huge challenge – even trying a number of different outlets for recruiting participants, interest and willingness was, unfortunately, quite low.

This led to a difficult problem with the organisation into groups. Willing groups of four people ready to arrive together to take part never materialised, and so from early on it was evident that willing pairs would probably have to be paired again into a pair of twos to make a group of four. Throughout the whole of the in-context study (which lasted around three months in total) only one group of four was ever sourced. Towards the end of the study, with all of the necessary groups of two having taken part, there were still considerably too few (only the one) groups of four already studied, and unfortunately it was becoming impossible to pair the willing groups of two into groups of four.

This was because pairs normally could not arrive at the same time as other pairs, and the times at which each group of two wanted to give up their time to participate could not be worked around the availability of other groups of two. In the end, and in danger of losing participants thanks to potential groups of two becoming frustrated at the constant requests to participate at different times in order to try and allow them to be paired up into groups of four, the decision was made to abandon groups of four altogether, and use the willing groups of two as they were to complete the in-context study with a sufficient and meaningful number of groups of two paired participants.

In *Section 7.3: Why the Proposed Solution Works*, the *RelicPad* system has been interpreted as being socially engaging in part by being socially scalable, with as many collaborators as are willing able to either a) pass around and share a single tablet device or b) connect themselves to a (possibly remote located) collaborator using their own tablet device. However, it would have been nice to be able, or would be useful in future studies, to explore this specifically, by exploring any effects that different groups sizes would have on the experience and participants' feelings towards it – should it be possible to actually recruit and organise those numbers, of course.

Cairns and Cox (2008) describe how there are two types of population in any study or experiment – the 'theoretical population', which is the one that a researcher may want to "generalise [their] research to", and the 'study population', which is that one that a researcher can actually acquire access to – as well as a 'sampling frame', which is "the reference point that will allow [a researcher] to select appropriate people for [their] study". In the case of this thesis, theoretically it would have been great to be able to experiment with sample populations from the different museum groups (physical or online visitors, museum staff, researchers or teachers), and also to be able to experiment with different group sizes of each of these samples.

However, due to the nature of running a study during weekday office hours in a Tasmanian city with a relatively low population and the difficulties that brings in attracting and organising potential participants, a sampling frame was used:

- Adult – from the 'student to professional' age range who could conceivably: a) visit a museum either for work or leisure, or b) encounter a desktop or a tablet interface during their work or study,
- With a genuine interest in participating in the study – which would likely stem from a genuine interest in museum artefacts and activities in general.

It was from this sampling frame that the actual study population who took part in the in-context study had to be sourced, resulting in pairs of participants from a variety of non-specific backgrounds and areas of interest.

7.5.3 Closing Thoughts – Bringing (Virtual) Artefacts to Life

To conclude, the "primary role" of museums was described in *Subsection 2.4.4: Engagement in Museums* as being to "engage audiences directly with collections", exhibiting in such a way that they grasp people's attention, maintain it, and encourage people to reflect on it (Black, 2005). The discovery-based experience of exploring virtual museum artefacts using manual, hands-on techniques grounded in reality-based principles (using a tablet-based interface such as *RelicPad*), coupled with the constructive experience of collaborative discussion and sense-making, is efficient in engaging communities of stimulated learners to contribute and to reflect on previously inaccessible collections. As hypothesised at the beginning of the thesis, tablet-based interfaces such as *RelicPad* are more engaging than the alternative methods currently used to make such experiences possible, such as fixed desktop-based interfaces, and thus facilitate an experience that is closer to that of physically handling objects and artefacts.

In keeping with new approaches to museum education, this offers something quite distinct to traditional and didactic museum learning experiences. Collaborative activities such as enquiry and the sharing of ideas often diverge as much as they converge, and can at times be problematic, but collaborative learning of this nature does "not just happen because individuals are co-present" but necessitates that collaborators make an effort to coordinate themselves, their activity, and their shared knowledge (Roschelle and Teasley, 1995). It's through this social engagement and working in tandem, facilitated by tablet-based interfaces such as *RelicPad*, that collaborators are able not only to engage with (virtual) artefacts, but also to maintain mutual engagement and shared understanding as part of a collaborative and constructive learning experience.

The success of such an experience for collaborative exploration and discussion of (virtual) museum artefacts is reliant on the accepting of collaborators from a wide variety of museum or cultural communities as “equal partners on a journey”, with everybody having the same opportunities to “explore material for themselves and reach their own decisions” (Black, 2005). Rather than museum artefacts and collections being supported by ‘anonymous’ information or “a voice of authority from on high” (Black, 2005), this allows for collaborators to bring their personal context with them to the exploration and the discussion, influencing the knowledge shared and constructed and ensuring that engagement with museum content is not just about engagement with a particular (virtual) artefact represented in a particular way, but potentially also with collaborators representative of the communities and cultures to which those artefacts continue to have a deep significance.

Falk and Dierking (2000) describe how “broadening collections, expanding audiences, and reaching out to historically underserved communities” are all great opportunities for museums, and this thesis has shown that an engaging tablet-based interface such as *RelicPad* can give interested members of these communities, as well as new audiences interested in exploring connecting with them, better access to virtual representations of museum artefacts, regardless of the condition or fragility of those artefacts or of the location of either the artefacts or those who wish to (collaboratively) explore them, in such a way that the experience of exploring and discussing it feels more akin to that of viewing and handling real-life, physical artefacts.

Using tablet-based interfaces such as *RelicPad* to explore 3D, virtual representations of artefacts using manual, hands-on interaction techniques designed according to reality-based principles has been shown to bring these normally inaccessible museum artefacts to life, taking advantage of “the natural tendency to wonder" (Basballe and Halskov, 2010) to engage users in the construction of shared knowledge and understanding, through the exploration of (virtual) artefacts from all sides and collaborative discussion with like-minded learners.

References

AMES, M. & NAAMAN, M. 2007. Why We Tag: Motivations for Annotation in Mobile and Online Media. *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems.* San Jose, California, USA: ACM.

AOKI, P. M., GRINTER, R. E., HURST, A., SZYMANSKI, M. H., THORNTON, J. D. & WOODRUFF, A. 2002. Sotto Voce: Exploring the Interplay of Conversation and Mobile Audio Spaces. *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems.* Minneapolis, Minnesota, USA: ACM.

BASBALLE, D. A. & HALSKOV, K. 2010. Projections on Museum Exhibits: Engaging Visitors in the Museum Setting. *Proceedings of the 22nd Conference of the Computer-Human Interaction Special Interest Group of Australia on Computer-Human Interaction.* Brisbane, Australia: ACM.

BENFORD, S., GIANNACHI, G., KOLEVA, B. & RODDEN, T. 2009. From Interaction to Trajectories: Designing Coherent Journeys Through User Experiences. *Proceedings of the 27th International Conference on Human Factors in Computing Systems.* Boston, MA, USA: ACM.

BENYON, D. 2010. *Designing Interactive Systems - A Comprehensive Guide to HCI and Interaction Design,* Harlow, Pearson.

BLACK, G. 2005. *The Engaging Museum: Developing Museums for Visitor Involvement,* Oxon, Routledge.

BLENDER. *About - Home of the Blender Project - Free and Open 3D Creation Software* [Online]. blender.org. Available: http://www.blender.org/about/ [Accessed 7th December 2014].

BOYES, A. & COUSENS, C. 2012. In the Hand - The Effect of Museum Handling Sessions on Student Learning. *Networks.* University of Brighton: Art Design Media Higher Education Academy Subject Centre.

BROOKE, J. 1996. SUS - A Quick and Dirty Usability Scale. *Usability Evaluation in Industy*, 189-194.

BROWN, B., MACCOLL, I., CHALMERS, M., GALANI, A., RANDELL, C. & STEED, A. 2003. Lessons from the Lighthouse: Collaboration in a Shared Mixed

Reality System. *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems.* Ft. Lauderdale, Florida, USA: ACM.

BUREAU OF LABOR STATISTICS. 2012. *Curators, Museum Technicians, and Conservators* [Online]. United States Department of Labor. Available: http://www.bls.gov/ooh/Education-Training-and-Library/Curators-and-museum-technicians.htm [Accessed 26th September 2012].

CAIRNS, P. & COX, A. L. 2008. *Research Methods for Human-Computer Interaction,* Cambridge, Cambridge University Press.

CHATTERJEE, H. J. 2007. Staying Essential: Articulating the Value of Object-Based Learning. *Proceedings of the 7th International Conference on University Museums and Collections.* Vienna, Austria: ICOM.

CHATTERJEE, H. J. 2010. Object-Based Learning in Higher Education: The Pedagogical Power of Museums. *University Museums and Collections Journal,* 3**,** 179-182

CHEN, M., MOUNTFORD, S. J. & SELLEN, A. 1988. A Study in Interactive 3-D Rotation Using 2-D Control Devices. *Computer Graphics,* 22**,** 121-129.

COSLEY, D., LEWENSTEIN, J., HERMAN, A., HOLLOWAY, J., BAXTER, J., NOMURA, S., BOEHNER, K. & GAY, G. 2008. ArtLinks: Fostering Social Awareness and Reflection in Museums. *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems.* Florence, Italy: ACM.

DEVINCENZI, A., YAO, L., ISHII, H. & RASKAR, R. 2011. Kinected Conference: Augmenting Video Imaging With Calibrated Depth and Audio. *Proceedings of the ACM 2011 Conference on Computer Supported Cooperative Work.* Hangzhou, China: ACM.

EVERITT, K. M., KLEMMER, S. R., LEE, R. & LANDAY, J. A. 2003. Two Worlds Apart: Bridging the Gap Between Physical and Virtual Media for Distributed Design Collaboration. *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems.* Ft. Lauderdale, Florida, USA: ACM.

FALK, J. H. & DIERKING, L. D. 1992. *The Museum Experience,* Washington, DC, Whalesback Books.

FALK, J. H. & DIERKING, L. D. 2000. *Learning from Museums: Visitor Experiences and the Making of Meaning,* Walnut Creek, CA, Altamira.

FISHKIN, K. P. 2004. A Taxonomy for and Analysis of Tangible Interfaces. *Personal and Ubiquitous Computing,* 8**,** 347-358.

FRASER, M., HINDMARSH, J., BEST, K., HEATH, C., BIEGEL, G., GREENHALGH, C. & REEVES, S. 2006. Remote Collaboration Over Video Data: Towards Real-Time e-Social Science. *Computer Supported Cooperative Work,* 15**,** 257-279.

GOODMAN, C., SCHMITZ, P., SHEPPARD, D. & CLARK, C. 2010. Architecting CollectionSpace: A Web-Based Collections Management and Information System for 21st Century Museum Professionals. *Museums and the Web 2010.* Denver, CO, USA: Archives & Museum Informatics.

HAYWOOD, N. & CAIRNS, P. 2005. Engagement with an Interactive Museum Exhibit. *In:* MCEWAN, T., GULLIKSEN, J. & BENYON, D. (eds.) *HCI: People and Computers.* Springer.

HEATH, C. & LEHN, D. V. 2010. Interactivity and Collaboration: New Forms of Participation in Museums, Galleries and Science Centres. *In:* PARRY, R. (ed.) *Museums in a Digital Age.* Milton Park: Routledge.

HEIN, G. E. 1998. *Learning in the Museum,* London, Routledge.

HENRYSSON, A., MARSHALL, J. & BILLINGHURST, M. 2007. Experiments in 3D Interaction for Mobile Phone AR. *Proceedings of the 5th International Conference on Computer Graphics and Interactive Techniques in Australia and Southeast Asia.* Perth, Australia: ACM.

HINCKLEY, K., TULLIO, J., PAUSCH, R., PROFFITT, D. & KASSELL, N. 1997. Usability Analysis of 3D Rotation Techniques. *Proceedings of the 10th Annual ACM Symposium on User Interface Software and Technology.* Banff, Alberta, Canada: ACM.

HINDMARSH, J., FRASER, M., HEATH, C., BENFORD, S. & GREENHALGH, C. 2000. Object-Focused Interaction in Collaborative Virtual Environments. *ACM Transactions on Computer-Human Interaction,* 7**,** 477-509.

HINDMARSH, J. & HEATH, C. 2000. Sharing the Tools of the Trade - The Interactional Constitution of Workplace Objects. *Journal of Contemporary Ethnography,* 29**,** 523-562.

HINDMARSH, J., HEATH, C., LEHN, D. V. & CLEVERLY, J. 2002. Creating Assemblies: Aboard the Ghost Ship. *Proceedings of the 2002 ACM*

Conference on Computer Supported Cooperative Work. New Orleans, Louisiana, USA: ACM.

HODDER, I. 1994. The Contextual Analysis of Symbolic Meanings. *In:* PEARCE, S. M. (ed.) *Interpreting Objects and Collections.* Oxon: Routledge.

HOOPER-GREENHILL, E. 2007. *Museums and Education: Purpose, Pedagogy, Performance,* Oxon, Routledge.

HORNECKER, E. & BUUR, J. 2006. Getting a Grip on Tangible Interaction: A Framework on Physical Space and Social Interaction. *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems.* Montréal, Québec, Canada: ACM.

HORNECKER, E. & STIFTER, M. 2006. Learning from Interactive Museum Installations about Interaction Design for Public Settings. *Proceedings of the 18th Australia Conference on Computer-Human Interaction: Design: Activities, Artefacts and Environments.* Sydney, Australia: ACM.

HUNTER, J., HENDERSON, M. & KHAN, I. 2007. Collaborative Annotation of 3D Crystallographic Models. *J Chem Inf Model,* 47**,** 2475-84.

HUNTER, J. & YU, C.-H. 2010. Supporting Multiple Perspectives on 3D Museum Artefacts Through Interoperable Annotations. *In:* NAKATSU, R., TOSA, N., NAGHDY, F., WONG, K. & CODOGNET, P. (eds.) *Cultural Computing.* Springer Berlin Heidelberg.

HÜRST, W. & HELDER, M. 2011. Mobile 3D Graphics and Virtual Reality Interaction. *Proceedings of the 8th International Conference on Advances in Computer Entertainment Technology.* Lisbon, Portugal: ACM.

HUTCHINS, E. 1995. *Cognition in the Wild,* Cambridge, MA, MIT Press.

IDEA.ORG. 2011. *Put 3D Objects at your Visitors' Fingertips: UVaM on the iPad* [Online]. Idea.org. [Accessed 5th December 2013].

JACOB, R. J. K., GIROUARD, A., HIRSHFIELD, L. M., HORN, M. S., SHAER, O., SOLOVEY, E. T. & ZIGELBAUM, J. 2007. Reality-Based Interaction: Unifying the New Generation of Interaction Styles. *CHI '07 Extended Abstracts on Human Factors in Computing Systems.* San Jose, CA, USA: ACM.

JACOB, R. J. K., GIROUARD, A., HIRSHFIELD, L. M., HORN, M. S., SHAER, O., SOLOVEY, E. T. & ZIGELBAUM, J. 2008. Reality-Based Interaction: A

Framework for Post-WIMP Interfaces. *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems.* Florence, Italy: ACM.

JUNG, T., DO, E. Y.-L. & GROSS, M. D. 1999. Immersive Redlining and Annotation of 3D Design Models on the Web. *In:* AUGENBROE, G. & EASTMAN, C. (eds.) *Computers in Building.* Springer US.

JUNG, T., GROSS, M. D. & DO, E. Y.-L. 2002. Annotating and Sketching on 3D Web Models. *Proceedings of the 7th International Conference on Intelligent User Interfaces.* San Francisco, California, USA: ACM.

KEARSLEY, G. & SHNEIDERMAN, B. 1998. Engagement Theory: A Framework for Technology-Based Teaching and Learning. *Educational Technology,* 38**,** 20-23.

KENDERDINE, S. & HART, T. mARChive: Sculping Museum Victoria's Collections. *In:* PROCTOR, N. & CHERRY, R., eds. Museums and the Web 2014, 2014 Baltimore, MD, USA. Silver Spring.

KNOWLES, M. S., HOLTON, E. F. & SWANSON, R. A. 2005. *The Adult Learner,* New York, Butterworth-Heinemann.

KORTBEK, K. J. & GRØNBÆK, K. 2008. Interactive Spatial Multimedia for Communication of Art in the Physical Museum Space. *Proceedings of the 16th ACM International Conference on Multimedia.* Vancouver, British Columbia, Canada: ACM.

KRATZ, S., ROHS, M., GUSE, D., MÜLLER, J., BAILLY, G. & NISCHT, M. 2012. PalmSpace: Continuous Around-Device Gestures vs. Multitouch for 3D Rotation Tasks on Mobile Devices. *Proceedings of the International Working Conference on Advanced Visual Interfaces.* Capri Island, Italy: ACM.

LAZAR, J., FENG, J. H. & HOCHHEISER, H. 2010. *Research Methods in Human-Computer Interaction,* Chichester, UK, Wiley.

LIAROKAPIS, F., SYLAIOU, S., BASU, A., MOURKOUSSIS, N., WHITE, M. & LISTER, P. F. 2004. An Interactive Visualisation Interface for Virtual Museums. *Proceedings of the 5th International conference on Virtual Reality, Archaeology and Intelligent Cultural Heritage.* Oudenaarde, Belgium: Eurographics Association.

MANCHES, A. & PRICE, S. 2011. Designing Learning Representations Around Physical Manipulation: Hands and Objects. *Proceedings of the 10th International Conference on Interaction Design and Children.* Ann Arbor, Michigan: ACM.

MARTINET, A., CASIEZ, G. & GRISONI, L. 2010. The Effect of DOF Separation in 3D Manipulation Tasks with Multi-Touch Displays. *Proceedings of the 17th ACM Symposium on Virtual Reality Software and Technology.* Hong Kong: ACM.

MASTORIS, S. n.d. *Learning Through Objects* [Online]. Group for Education in Museums. Available: http://www.gem.org.uk/res/advice/ball/res_lto.php [Accessed 5th October 2012].

NATIONAL MUSEUM OF AUSTRALIA. n.d. *Research and Museology* [Online]. National Museum of Australia. Available: http://www.nma.gov.au/history/research [Accessed 27th September 2012].

NORMAN, D. A. 1990. *The Design of Everyday Things,* New York, Doubleday.

O'BRIEN, H. L. & TOMS, E. G. 2008. What is User Engagement? A Conceptual Framework for Defining User Engagement with Technology. *Journal of the American Society for Information Science and Technology,* 59**,** 938-955.

O'NEILL, J., CASTELLANI, S., ROULLAND, F., HAIRON, N., JULIANO, C. & DAI, L. 2011. From Ethnographic Study to Mixed Reality: A Remote Collaborative Troubleshooting System. *Proceedings of the ACM 2011 Conference on Computer Supported Cooperative Work.* Hangzhou, China: ACM.

OATES, B. J. 2006. *Researching Information Systems and Computing,* London, UK, SAGE.

OOMEN, J., BALTUSSEN, L. B. & ERP, M. V. 2012. Sharing Cultural Heritage the Linked Open Data Way: Why You Should Sign Up. *Museums and the Web 2012.* San Diego, CA, USA: Archives & Museum Informatics.

OTITOJU, K. & HARRISON, S. 2008. Interaction as a Component of Meaning-Making. *Proceedings of the 7th ACM Conference on Designing Interactive Systems.* Cape Town, South Africa: ACM.

PEARCE, S. M. 1994. Museum Objects. *In:* PEARCE, S. M. (ed.) *Interpreting Objects and Collections.* Oxon: Routledge.

PEARSON, J., BUCHANAN, G. & THIMBLEBY, H. 2012. Investigating Collaborative Annotation on Slate PCs. *Proceedings of the 14th International Conference on Human-Computer Interaction with Mobile Devices and Services.* San Francisco, California, USA: ACM.

PETERS, C., CASTELLANO, G. & FREITAS, S. D. 2009. An Exploration of User Engagement in HCI. *Proceedings of the International Workshop on Affective-Aware Virtual Agents and Social Robots.* Boston, MA, USA: ACM.

POUPYREV, I., WEGHORST, S. & FELS, S. 2000. Non-Isomorphic 3D Rotational Techniques. *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems.* The Hague, The Netherlands: ACM.

PRICE, S., SHERIDAN, J. G. & FALCÃO, T. P. 2010. Action and Representation in Tangible Systems: Implications for Design of Learning Interactions. *Proceedings of the Fourth International Conference on Tangible, Embedded, and Embodied Interaction.* Cambridge, Massachusetts, USA: ACM.

PRICE, S., SHERIDAN, J. G., FALCÃO, T. P. & ROUSSOS, G. 2008. Towards a Framework for Investigating Tangible Environments for Learning. *International Journal of Arts and Technology,* 1**,** 351-368.

PYE, E. 2007. The Power of Touch. *In:* PYE, E. (ed.) *The Power of Touch: Handling Objects in Museum and Heritage Contexts.* Walnut Creek, CA: Left Coast Press.

ROSCHELLE, J. & TEASLEY, S. D. 1995. The Construction of Shared Knowledge in Collaborative Problem Solving. *In:* O'MALLEY, C. (ed.) *Computer Supported Collaborative Learning.* Springer Verlag.

SCHROETER, R., HUNTER, J., GUERIN, J., KHAN, I. & HENDERSON, M. 2006. A Synchronous Multimedia Annotation System for Secure Collaboratories. *Proceedings of the Second IEEE International Conference on E-Science and Grid Computing.* IEEE Computer Society.

SCHROETER, R., HUNTER, J. & KOSOVIC, D. 2003. Vannotea - A Collaborative Video Indexing, Annotation and Discussion System for Broadband Networks. *K-CAP 2003: Proceedings of the 2nd International Conference on*

Knowledge Capture - Knowledge Markup and Semantic Annotation Workshop. Sanibel, Florida: ACM.

SHARP, H., ROGERS, Y. & PREECE, J. 2007. *Interaction Design: Beyond Human-Computer Interaction,* West Sussex, Wiley.

SILVA, J., CABRAL, D., FERNANDES, C. & CORREIA, N. 2012. Real-Time Annotation of Video Objects on Tablet Computers. *Proceedings of the 11th International Conference on Mobile and Ubiquitous Multimedia.* Ulm, Germany: ACM.

SIMON, N. 2008. What's a Virtual Visitor Worth? *Museum 2.0* [Online]. Available from: http://museumtwo.blogspot.de/2008/12/whats-virtual-visitor-worth.html [Accessed 28th September 2012].

SNIBBE, S. S. & RAFFLE, H. S. 2009. Social Immersive Media: Pursuing Best Practices for Multi-User Interactive Camera/Projector Exhibits. *Proceedings of the 27th International Conference on Human Factors in Computing Systems.* Boston, MA, USA: ACM.

STAHL, G., KOSCHMANN, T. & SUTHERS, D. D. 2006. Computer-Supported Collaborative Learning. *In:* SAWYER, R. K. (ed.) *The Cambridge Handbook of the Learning Sciences.* New York: Cambridge University Press.

TILLEY, C. 1994. Interpreting Material Culture. *In:* PEARCE, S. M. (ed.) *Interpreting Objects and Collections.* Oxon: Routledge.

TREWINNARD-BOYLE, T. & TABASSI, E. 2007. Learning Through Touch. *In:* PYE, E. (ed.) *The Power of Touch: Handling Objects in Museum and Heritage Contexts.* Walnut Creek, CA: Left Coast Press.

ULLMER, B. & ISHII, H. 2000. Emerging Frameworks for Tangible User Interfaces. *IBM Systems Journal,* 39**,** 915-931.

UNITY TECHNOLOGIES. 2014. *Unity - Game Engine, Tools and Multiplatform* [Online]. Unity Technologies. Available: http://unity3d.com/unity.

VAN DAM, A. 1997. Post-WIMP User Interfaces. *Communations of the ACM,* 40**,** 63-67.

WIKIPEDIA. *Scrimshaw* [Online]. Available: http://en.wikipedia.org/wiki/Scrimshaw.

WOODS, E., BILLINGHURST, M., LOOSER, J., ALDRIDGE, G., BROWN, D., GARRIE, B. & NELLES, C. 2004. Augmenting the Science Centre and Museum

Experience. *Proceedings of the 2nd International Conference on Computer Graphics and Interactive Techniques in Australasia and South East Asia.* Singapore: ACM.

WYETH, P. 2008. Understanding Engagement with Tangible User Interfaces. *Proceedings of the 20th Australasian Conference on Computer-Human Interaction: Designing for Habitus and Habitat.* Cairns, Australia: ACM.

YU, C.-H. 2010. Semantic Annotation of 3D Digital Representation of Cultural Artefacts. *Bulletin of IEEE Technical Committee on Digital Libraries,* 6.

YU, C.-H., GROZA, T. & HUNTER, J. 2011. High Speed Capture, Retrieval and Rendering of Segment-Based Annotations on 3D Museum Objects. *Proceedings of the 13th International Conference on Asia-Pacific Digital Libraries: For Cultural Heritage, Knowledge Dissemination, and Future Creation.* Beijing, China: Springer-Verlag.

YU, C.-H. & HUNTER, J. 2011. Assessing the Value of Semantic Annotation Services for 3D Museum Artefacts. *Sustainable Data from Digital Research: Humanities Perspectives on Digital Scholarship.* Melbourne, Australia: Custom Book Center.