Use of 3D Virtual Models and Physical Replicas to enhance user experience within Heritage Applications

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Cheers

Paul F Wilson

DECLARATIONS

The contents of this thesis are the candidate's own work, except where it contains work based on collaborative research. In these cases, the nature and the extent of this research shall be indicated as well as the author's contribution to that research.

The research outcomes that the author has contributed to academia are summarised in the section entitled *Research Outcomes* following the abbreviations section.

This thesis has not been submitted for examination for another degree at another university.

ABSTRACT

Museums are dedicated to preserving the legacy of the past and educating their visitors, both practices at odds with each other. The rise of multisensory experiences in museology has emphasized the use of touch as a pedagogical tool, but this risks destruction of precious museum objects. The art of 3D printing has the potential to overcome this conservational barrier, but such applications are typically *ad-hoc*, with little design consideration. Furthermore, there is a lack of research into developing best practices for the creation of tangible 3D printed replicas.

This thesis employed user experience (UX) methods from consumer industries with pragmatic mixed-methods in order to explore this issue. The research questions addressed a number of issues: 1) The perceptions of museum visitors in regard to 3D printed replicas; 2) The design considerations for replicas in order to provide positive UX for audiences; 3) How they can benefit museum audiences; 4) How they can benefit blind and partially-sighted (BPS) individuals; 5) How replication impacts wider museum practice; 6) How effective UX methods are in understanding museum audiences.

Over the course of four studies, a number of key findings were elucidated:

- Museum visitors expressed positivity towards the concept of tangible 3D printed replicas but had a limited understanding of it.
- Preference was strongly dependant on verisimilitude, a one-dimensional requirement, while print quality was a must-be requirement.
- BPS perception was reliant on multisensory interpretation. Object and material judgements were interrelated, highlighting the complex design problems in 3D printing for BPS audiences.
- Replicating an object can result in unexpected insights, resulting in novel research opportunities.

A set of best design practices were created and a number of emergent research topics highlighted that were unable to be fully explored. These included the preferences of younger visitors, empirical assessment of the impact of 3D printed replicas and how print properties truly influence BPS perception.

ABBREVIATIONS

3DP	‘3D Printing’. A method of powder-binder based printing.
BPS	Blind and Partially Sighted
CAD	Computer Aided Design
CJP	ColourJet Printing
EDS	Energy-Dispersive X-ray Spectroscopy
FDM/FFF	Fused Deposition Modelling/Fused Filament Fabrication. Synonyms.
HMI	Human-Machine Interfaces
OBL	Object-Based Learning
OUMNH	Oxford University Museum of Natural History
LOM	Laminated Object Manufacturing
MJ	Material Jetting
SLA	Stereolithography
SLS	Selective Laser Sintering
UCD	User-Centred Design
UD/UDT	Universal Design/Universal Design Theory
UX	User Experience
XCT	X-ray Computed Tomography
XRF	X-Ray Fluorescence

RESEARCH OUTCOMES

<u>*Journal Papers:*</u>

Wilson, P, Stott, J, Warnett, JM, Attridge, Smith, MP and Williams, MA. 2017a. Evaluation of Touchable 3D-Printed Replicas in Museums. *Curator: the Museum Journal*, 60: 445-465.

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Wilson, PF, Smith, MP, Hay, J, Warnett, JM, Attridge, A and Williams, MA. 2018b. X-ray computed tomography (XCT) and chemical analysis (EDX and XRF) used in conjunction for cultural heritage conservation: the case of the earliest scientifically described dinosaur *Megalosaurus bucklandii*. *Heritage Science*, 6: 58.

<u>*Conference Papers:*</u>

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<u>*Conference Contributions:*</u>

ToScA 2016. Tomography for Scientific Advancement. *A Sense of Touch: Getting to Grips with Museum Artefacts*. **Poster and Lightning Talk**. Bath, England, 6 – 7 Sept. 2016.

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I2MTC 2017. IEEE International Instrumentation and Measurement Technology Conference. *Utilizing X-Ray Computed Tomography for Heritage Conservation: the Case of Megalosaurus bucklandii*. **Paper and Full Talk**. Torino, Italy, 22 – 25 May.

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1.0 INTRODUCTION

1.1 THE ORIGIN OF THE PUBLIC MUSEUM

At the heart of every museum institution is the need to safeguard the legacy of the past and teach its lessons to the public. This practice has fuelled the development of cultural institutions over the centuries. However, the form in which this practice has been upheld has varied wildly. Arguably the earliest usage of the word museum can be found in the name of the legendary 'Mouseion of Alexandria', erected by Ptolemy I Soter of the Macedonian Empire in Alexandria in c. 280 BCE (Findlen, 2004; Abt, 2006). Created to mimic the fabled Lyceum of Aristotle, the greatest scholars of the Hellenic world gathered to categorize all knowledge, although this was not its primary purpose. It is thought that Ptolemy I Soter used the Mouseion as a way of declaring his own sovereignty over both the realm of all knowledge and his empire (Abt, 2006). This sentiment reflects the dominant purpose of the museum in its earliest form, as a symbol of wealth, state and power.

Following the fall of the Roman Empire and the descent into the Middle Ages, the museum makes no appearance in any form until the appearance of the Palazzo Medici in Florence in 1444. This was the wealthy estate of the Florentine banking magnates, the House of Medici (Hooper-Greenhill, 1992). While initially little more than a hoard of treasures built to impress private visitors, the onset of the Renaissance began to change the way in which this collection was used. It became a miscellany of unusual trinkets kept for study by scholars wishing to uncover the secrets of the world (Hooper-Greenhill, 1992; Findlen, 2004). This practice continued throughout the Renaissance era throughout Europe in the form of *studiolos* and *kunstkammer* of a similar nature, collections of items used to impress visitors and for private study (Hooper-Greenhill, 1992; Abt, 2006). Eventually the word *musaeum* emerged as the preferred term for these collections, and they began to transition into a setting for learned discourse (Abt, 2006). However, the important aspect of these early 'museums' is that they were entirely private, the domain of the wealthy who only allowed their favoured visitors to partake of their collections (Hooper-Greenhill, 1992; Abt, 2006).

The realization of the museum in its modern form, a cultural institution for public use, was not realised until sometime later. The two institutions most commonly highlighted for the conception of the public museum are the Ashmolean in Oxford and the Louvre in Paris (Abt, 2006). During the Era of Enlightenment, John Tradescant Jnr. had inherited a large collection from his father known as 'the Ark of Lambeth' which he allowed public visitors to enter for the fee of 6p starting in 1649 (Smith, 1989; Abt, 2006). On his death, he donated his collection to his friend, Elias Ashmole, who eventually donated the combined collection to Oxford University. This was followed by the opening of the Ashmolean Museum in 1683. Like the Ark of Lambeth, the museum allowed access to the general public for a small fee, with the lofty intent of enlightening the working class of the wonders of the world (Smith, 1989; Hooper-Greenhill, 2000a; Abt, 2006). The Louvre also represents a similar noble educational goal, founded in 1783 following the French revolution and named the *Muséum Français*. This public institution was designed to allow the poor to rub shoulders with the rich and to demonstrate the imperial might of the newly emerging post-revolutionary France (Hein, 1998; Abt, 2006). These institutions became the progenitors of the modern public museum and their influence can still be observed in modern museum practice.

1.2 THE RESEARCH BACKGROUND

1.2.1 The Purpose of the Modern Museum

As museums became more widespread, the public-oriented educational aspect of practice began to grow, with more institutions designed to entertain and amuse the general public beginning to open across the western world throughout the late 19th Century (Abt, 2006). However, into the 20th Century, public museums began to turn towards their own research interests and the original altruistic educational aims that were core to their inception became a matter of secondary importance (Smith, 1989; Talboys, 2011). Displays became strictly academic, taxonomic, and difficult for inexpert visitors to properly comprehend, curators assuming that the objects would speak for themselves (Smith, 1989; Hein, 1998; Talboys, 2011; McManus, 2015). However, in the latter half of the 20th Century this paradigm was to be overturned as museum workers began to realise that objects could not communicate their stories alone, fuelling the inclusion of sound, text, and images to better communicate their educational messages (Radywyl et al. 2015). Through the 70’s and 80’s, museum professionals began to adopt these new museum pedagogies and research began to show that such changes helped visitors to better engage and understand museum content. This was the beginning of a new approach to exhibition design, one focussed around better presenting and communicating exhibition content (Baker, 2015; McManus, 2015; Radywyl et al. 2015).

In the UK, this culminated in a major paradigm shift in the 90’s, as the recognition of the educational role of the museum and their inclusion into the National Curriculum demanded that museums prioritize their historically neglected pedagogical strategies (Hooper-Greenhill, 2007; Reeve and Woollard, 2015). A number of government-sanctioned reports started to highlight the poor provision of education in British museums, the most infamous of which was the ‘Anderson Report’ (Anderson, 1997; 1999). This report found that 37% of British museums provided only limited educational supplements while 49% did nothing to educate visitors, while only 3% of museum staff nationwide were employed as educational staff (Hooper-Greenhill, 2007). Museums slowly began to remedy this issue and the introduction of regular evaluation of museum exhibits helped refine exhibition design and the presentation of museum content to audiences (Hooper-Greenhill, 2007). A report by the now defunct MLA (2006) showed vastly improved provision of educational facilities, finding that 86% of English museums were used by formal education groups, 69% of museums had an educational policy and 87% of curators were involved in educational activities.

Today, museum practice is dedicated to communicating important issues and concepts to their audiences as well as ensuring that visitors have an enjoyable and engaging experience. The museum's ability to achieve these objectives is coming under increasing threat however, in part thanks to a number of recent trends. The first of these is a shift towards the visitor-centred museum, where content is developed around the needs and interest of the visitor, rather than simply curator-led (Hein, 1998; Hooper-Greenhill, 2000a; 2007). The rise of this 'constructivist' practice, as shall be discussed later, mirrors the above-mentioned change in educational practice within the cultural heritage sector. However, while the literature evokes the importance of this approach and its widespread acceptance certainly advocates this, practice in many museums globally still lags behind as many struggle to adapt to this new way of promoting visitor engagement. In British museums this is in part due to ever-increasing funding cuts, which makes it difficult for many public museums to properly adopt these visitor-centred display practices. The net result of this is severe reduction of staff, unprecedented closure of institutions across the country and large budget cuts in spite of increasing visitor attendance figures (Museums Association, 2015; 2018).

A knock-on effect of the rise of visitor-centred museum practice is that they are now increasingly viewed by their visitors as a place for enjoyment, one that is in direct competition with other tourist activities and destinations (Falk and Dierking, 2012). This means that museums are under increasing pressure to provide experiences that are not only enjoyable and educational but also have the attractive power to draw visitors who might be considering a number of other activities in the area. With many public museums trapped in limbo between transitioning from curator-led academic to visitor-centred narrative display methods, the issue is complicated as museum professionals are pressured to provide ever more competitive, engaging and novel experiences to attract visitors.

Complicating matters is the arrival of new technologies to enhance visitor engagement. Digital displays and touch-screens have become increasingly more common fixtures within museums over the past decade, but even more cutting-edge visualization techniques, such as virtual reality (VR) and augmented reality (AR), have the potential to further enhance the visitor-centred museum experience (Jung et al. 2016; Jung and tom Dieck, 2017). Integration of these novel approaches into museum galleries is difficult however and many museums simply place such solutions *ad hoc* into galleries with little consideration for the experiences they might produce, save a simple evaluation. The current nature of evaluation practice in cultural heritage leans towards the summative, only assessing whether the exhibition was successful rather than detailed insights into practice constraints (Davies and Heath, 2013; 2014). This generally means that museums are generally poorly equipped to properly adapt to these emerging exhibition technologies.

Overall then, the modern museum is under pressure to provide novel, visitor-centred experiences with cutting edge display approaches despite a lack of a holistic, generalizable research base and on ever-dwindling funding.

1.2.2 The Multisensory Museum

The shift towards the visitor-centred museum and the difficulties in practice associated therein is a challenge that is being met by an increasing research interest into the importance of engaging multisensory experiences. Multisensory experiences are believed to be much more effective learning tools within an informal learning environment over purely visual ones (Paris, 2002; Chatterjee, 2008; Pye, 2008a; Levent and Pascual-Leone, 2014). This has been fuelled in part by research into the learning effectiveness of multisensory experiences, but also due to the need to provide inclusive support under the Disability Discrimination Act (DDA, 1995) and the Equality Act (2010). These mandate that facilities must be provided for all citizens, regardless of their ability (Candlin, 2008; 2010; Spence and Gallace, 2008). The need to reintroduce sensory involvement back into the museum space is advocated by many authors (Dudley, 2012ab; Bacci and Pavani, 2014; Levent and McRainey, 2014; Eardley et al. 2018; Pursey and Lomas, 2018). This has been met with resistance however due to the contradiction of this approach with the purpose of the museum, to preserve artefacts so that future generations can appreciate them (Cassim, 2008; Spence and Gallace, 2008; Candlin, 2017). As a result, touch is generally prohibited within the museum, with a few exceptions that are strictly controlled by curators in typically one-off events (Gaskell, 2015; Candlin, 2017). Allowing visitors to freely handle precious museum artefacts risks destruction and thus undermines this core purpose.

The most common method through which museums have circumvented this issue is through the use of casts, copies of the original object, typically made using plaster, that accurately replicate its geometry, often to the point where the two are indistinguishable (Bohn, 1999; Malenka, 2000; Bearman, 2011). Cast creation, however, risks damaging the object during the process of moulding, which needs to be administered carefully and with great skill to prevent the moulding medium from destroying parts of the specimen during extraction. As such, these traditional methods are effective but risky and can only be properly utilised on robust objects provided that due care and consideration by a trained conservator is afforded.

1.2.3 An Emerging Solution

An alternative approach to using casts is that of 3D printing or additive manufacturing technology. 3D printing is a method of fabricating complex objects in a wide array of different materials (Gibson et al. 2015; Chua and Leong, 2017). In the past decade, the technique has grown so rapidly that it now pervades a huge diversity of industries and fields, including medicine (Murphy and Atala, 2014; Torabi et al. 2015; Mahmoud and Bennett, 2015), engineering and industry (Mahindru and Mahendru, 2013), education (Gerber et al. 2015; O'Reilly et al. 2016), archaeology (Laycock et al. 2015; Du Plessis et al. 2015), palaeontology (Lautenschlager and Rücklin, 2014) and cultural heritage (Scopigno et al. 2017; Balletti et al. 2017). Within the latter, the technology is regarded as an invaluable tool for many diverse applications, as is discussed later (*2.4.2.1 General Museum Use*). It has found particular use in engaging museum audiences, including the creation of tactile images and other initiatives to help facilitate blind and partially-sighted (BPS) visitors (Neumüller et al. 2014; Urbas et al. 2016; Stanco et al. 2017), exhibition planning and design (Celani et al. 2008; Callieri et al. 2015), for creating souvenirs and merchandise (Scopigno et al. 2014; Anastasiadou and Vettese, 2019), and, most importantly for the purpose of this discussion, for exhibition and educational purposes (Schwandt and Weinhold, 2014; D'Agnano et al. 2015; Younan, 2015).

Their purpose as engagement tools within museums is one that has seen growing interest over the past few years, and many workers within cultural heritage are beginning to take advantage of 3D printed replicas to provide more immersive, multisensory experiences to visitors (Sportun, 2014; Jakobsen, 2016). Indeed, many museums are just beginning to utilise 3D printing technologies to supplement existing or new exhibitions or initiatives (Sportun, 2014; Capurro et al. 2015; Dima et al. 2014; D'Agnano et al. 2015; Marshall et al. 2016; Turner et al. 2017). However, a major issue is that much of the literature on the efficacy of this approach is purely hypothetical and speculative, the vast majority of authors typically advocating positivity without exploring why or how (Rahman et al. 2012; Soile et al. 2013; Neely and Langer, 2013; Laycock et al. 2015; Solima and Tani, 2016; Turner et al. 2017). Some authors go a little further and include simple evaluations of limited scope and generalizability, rarely deviating from a positive result (Dima et al. 2014; Marshall et al. 2016). Researchers are now beginning to ask vital questions as to the usefulness of such replicas and slowly but surely, an increasing number of studies are being released to address key issues within the field (Neumüller et al. 2014; Di Franco et al. 2015; 2016; Turner et al. 2017). Others question what design considerations or guidelines should be adopted, an area that has been shown little interest up to this point (Neumüller et al. 2014; Di Franco et al. 2015; 2016), an issue that becomes further complicated when taking into consideration the needs of historically marginalised museum audiences, such as BPS visitors (Candlin, 2003; Neumüller et al. 2014; Götzelmann, 2017; Ballarin et al. 2018). However, these studies are arguably few and far between and given the general reluctance of museums to publish work on their practices (Davies and Heath, 2014), it is likely that many museums are utilising 3D printing technologies for exhibition purposes despite the lack of a guiding framework for best practice in their design and use.

As a result, an opportunity to rigorously explore the theme of 3D printed tangible replicas emerges. This topic will be the subject of this thesis, namely the impact on visitor experiences with tangible 3D printed replicas, a subject poorly understood by museum specialists at this moment in time. This perspective needs to be considered when creating such replicas for public consumption.

1.3 IDENTIFYING THE RESEARCH PROBLEM

The purpose of this thesis is to explore the above-mentioned research theme, here summarised as:

"How can tangible 3D printed replicas influence the user experience of museum visitors?"

In this thesis, the influence that 3D printed replicas exert over the museum experience of visitors will be explored and what design considerations need to be taken into account for them to properly fulfil their role as key elements of exhibitions and galleries. This is necessary to encourage the creation of meaningful, engaging multisensory experiences through the medium of 3D printing. The outcome of this research will elucidate the key design decisions that need to be taken into account for museum practitioners and to draw up a tentative set of guidelines to follow, as well as to provide some early insights into the efficacy of the approach.

At this stage, a preliminary set of research questions to address the so-far highlighted research problem can be drawn up. These are:

- How do museum visitors perceive 3D printed replicas and how readily can they be accepted?
- How do such tangible 3D printed replicas affect the experience of the museum visitor?
- How can they assist marginalised communities, such as the blind and partially sighted?

Throughout this thesis, these questions will be explored and answered in an effort to properly elucidate this research-poor subject area. These research questions are developed further throughout the thesis, being refined in the literature review (*2.0 Literature Review*) and finalised in the research methodology chapter (*3.0 Research Methodology*).

1.4 THESIS OUTLINE

In this chapter, the general background and research problems have been highlighted with some preliminary ideas about general research questions. In the remainder of this chapter, the general structure of this thesis will be highlighted (Fig. 1.1).

In Chapter 2, the literature surrounding the subject of tangible 3D printed replicas within cultural heritage, their potential benefits, the current state of the art and, finally, the state of the art in 3D printing technologies is explored. This literature review will cover a number of major themes to establish a more refined set of research questions.

First covered is the chequered history of touch and how museums first embraced the handling of their collections, before turning away from this approach for the vast majority of their history. This is then followed by an exploration of current ideas in multisensory experiences within museums, the theory supporting their positive impact on museum practice and the resultant conservational problems implicit within. Then, the potential solution in the form of tangible 3D printed replicas and the current state of the art with regard to how museums use 3D printing in general and for multisensory experiences are explored. Finally, the nature of museum evaluation is elucidated and a better route for answering the research questions proposed, that of user experience (UX).

This chapter finishes up by updating the research questions with respect to the literature review and giving thought as to the key research questions of interest within the subject of tactile, 3D printed replicas.

In Chapter 3, the research methodology, evaluatory techniques and the adopted research approach for tackling the proposed research questions are elucidated. The chapter concludes with a finalised set of research questions to be explored within the subsequent chapters that follow several topics of key interest that will be explored throughout the remainder of the thesis.

In Chapters 4, 5, 6 and 7 each of the major studies highlighted in the research methodology will be introduced, their methods and materials detailed, the data analysed and discussed within the lens of that particular study. These represent different phases of exploration of the research questions and are briefly summarised below:

- *Chapter 4: Evaluation of Tangible 3D-Printed Replicas in Museums*: A study looking into the perspective of the museum visitor regarding 3D printed replicas within the exhibition space. This will investigate whether or not visitors welcome the idea of such 3D printed replicas and initial perspectives.

- *Chapter 5: Visitor Preference for the Physical Properties of Tangible 3D Printed Replicas*: A study evaluating the physical preferences of museum visitors with regard to tangible 3D printed replicas, attempting to identify which characteristics of these models are most preferred.
- *Chapter 6: What can you feel?: Blind Perception of Museum Objects*: A study looking into what features of museum objects can BPS visitors perceive and how easily they can identify genuine objects using touch. This will inform practitioners of design considerations to be taken into account when printing replicas for BPS individuals.
- *Chapter 7: Additional Benefits of Digitizing Museum Objects*: *Megalosaurus bucklandii*: A discussion of the additional benefits that can be passed on to wider museum practice when digitizing valuable specimens, focusing on the first scientifically described dinosaur, *Megalosaurus bucklandii*.

In Chapter 8, the broad findings of each of the four studies will be discussed and related research questions in an attempt to answer them. A number of emergent topics of interest will be discussed, along with recommendations of how to present to specific audiences. Furthermore, the shortcomings of the research approach and particular fields that merit further exploration will be highlighted for future research efforts.

In Chapter 9, the final major chapter of the thesis, the findings from the thesis will be summarised in totality, leading from findings of the literature review, the individual studies that make up this thesis and finishing up with the major trends discussed in the discussion and the potential for future work. A set of guidelines of best practices will be created with the express intent of their further development of research within the sphere of cultural heritage.

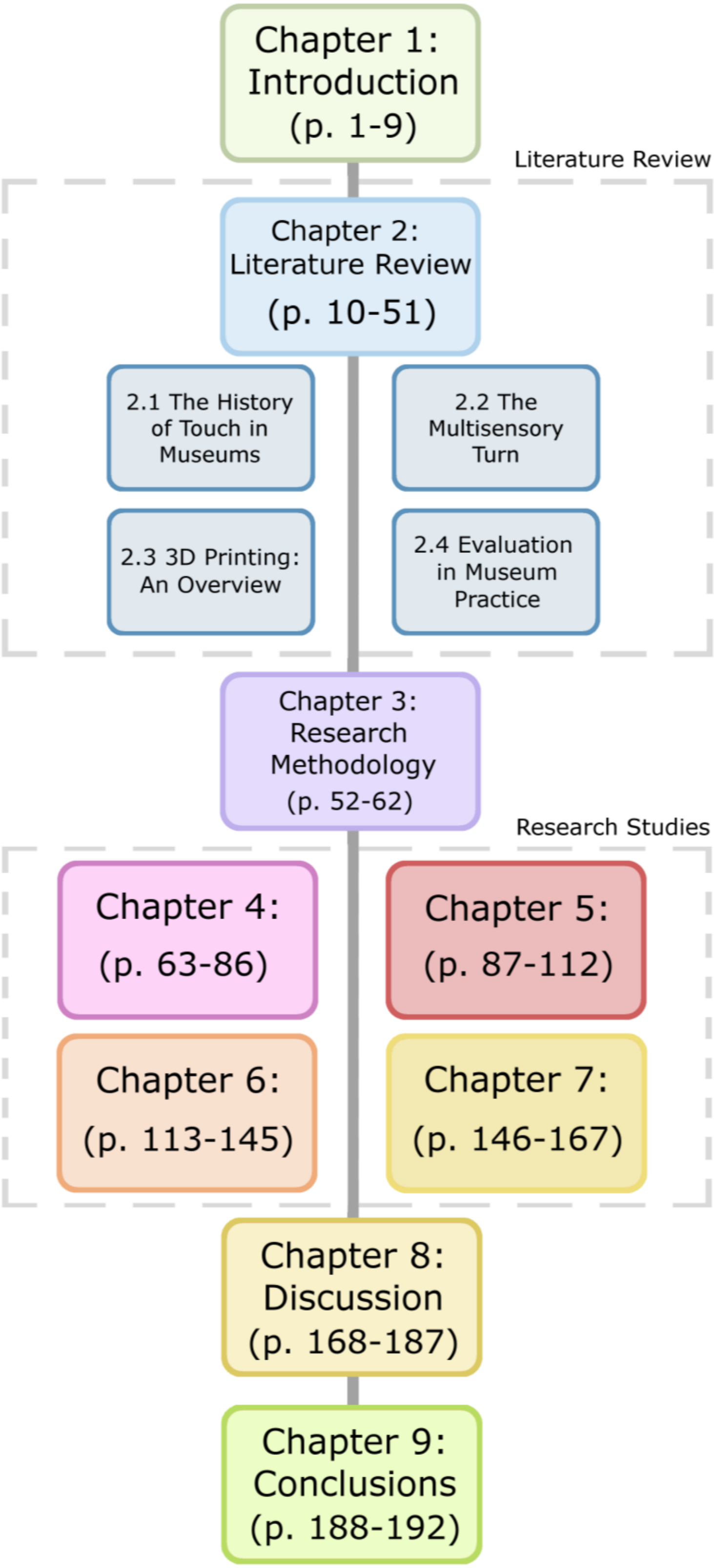


Fig. 1.1: Structure of the Thesis: The overall structure of the thesis, following a linear series of developments of the research questions and their discussion.

2.0 LITERATURE REVIEW

Thus far, the overall skeleton of a topic of pertinent interest has been highlighted, how tangible 3D printed replicas could both enhance the experience of museum visitors but also provide accessibility to the BPS community. The emergence of this cutting-edge technology needs to be properly integrated into museum practice and in order for this to be achieved, the design considerations, user experience and visitor perceptions of tangible 3D printed replicas must be explored so that any such applications do not fail to meet the expectations of the visiting public.

2.1 STRUCTURE OF THE LITERATURE REVIEW

The above themes will form the backbone of this thesis, which will attempt to ascertain how tangible 3D printed replicas can influence the experience of museum visitors. Before this topic can be formally addressed, some important themes must be discussed. These include the background of how institutions have dealt with the controversial subject of touch in museums in the past and how research shows that engagement with tangible 3D printed replicas could be extremely beneficial to visitors' learning experiences and enjoyment within museums. How 3D printing is currently exploited in cultural heritage must also be explored. From these insights, a set of research questions that will guide this thesis can be derived and the resulting studies detailed throughout. This is the primary purpose of this section of the thesis. Each of these major themes will be explored in some detail and critiqued, in order to develop a set of core research questions. These topics include:

1. *The History of Touch in Museums*: Before exploring the nature of touch and its role in the museum, the chequered history of touch within the museum will be highlighted and how professional views have shifted over time to embrace this once marginalised sense again.
2. *The Multisensory Turn*: Continuing on from the history of touch, this section attempts to explore why touch is now more important than ever to museum practice and the potential educational and experiential benefits that it brings for museum visitors, especially to those who live with sight loss.
3. *3D Printing: An Overview:* The current applications of 3D printing within cultural heritage are also reviewed and how it is being applied to engage museum audiences through multisensory interaction.
4. *Evaluation in Museum Practice*: A review of museum practice and the evaluation of exhibitions and galleries. This is followed by a comparison to other competitive sectors and the potential benefits of a rigorous, consumer-oriented approach discussed.

Once these areas of interest are reviewed, the key research questions will be identified that will form the basis of the thesis going forward. However, there are a number of subjects deemed too broad to address concisely within this review. An in-depth review on learning, both within formal and informal contexts, will not be carried out. Only the pedagogy of multisensory interaction, that of Object-Based Learning (OBL), will be discussed. Other modes and theories of learning in museums are largely irrelevant to this and will only provide unnecessary detail. This review will also address more generally the topic of 3D printing but will refrain from delving into the manufacturing methods, computational systems, and processes required for the additive fabrication of objects. Instead, the discussion will be kept to a general overview of 3D printing with reference towards some of the more common methods where necessary. Finally, this review will mainly focus on museum practice in the United Kingdom, but will at stages reference practice in other countries if relevant. The major purpose is however to provide a holistic framework for multisensory interaction within British museum practice.

2.2 THE HISTORY OF TOUCH IN MUSEUMS

The stance of museums towards touch has changed multiple times over the long history of museology in response to changing attitudes towards visitors. Here, these general changes will be briefly reviewed to set the stage for why multisensory interaction, particularly touch, is a major topic of interest within museology today.

2.2.1 The Exile of the Senses

As discussed in the introduction to this thesis, over the 17th and 18th Centuries museums transitioned over time from private collections for elite study towards the first true museums designed for 'public' consumption, the Louvre of Paris and the Ashmolean of Oxford (Hein, 1998; Abt, 2006). These museums still remained the preserve of the rich and powerful who were privileged enough to be able to explore the depths of history at a personal level in return for patronage or a modest fee (Classen and Howes, 2006; Candlin, 2008; 2010). Well-documented archival history shows numerous cases where these initiated few were able to directly handle museum objects (Classen and Howes, 2006; Candlin, 2008; 2010), as in the words of the wealthy European traveller, Sophie de La Roche:

> *"Nor could I restrain my desire to touch the ashes of an urn on which a female figure was being mourned. I felt it gingerly, with great feeling…"*
>
> Candlin (2010)

This practice rapidly died out in the 18th Century for two hypothesised reasons. First and foremost, curators and wealthy patrons were becoming increasingly concerned over classist views of the newly visiting general public, namely that their 'ignorance' would damage, degrade or sully the priceless artefacts on display (Classen and Howes, 2006; Candlin, 2008; 2010). This hostility is echoed in the words of the former Poet Laureate, Robert Southey:

"The monuments which are within reach of a walking stick are all more or less injured, by that barbarous habit which Englishmen have of seeing by the sense of touch, if I may so express myself."

Candlin (2010)

Secondly, as forwarded by Classen and Howes (2006), the rise of modernist scientific principles of objective observation began to undermine the importance of touch as a sense, with the ocularcentricity becoming the dominant paradigm while the other senses, most significantly touch, came to be viewed as vulgar and unreliable (Candlin, 2006; Pye, 2008a; 2010a; Golding, 2010; Howes and Classen, 2014; Witcomb, 2015). As a result, touch became reviled among museum workers and remained the territory of the expert curator or connoisseur responsible for safeguarding collections (Candlin, 2008; Weisen, 2008; Dudley, 2012b). This paradigm has dominated the history of the public museum, objects being displayed in rigorously controlled glass cabinets designed to present objects for visual enjoyment only, placed tantalisingly out of reach of the visitor and out of their original context for the primary purpose of conservation (Classen and Howes, 2006; MacDonald, 2008; Dudley, 2010b; 2012a; 2015; Di Franco et al. 2015). This is known as the **Glass-Case paradigm**, the overriding mode of museum display that still dominates to this day. A similar concept is expressed by Pursey and Lomas (2018), who articulate the 'White Cube' paradigm of sensory deprivation, where stringent rules and regulations create an aura of neutrality and ocularcentric domination, a concept echoed by Eardley et al. (2018). However, as highlighted in the introduction, there have been calls to overcome this practice and bring touch and other sensory modes back into the museum. This is in order to both better align with the constructivist leanings of modern museums and to better provide for BPS visitors (Pye, 2008a; Dudley, 2010a; 2012a; 2012b; Petrelli et al. 2013; Christidou and Pierroux, 2018; Pursey and Lomas, 2018).

2.2.2 The Multisensory Resurgence

Today, the senses are slowly beginning to return to the museum through a number of different influences, namely through governmental legislation, changing ideas of learning and enjoyment in museums and increased research interest in multisensory interaction in psychology and museum studies.

The first major driver for this modern shift is the introduction of legislation in the UK that mandates that museums are equally accessible to all, regardless of disability. The first of these was the Disability Discrimination Act (DDA, 1995) followed by the Equality Act (2010) that superseded it. This has driven museums to provide more services for visitors across the spectrum, including hearing loops for those with partial deafness, audio guides and increased staff training to assist visitors with extra needs (Small et al. 2012; Mesquita and Carneiro, 2016). However, a primary concern for museums is attending to the needs of BPS visitors. Museum exhibitions are still dominantly visual and typically rely on text and images to impart information to the visitor under the glass-case paradigm. This offers a near-impenetrable wall of accessibility for BPS visitors. Efforts have been made to provide more inclusive, multisensory experiences for BPS visitors and many institutions have adopted strategies for inclusive access, including; tactile images for physical interaction (Neumüller et al. 2014; Cantoni et al. 2016; Gupta et al. 2017), braille labels, audio guides, touch tours (Bieber and Rae, 2013) and handling sessions (Phillips, 2008). However, the number of institutions that provide these services is still rather limited, as demonstrated by Mesquita and Carneiro (2016). In their study, they evaluated a number of museums in prominent European capitals and found that multisensory experiences for BPS visitors were poorly provided for and a lot more could be done for those who live with sight loss, London and Paris-based museums providing more than those in Madrid or Lisbon. A myriad of other authors have also highlighted the lack of effort on the part of museums in general to provide for BPS individuals and the efforts made so far are typically regarded as palliative cures rather than true efforts to transform museum practice (Candlin, 2010; Argyropoulos and Kanari, 2015; Guarini, 2015; Chick, 2017). The situation is improving, but there is mounting pressure on museums to provide more inclusive access to their collections.

Another major driver for the movement towards the multisensory experience is a paradigm shift in museum learning. For much of the history of the museum, educational practices leaned towards didactic, teacher-focused experiences in which visitors would learn from the information provided through the text and images designed by the curator as part of the exhibition. The same way as a teacher plans the lesson for their students in formal education (Hein, 1998, Hooper-Greenhill, 2000a; Talboys, 2011). Knowledge in this **transmission-absorption** model is additively gained from exhibition content and the individual needs of the learner, their prior experiences, motivations and socio-cultural influences are ignored, likening them to an empty jug in need of filling (Hein, 1998, Hooper-Greenhill, 2000a). The issue with this approach was mostly in part due to the method it was carried out in, through arcane displays and overdetailed labelling that were rarely intelligible to a non-specialist audience (Hooper-Greenhill, 2000b; 2007; Talboys, 2011).

This pedagogy dominated museum practice until the latter half of the 20th century where, in the UK, governmental reports began to highlight that this approach was no longer working (Boodle, 1992; Anderson, 1999) in addition to legislation changes that began to include museums within the national curriculum, the Educational Reform Act of 1988 (Hooper-Greenhill, 2007; Reeve and Woollard, 2015). The resultant need to justify their funding forced British museums to adapt or die, prompting a revolution in ideas throughout the 80's and 90's that lead to the rise of **constructivist** education, primarily advocated by Hein (1998) and Hooper-Greenhill (2000a) among others with few difficulties. This paradigm shift towards constructivism, mirroring similar, earlier paradigm shifts in philosophy, psychology, and the social sciences, involved putting the focus of learning on the learner themselves, being more interpretive and personally involved than the didactic approach (Marchietti, 2013; Reeve and Wollard, 2015). Constructivist learning involves interpretative, idiosyncratic learning experiences that are based on the learner's prior knowledge of the subject. It is typically unpredictable and arbitrary, based on intrinsic motivation and is influenced by social interaction, the physical environment and changes over time (Hein, 1998; Falk and Dierking, 2000; Hooper-Greenhill, 2007; Smith, 2015). This naturally is in stark contrast to the didactic model of learning used in formal education noted above (Table 2.1) and these characteristics emphasize the unstructured, personally-driven nature of informal learning. This change in educational ideas naturally lends itself towards multisensory engagement, which is more interpretive and self-driven than visual experiences (*2.3 The Multisensory Turn*). These ideas have long been used in the form of interactive exhibits, or interactives, within museums that allow visitors to actively learn about concepts through exploration and discovery, as best emphasised by the Exploratorium in San Francisco (Falk et al. 2004; Yoon et al. 2014; Witcomb, 2015). Thus, exhibition content has begun to move towards more interpretive perspectives that encourage the visitor to carefully consider exhibition content rather than just take it at face value.

The final drive behind the move toward multisensory experiences within museums is the increased interest in the multisensory nature of perception within psychology and museology. In psychology, this began sometime in the 60's when practitioners began to research the sense of touch, a sense that saw little study prior compared to sight and sound. Ideas that touch was subservient to sight were quickly shattered as the complexities of the sense

Table 2.1: Comparison of Museum Pedagogies

Properties	Transmission-Absorption	Constructivist
Facilitator	Didactic - Teacher-driven	Personal - Learner-Driven
Involvement of Learner	Passive	Active
Epistemology	Realistic – Knowledge exists externally to the learner and is objective	Relativistic – Knowledge exists only in the mind and is subjective
Axiology	Extrinsic – Teacher decides learning goals	Intrinsic – Student decides learning goals
Social Influence	Social aspect of learning is either ignored or suppressed. Learning is atomistic	Learning is influenced by the social context in which it takes place
Role of Prior Knowledge	Prior understanding is disregarded or overwritten	Prior understanding is taken into account and transforms understanding
Structure	Scaffolding of Increasingly Complex Subjects	Arbitrary and Unstructured. Based on Personal Interest.
Change over Time	Understanding remains static until overwritten	Longitudinal change in understanding over time

of touch were elucidated for the first time, a complex and troublesome research area that is still undergoing intense study (Gallace and Spence, 2014; Etzi et al. 2014). This gave way to a focus on studying how touch and sight, among other senses, interact with one other to form our perception of the world around us and how the senses interact neurologically with each other, similarly difficult research topics still at the cutting edge of sensory psychology today (Spence and Gallace, 2008; Gallace and Spence, 2014; Ward, 2014).

Multisensory interpretation began to become of interest within museology at the start of the 21st century, when museum practitioners expressed interest in how touch could be integrated into museum practice, resulting in the publication of a number of influential books that bridged the gaps between psychology, neuroscience and museum practice (Paris, 2002; Pye, 2008a; Chatterjee, 2008; Levent and Pascual-Leone, 2014). This helped to fuel research interest within cultural heritage into how multisensory interaction can be beneficial to museum visitors, an important research trend that still persists today (Ward, 2014; Lacey and Sathian, 2014).

These three driving forces have fuelled interest within the field of multisensory interaction within museums and together have placed the issue of accessibility and multisensory interaction at the forefront of the discipline. Now that the background for the importance of multisensory experiences within cultural heritage has been established, what exactly they entail, their benefits and drawbacks and how they are exploited in museums currently can be explored.

2.3 THE MULTISENSORY TURN

2.3.1 Multisensory Experiences

A multisensory experience, in the words of Levent and Pascual-Leone (2014), can be broadly defined as:

> *"An experience in which senses beyond that of sight are exploited in order to interpret and understand the environment around us, typically involving touch, smell, sound, and taste."*

Within the context of museums, this refers specifically to exhibition strategies that permit visitors to directly interact with museum objects in a way that would normally be impossible under the glass-case paradigm. There is a general understanding among museum professionals that multisensory experiences are extremely beneficial for visitors of all ages and help to make visits more meaningful, enjoyable and promote learning (Dudley, 2012a; Schorch, 2014). It is a method rapidly growing in popularity within museum practice and many multidisciplinary initiatives have been called for to look into the benefits of this approach to exhibition and content design (Paris, 2002; Pye, 2008a; Chatterjee, 2008; Levent and Pascual-Leone, 2014; Schorch, 2014; 2015; Dudley, 2015; Kreps, 2015). However great the general enthusiasm for this approach, there remains a significant barrier in the form of the conservational concerns that have become a central issue in the debate of multisensory access, for valid reason. To permit the handling of an object is to risk its survival and for this very reason, museums typically build a corpus of 'interesting-but-disposable' items in the form of a teaching collection (Willcocks, 2015). These do provide some form of engagement but as shall be discussed later, are generally less appealing than the unique object due to their relative lack of importance.

The overall consensus within museum education is that direct interaction with objects appears to be a memorable undertaking that seems to be enjoyed by museum-goers and facilitates strong meaning-making process that results in lifelong learning (Spence and Gallace, 2008; Duhs, 2010; Baker, 2015; Dudley, 2015; Claisse et al. 2016). There is plenty of loose, anecdotal evidence within the literature that visitors, especially children (Hooper-Greenhill, 1999; Ingle, 1999; Leinhardt and Crowley, 2002; Hooper-Greenhill, 2007; Jant et al. 2014; Schorch, 2014), enjoy interacting with objects in handling sessions and many museum educators report the awe inspired by participants in the presence of genuine museum objects (Bain and Ellenbogen, 2002; Paris and Hapgood, 2002; McGlone, 2008; Phillips, 2008; Stevenson, 2014). Other researchers have proven the potential therapeutic nature of object handling in reminiscence sessions and the benefits they can bring for ailing mental health (Ander et al. 2013; Solway et al. 2015). It is for this reason that objects are viewed as powerful learning tools that connect abstract concepts to physical entities in an active, interrogative manner which meshes well with the constructivist ideas dominant in postmodern museum education as discussed above (Bain and Ellenbogen, 2002; Duhs, 2010). The process by which people learn via direct interaction with objects in this manner is commonly referred to as **Object-based Learning** (Paris and Hapgood, 2002; Borun, 2002; Bain and Ellenbogen, 2002; Duhs, 2010; Chatterjee, 2009; 2010; Pollalis et al. 2018). This is an approach to education that has been championed by researchers at the University College London (UCL) and their work provides an excellent template for this approach, and its potential benefits within both higher education and museum learning (Chatterjee and Hannan, 2015; Pollalis et al. 2018).

Object-based learning (OBL) is an interpretive approach whereby the learner actively interprets the object of interest, investigating it based upon their own intrinsic motivations and allowing them to gain complex understanding derived from the creation of personal meaning (Duhs, 2010; Chatterjee et al. 2015; Hardie, 2015). This method of learning is student-centred and promotes active engagement on the learner's part with the object, leading to the creation of strong memories, narratives and inspirational moments in which these objects play a key part, and thus lends itself towards the general constructivist nature of current museum practice (Paris and Hapgood, 2002; Chatterjee, 2008; 2010; Duhs, 2010; Ward, 2014). OBL borrows heavily from Experiential Learning (Kolb, 2015). Kolb developed his theory of learning by drawing from the works of eminent educational psychologists of the time, including the works of Jean Piaget, John Dewey, and Kurt Lewin among other famous advocates of constructivism. This learning model envisages the learning process as a cyclical interaction between concrete experience and interpretation (Duhs, 2010; Kolb, 2015) (Fig. 2.1). As applied to OBL, the object is first investigated in order to generate a concrete experience from the physical evidence, such as its weight, temperature or texture (Stage 1). These experiences are then observed, dissected and reflected on at a personal level by the individual (Stage 2) before being turned into abstract conceptual ideas about the object, such as authenticity, provenance or materiality (Stage 3). Finally, this abstract understanding is reapplied to the object through active experimentation in order confirm or disconfirm these putative ideas (Stage 4), whereupon the cycle begins anew as more concrete experience to reflect upon and conceptualize is accrued.

Kolb's Theory of Experiential Learning has garnered support from educational professionals, particularly in formal education, but support in informal learning is growing due to its alignment with current ideas of museum learning (Tam, 2015). Most studies into the effectiveness of OBL are situated within higher education however. For instance, Sharp et al. (2015) carried out an evaluation of OBL in teaching modules in higher education, finding that students that engaged with objects through OBL generally showed higher graded scores, though increases were higher in those who had no prior experience with object handling. Hardie (2015) provides another such evaluation in higher education, on a student activity named ‘A Matter of Taste’, providing positive responses from open-ended questions from questionnaires filled out by students, though advocated that some students did not prefer this particular approach, a finding supported by other authors (Meecham, 2015). Others provide more anecdotal or less systematic evidence for the benefits of OBL in education, Tam (2015) providing a few case studies with undergraduate and postgraduate students at a number of institutions, concluding that while beneficial, more research needs to be undertaken into the benefits of OBL. Likewise, Tiballi (2015) provides an example of its use in higher education at the University of Pennsylvania Museum of Archaeology and Anthropology and the positive impacts on student learning but again lacks thorough evaluation. Kador et al. (2018) also discuss four examples of OBL in higher education classes, from taxonomy to arts, and while these are basic discussions of the benefits, certainly advocate the OBL approach in higher education. However, few researchers have applied this particular learning model in informal museum settings. This does not mean that there is no evidence for the positive impact of multisensory interaction in informal settings. On the contrary, many studies exist of the potential of multisensory museum exhibits as is further discussed below.

Further reinforcing the idea of the benefits of multisensory interaction is that of current psychological research, which supports the idea that the senses are integrated and not processed individually. These insights have been predominantly derived from a large corpus of research that has been dedicated to the study of the senses, particularly touch. These have found that each sense has different perceptual proficiencies and can provide complementary information that, when fully integrated, creates a synergistic multisensory interpretation of the object (Lederman and Klatzky, 2004; Gallace and Spence, 2014). Sight yields properties associated with light, such as glossiness and colour, but may yield inaccurate interpretations of texture, a common misconception being that a snake’s skin is cold and slimy while in fact it is warm, smooth and dry. Likewise, touch may be able to pick out the individual scales of the snake’s skin but how they interlock and their wider structure will be difficult to interpret, information derived easily from sight. Sound can also provide essential properties that may be missed from visual and tactile exploration, a simple tap revealing much about the internal structure of an object. Importantly, the integration of the senses leads to a sensory redundancy as the stream of overlapping information from each sense supports the interpretation of the object (Lederman and Klatzky, 2004; Millar; 2006; Gallace and Spence, 2014). Thus, multisensory interaction provides more information about an object, which would be of significant benefit to the museum visitor beyond simply utilising sight, which can in many cases be easily fooled as in the snakeskin example above.

These ideas are not just present in psychological theory, however, and experiments in visualising brain activity *in vivo* show that the integrated, multisensory nature of interaction is present within the brain (Macaluso and Driver, 2005). Positron Emission Tomography (PET) and Transcranial Magnetic Stimulation (TMS) studies show that tactile interaction with objects often results in recruitment of the visual cortex, and other parts of the brain, such as the Lateral Occipital Complex (LOC) being responsible for shape recognition in both sight and touch, being capable of even responding to sound with some training (Grill-Spector et al. 2001; Sathian, 2005; Lacey and Sathian, 2014; Voss et al. 2016). The Primary Somatosensory Cortex (S1) is another region that responds to multisensory input, a region primarily responsible for processing tactile information (Lacey and Sathian, 2014) and the hippocampus, the part of the brain in the limbic system associated with memory generation and recall, responds strongly to multisensory stimuli, resulting in the generation and recall of strong episodic memories (Ward, 2014). Thus, psychological research certainly advocates that the brain is geared towards integrating multiple senses, rather than simply interpreting the world through sight below as most museums would deem suitable (Christidou and Pierroux, 2018).

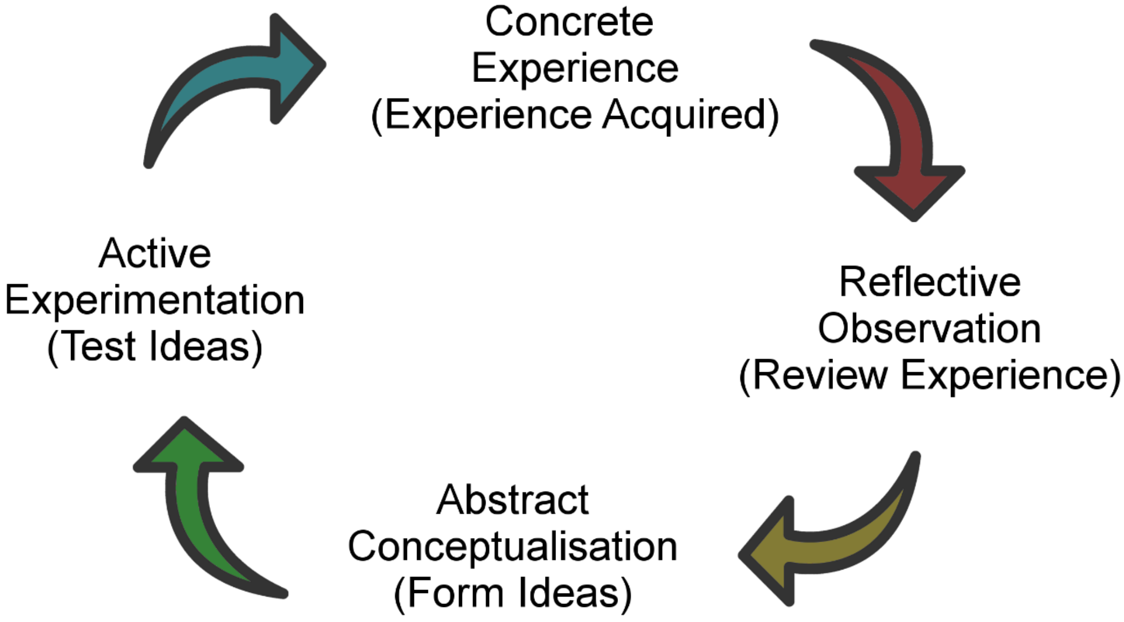


Fig. 2.1: Kolb's (2015) Experiential Learning Cycle: Envisaged by Kolb (2015) as a way of envisaging the process of learning from experience, the Experiential Learning Cycle is a core part of Object-Based Learning (OBL) theory. From a concrete experience, an individual reflects on this experience, conceptualises new ideas based on those reflections before testing them actively, feeding back into the iterative loop.

Overall, theory shows that multisensory experiences could indeed beneficial for museum audiences but now the evidence for such advantages within a museum a context must be considered. There are a number of such studies within the literature, and it is these that must now be addressed in order to ascertain the benefits of multisensory interaction within a museum environment.

2.3.2 Multisensory Experiences in the Exhibition Hall

Multisensory experiences are becoming increasingly more common within museums and outreach projects as educators have come to realise their educational impact and their ability to generate significant, meaningful experiences (Pye, 2008b). The use of museum objects in this manner has seen a wide diversity of applications, ranging from in-house exhibitions to museum loan-boxes (Davidson et al. 1999; Samuels, 2008). The effectiveness of these approaches is generally positive although published studies on them are generally few and far between.

There are a wide variety of examples of multisensory museum experiences that can be found within the literature and currently on display across the UK and worldwide. A cursory exploration of many museums will reveal some form of multisensory engagement with exhibition content of some description, many of which remain unpublicised beyond the museum's website or a visit in-person. The author himself has noticed many such examples of which no record exists in the wider literature, such as the *Sensing Evolution* touch tables at the Oxford University Museum of Natural History (OUMNH) (Fig. 2.2ab), the Staffordshire Hoard Gallery at the Birmingham Museum and Art Gallery (Fig. 2.2c), Gallery 08 in the Coventry Transport Museum (Fig. 2.2d), the Tokyo National Museum of Nature and Science (Fig. 2.2e), the Natural History Museum in London (Fig. 2.2f), the Confucius Temple in Taipei (Fig. 2.2g) and the Gutenberg Museum in Mainz (Fig. 2.2h), among many more undocumented examples too numerous to detail here.

Others delve more deeply into the subject of the impact of these experiences on museum visits. These are summarised in Table 2.2. Among these examples are multisensory experiences designed for general audiences, those designed for BPS audiences and also those that incorporate smart objects, replicas, and models that trigger digital content based in response to touch. The extent of the examination and inspection of these multisensory experiences varies immensely, but a number of overriding trends may be noted. First and foremost is the relative scarcity of studies exploring the effectiveness of multisensory interaction, many examples outlining a particular approach but lacking a formal evaluation (Claisse et al. 2016; Nofal et al. 2018). This is further compounded by the fact that the majority of these papers examine temporary installations rather than permanent ones, so the insights they yield are rarely useful in the long term. Most studies are also evaluative, simply confirming the success of the approach rather than producing generalizable insights into exhibition design. While the evidence provided in each paper is generally positive with audiences advocating the benefits of multisensory interaction, many suffer from methodological issues such as small and biased samples. Many simply advocate in simple terms that the exhibition or initiative was good, rarely looking into how they influenced visitor engagement or learning, using fairly simplistic measures of effectiveness. While mixed-methods research is becoming more popular in museum evaluation, many studies rely purely on quantitative data that lacks meaningful information on what exactly has been learnt by visitors. Others instead are over-reliant on qualitative data from a small number of research participants that, while expressing good evidence of engagement, is extremely anecdotal and does little to describe the experiences of a whole sample of visitors. These shortcomings are prevalent in the wider museum evaluation literature, as shall be discussed later in the literature review.

Overall then, whilst there is a wide variety of generally positive evidence for the effectiveness of multisensory experiences, the research field is arguably still young and so research is scant and theories on the matter are as of yet underdeveloped. Another key issue with these multisensory experiences is that of the objects utilised. While a number of the case studies in Table 2.2 use genuine artefacts in their applications, these are generally derived from teaching collections to minimise the risk to the true collections (Noble and Chatterjee, 2008; Christidou and Pierroux, 2018). Oftentimes the objects used are designed specifically for an exhibit and while interesting in their own right, lack the sense of awe generated by objects deeply steeped in history (Candlin, 2010). This brings us to the age-old curatorial conundrum; should ancient artefacts be sequestered away within the bowels of an institution and preserved for future generations or used to facilitate learning and enjoyment for the people of today (Cassim, 2008)? Invaluable objects are strictly conserved within museum collections or in regulated glass cases, in which they may be observed by enterprising visitors, but to directly interact with these objects without the expert hand of the curator risks their destruction (Pletincx, 2007; Candlin, 2010). There is an overriding need prevalent within museology to bring the multisensory experience into the forefront of exhibitions but this very aim seems to undermine the preservation of the rare and fragile artefacts that make up the majority of museum collections.

2.3.3 A Solution: 3D Printing Technologies

3D printing, the process by which an object is fabricated from a 3D mesh file, is a potential tool that could overcome the challenges associated with object sensitivity and conservational concerns. By simply printing a replica of an object to act as a handling surrogate, the original could be preserved while the replica, a disposable object that can be easily replaced, is used for

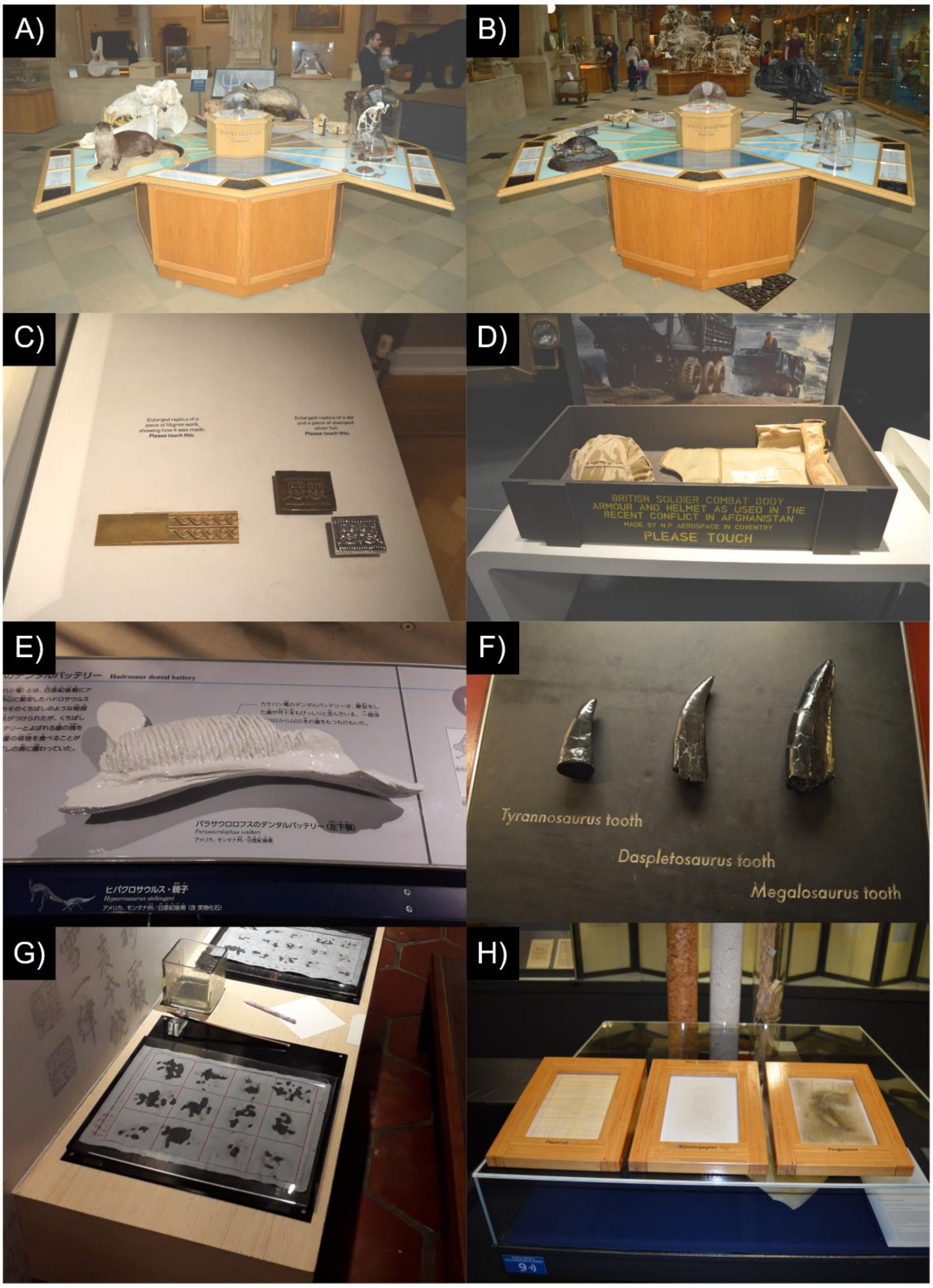


Fig. 2.2: Other Undocumented Multisensory Experiences: A) Sensing Evolution (Mammals) table at the OUMNH; B) Sensing Evolution (Reptiles) table at the OUMNH; C) Models of Objects from the Staffordshire hoard at the Birmingham Museum and Art Gallery; D) One of many ‘touch boxes’ in Gallery 08 at the Coventry Transport Museum; E) Model demonstrating Hadrosaur tooth batteries and replacement at the Tokyo Natural History Museum of Nature and Science; F) Theropod tooth models at the Natural History Museum of London in the Dinosaur gallery; G) Calligraphy practice at the Confucius Temple in Taipei city; H) Tangible printing materials at the Gutenberg Museum in Mainz, German.

Table 2.2: Research into Multisensory Experiences in Museology

Case Study	Description	Major Findings	Methods	Limitations	Reference
Renovation of Boettcher Hall (Denver Museum of Natural History)	Pre and Post-renovation Evaluation of Natural History Gallery adding multisensory components	Exhibit attractiveness, engagement and time spent increased; Multisensory features key	*Quantitative*: Observation and Questionnaires	Solely Quantitative; Methodological issues	Harvey et al. (1998)
New England Lifezones Hall (Boston Museum of Science)	Pre and Post-renovation Evaluation of Natural History Gallery adding multisensory components	Visitor numbers increased; Evidence of increased learning; Change in visitor demographics	*Quantitative*: Questionnaires and Interviews	Lack of Qualitative Insights	Davidson et al. (1999)
Raised Awareness (Tate Modern)	Temporary exhibition ran for BPS individuals, with artworks designed for interaction with touch	None	None	No Real Analysis; Poor Design of Objects	Candlin (2006; 2010)
Sense and Sensuality (Royal College of Art)	Temporary exhibition ran for BPS individuals, with artworks designed for interaction with touch	General Positivity	*Qualitative*: Comments from Involved Parties	No Real Analysis	Khayami (2008)
Tactual Explorations (Northlight Gallery)	Temporary exhibition on a number of objects presented in a multisensory fashion, including haptic technologies	Positive responses to tactile artworks; constructive criticism	*Quantitative:* Observations and Questionnaires	Small sample; Very light evaluation	Onol (2008)
Coin Handling Workshops (British	Coin handling sessions for sighted and BPS visitors	None	None	No Real Analysis	Phillips (2008)

Case Study	Description	Major Findings	Methods	Limitations	Reference
Touch Me (Victoria & Albert Museum)	Exhibition on how touch is used by designers to create more affective products	None	None	No Real Analysis	Candlin (2010)
Sensing Sculpture (Wolverhampton Art Gallery)	Temporary exhibition ran for BPS individuals, using sculpture to allow interaction with touch	None	None	No Real Analysis	Candlin (2010)
African Worlds (Horniman Museum)	Exhibition incorporating African cultural objects and their engagement by school groups	General Positivity	None	No Real Analysis	Golding (2010)
Australian Journeys (National Museum of Australia)	Sensory stations placed alongside objects to provide engagement of various types	None	None	No Real Analysis	Wehner and Sear (2010)
Kelvingrove Art Gallery and Museum	Refurbishment of museums results in the incorporation of manual and electronic interactives	None	None	No Real Analysis	Morgan (2011)
'Hands On Desks' (British Museum)	Evaluation of in-gallery multisensory desks in the British Museum	Design considerations; Visitors liked handling objects; Large proportion thought it improved visit quality	*Mixed Method*: Observations, Questionnaires, and Focus Groups	Solely Evaluative; Ungeneralizable	Monti and Keene (2013)

Case Study	Description	Major Findings	Methods	Limitations	Reference
Touch and the Enjoyment of Sculpture (Walters Art Museum)	Interaction with bronze replica sculptures that fit in the palm of the hand	None	None	No Real Analysis	Levent and McRainey (2014)
Louvre Touch Gallery (the Louvre)	A touch gallery that has gone on world-wide tour at times	None	None	No Real Analysis	Levent and McRainey (2014)
Museum of New Zealand Te Papa Tongarewa Exhibits	A number of multisensory exhibits of indigenous New Zealand culture and society	Subjective Positive Comments	*Qualitative*: Interviews	Solely Qualitative; Ungeneralizable	Schorch (2014)
Hague and the Atlantic Wall (Museon the Hague)	An exhibit incorporating smart objects which visitor could use to trigger different perspective - based content	Usage statistics; Design Concerns; Major Findings Unpublished	*Mixed-Methods*: Observations, Interviews and Questionnaires	Solely Evaluative; Ungeneralizable	Damala et al. (2016); Marshall et al. (2016)
Feint: illusion in Ancient Greek Art (Allard Pierson Museum)	An exhibit incorporating smart objects which visitors could interact with, triggering changes in wall projections	Usage behaviours; Major Findings Unpublished	*Mixed Methods*: Observations, Interviews, Questionnaires, and PMM's	Solely Evaluative; Ungeneralizable	Damala et al. (2016)
National Tile Museum (Lisbon)	Multisensory guide and tile replicas made for use by BPS visitors in the museum	Audio guides rated highly; General Positive Comments; Increase in Disabled visitor Influx	*Qualitative*: Questionnaire and Comments	Small, undetailed analysis	Eardley et al. (2016)

Case Study	Description	Major Findings	Methods	Limitations	Reference
Community Museum of Batalha (Portugal)	Development of multisensory exhibits for BPS visitors to the museum	Design considerations	None	No Real Analysis	Eardley et al. (2016)
Rebuilding the Tong-an Ships (National Palace Museum)	Temporary exhibition incorporating multisensory elements and AR for Taiwanese Nautical History	High satisfaction rates; topic interest increase from pre to post-visit	*Quantitative*: Questionnaires	Lack of Qualitative Insights; Solely Evaluative	Kuo et al. (2016)
Bishop's House (Sheffield)	Use of smart objects in a Tudor house, incorporating characters who interact with the visitor	Positive qualitative comments; Average visit time increased	*Quantitative*: Observation and Questionnaires	Solely Evaluative; Ungeneralizable	Claisse et al. (2016)
Tate Sensorium (Tate Britain)	Multisensory temporary exhibit incorporating sound, touch, smell and taste to explore paintings	Increased artistic arousal; Multisensory aspects added depth	*Mixed-Methods*: Interviews and Questionnaires	'Raid-roaded' exhibition; Lacks true tactile elements	Vi et al. (2017)
Eternity's Form (National Museum of Art, Architecture and Design)	Abstract modernist sculptures that were able to be touched in the gallery	No statistical corroboration; Increased retention time in touch condition; participants thought touch aided understanding	*Mixed-Methods*: Observations, Interviews and Questionnaires	Small sample size; Ungeneralizable	Christidou and Pierroux (2018)
Turathiaat (Museum of Modern Art)	An evaluation of a multisensory toolkit called *Turithiaat*, investigating its effectiveness in engaging families in Art Museums	Families found touch toolkit more enjoyable than only visual; Longer engagement time with touch toolkit	*Mixed-Methods*: Observation and Questionnaires	Lack of Observer Control; Observer biases	Eardley et al. (2018)

object handling. While seemingly a novel concept, arguably museums have already been practicing this in the form of plaster replicas of their rarest objects. These models don't suffer from some of the optical and material challenges associated with 3D printed replicas, but bring themselves their own suite of problems.

Traditional moulding and casting involves moulding a replica from the surface of the original object, typically in silicone rubber, and casting a replica in a semi-liquid material that sets, most commonly plaster or resins. The process involves significant post-processing, involving extensive sanding, painting and treatment painstakingly carried out to accurately represent the colour, weight and surface texture of the object (Bohn, 1999; Müller, 2002; Bearman, 2011). The end product can be near indistinguishable from the original object but the process can take months to complete (Staatliche Museen zu Berlin, 2018). This approach is however marred by a number of difficulties that make the process risky and time-consuming, namely the need for extensive labour to create a verisimilar cast, including painting, finishing and the application of internal weights to replicate accurate density properties. This mandates a skilled conservator with sufficient expertise to provide many labour-intensive hours and their associated costs, a fact that may make museums reluctant to use such replicas for the purpose of handling (Lindsay et al. 1996). The other major issue is that of the moulding and casting process itself, a risky process that can result in irreversible damage to the original specimen. For instance, the act of moulding can break objects if care is not taken to remove the mould safely and silicone rubber can leach into the object if due care is not given (Goodwin and Chaney, 1995; Monge and Mann, 2004; Le Cabec and Toussaint, 2017). Finally, there is a need to employ conservators who are experienced in working with the particular material and the kind of object in question, further driving up the cost of creating casted replicas. These reasons make the use of casts somewhat unviable for tangible replicas, particularly if repeated handling will result in frequent replacement.

3D printing, by comparison, is quicker and easier, the manufacturing process being largely hands-free once initiated. Printing costs do however vary with the machine and materials used (Scopigno et al. 2014; 2017; Balletti et al. 2017). Replication involves scanning the surface geometry of an object also utilises non-invasive digitization methods common in cultural heritage practice, including photogrammetry (Arias et al. 2005), laser scanning (Quagliarini et al. 2017) and CT scanning (Tembe and Siddiqi, 2014). As no moulding is required, the risk of damage to the object is minimised. 3D printing can also produce finished parts that can be extracted from the printing bed and be ready for use, although this does depend on the printing method used, how the material is supported during the printing process and the need for secondary curing or post-processing, which varies widely depending on method. Fused Filament Fabrication (FFF), which involves the melting and deposition of solid filaments, typically relies on hard support structures affixed to the part's surface, which must be trimmed and smoothed for a presentable finish. Some resin printers, typically Stereolithography (SLA) machines, require similar treatment while others instead utilise soluble supports that may simply be immersed in the manufacturer recommended solution overnight. A major drawback of 3D printing, however, is that such replicas are arguably less verisimilar to the original object. The additive nature of the process results in an approximation of the surface, with typically prominent layering, the removal of which requires considerable sanding (Olson et al. 2014; Scopigno et al. 2014). Additionally, photorealistic 3D printing is limited in terms of colour resolution, with few machines being capable and the results generally being of insufficient quality, as is further discussed later (*8.2.2.1 Verisimilitude*). This is likely to be overcome by improvements in colour 3D printing within the next few years (Scopigno et al, 2014; 2017; Gibson et al. 2015; Chen et al. 2016).

3D printing then represents, despite the initial costs of machine investment, a cheaper, quicker way of creating replicas that circumvents the risks of moulding precious or fragile museum objects. This is at the expense of accuracy, in part due to its layer-based approximation of the geometry of the object and similar levels of post-processing may be required to get a model acceptable for handling applications. Their relative disposability compared to casted replicas, which require months of labour-intensive care and attention, is traded off against a lack of verisimilarity inherent within a 3D printed replica and arguably a loss of 'perceived authenticity' that comes with a carefully crafted replica. There is no reason why a 3D print cannot be afforded the same level of care however. As for which is better, this is impossible at this stage to determine without further exploration, a theme that, to the author's knowledge, has not been adequately explored in the wider literature.

Thus, 3D printing presents a way to fabricate an object cheaply and quickly, at the expense of the 'authenticity' provided by a master-crafted replica. 3D printing as a technology is also rapidly gaining popularity as a method of fabricating museum objects for these very reasons for many varied applications. Next, 3D printing, its background, and exploitation within cultural heritage are explored to better understand how museums are making use of this cutting-edge technology to enhance the experiences of museum visitors through multisensory interaction.

2.4 3D PRINTING: AN OVERVIEW

2.4.1 The Basics of 3D Printing

3D printing is the more colloquial name for the process of Additive Manufacturing (AM), as it is more formally referred to in engineering (Gibson et al. 2015). It is the blanket term that refers to a number of disparate methods that rely on the concept of additive fabrication, the addition of layers of material on top of one another where each layer represents a cross-section through the original computer-aided design (CAD) data. The layer thickness remains constant (T), which means that the final product is an approximation of the original data, which has greater fidelity the finer the layer thickness is (Gibson et al. 2015). While all 3D printers share this basic concept, the fabrication process varies in terms of the materials used, the chemical and physical processes used to bond layers together and the amount of post-processing needed to create an acceptable part (Gibson et al. 2015; Chua and Leong, 2017).

3D printing is a technology that was first developed in 1984 by Chuck Hull, who patented the procedure known as stereolithography (SLA) two years later in 1986 (Bose et al. 2013; Chua and Leong, 2017). Hull went on to found the first company dedicated to 3D printing, 3D Systems, who still remain a dominant market leader today (Chua and Leong, 2017). While revolutionary in its capacity to create prototypes of complicated objects on short timescales, the technology remained relatively specialist throughout the 90's and 00's as new methods were developed and refined (Chua and Leong, 2017). In the past decade, 3D printing has seen a massive rise in popularity both in the media and in many modern industries for a number of reasons, as discussed by Gibson et al. (2015). The unprecedentedly rapid development of computing has reduced the time it takes to load and slice CAD data and assisted in maintaining build accuracy during fabrication. This has been accompanied by the development of more efficient CAD software that have provided improved usability, speed, accuracy and realistic rendering, speeding up the process of CAD file creation and quality. The

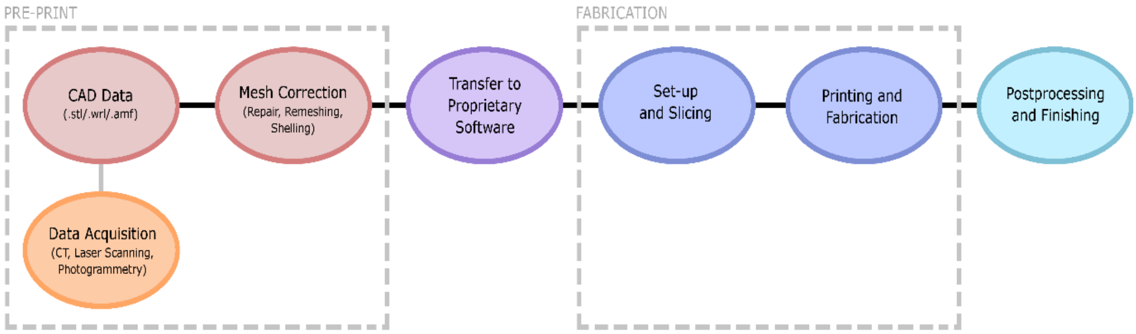


Fig. 2.3: A Workflow of the 3D Printing Process: The process of 3D printing follows this workflow, from the initial capture of the CAD data to a finished, post-processed part. Grey lines indicate optional parts of the process.

development of other key technologies such as lasers, inkjet printing, specialist printing materials and Programmable Logic Controllers (PLC) has also resulted in more accurate, robust parts and greater efficiency. In addition, lapsing patents, particularly that for Fused Filament Fabrication (FFF), have encouraged the rapid development of low-cost printing solutions that are available for the average consumer (Hofman, 2014; Chua and Leong, 2017). The net result is that 3D printing now pervades a huge number of disparate industries, including medical bioprinting (Bose et al. 2013; Murphy and Atala, 2014), medical education (Mahmoud and Bennett, 2015), the food industry (Liu et al. 2017), the aerospace industry (Chua and Leong, 2017), archaeology (Du Plessis et al. 2015), palaeontology (Lautenschlager and Rücklin,

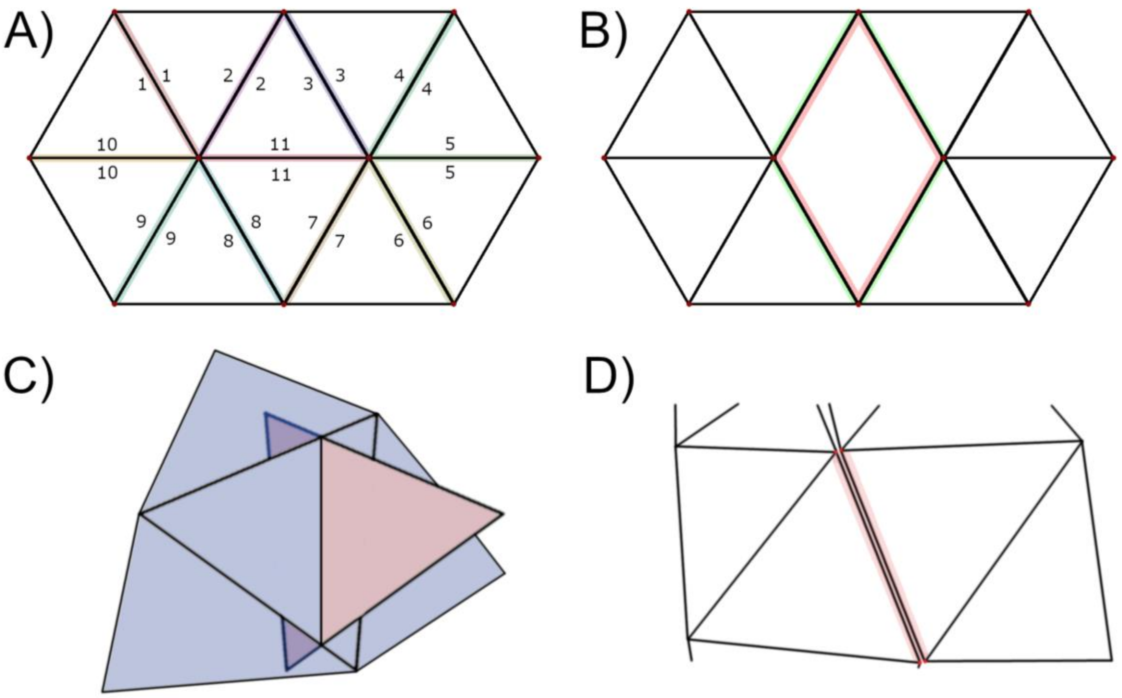


Fig. 2.4: Pre-requisites in Mesh Preparation: A) Demonstration of manifold geometry. Each triangle or facet shares each of its edges (coloured) with only one other facet. B) Holes (Red) disrupt slicing software and result in volume miscalculation. C) Overlapping triangles are degenerate facets that interrupt the manifold geometry and must be resolved. D) Collinear edge (red) are separate edges occupying the same space but connect two different pairs of vertices. They interrupt manifold geometry and must be deleted.

2014), product prototyping (Mahindru and Mahendru, 2013; Chua and Leong, 2017), arts and architecture (Chua and Leong, 2017), the military (Chua and Leong, 2017), the automotive industry (Chua and Leong, 2017) and cultural heritage (Baletti et al. 2017; Scopigno et al. 2017), the last of which is further discussed below (*See 2.3.5 Current Usage of 3D Printing in Cultural Heritage*). As a result, 3D printing technology stands in a unique position to revolutionise many industries within the near future.

3D printing as a process requires a number of steps in order to transition from digitised CAD data to a fully finished physical model, summarised in Fig. 2.3. This workflow starts with some form of CAD data, either created in a CAD software suite such as AutoCAD (Autodesk) or captured from real objects using one from a number of methods, including laser scanning (Santagati et al. 2013a), photogrammetry (Santagati et al. 2013b) or computed tomography (Laycock et al. 2015). These CAD files are meshes, an interlocking weave of triangles or facets that represent the external surface of the object it represents, the inside being hollow (Gibson et al. 2015; Chua and Leong, 2017). These meshes must adhere to a number of criteria in order to be viable for 3D printing and the phrase 'garbage in, garbage out' is often used to emphasize that a poor CAD model typically results in a failed print. These are corrected in a phase of pre-

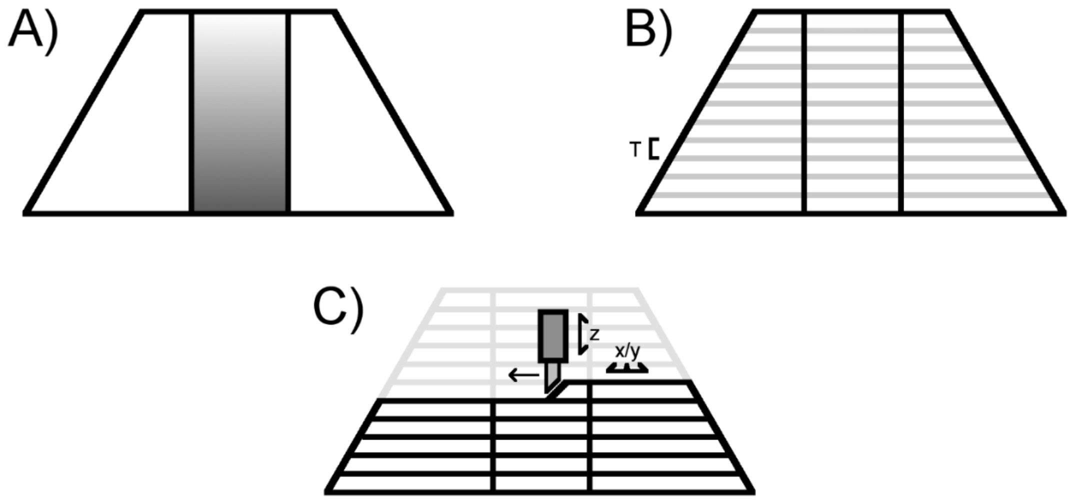


Fig. 2.5: Basics of Additive Manufacturing: A) The CAD file represents the manifold, closed surface of the object, which is passed through the 3D printer's proprietary software. B) This CAD file is separated into a number of layers composed of vector-based instructions that are passed to the computer system on board the 3D printer for construction. Normally, a layer thickness is defined (T) that has an influence on the strength, quality, detail and surface texture of the built part. C) The printer carries out the instruction passed to it, building up the object layer by layer until it is complete.

processing before the object can be printed. First and foremost, the mesh must be manifold, a continuous, watertight surface where each facet shares each edge with only one neighbour (Fig. 2.4a) and not contain any holes (Fig. 2.4b). Failure to achieve this requirement will render a model unprintable (Chua and Leong, 2017). Degenerate facets are also an issue, caused by triangles with overlapping facets (Fig. 2.4c) as well as distinct vertices sharing collinear edges (Fig. 2.4d), both of which need to be corrected before the object can be printed (Chua and Leong, 2017). If this condition is not met, the mesh is deemed non-manifold and printing will be impossible (Chua and Leong, 2017). Fortunately, these mesh errors can be corrected using automated mesh repair tools that come with most mesh editing software and with some proprietary printing software, such as Geomagic (3D Systems) or Magics (Materialise). Finally, the mesh needs to be exported in a viable format that the printer can read. The industry standard file format is the .stl (STereoLithography) file format, although for colour the VRML2 (.wrl) is often used (Gibson et al. 2015; Chua and Leong, 2017). Most mesh editing software have the ability to read and export files in all of these formats, meaning that conversion between file formats is a simple process. Once the mesh file is ready, it is transferred to the 3D printing system to be fabricated.

This process is straightforward (Fig. 2.5). The mesh is loaded into the proprietary software of the printer and error detection algorithms check if the mesh is manifold. If false, then more corrections need to be implemented whereas if true, the software proceeds to the next

Table 2.3: A Summary of Common 3D Printing Methods

Method	Mode of Operation	Materials Used	Colour	Advantages	Issues
Stereolithography (SLA)	Photopolymerisation of resin using UV light beam or mask	Resins	No	Smooth Finish; Fine Layer Resolution	Fragile; Expensive
Selective Laser Sintering (SLS)	Sintering of powder using focused laser beam	Powdered metals, ceramics and plastics	No	Durability; Versatile	Expensive Equipment and Materials; Uneven Finish; Requires Consolidation
3D Printing or ColourJet Printing (3DP/CJP)	Binding of powers using an inkjet printer head with ‘glue’ binder	Powdered metals, ceramics, plastics, and gypsum	Yes (24-bit CMYK)	Rapid; Full-Colour Printing in some Materials	Fragile; Uneven Finish; Post-processing Required; Weak
Fused Filament Fabrication (FFF)	Extrusion of partially-molten or rapidly hardening solids through print head	Plastics, Cement, Food, Ceramics, Biomaterial, Metals	Yes (24-bit CMYK)	Affordable; Versatile; Durable Parts; Colour Printing on some Machines	Coarse Layer Resolution; Strange Material Properties; Unreliable
Laminated Object Manufacturing (LOM)	Cutting of sheets of paper using focused laser beam or knife	Sheet paper, metals, plastic and ceramics	No	Woody Finish; Cheap Materials	Post-processing Required; Fragile; Deals poorly with Thin Walls
Material Jetting/Projet (MJ)	Deposition and rapid UV curing of photopolymeric resins using a multi-channel inkjet print head	Resins	Yes (24-bit CMYK)	Smooth Finish; Fine Layer Resolution; Can Synthesize materials	Expensive Equipment and Material; Post-processing required

Key References: Gibson et al. (2015); Chua and Leong (2017) phase. The part must be sliced in order to generate instructions for the 3D printer to replicate the object. This is done for a specified layer thickness (T), either a default value that the printer is limited to or specified by the user (Lipson and Kurman, 2013; Chua and Leong, 2017). This process involves dividing the 3D geometry into 2D layers, which are then each converted into 1D vector scan lines which are used to guide the placement of material on the build platform (Chua and Leong, 2017). Some methods also require that support material is added to the model, particularly true of FFF methods so that the model does not collapse part-way through the printing process. This process is typically automated. Once this is done, the printer is ready to fabricate the object. The way this is implemented depends strongly on the type of machine used, which may involve the use of solids or liquids, heat, light or chemical reactions in order to deposit and bond the individual layers together to form the final object. The most common methods are summarised in Table 2.3 and also depicted in Fig. 2.6.

Once printed, many printing methods, typically those involving powders, need some degree of post-processing to give a more desirable or robust finish (Chua and Leong, 2017). This can involve abrasive finishing, consolidation with resins, post-curing, thermal treatment or coating to help increase strength. Many parts may need sanding or polishing in order to remove some of the surface roughness that results from the layer-by-layer construction. Each of these processes are typically labour-intensive and substantially increase the time it takes to go from CAD data to finished part (Chua and Leong, 2017).

With the basic foundations of the 3D printing process laid out, it is now possible to examine how the technology has begun to revolutionise museum practice. The next section will explore this topic and evaluate how 3D printing technology is currently utilised for general museum practice but more particularly, for enhancing museum visitor engagement.

2.4.2 Current Usage of 3D Printing in Cultural Heritage

The exploitation of 3D printing is a relatively recent phenomenon in cultural heritage. There are a number of examples of its use going as far back as the late 90’s, but these are rare by comparison to today (Olson et al. 2014; Hancock, 2015). There has been a resurgence within the past few years in association with the boom in popularity of 3D printing technology, most likely due to the affordability of cheaper equipment within the price range of museum institutions. Today it is being utilised heavily in museums for a variety of different purposes, which will now be explored.

2.4.2.1 General Museum Use

3D printing has become a useful technique in cultural heritage research, as is evidenced by a large number of studies on the subject. Many authors have utilised technology for creating replicas of artefacts for study in publications. Olson et al. (2014) demonstrate this idea using

Palaeolithic hand axes while McKnight et al. (2015) use 3D printing to assist identification of anomalous bones in a mummified animal bundle, finding that human bones were present with the sample as well. The technology is quite commonly used in this regard as is evidenced by a number of articles utilising 3D printing technology, including replicating cuneiform tablets (Ch'ng et al. 2013), Roman coins (Miles et al. 2015) and other various historical objects, both man-made and natural (Schwandt and Weinhold, 2014; Alemanno et al. 2014). The technology has also seen use in conservation and restoration. In conservation it has been used in artefact documentation of a bust mould, that was later adapted into a temporary exhibition at the London Science Museum (Hess and Robson, 2013). Neely and Langer (2013) also apply the technology for building conservation at the Georgia O'Keeffe Museum, a printing replica of the home to be compared against shifts in the building state over time. For the purposes of restoration there are many more examples, Laycock et al. (2012; 2015) using 3D printing to reconstruct 15th century Cantonese chess pieces from the original damaged artefacts, Tucci et al. (2017) using the technology to reconstruct a sculpture missing its face into a reconstructed whole and by Stanco et al. (2017) to reassemble an Archaic Greek statue from Ancient Sicily, among many other examples (Antlej et al. 2011; Neely and Langer, 2013). 3D printing has also seen some use in repatriation, the return of museum items back to their original communities. Hollinger et al. (2013) and Isaac (2015) for example returned a Tlingit Killer Whale hat back to the Tlingit community from the Smithsonian, replicating the object using 3D printing for museum use prior to full repatriation. The technology has also become popular in museum and library communities in the form of hackathons and makespaces, events that encourage members of the public to come along and scan, design and print various objects and specimens (Osborn, 2014; Hancock, 2015).

Other applications of 3D printing technology include the creation of bespoke packaging for artefacts for use in transportation (Sá et al. 2012), planning exhibition layouts (Celani et al. 2008; Celani and Piccoli, 2010), for souvenirs and shops within museums (Scopigno et al. 2014; Anastasiadou and Vettese, 2019), digital databases from which visitors can download and print various artefacts at home (Osborn, 2014; Mitsopolou et al. 2015; Smithsonian, 2018a), tactile floor plans for BPS visitors (Reichinger et al. 2012; Urbas et al. 2016) and within many exhibitions across the globe that either use 3D printed objects or the process of 3D printing as content for visitors to enjoy (Olson et al. 2014; Schwandt and Weinhold, 2014; Cantoni et al. 2016).

2.4.2.2 Exhibition Use

3D printing, with its increased presence within modern media, has become rapidly used in museum exhibitions and workshop events in line with its general use within museums. Many of these applications forego the benefits of tangible interaction with such replicas, instead choosing to display these replicas in glass cases as is typical of museum practice, as highlighted

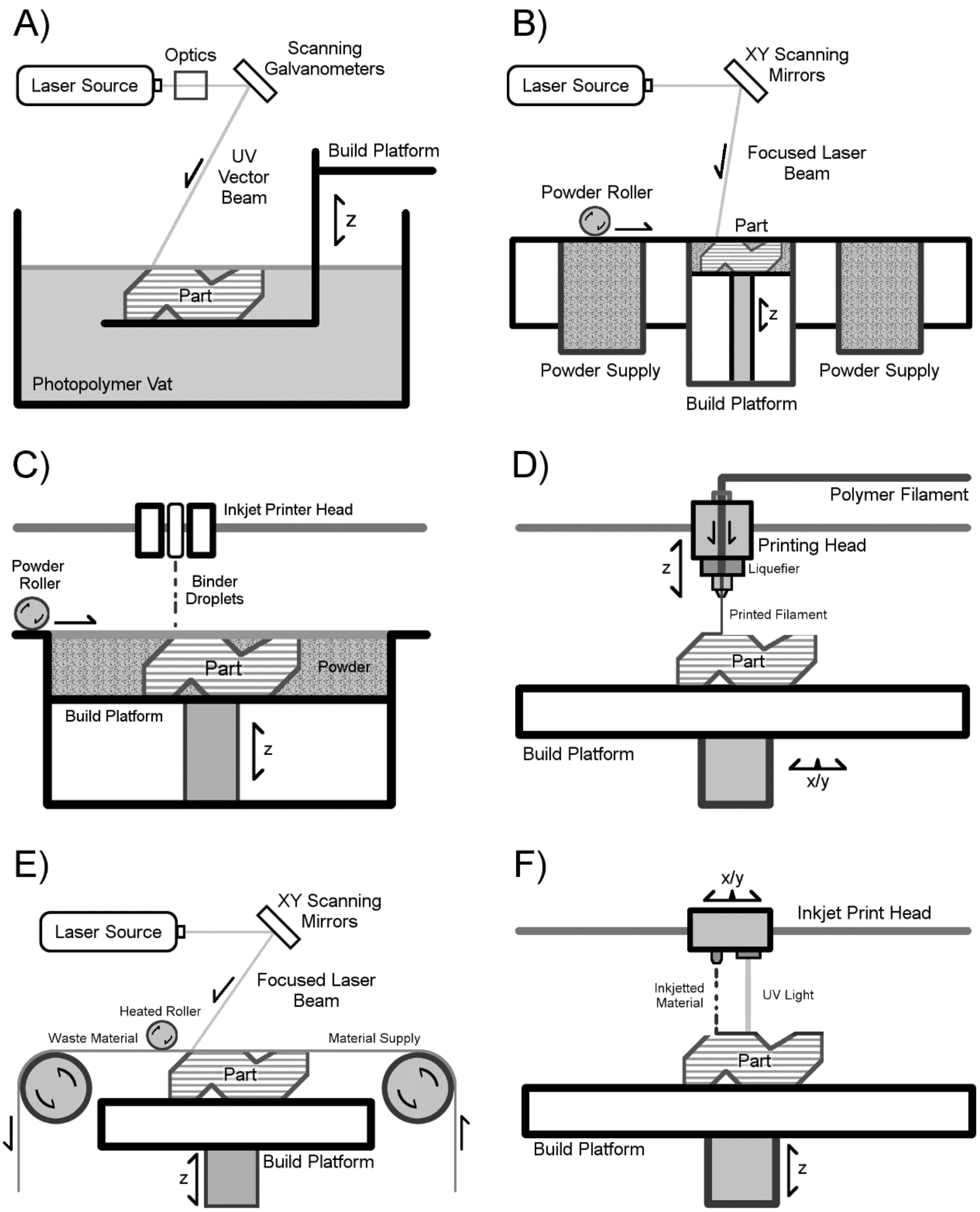


Fig. 2.6: Common Methods of 3D Printing: A number of the most common 3D printing methodologies. A) Stereolithography (SLA); B) Selective Laser Sintering (SLS); C) Traditional '3D Printing' or 3DP (3DP/CJP); D) Fused Deposition Modelling or Fused Filament Fabrication (FDM/FFF); E) Laminated Object Manufacturing (LOM); F) Multi-Jetting or Projet methods (MJ).

by Amico et al. (2018) in the display of a replica of the 'Kazaphani Boat' at the Smithsonian and by Maxwell et al. (2015) in the display of a designed Pictish drinking horn sculpture at the National Museum of Scotland. Others have embraced the potential for handling replicas through 3D printing. Some of these major applications within the exhibition environment will now be explored as well as how they are being utilised and notably, the impact of these approaches on exhibition practice.

Allard et al. (2006) for instance demonstrate the use of laser scanning and binder jet 3D printing in plaster to replicate human skeletal remains for an exhibit entitled 'Funeral as a Rite of Passage' at the Mennonite Heritage village as a way around the cultural sensitivities of displaying human remains. This is one of the earliest examples of the use of 3D printing within a museum exhibit and over time, the number of such exhibits has only increased, especially in response to the large boost in awareness and accessibility to 3D printing technology over the past few years. Examples of its usage are wide and diverse in many different museum institutions, covering a broad array of cultural heritage subjects and in the form of temporary exhibitions, workshops, and permanent museum installations, although the latter of these are far less common.

Harley et al. (2016) for example demonstrate the use of 3D replicas of prayer nuts, enhanced through scents, ambient audio, and accompanying video projections to help shape the interpretations of visitors (Chu and Mazaleki, 2019), while Jung and tom Dieck (2017) provide an example in which visitors to the Geevor Tin Mine Museum were able to print off certain objects after a visit to take home as a souvenir. Dima et al. (2014) provide an example of a 3D printed Lewisian Chess piece enhanced using the theatrical technique 'Pepper's Ghost' and Galeazzo (2017) show the potential of 3D printed objects accompanied by AR-like overlays. These few example represent just a few of the many different exhibition applications that have been explored in museums worldwide and many others, ranging in terms of their scale and objectives (Hess and Robson, 2013; Schwandt and Weinhold, 2014; Callieri et al. 2015; Short, 2015; Younan, 2015; Cantoni et al. 2016; Galeazzo, 2017; Karnapke and Baker, 2018).

Other interesting applications of the technology in exhibition media include that of the 'smart replica', 3D printed replicas that incorporate tangible sensors that trigger additional audio, video and environmental content that elaborate on the themes of the exhibition. Marshall et al. (2016) demonstrate the concept well with a part of an exhibit titled 'The Hague and the Atlantic Wall' at the Museon Hague, where visitors to the exhibit could choose an object, some of which were smart 3D printed replicas, to take into the exhibit. Placing the object on certain panels triggered audio content from the perspective of a person who might have owned such an object, adding a layer of intersubjective interpretation for visitors. The forerunners of this approach, 'Tooteko' and 'Virtex' utilise the same concept, using 3D replicas to provide additional content that would normally be textual, or missing from the display (Pletincx, 2007; Capurro et al. 2015; D’Agnano et al. 2015).

2.4.2.3 BPS Engagement Use

There are also numerous examples where 3D printing has been exploited to benefit BPS audiences within museums, typically involving the creation of tactile images of traditionally two-dimensional artworks to allow interpretation, such as a tactile relief of the ‘Battle of Pavia’ (Cantoni et al. 2016) or the Jackson Pollock art-piece, ‘Alchemy’ (Callieri et al. 2015) among many others (Neumüller and Reichinger, 2013; Neumüller et al. 2014; Cantoni et al. 2016; Urbas et al. 2016).

Others have used 3D printing to create replicas of valuable or fragile museum objects for BPS handling, Eardley et al. (2016) for example documenting two examples of tangible 3D printed tile replicas in two Portuguese museums, along with audio-assistive technologies in order to aid their interpretations. Themistocleus et al. (2016) demonstrate the use of UAV photogrammetry to create 3D printed replicas of the Curium Amphitheatre in Cyprus for tactile handling of an object that would otherwise be impossible to interpret for BPS individuals. Ballarin et al. (2018) also express a similar concept for usage, creating a depth-enhanced replica of a Venetian tile for handling, in an effort to make the low-relief features on the tile easier to interpret for tactile handling. A similar application is summarised by Karnapke and Baker (2018), where a low-relief Italian prehistoric carving was replicated using 3D printing in full 3D dimensions, allowing BPS audiences to interpret the object more clearly and to understand for themselves the different potential interpretations of an enigmatic carving.

2.4.2.4 User Research into 3D Printed Replicas in Cultural Heritage

These applications all show the potential for this approach to enable the handling of replicas of objects that would never see such public exposure normally, either due to their fragility or rarity. In all of these applications, the authors generally advocate the positivity of 3D printing as an approach for engaging museum audiences. Many of them are *ad-hoc* however, with little regard paid to the materials, the design considerations and reasoning for their use.

Moreover there is a severe lack of peer-reviewed research looking into what the museum visitor expects from such 3D printed replicas and more importantly, what impact they have on visitor experience. Many authors simply assume that the technology could be beneficial for learning and the enjoyment of museum visitors as part of their specific research application or case-study, rarely following up on their claims with robust research (Rahman et al. 2012; Hancock, 2015; Jafri and Ali, 2015; Laycock et al. 2015; Eardley et al. 2016; Harley et al. 2016; Jung and tom Dieck, 2017). Other published research projects instead delve deeper, attempting to properly explore the potential of 3D printing for engagement and learning. These are summarised in Table 2.4.

In terms of what can be actually done to enhance 3D printed replicas and assist BPS visitors in their interpretation of objects, even less is evident within the literature. Most research of this type typically falls into the outlining of guiding principles for creating tangible replicas of two-dimensional artworks, typically paintings, for handling (Neumüller et al. 2014; Rener, 2017). Others attempt to evaluate methods in making three-dimensional objects for BPS use. Ballarin et al. (2018) for example replicated a Palaeolithic engraving using 3D printing for both study and for museum applications at the Palazzo Ducale (Venice), exaggerating the geometry of the print in order to make the object more tactually accessible to BPS audiences, although they provide no evaluation. Karnapke and Baker (2018), as mentioned above, also carried out a similar approach, though actually converted the low-relief two-dimensional image into a fully three-dimensional object for clearer interpretation, although again this lacks an evaluation. Anagnostakis et al. (2016) and Lombardi et al. (2018) provide more in-depth studies, as summarised in Table 2.4.

These research approaches all highlight a number of extant issues within the state of the literature with regards to museum visitor experience with 3D printed replicas. First and foremost is the general lack of research and coherence, the majority of the research in this subject being speculative with little follow up to determine the actual effectiveness of such approaches. Many examples are also eclectic, focussing on single-use case studies with limited transferability between applications. Moreover, the level of rigor in these studies varies, some utilising quantitative approaches and others qualitative, although many authors do utilise mixed-methods. A failure to properly incorporate mixed-methods results in qualitative studies losing their generalisability while quantitative studies lose the deep insights that can be gleaned from qualitative analysis. Sample sizes are lacking in many of these studies and many are simply evaluations of applications of 3D printed replicas, rarely exploring the reasons they were successful or how they impacted the experience of their participants. Finally, the majority look at a higher conceptual level, generally comparing 3D printing to other presentation methods, rather than focussing specifically on 3D printing.

Overall, it can be concluded that the research area of the museum visitor’s experience with regard to 3D printing is a poorly researched field with spotty findings, except in a few cases. It is a research field that is relatively underdeveloped, mostly in part due to the methods and rigor of user experience practice within cultural heritage applications. The evaluation methods currently available to museum professionals are limited in scope and depth, as are the general research approaches used to evaluate museum applications.

Table 2.4: Research into Experiences with 3D Printed Replicas

Paper	Area	Description	Findings	Methods Used	Limitations
Lindgren-Streicher and Reich (2007)	Comparison of Presentation Methods (3D Prints, Real, Models and Digital)	Analysis on use of different presentations methods in workshops for younger visitors	3D prints used less than real artefacts; Objects usage depends on task	*Mixed-Methods*: Observation and Interviews	Workshop environment
Di Franco et al. (2015)	Comparison of Presentation Methods (3D Prints, Traditional and Powerwall)	Analysis on different forms of interaction between different potential display conditions	Tangible interaction with replica preferred over just looking at original.	*Quantitative*: Questionnaire	Unrepresentative sample
Anagnostakis et al. (2016)	Evaluation of Audio-touch Prints for BPS Audience	Analysis comparing different interaction methods and their enjoyment	Good performance regardless of sight condition; enthusiasm of participants	*Mixed-Methods*: Observation and Interviews	Small sample; Evaluative
Di Franco et al. (2016)	Comparison of Presentation Methods (3D Prints, Traditional)	Analysis comparing engagement with different interaction methods in higher education	Tangible interaction with replicas encouraged greater engagement	*Quantitative*: Gesture Analysis	Unrepresentative sample
Turner et al. (2017)	Learning from 3D Printed Replicas	Analysis of a workshop on the subject of designing and 3D printing shoe buckles	Some learning was evident	*Qualitative*: Interviews	Anecdotal quotes as evidence of learning
Lombardi et al. (2018)	Evaluation of 3D Printed Replicas for BPS Audience	Analysis of 3D printed Bas-reliefs for BPS audience	Participants could understand with some assistance; Audio description would be useful	*Qualitative*: Interviews	Small sample
Nofal et al. (2018)	Comparison of Presentation Methods (3D Prints and Digital Displays)	Analysis comparing different display methods in an Egyptian exhibition	Digital better for interpreting, but 3D prints better for interpreting symbolism	*Mixed-Methods*: Observation, Questionnaire and Interviews	Small sample
Pollalis et al. (2018)	Comparison of Presentation Methods (3D Prints, Model Viewers and AR)	Analysis comparing interaction styles and learning with Egyptian Sculptures	No difference in learning between conditions; 3D Prints least enjoyable	*Mixed-Methods*: Questionnaire	Replicas substandard; Unrepresentative sample

These shortcomings must be overcome if 3D printing is to be properly utilised as a useful tool for museum practice. In order to better understand the reasons why and how this issue may be overcome, the nature of museum evaluation practice is now explored in order to identify its inherent major issues and identify potential solutions.

2.5 EVALUATION IN MUSEUM PRACTICE

2.5.1 Methods of Museum Evaluation

Within cultural heritage, the notion of evaluatory practice is fairly modern as exhibition designers and staff now seek to understand how visitors interact with exhibition content. For much of the history of public museums, however, it was assumed that merely placing an artefact on display with no supplementary information save a name or time period allowed perfect transmission of their messages without issue to the museum visitor. This was later realised to be false (Miles et al. 1988; Smith, 1989; Hein, 1998; Talboys, 2011; McManus, 2015). The first attempt to evaluate the effectiveness of museum exhibitions were carried out in 1916 by Benjamin Ives Gilman (1916), who identified the phenomenon that became to be known as ‘museum fatigue’, the drop in visitor attentiveness and interest towards the end of a visit (Hein, 1998; Lindauer, 2005; Hooper-Greenhill, 2006; Bitgood and Loomis, 2012). It was not until the empirical approach of Robinson (1928) and his Ph.D. students Melton (1936) and Porter (1938) that rigorous positivistic inquiry grounded in behavioural psychology was introduced to museum evaluation. The involved testing what variables, such as label height and installation types, were correlated with more extreme museum fatigue (Lindauer, 2005; Bitgood and Loomis, 2012). These authors saw the untapped potential of museums as a body for teaching but this was not sufficient to encourage further investigation, resulting in a long hiatus in the pursuit of museum evaluation until the late 1960’s (Lindauer, 2005; Hooper-Greenhill, 2006; Bitgood and Loomis, 2012).

Interest in museum evaluation picked up, particularly in the US, in response to legislation mandating that all educational programs must be evaluated, at a time where American museums were just beginning to be acknowledged as bodies eligible for external funding (Lindauer, 2005; Hooper-Greenhill, 2006). The implication was that of accountability for museum staff. Workers through the 70’s began to adopt a goals-based evaluation approach to assess the effectiveness of exhibits, mainly relying upon studying visitor behaviour in an empirical and positivistic fashion, revealing many design features that influence the effectiveness of an exhibition (Miles et al. 1988; Lindauer, 2005; Bitgood and Loomis, 2012). In parallel with the so-called paradigm wars in the social sciences referred to above, a new research paradigm began to emerge in the 80’s as researchers began to realise that museum visitors were not a homogenous mass and that they were not particularly inclined to pursue the educational goals laid out by the curator (Hooper-Greenhill, 2006). The audience began to be recognised as active and varied and the focus moved towards creating ‘goalless’ research methods where the meaning and the understanding of the visitor were taken into account (Miles and Tout, 1994; Hooper-Greenhill, 2006). This triggered a change from positivistic research methodologies to constructivist, qualitative methods, that reflected the dominant changes occurring in the field of social sciences and research noted previously (Hooper-Greenhill, 2006; Davies and Heath, 2014). More recently, as with the rise of the mixed-methods approach, qualitative methods have become accepted as being powerful tools for investigating the experiences of museum-goers alongside quantitative methods and are now commonly used side-by-side to complement each other's strengths and weaknesses (Davies and Heath, 2014).

Modern museum evaluation techniques generally subscribe to both qualitative and quantitative research methodologies on a case-by-case basis depending on the needs of the project, allowing evaluations to utilise the strengths of the mixed-methods approach (Rennie and Johnston, 2004; Davies and Heath, 2014). The primary purpose of these is to typically justify their continued support and to ensure that funding for a particular institution continues (vom Lehn and Heath, 2016). This is especially important with regards to museum learning, which requires in-depth exploration of what messages and meanings are constructed by not only individual museum visitors but also the social groups with which they interact. A large variety of techniques are used in a wide number of different combinations depending on the needs of the project; including research interviews, surveys, behavioural observation, and focus groups alongside more specific research approaches (Davies and Heath, 2014; Diamond et al. 2016).

However, museum evaluation does have its issues. Davies and Heath (2014) provide a critique on general methodologies used in museum evaluation, stating that summative evaluation, that which typically occurs once an exhibition is completed, is not particularly impactful on short or long term practice within museums despite the large corpus of research within the literature (vom Lehn and Heath, 2016). The authors also criticise the regulation with which such projects are carried out, commenting that there are great variations in design between institutions, for both data collection and analysis. This produces results that are eclectic and too specific to a particular project and are thus ungeneralizable (Arts Council England, 2011; Davies and Heath, 2013; vom Lehn and Heath, 2016). Some criticize poor adherence to the strict guidelines of social science research, resulting in poor quality studies that are of little use in addition to a general methodological conservatism, an unwillingness to use less popular, advanced techniques to try and evaluate novel programs and exhibitions (Davies and Heath, 2014).

Another issue is the lack of effort to build a solid body of knowledge on museum evaluation within cultural heritage. Evaluation frameworks are not typically part of standard museum practice and are carried out if needed to justify the success of an exhibit, rather than as part of the whole design process (Davies and Heath, 2013). This can be equated to the idea of usability in other business sectors, such as HCI (Palmer, 2002; Sauro and Lewis, 2012), the justification of the success of a product or experience rather than an exploration of how to improve practice, as discussed below. Tied to this is the fractured nature of the field, individual studies being isolated, rarely considering the wider picture of museum practice on top of a general unwillingness for institutions to make their evaluations public (Davies and Heath, 2013; 2014). Also prevalent is the so-called 'positive evaluation' phenomenon, in which such evaluations nearly always report positive results (Johanson and Glow, 2015). This is typically due to research participants being unwilling to bad-mouth exhibitions in front of the invested researchers or the agencies responsible for evaluation having a vested interest in the success of the project, subtly shifting any evaluations towards a positive outcome (Davies and Heath, 2014; Johanson and Glow, 2015).

Also problematic is the limited range of methods used. Museum evaluation typically only exploits a number of old, historically well-established approaches prevalent in any industry that wishes to evaluate or assess the success of its applications. Methods like questionnaires, focus groups, observations, and interviews form the bulk of museum evaluation approaches (Diamond et al. 2016). These are suitable for their purpose but are often used in a raw form, drawing basic quantitative or qualitative insights from the data and using that as evidence, rather than using more sophisticated forms of analysis that can provide deeper, more meaningful insights into their evaluation. The net result is that these techniques in their raw form can only yield superficial, surface level insights rather than probing the underlying controls on museum visitor experience. This again results in the inability to create generalizable knowledge that would be of wider use to general museum practice.

Overall then, museum evaluation practice, as has been discussed over the literature review thus far, is flawed. It is limited methodologically, the methods exploited and the robustness and validity of the findings of many studies. Many have extremely small sample sizes that limit generalisability in addition to a reliance on qualitative data and analyses with little criteria to assess the validity and reliability of the methods used and their inferences. As a result, current methods used in the cultural heritage sector are insufficient for properly exploring the topic at hand, that of tangible 3D printed replicas. These major issues can be resolved however and the answer lies in other consumer industries, which have a long history in exploring the needs of their customers in regard to products and services.

2.5.2 User Experience in Other Consumer Industries

The perspective of the consumer is something that has been explored with vested interest by industries seeking to improve their products. The advantages of doing so are fairly obvious. An attractive and functional product is a desirable one from the perspective of the consumer. A desirable product is one that is more likely to be profitable. Thus the onus is placed on manufacturers and companies to make their products and services as desirable as possible. As a result, the experience of the consumer and the usability of the product have become critical goals for creating an ultimately successful product (Wellings et al. 2010; Zheng et al. 2017). Failure to properly design products around the needs and desires of the user can be disastrous, as in the case MyFord Touch, a communications and entertainment system for Ford vehicles released in 2011. The product was deemed an abject failure, which suffered from poor performance and triggered a large decline in Ford's ranking in the 2011 Initial Quality Survey (IQS), a trusted survey concerning the opinions of new car purchasers (JD Power and Associates, 2011). This was accompanied by extremely negative press, despite the release of a free upgrade in 2012 to mitigate these issues, many of which still remained afterward (Consumer Reports, 2012). The ramifications of this example are obvious, resulting in wasted expenditure on fixing major issues, wasted development time and delays to future products in the fallout. This naturally leads to an erosion of productivity and profit. To avoid such disaster, the experience of the intended user must be taken into account when designing and prototyping a new product or service.

2.5.2.1 User Experience

User Experience (UX) is a relatively young concept within the realm of product development, a term coined by Norman et al. (1995; Hassenzahl and Tractinsky, 2006; Lallemand et al. 2015). The term was popularised and rapidly adopted in the field of Human-Computer Interaction (HCI) before spreading to other research fields and itself is regarded as a subset of UCD, as shall be discussed later (*8.3 A New Approach to Exhibition Design*) (Wellings et al. 2010; Lallemand et al. 2015). UX and UX design in particular deal with the creation of desirable experiences when a user or consumer interacts with a product, although the term itself, its definition and how the concept is used in practice is somewhat nebulous, even today (Wellings et al. 2010; Roto et al. 2011; Lallemand et al. 2015). There is little consensus even over a definition of UX, AllAboutUX.org listing 27 different definitions for the term (AllAboutUX, 2018). This discrepancy mainly revolves around the different perspectives of UX academics and practitioners on the subject. Academics typically focus on the experiential aspect of UX, defining UX as a subset of an experience with a product and how the user is affected by the interaction. This typically focusses on both the incidental pragmatic and positive hedonic and emotional aspects inherent within an experience with a product (Hassenzahl and Tractinsky, 2006; Hassenzahl, 2008; Hornbæk and Hertzum, 2017). These UX models typically separate pragmatic (instrumental) qualities from hedonic (non-instrumental) qualities so that factors related to how a system or product works are separate to aesthetic, emotional qualities (Hassenzahl, 2003; Hassenzahl et al. 2006; Hornbæk and Hertzum, 2017). It is also considered to be subjective, dynamic, interpersonal, socially and contextually mediated and changes through time and use (Roto et al. 2011; Lallemand et al. 2015; Hornbæk and Hertzum, 2017). UX practitioners in industry however typically focus on the product itself rather than the experience, regarding UX as a synonym for usability, the evaluation of the efficiency of a product or service and the satisfaction that it brings when used (Sauro and Lewis, 2012; Lallemand et al. 2015). Usability is more objective and behavioural, focussing on measuring the pragmatic elements of use, such as task times and satisfaction ratings to meet critical thresholds and standards during product design (Hassenzahl et al. 2006; Lallemand et al. 2015). As a result, the practical form of UX rarely considers the hedonic aspects of product interaction and the positive experiences that can be invoked in the process. These differences are firmly entrenched and attempts to produce consensus have been relatively limited (Roto et al. 2011; Lallemand et al. 2015). Here, the UX definition of Hassenzahl (2008) is adopted:

> *"A momentary, primarily evaluative feeling (good-bad) while interacting with a product or service"*
>
> *Hassenzahl (2008)*

This is further extended by the author by summarising what constitutes 'good UX':

> *"Good UX is the consequence of fulfilling the human needs for autonomy, competency, stimulating, relatedness and popularity through interacting with the product or service…"*
>
> *Hassenzahl (2008)*

This definition is suitable as it captures both the pragmatic and hedonic qualities of a product while focussing on the experience of the user over just the usability of the product. Both sides contribute to the overall experience a user has with a product or service, its pragmatic qualities facilitating positive hedonic qualities to provide a good UX (Hassenzahl, 2008).

Overall then, UX and UX design are about the design and creation of experiences with a product whose pragmatic elements, such as performance, and whose hedonic elements, such as aesthetics, both contribute to a positive overall experience. Through UX research, designers are able to leverage insights into consumer UX and create desirable experiences for their customers. As a result, UX methodologies have gone on to pervade a number of competitive industries. These approaches have their origin in HCI and have been used by other industries to explore consumer-related issues, such as in web design (Garrett, 2010), mobile devices (Yu and Kong, 2016), the automotive industry (Wellings et al. 2010; 2012), the food industry (Labbe et al. 2015) and the video game industry (Bernhaupt, 2010). Its adoption in the food industry is of particular note, however, as it represents an exploration into a complex multisensory design problem involving not only taste, but olfactory, tactile and optical design issues alongside the affective and aesthetic ramifications of consumer choice. The food industry, as a result, has much experience in using UX research due to these unique multisensory design challenges, which mandate the need to properly understand the experience of the consumer with their products (Schifferstein, 2010; Gómez-Corona et al. 2017).

Thus, UX research could be of use to cultural heritage and the exploration of museum visitor experiences, particularly in the instance of the multisensory nature of tangible 3D printed replicas. Its ability to reduce the complexity of consumer experience to its basic ingredients should allow the clear identification of how museums can best leverage 3D printed replicas to create desirable handling experiences. In order to underline the benefits of UX-based research however, it is worth exploring an example of an industry that makes use of it. Instead of focussing on the food industry, a larger-scale industry that faces many of the same design considerations that museums face shall be explored. That of the automotive industry.

2.5.2.2 User Experience in the Automotive Industry

The automotive industry is a major contributor to the global economy, a trillion-dollar industry that has been heavily invested into by all major world economies. In the UK alone, the automotive industry turned over £82 billion in 2017 and accounted for 12.8% of all of the UK's total exports in the same year (SMMT, 2018). Globally, the automotive industry sold ~79 million vehicles in 2018, a figure that is expected to rise towards 81 million this year (Statista, 2019). This massive industry, despite its scope and relative maturity, has only previously focussed on researching safety, ergonomics and the usability of its vehicles (Körber et al. 2013; Gkouskos et al. 2015). There has been an increasing interest in UX research however within the discipline, namely driven by a lack of understanding of how to design around the UX of the driver (Gkouskos and Chen, 2012; Gkouskos et al. 2015).

There are a few reasons for this. First and foremost, due to the maturity of the automotive industry, most manufacturers have for the most part perfected the more pragmatic technological aspects of car design specifications. As a result, the actual technological gap between competing manufacturers is relatively narrow, meaning that different automotive brands have very little to differentiate their products from their competitors (Wellings et al. 2008; Wellings et al. 2010; Körber et al. 2013). As a result, many companies have begun to focus on designing and creating 'brand experiences' through UX methodologies to attract customers new and old and to create a more distinct brand identity (Wellings et al. 2010). Secondly, the automotive industry is currently undergoing rapid change. The rise of new trends and technologies in the industry, such as electric vehicles (EV) and automated vehicles (AV), promise to revolutionise the way that people travel. These technological innovations need to be understood however if manufacturers wish to monopolise on new emergent market trends. Through UX, car manufacturers can better understand the needs of their customers, their attitudes towards these new technologies and design human-machine interfaces (HMI) that facilitate positive UX. The automotive industry has made good use of UX to elucidate the underlying controls on pleasurable hedonic experiences with vehicle HMI's, although its use within the industry is arguably still immature. Here, a few key examples will now be explored to underline the benefits of UX research.

Wellings et al. (2008) describe a study looking into customer perception of switch-feel in luxury sports vehicles. Their exploration of a complex multisensory issue with no simple design solution incorporated holistic, mixed-methods exploratory research to identify what characteristics of switches led to positive hedonic experiences. Using survey research utilising the semantic differential method, analysis using ANOVA, principal components analysis (PCA), differential frequency and content analysis elucidated the underlying controls on switch-feel preferences. The authors noted three main factors that exhibited some correlation to switch preference. The first of these was ‘affective’, which strongly correlated with preference and referred to the user’s emotional connection to the switches, such as its apparent expense or ‘interestingness’. ‘Robustness and precision’ was another major factor, exhibiting a moderate correlation to preference rating and referred to the physical operation of the switch. The final factor was that of the ‘silkiness’ of the switch, being weakly correlated with preference and relating to its smoothness of operation. Other qualitative comments favoured large switches which were easier to use among a number of other advantages. Cheap, small and old-fashioned switches were criticised, again among a number of other switch elements that participants derided. From this study, Wellings et al. (2008) were able to succinctly explore and derive some initial insights into the design of switches, which were subsequently explored in greater depth in Wellings et al. (2010).

Pitts et al. (2009) also explored a complex multisensory problem in automobile UX, that of touch displays in automobiles. Despite their popularity, the lack of tactile response on most touch screens has the implication of distracting the driver’s attention, increasing the risk of accidents. The authors carried out a study to investigate different forms of multisensory feedback when using touch-screen interfaces via trials with questionnaire-based responses, to ascertain not only which feedbacks minimised distraction but provided positive hedonic experiences, analysed using ANOVA on Likert scales. The authors found that tri-modal feedback when interacting with buttons, incorporating visual, tactile and auditory feedback, showed significantly higher hedonic preference than the unimodal and both bimodal conditions. Thus, the authors were able to elucidate the fact that the inclusion of multisensory components in touch-screen interfaces in cars was beneficial to the overall UX.

In a more modern example, Jung et al. (2015) explored the issue of ‘range anxiety’ in electric cars, the phenomenon of anxiety over the remaining power left when driving and the car’s ability to reach its destination before running out. The authors specifically wanted to explore the effects of the precision of estimated range left, using two experimental conditions in a field experiment. The first was that of a precise display, a numeric display of range in miles, while the second was a non-numeric, ambiguous display. A further pair of experimental conditions, high-remaining energy, and low-remaining energy were also employed to create four in total. Feedback was collected from questionnaires, and the efficiency of their driving behaviour and analysed using ANOVA to ascertain driver trust towards the vehicle, pleasure, anxiety, and calmness. The authors found that the less precise and ambiguous scale resulted in less anxious drivers and greater calmness, even when the participants started their journey in a low-remaining energy vehicle. Higher-remaining charged vehicles naturally led to more pleasurable journeys and led to higher vehicle trust, the ambiguous display only being slightly more trustworthy than the precise one. Thus, the authors were able to identify some key design insights in displaying remaining power levels in electric cars to the drivers, to the benefit of creating a superior UX with EV's.

Politis et al. (2018) present a study on AV's, evaluating how different methods of driver takeover in semi-autonomous vehicles impact on driving experience. The purpose of this was to explore how different methods of priming driver awareness during a transition could assist the driver's taking over from the autonomous driving. They explored the use of four different systems, a simple countdown-based system (CB), a repetition-based system used in aerospace (RepB), a more complex response-based system involving answering questions (ResB) and a multimodality-based system involving LED lights and vibrations (MB). They utilised a driving simulator in which changeover occurring at several stages during the journey. Data was collected using questionnaires and analysed using ANOVA, with short interviews being carried out afterwards. The authors found that the participants favoured the most simplistic takeover systems over the more complex ones. The CB interface had higher perceived usability and showed higher levels of acceptance than the other modalities, despite the other methods resulting in generally increased situational awareness. The MB method in particular was deemed too subtle to assist drivers, despite evidence from other studies suggesting that it might be beneficial. Thus, through an analysis of the UX with AV takeover approaches, the authors were able to elucidate some of the key design philosophies of creating acceptable and usable control transition methods, focussing on the simplicity on the system.

All of these examples, while representing disparate applications of UX in the automotive industry, advocate the power of UX methodologies. The application of rigorous enquiries recruiting both quantitative and qualitative research methods allows the unpicking of complex design challenges. In each of these examples, the authors identify a unique, poorly understood problem and reduce it to readily graspable insights that are of immediate use to product designers. While arguably UX practice is still in its infancy within the automotive sector, with much of the research likely taking place behind closed doors for the creation of a competitive advantage, these methods have the potential to revolutionise the way that designers go about creating pleasurable and practical driving experiences.

The issue of tangible 3D printed replicas in museums represents a similar complex multisensory design problem. The car, as is highlighted in the above examples, represents a holistic multisensory environment with many 'moving parts'. The 'clickiness' of the buttons, the texture of grips on the steering wheel and the smell of fresh leather, while seemingly alien aspects to the humble museum exhibition, in truth represent similar multisensory design components. The ‘moving parts’ of the tangible 3D printed replica, its scent, texture and the optical properties imposed by material all need to be carefully considered in terms of their influence on the overall experience with the object. Furthermore, the gulf of research available thus far on the topic bears similarities to many of the design issues highlighted above, where poor understanding of the needs of consumers, in this case museum visitors, results in an inability to effectively design desirable experiences. Thus, UX methodologies could be instrumental in unravelling the poorly understood user requirements of tangible 3D printed replicas and help create desirable, enjoyable and above all pleasurable museum experiences with them.

2.5.3 User Experience and Museums

There is a question of justification for the need for UX within museum practice however. Museums arguably operate at much smaller, lower-stakes levels of business operation compared to that of the automobile industry. Reliance on public funding means that there is no real risk in failure nor pressure to meet profit targets. An exhibition that is unpopular is unlikely to be responsible for substantial loss of profit and be ruinous to the reputation of the institution. While this is certainly true, museums ideally should adopt UX methodologies for a number of reasons.

First, museums are still obligated to create engaging exhibitions that encourage their visitors to think and learn. To provide poor quality exhibition content to museum-goers that ignores their preferences undermines the overall purpose of museum institutions and will, if such issues become prevalent, result in dwindling visitorship and loss of revenue. Secondly, museums are a key contributor to the UK economy, generating £24.5 billion in spending by 39.2 million overseas visitors in 2017 and is forecast to increase to £24.7 billion in 2019 (VisitBritain, 2019). Popular tourist destinations are also dominated by museum institutions, with six of the top ten most-attractive tourist sites in the UK being museum institutes in 2017 (VisitBritain, 2018). Thus, museums are an important contributor to the UK economy. They are also competitive with other leisure activities and cultural institutions that vie for the attention of tourists, locally, regionally and globally (Tanja et al. 2017). A tourist only has so much time, so museums must be able to attract visitors through exciting tailored experiences or visitors may turn elsewhere. Thirdly, museums subsidise their revenue from in-house sales via gift-shops, cafeterias and special exhibitions to supplement their arguably limited public funding. Well-designed museum experiences will naturally increase overall visitor throughput, in turn resulting in greater revenue. Finally, much like the automotive industry, museums are now being exposed to brand new technologies that could potentially revolutionise how they create experiences for their visitors (Pop and Borza, 2016; Jung and tom Dieck, 2017). The increasingly commercial affordability of AR, VR and 3D printing means that their application will only become more prevalent with time. These approaches have no analogue real in historical museum practice and thus the onus is on museums to properly understand these technologies and their impact on the museum experience, especially given the reluctance of many cultural institutions to adopt new technologies (Pop and Borza, 2016). The only way to truly understand what constitutes a good or bad visiting experience can only be understood through UX research, rather than simple evaluation. Thus, there is a real impending need for museum professionals to adopt UX methodologies and practice to improve their competiveness and remain relevant in an era of unprecedented technological growth.

As highlighted over the course of the literature review, museum evaluation is dominantly evaluative. Practitioners explore the summative success of an application and for the most part, deem it a success. Some qualitative insights into what worked or did not work may be gleaned, but generalizable design insights are not typically apparent. This evaluative practice correlates roughly with that of usability, a justification of the pragmatic effectiveness of a program rather than deep insights into the UX of visitors. This is odd considering the renewed focus on 'the museum experience' that is prevalent within the field (Falk and Dierking, 2000; 2012). Following the rapid change towards constructivism in the late 90's and early 00's, the work of Falk and Dierking (1992; 2000) proved instrumental in exemplifying the importance of the experience of the museum visitor and many professionals have latched onto the concept of the museum experience and attempt to design around it (Roussou and Katifori, 2018). A search of the phrase "museum experience" on Google Scholar returns 15,900 results, a testament for the widespread adoption of this phrase. In spite of this however, the majority of this research represents either discussions on the nature of museum experience or evaluative studies into methods for enhancing it (Pallud and Monod, 2010). This is not to say that museums do not practice UX research in any form. Shah and Ghazali (2018) for example provide a literature on 22 examples of studies exploring the UX of digital technologies in museums, although many of these examples either simply present their ideas with no supporting analysis or present a small evaluatory study that proves its potential, rather than rigorous, generalizable results of use to the wider museum population. In fact, many studies that advocate the 'user experience' of the museum visitor generally fall into the pitfall of evaluation as in most of museum practice, focussing explicitly on the evaluation and usability of an exhibition or service, as in Seppälä et al. (2017), Koutsabasis and Vosinakis (2018) and Roussou and Katifori (2018). This again highlights the evaluative nature of museum practice, the un-generalisability of findings and the overall lack of exploratory research.

Thus there is a need for what Wellings et al. (2010) refers to as generative research alongside evaluative research in museum practice, former corresponding more with the hedonic user experience and the latter with pragmatic usability. Overall then, museum practice could benefit greatly from adopting UX practices already employed by other competitive industries. A move towards properly addressing the museum experience of visitors and properly exploring their experiences using rigorous, generalizable inquiry could help to elucidate the key design considerations behind many applications. Thus, UX methodologies should be a suitable fit for exploring the design considerations of tactile 3D printed replicas.

2.6 KEY RESEARCH QUESTIONS

2.6.1 The Gap in the Knowledge

Thus, a substantial gap in understanding has been identified with regards to how museum visitors use and interact with tangible 3D printed replicas, the majority of research being eclectic case studies which provide some shallow insights into the user experience of their visitors. Many studies are not ecologically valid and instead focus around temporary applications and workshops, rather than permanent solutions within exhibition galleries. Moreover there is simply a general lack of research into this subject, a trend noted by a number of authors with regards to research in learning with tangible 3D printed replicas (Turner et al. 2017) and research in general with regards to best practices (Neumüller et al. 2014; Cantoni et al. 2016). Finally, their exposure within museum literature is very low, most evaluations likely being kept private, resulting in a failure to accumulate a corpus of shared knowledge. Many studies represent broad evaluations between technologies that rarely explore the specific design insights of 3D printed replicas. Better methods grounded in understanding the UX of consumers are also evident, which are better equipped to unpick the complex issue of multisensory engagement with tangible 3D printed replicas.

As a result, more needs to be done to better characterise 3D printing technology and its use within museum applications and how it can influence how museum visitors interact with museum content. With the area of research thus defined, the major research questions that this thesis will tackle can now be outlined.

2.6.2 Preliminary Research Questions

In the previous chapter, a number of tentative research questions were drawn up and are again summarised below:

- How do museum visitors perceive these technologies and how readily can they be accepted?
- How do such tangible 3D printed replicas affect the experience of the museum visitor?
- How can they assist marginalised communities, such as the blind and partially sighted?

All of these questions still stand after the literature review, but can be further refined. Very little user research has been carried out into this subject, meaning that a diverse array of subjects must be tackled to ascertain not only the impact that 3D printing technology has within the exhibition gallery, but whether or not the technology is even welcome within a museum environment. This latter subject is of key importance, as if such replicas are undesirable exhibition tools, further analysis is unnecessary. Next, in the case of acceptance, it will be necessary to determine what aspects of such models are most important to enjoyment. Which physical or hedonic characteristics should be preserved or focused on when fabricating a replica for tactile experiences? These design considerations are essential to creating a desirable handling experience and must be ascertained. Next, it is worth considering the same in subject BPS audiences and how 3D printing technology can be leveraged in order to enhance and assist BPS individuals in interpreting such objects, or if any alterations should be made at all. Finally, it is worth considering the convergent benefits to other aspects of museum practice and how scanning and printing can lead to novel findings beyond public engagement. It is also worth assessing if UX methods can truly be leveraged to tackle these complex design problems. Thus, a number of more detailed research questions can be generated:

- What do museum visitors understand about 3D printing and are such replicas welcome within a museum environment?
- What design considerations and factors need to be taken into account when creating a tangible 3D printed replica?
- How can they impact the experience of BPS visitors and what can be done to assist their interpretation?
- What further impact can the process of digitisation have on museum practice?
- Are user experience methodologies applicable and informative in understanding the needs of museum audiences?

These questions will form the backbone of the thesis and will be answered in the discussion section. Before these questions can be answered however, the research perspective, philosophy and methods to be utilised must be addressed, which are covered in the next section.

3.0 RESEARCH METHODOLOGY

As has been discussed in the literature review, 3D printed replicas could potentially be an invaluable tool in enabling visitors to better engage with museum content. However as has been shown, beyond general positivity towards this approach and a small number of eclectic, often methodologically, limited studies, there is very little clear research consensus on the subject. Without addressing the needs, requirements and preferences of the museum audience, any attempts to incorporate tangible 3D printed replicas into museum practice are likely to be expensive and ineffective endeavors. Thus, the key user requirements of visitors must first be understood before implementing such solutions.

From the literature review, a number of important topics that necessitate further exploration were derived, which can be formulated into a number of crude research questions at this stage:

- What do museum visitors understand about 3D printing and are such replicas welcome within a museum environment?
- What design considerations and factors need to be taken into account when creating a tangible 3D printed replica?
- How can they impact the experience of BPS visitors and what can be done to assist their interpretation?
- What further impact can the process of digitisation have on museum practice?
- Are user experience methodologies applicable and informative in understanding the needs of museum audiences?

At this stage, these questions represent topics of pertinent interest within cultural heritage and need to be further refined to create a more rigorous set of questions fit for further analysis. In order to do this, a research design must first be formulated that is able to properly analyze this poorly explored field.

In this chapter, this research design is detailed. First, the broader aspects of the research design are formulated, focusing in turn on the overriding philosophical framework, the chosen research approach, and methodology used to explore the research questions. Next, the specific research methods used in the highlighted studies will be discussed, detailing the methods of each of the major studies carried out over the remainder of the thesis, their design considerations, and justification. Finally, the above research questions are reiterated, refined and finalised which the remainder of the thesis will explore in detail.

3.1 FORMULATING A RESEARCH DESIGN

3.1.1 Philosophical Framework

First and foremost, a philosophical framework must be selected. Among the social sciences there are a number of such frameworks, more commonly referred to as philosophical paradigms. Their nature has been controversial since the 'paradigm wars' of the 1990's, an ongoing debate still of major significance (Johnson and Onwuegbuzie, 2004; Morgan, 2007; Teddlie and Tashakkori, 2009; Morgan, 2014b). Historically, *positivism* (post-positivism as per Creswell, 2013) and *constructivism* have been the dominant paradigms, both starkly opposed in their overall philosophical approach and are considered to be mutually exclusive to one another (Creswell, 2013). Workers in each respective camp often regard their ontological, epistemological and axiological ideals as incompatible and incommensurable, resulting in an irreconcilable circular debate (Johnson and Onwuegbuzie, 2004; Morgan, 2007). Positivism champions a logical, objective, theory-driven approach to research that typically uses exclusively quantitative techniques. Constructivism instead advocates the inverse, with data-driven research procedures that are typically subjective, inductive and qualitative with a focus on data exploration rather than hypothesis-testing (Guba and Lincoln, 2005; Teddlie and Tashakkori, 2009; Feilzer, 2009; Morgan, 2014b).

In response to this deadlock, a third paradigm has since emerged known as *pragmatism*. It overcomes the issues in both positivism and constructivism by evading the philosophical aspects of this debate and focusing on the research questions and what methods are best for the task of answering them (Feilzer, 2009; Creswell, 2013; Morgan, 2014a). The pragmatic paradigm is not wedded to any particular dualist principle, much unlike positivism and constructivism, and views these arguments as unrelated and unhelpful. It instead prefers to choose the philosophical perspective best suited to the research questions, context and consequences of said project, typically utilizing a mixture of quantitative and qualitative methods as required (Saunders et al. 2012; Morgan, 2014a; Creswell and Plano Clark, 2018). The major philosophical perspectives of positivism, constructivism, and pragmatism are summarised in Table 3.1. Other paradigms exist, such as critical theory, a wide scope of philosophical approaches that typically encompass a worldview geared towards empowering cultural, ethnic and gender groups. Participatory research (sometimes known as transformative or postmodern) is also common, which takes a philosophical approach that bridges the gap between the subjective-objective and that meaning is enacted through the participation of the human mind with the world (Guba and Lincoln, 2005; Creswell, 2013). However, both of these paradigms are highly specific to certain research domains and are less widely applicable.

For the topics of interest raised during the literature review, only one paradigm is suitable, that of pragmatism. There are a few reasons for this, the first being the lack of research

Table 3.1: Summary of Philosophical Research Stances

Philosophical Ideas	Positivism (Post-positivism)	Constructivism	Pragmatic
Ontology (Nature of Reality)	Naïve Reality; reality is apprehendable	Relativism; multiple realities between persons	Reality is both real and relative
Epistemology (Nature of Knowledge)	Objectivist; findings are factually true	Subjectivist; findings are interpreted	Practicality; depends on
Axiology (Nature of Value)	Unbiased; researchers views are distant	Biased; researchers views are integrated	Multiple Stances; both biased and unbiased
Methodological Approach	Deductive and Experimental	Inductive and Dialectical/Hermeneutic	Abductive and Combined Approaches
Mode of Analysis	Quantitative	Qualitative	Quantitative and Qualitative

Adapted from Guba and Lincoln (2005) and Creswell and Plano Clark (2018).

applied into the area of UX with 3D printed replicas within cultural heritage. Such an approach necessitates the need to primarily explore the needs and opinions of users and then attempt to explain the reasons for their preferences and desires. Both of these aims cannot be achieved by either qualitative or quantitative methods alone, the former being exploratory and inductive while the latter is explanatory and deductive (Johnson and Onwuegbuzie, 2004; Teddlie and Tashakkori, 2009; Morgan, 2014b). Naturally, this precludes the use of either positivism or constructivism which are firmly entrenched in either camp. Secondly, this approach lends itself best to mixed-methods research, an extremely versatile research approach that has multiple strengths, including the ability to adjust research methods to accommodate the unexpected, corroborate findings and triangulate inferences from multiple data sources (Teddlie and Tashakkori, 2009; Creswell and Plano Clark, 2018). This mixed-methods research approach is further discussed below. Finally, other paradigms, like critical theory and participatory research, do not lend themselves to this particular research field and are inapplicable and can be discarded. Thus, a pragmatic philosophical framework is adopted for this research project.

3.1.2 Research Approach and Methodology

As highlighted above, the pragmatic approach lends itself best to a mixed-methods research methodology, namely owing to the fact that it allows versatility in the selection of its methods.

It disregards the often top-down restriction on methods that either a pure constructivist or positivist philosophy locks the researcher into and gives the researcher the freedom to address the research questions in their original context (Teddlie and Tashakkori, 2009; Creswell and Plano Clark, 2018). Mixed-methods research can be defined as:

> *"Research in which the investigator collects and analyses data, integrates the findings, and draws inferences using both qualitative and quantitative approaches or methods in a single study or a program of inquiry"*
>
> Whitehead and Schneider (2012)

In all, it focuses on the integration of the useful aspects of both qualitative and quantitative data types to cover each other's weaknesses (Saunders et al. 2012; Creswell and Plano Clark, 2018). Qualitative data is normally subject to interpretive biases and relatively ungeneralizable but makes up for this with the depth of its inquiry and the deep insights which it brings to a research project (Creswell, 2013; 2014; Creswell and Plano Clark, 2018). Quantitative research, by comparison, is directly opposed, the aim being to provide generalizable claims free from subjective biases, representing objective, factual reasoning and proof of the researched phenomena. The drawback of this is the reduction of data to its simplest components, a process that typically causes a loss of depth of information as a trade-off (Creswell, 2014; Creswell and Plano Clark, 2018). By combining the two, researchers can create a holistic interpretation of the quantitative data gathered by backing it up with a qualitative approach and vice versa. This is the primary strength of the mixed-methods approach and the major reason for its inception (Tashakkori and Creswell, 2007; Creswell and Plano Clark, 2018).

Mixed-methods research also carries with it a swathe of advantages as briefly highlighted above, including:

- The ability to triangulate recurring themes from different data sources, resulting in stronger inferences (Saunders et al. 2012; Morgan, 2014b; Creswell and Plano Clark, 2018).
- It allows unrestricted choice of research methods, allowing versatility in the selection of a research approach (Creswell and Plano Clark, 2018).
- It enables the exploration of complex research questions, both confirmatory and exploratory, that are unsolvable by either quantitative or qualitative methods alone (Teddlie and Tashakkori, 2009; Creswell and Plano Clark, 2018).
- It permits conversion between qualitative and quantitative data, allowing researchers to analyze the same data from different perspectives (Teddlie and Tashakkori, 2009; Feilzer, 2009).

- It can provide the opportunity to incorporate a greater assortment of divergent views, allowing the re-assessment of potentially incorrect assumptions and their subsequent correction, to the strength of the overall research field (Teddlie and Tashakkori, 2009; Saunders et al. 2012).
- It allows for the emergence of new insights that can be studied using other methods quite different from those that discovered it (Saunders et al. 2012).

For these reasons, a mixed-methods research approach is selected here for similar reasons for the choice of a pragmatic philosophical worldview. These are namely the complex, exploratory nature of the research questions being asked and the need to integrate both qualitative and quantitative data methods in order to explore the perspective of the museum visitor. Other marginalised groups, particularly those who live with sight loss, also need to be explored and the complex issues involved in preference, design and practical concerns ascertained. This research strategy will utilize an abductive approach, an inferential method that incorporates the strengths of both induction, the creation of theory from data, and deduction, the verification of theory using data, by combining both approaches (Morgan, 2007; 2014b; Saunders et al. 2012). Using abductive inference, researchers may move between the generation of plausible theory from exploratory data via induction to moving to test the empirical value of said theory via deduction, adjusting as necessary (Morgan, 2007; Feilzer, 2009; Saunders et al. 2012). Naturally, this approach lends itself best to a mixed-methods design where the inductive approach leans towards qualitative data analysis and the deductive approach leans towards quantitative data analysis, where integration of the two may be used to fluidly move back and forth between theory and data (Morgan, 2007; Feilzer, 2009).

For the purpose of selecting a specific mixed-methods design, the concepts of Creswell and Plano Clark (2018) are adopted. Under their classification, an *exploratory sequential design* is selected (Fig. 3.1), referred to as a multipart sequential design by Morgan (2014b) or a multi-strand sequential mixed design by Teddlie and Tashakkori (2009). However, rather than following up the second stage with another quantitative stage, it is instead followed up by a mixed-methods conversion design to explore another issue and a case study to evaluate a topic of further interest. This approach involves the use of multiple phases of research that build upon each other in a linear order. The first study informs the second, which in turn informs the third and so on (Teddlie and Tashakkori, 2009; Morgan, 2014b; Creswell and Plano Clark, 2018). The reason for this is prominently due to the need to initially explore the perspective of visitors with regard to 3D printed replicas and understand what aspects of multisensory engagement with 3D printed replicas are of key concern. These initial ideas will be further investigated with studies delving into some of the deeper issues raised using an integrated mix of qualitative and quantitative approaches. This design is the most applicable to the research problem, as a single mixed-methods study is unlikely to be able to fulfill the needs of the myriad of potential

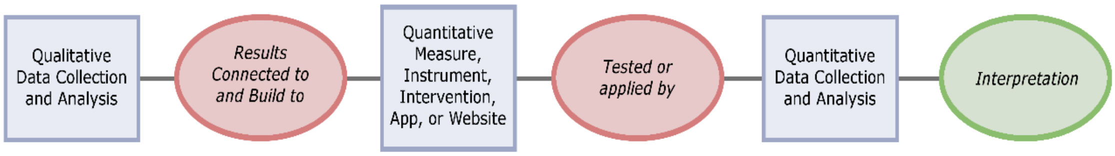


Fig. 3.1: The Exploratory Sequential Mixed-Method Design: This mixed-methods approach combines an initial stage of qualitative research, which informs the design and ideas that will be evaluated or established in a later quantitative research stage, followed by an interpretation. Adapted from Creswell and Plano-Clark (2018).

questions that need to be asked within this field and the likeliness of new, intriguing lines of inquiry emerging during the process. Its strengths are primarily this, to grant flexibility for the researcher to deal with emerging themes of pertinent interest and the ability to work on multiple studies over a long time period that will contribute to the overall research agenda (Creswell and Plano Clark, 2018). For these reasons, the sequential multiphase design is selected. A diagram detailing the overall research approach is depicted in (Fig. 3.2), which is further explored in the next section.

3.2 RESEARCH METHODS

3.2.1 Research Methods Outline

In this section, the research methodologies used in each of the studies that make up the backbone of this thesis are described and justified. These will be more focused on the general structure and research approach of each, rather than the reasoning for each study as these are covered by each of these major chapters.

3.2.2 Evaluation of Tangible 3D-Printed Replicas in Museums

The major focus of this phase of research is an initial foray into the perspective of the museum visitor with regards to 3D printing technology, a subject which has been poorly explored in the literature (Neumüller et al. 2014; Di Franco et al. 2015). This study represents a front-end evaluation, a study carried out to determine the visiting public's reactions and thoughts towards a specific idea or concept, as well as giving designers some idea of the visitor's prior knowledge, experience and their expectations (Hooper-Greenhill, 2006; Diamond et al. 2016).

The study seeks to explore some basic questions that would be of concern to museum professionals with regard to 3D printed replicas, namely their potential attracting power, the understanding of their audiences about 3D printing technologies and whether or not such objects have the potential to enhance the museum experience of visitors. These questions have not been addressed in any study to date, and are thus of pertinent interest.

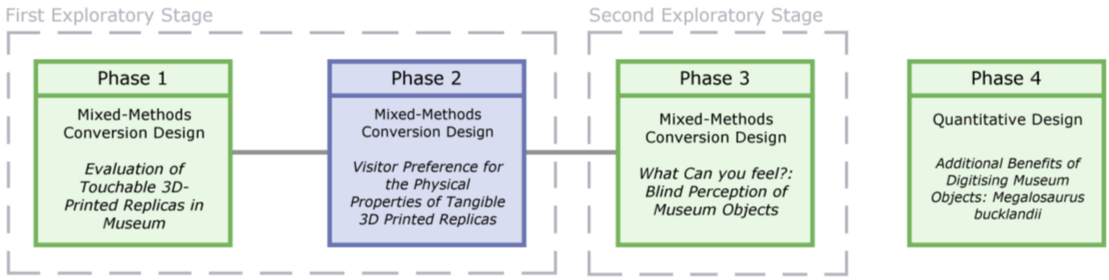


Fig. 3.2: The Research Design: The research design in this thesis will consist of a sequential exploratory design, followed up by a mixed-methods conversion approach in a secondary exploratory stage into another research area. Finally, a case study concerning other benefits will be carried out.

This study utilizes a conversion mixed-methods approach utilizing semi-structured research interviews combined with content analysis. The research interview is an approach that is best suited towards gathering rich, qualitative data that is necessary for exploring the views and opinions of users and is a standard methodology used in a huge variety of research fields to examine similar questions (Creswell, 2015; Diamond et al. 2016; Yin, 2018). Content analysis was chosen as an accompanying method due to the advantages of data conversion, where one data type is re-examined using a different approach in order to both triangulate inferences from either and aiding interpretation. In this case, the qualitative interview data is quantised into categorical frequencies of interview responses (Teddlie and Tashakkori, 2009; Feilzer, 2009; Morgan, 2014b). Content analysis was chosen over thematic analysis, two approaches that are often mistaken for each other (Vaismoradi et al. 2013), due to its focus on reproducibility through the unit of analysis and mandating the use of reliability analysis, a process that increases the strength of the final inferences drawn from the data. It is also remarkably effective at reducing complex qualitative data into informative, quantifiable insights (Krippendorff, 2009; 2013).

This study has been formally published in a peer-reviewed journal article (Wilson et al. 2017b).

3.2.3 Visitor Preference for the Physical Properties of Tangible 3D Printed Replicas

The second phase of this project follows directly on from the first phase and explores an issue that quickly became apparent from the qualitative interview data of museum visitors in the prior chapter, namely that of the verisimilitude and what material properties were most important for handling (Wilson et al. 2017b). Again, this topic is poorly covered in the literature though is hinted at by a few authors and the importance of the authentic replicas has been highlighted on a few occasions (Candlin, 2003; Di Franco et al. 2015; Hampp and Schwan, 2015; Lombardi, 2018). These are key design decisions that need to be taken into account when creating a 3D printed replicas and as a result, represents a research area of clear interest.

This study utilises a conversion mixed-methods approach as before, using a survey methodology that makes use of continuous semantic differential scales to measure the preference of museum visitors towards certain printing materials in addition to content analysis. This study design has been adapted from the work of Wellings et al. (2008; 2010; 2012) as earlier described, who use this exact approach to test how the hedonic and physical properties of car switches influence UX. This method is excellent for exploring the complex phenomena of subjective, multisensory quality and is a perfect fit for the overall research aim. Content analysis was selected for the same reasons as above, its reliability and quantification benefits, while continuous semantic scales were chosen to represent the different physical and subjective property continua. Continuous scales are noted for being less reliable and precise than typical discrete Likert scales with some controversy (Markon et al. 2011; Funke, 2012), but were selected to allow participants to better express their attitudes towards the prints, typically restricted by shorter-point scales (Krosnick and Fabriger, 1997; Belz and Kow, 2011). These are analysed using a suite of statistical techniques, including exploratory factor analysis, ANOVA and correlation coefficients to determine which printing materials are the most preferred, which print qualities correlate with preference and to extract underlying factors from the scale elements, standard quantitative approaches used in a variety of different fields (Field et al. 2012).

This study has been formally published in a peer-reviewed journal article (Wilson et al. 2018a).

3.2.4 What can you feel?: BPS Perception of Museum Objects

The third chapter, rather than following on directly from the previous, looks at another phenomenon that must be understood before tackling the question of the convergent preferences of sighted and BPS audiences. That of their perception of natural history objects, the major factors in their interpretations of these objects and how 3D printing can assist these interpretations. In general, provision for BPS audiences within museums is a problematic affair due to the predominantly visual nature of museum exhibition approaches and historically been a point of great contention within museum practice (Candlin, 2010; Mesquita and Carneiro, 2016; Chick, 2017). Research as such is also fairly lacking, few authors within museum studies carrying out research directly addressing the subject of 3D printing for BPS visitors, the currently employed approaches generally being somewhat *ad-hoc* with little supporting empirical evidence. As such, understanding these needs is essential before ideal design considerations for such replicas can be considered.

The approach employed bears some similarities to that of the first phase, again utilizing a conversion mixed-methods approach with semi-structured interviews that were analyzed by content analysis according to the responses to individual questions for each participant, for similar justifications. Observation was also employed alongside, a technique commonly used in museum evaluation (Diamond et al. 2016), in order to assess the degree to which BPS participants utilised their senses to understand the objects in question, information that would be very difficult to acquire without bias through regular questioning. The think-aloud method was also employed to encourage the participants to describe the shape and materiality of the object, a common method employed in consumer industries to explore how people react to products and services (Eccles and Arsal, 2017). The purpose of this chapter is to understand what aspects of museum objects are necessary to the understanding of BPS persons, so that these constraints can be designed around for future 3D printing applications.

This study is in the process of being written up as a peer-reviewed paper.

3.2.5 Additional Benefits of Digitizing Museum Objects: Megalosaurus bucklandii

The final phase marks a significant departure from the other studies in this thesis, instead examining the other potential benefits of museum practice that can emerge from the process of 3D printing precious museum objects for public consumption. The study looks at the lectotype dentary, the lower jawbone, of *Megalosaurus bucklandii*, the first scientifically described dinosaur housed at the Oxford University Museum of Natural History (OUMNH) and the additional findings that came about as a result of its digitization. These include its conservational history and additional palaeontological insights discovered, despite the specimen being in the museum for nearly 200 years (Howlett et al. 2017).

The study takes the form of a single exploratory case study advocating the advantages of digitizing austere museum specimens that, due to conservation concerns, are less likely to be utilised for formal analysis. The case study, as defined by Yin (2018), is an in-depth study of a contemporary phenomenon within its real-world context, particularly when the boundaries between the phenomenon and context are not clear. This particular research approach has a broad scope and is quite adaptable to a wide variety of different research fields and topics, and will provide the perfect way to explore this complex phenomenon. The ‘case’ in this instance is the XCT scanning of the *M. bucklandii* lower jawbone which will be explored in terms of the outcomes stemming from this action and their use to museum practice on the whole, particularly within the OUMNH and further research. A single case study arguably has less explanatory power than a multiple case study design, but this could not be exploited due to the ‘one-off’ nature of this study of a particularly important and sensitive museum object (Yin, 2018). A number of arguably quantitative scientific approaches quite far removed from social science approaches were utilised, namely micro-CT scanning (XCT) to visualize the internal structure of the specimen and chemical analysis techniques, including both energy dispersive x-ray spectroscopy (EDX) and x-ray fluorescence (XRF). Two approaches were used as the first EDX analysis was only able to reveal the general bulk composition of the specimen, while XRF allowed the identification of individual grains. Finally, inspection using a petrological microscope further confirmed the composition of the material. The study utilised a holistic approach that is rarely combined in museum conservation work, and provides an excellent novel case study of how the conservational history of problematic museum objects can be reverse-engineered.

The results from this study are published in two separate peer-reviewed articles: Wilson et al. (2017a) and (2018b).

3.3 FINALIZING THE RESEARCH DESIGN

3.3.1 The Research Questions

From the nature of the research studies that will be carried out as part of this project, the research questions that arose from the literature review can be finalised. These can be further refined given the nature of the major studies that will be pursued and may be summarised as:

- How do museum visitors regard 3D printed replicas and how might they influence their expectations of museum content?
- What design considerations need to be taken into account in order to create user-friendly 3D printed replicas for sighted and BPS audiences?
- How can 3D printed replicas benefit museum audiences and enhance their experiences?
- How can tangible 3D printed replicas assist BPS persons in their interpretation and enjoyment of exhibitions?
- What benefits can the replication of museum objects have in wider museum practice?
- Are user experience methodologies applicable and informative in understanding the needs of museum audiences?

These are the principal research questions that this thesis will attempt to answer via the studies detailed above.

3.3.2 The Research Design

The study will utilize a pragmatic philosophical design, utilizing a sequential, multiphase mixed-methods approach in order to explore each of the above-highlighted research questions while allowing emerging themes to be explored and analyzed. Abductive reasoning will be used, allowing movement between deductive and inductive reasoning to both explore and explain the results emerging from each of the major research themes.

The individual studies are set within an evaluation environment in museums in which evaluation is typically non-rigorous, eclectic and fairly ungeneralizable, and strives to use more rigorous UX approaches employed in other industries to explore these issues. Four major sequential studies will explore the research questions:

1. *Evaluation of Tangible 3D Printed Replicas in Museums*: A study into museum visitor perception of tangible 3D printed replicas utilizing research interviews and content analysis, in order to understand the perspective of the museum visitor with regard to 3D printed replicas and how they might influence their visiting experience and habits.
2. *Visitor Preference for the Physical Properties of Tangible 3D Printed Replicas*: A study into the physical preferences of museum visitors which utilizes a semantic differential survey design with a suite of statistical methods, including ANOVA, exploratory factor analysis, content analysis, and correlation analysis.
3. *What can you feel? BPS Perception of Museum Objects*: A study looking into what BPS visitors can perceive from museum objects, so as to inform the creation of 3D printed replicas that are informative to BPS individuals. This study utilizes research interviews, content analysis, and observations.
4. *Additional Benefits of Digitizing Museum Objects: Megalosaurus bucklandii*: A study looking into the other potential benefits of visualization for the purposes of public engagement, the new information that can be uncovered from even the most austere museum objects. This study utilizes quantitative methodologies, such as XCT and chemical analysis techniques.

After each study has been carried out, the findings of each shall be brought together in an effort to answer the above research questions. The further ramification for museum practice will be further discussed following this and the final conclusions of the study will be brought together in the form of a number of suggestions that will be key for the use of 3D printed replicas in museum practice.

4.0 EVALUATION OF TANGIBLE 3D PRINTED REPLICAS IN MUSEUMS

4.1 PUBLICATION RECORD

The results of this chapter have been published in the following peer-reviewed article:

Wilson, P, Stott, J, Warnett, JM, Attridge, A, Smith, MP and Williams, MA. 2017b. Evaluation of Tangible 3D-Printed Replicas in Museums. *Curator: The Museum Journal*, 60: 445-465.

4.2 INTRODUCTION

As has been discussed, there is a marked research interest into the potential for 3D printed replicas to enhance the museum experience of visitors through tangible interaction with objects beyond the 'glass-case paradigm'. As the literature review elucidated however, current research into these practices is both limited in scope and depth and marred by inconsistent research practice. Authors who utilise this approach may speak in very general terms of how the use of tangible 3D printed replicas may be beneficial to museum visitors (Rahman et al. 2012; Leakey and Dzamabova, 2013; Laycock et al. 2015). Alternatively, they carry out broad comparisons with other methods of presentation, such as tangible devices (Stanco et al. 2017) and powerwall displays and traditional media (Di Franco et al. 2015; 2016), many of which are carried out in unecologically valid conditions. As has also been highlighted, many studies are typically methodologically light, either employing simple methods of analysis from observation or interview-based data, small sample sizes or being rather unsystematic and general in conclusions, meaning they are of limited use for museum policy and decision making (Jakobsen, 2016; Turner et al. 2017). As the literature review has shown, this lack of overall research into the user experience of museum visitors with regard to tangible 3D printed replicas provides an excellent opportunity to carry out informative and meaningful research into this area (Cantoni et al. 2016; Turner et al. 2017).

However, before the user experience of museum visitors with 3D printed replicas can be understood, a more pertinent question must be asked. Do museum visitors want to handle 3D printed replicas? Even less attention has been afforded to the subject of the feasibility of tangible 3D printed replicas as a form of exhibition media and its practicality. The museum visitor's perceptions of the technology, understanding and ability to accept the use of the technology within the exhibition hall also represent a similarly unexplored area. Understanding these issues is an essential first step and thus a front-end evaluation of the feasibility of this approach is mandated.

This chapter will explore this poorly understood aspect of tangible 3D printed replicas by carrying out a study focussing on the views and opinions of museum visitors at the Oxford

University Museum of Natural History (OUMNH) with regard to the concept of tangible 3D printed replicas as a display medium. The opinions of museum visitors are analysed using a robust systematic approach, involving short interviews with museum visitors of all ages on the exhibition floor. These opinions are then analysed using content analysis in order to extract more generalizable information for use in informing museum policy.

4.3 METHODS AND MATERIALS

4.3.1 Research Questions and Design

The aim of this study was to explore visitor perceptions of 3D printing technology and to determine whether or not museum visitors had any desire to see tangible 3D printed replicas within the exhibition hall. Thus the study was focussed around answering the following research questions:

How do museum visitors regard 3D printed replicas and how might they influence their expectations of museum content?

How can 3D printed replicas benefit museum audiences and enhance their experiences?

The study was designed around answering this research question and a number of sub-research questions on this theme can be identified:

- What exposure do museum visitors have to 3D printing technology and 3D printed replicas?
- How do museum visitors think that 3D printed replicas would affect their museum experience?
- How do museum visitors think that 3D printed replicas would influence their visiting behaviour?

To explore these sub-research questions, an interview study was designed which asked six questions on the above themes. These are detailed in Table 4.1.

The design employed semi-structured interviews in order to better understand these issues and allow participants to provide more detailed responses. Participants were further probed to explore their reasonings until the participant had provided a valid, justified reason for their response. The intent of this was to provide insights into the reasoning for their responses. These responses were then subsequently analysed using content analysis, as is highlighted below.

4.3.2 Participants

A total of 76 participants took part in 50 interviews, representing a sample of visitors to the Oxford University Museum of Natural History (OUMNH), a number being double or triple interviews. A minimum age of 8 was placed on participants, to ensure that all sampled participants could answer the questions satisfactorily, requiring the written consent of a parent or guardian. Participant recruitment used a convenience sampling approach, taking place within the exhibition gallery in the form of a museum workshop.

The principal researcher sat at this workshop and interacted with museum visitors, discussing the *Phascolotherium bucklandii* specimen and encouraging them to handle the 3D prints in addition to a plaster cast of the original. Visitors were then asked to take part in a short interview on the subject of 3D printing. Rejection rate data was not collected, being impossible to estimate for this sampling method. No incentives were given.

The recruited participants were then asked to read an information sheet detailing the nature of the project, what to expect from the interview and information on how to contact the relevant authorities in the event of any issues. Following this, all participants were asked to sign a consent form confirming their willingness to take part in the study and to agree or disagree to the use of audio-recording. No participants declined audio-recording. All participants were also asked to fill out a short demographic form on age and gender. This process was ethically approved by the University of Warwick BSREC ethics committee and the OUMNH IRB and complied with their standards of informed consent.

The demographic information collected can be found in Fig. 4.1. The gender split is slightly biased towards males (58%) (n = 44) rather than females (42%) (n = 32). It is unclear whether or not this reflects a greater level of interest towards 3D printing for males, but given that the inverse is found in sampling in the next chapter, it may just be a limitation of the sample size (*See 5.3.4 Demographics*). For age, the 74% of the participants sampled belonged to the youngest and middle-aged categories, with 24% being 8-16 (n = 18), 30% being 35-44 (n = 23) and 20% being 45-54 (n = 15). The other age groups show much smaller representation, 5% being 18-24 (n = 4), 8% being 25-34 (n = 6), 7% being 55-64 (n = 5) and 7% being 65+ (n = 5). It is likely that this lower representation from younger and older adults is down to lesser interest in the workshop format that the study used.

The participants have been anonymised and the names used in this study assigned via a random name generator.

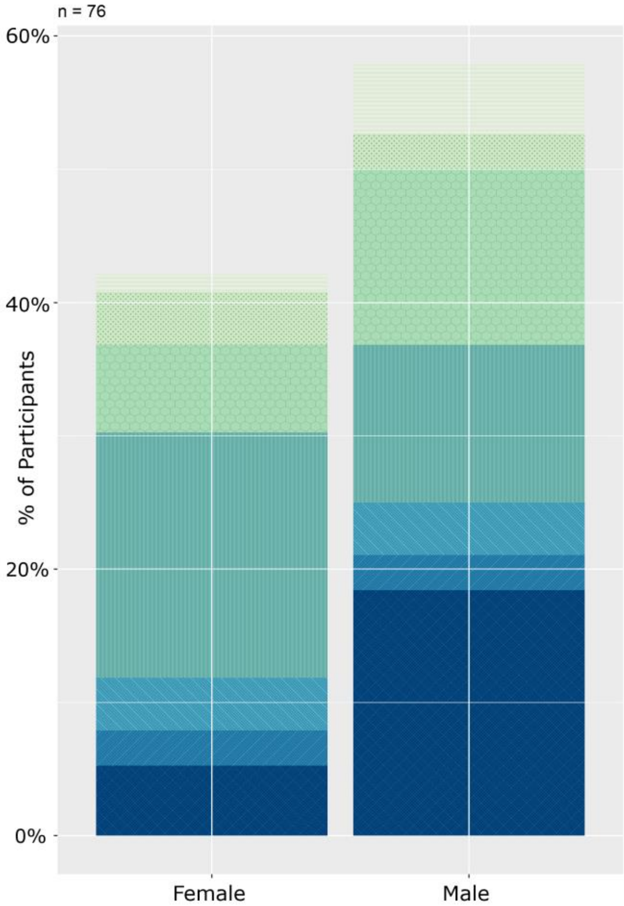


Fig. 4.1: Demographics of Sampled Museum Visitors: Gender and age of the sampled participants interviewed during the study. Colours represent age categories: Royal Blue (Cross-hatched): 08-17, Blue (Left Diagonal): 18-24, Light Blue (Right Diagonal): 25-34, Turquoise (Vertical): 35-44, Green (Hexes): 45-54, Light Green (Dots): 55-64, Yellow (Horizontal): 65+.

4.3.3 Materials

This study utilised the paratype dentary of *Phascolotherium bucklandii* (OUMNH J.20077), the lower right jawbone of a fossilised Mesozoic mammal from the Middle Jurassic (Fig. 4.2a). The specimen was transported for X-ray computed tomography scanning (XCT) at CIMAT - University of Warwick. An XCT scanner consists of an X-ray source, a detector array and an object of interest set on a mechanical stage that manipulates the object (Fig. 4.3). The most common machine architecture, the 'third generation' configuration, is depicted in Fig. 4.3 and is described below (Ketchum and Carlson, 2001; Goldman, 2007). XCT relies on the principle of the linear attenuation of X-rays through an object, much like conventional radiography, to visualise internal structures within an object (Copley et al. 1994; Kruth et al. 2011; Racicot, 2017). To do this, the X-ray source fires a continuous cone-beam of X-rays which pass through the object of interest and attenuated before being registered as events by the detector. The intensity of the X-rays received being proportional to the thickness, density and the

Table 4.1: Interview Questions and their Justifications

No.	Question	Intent
Q1	What do you know about 3D Printing?	To determine the level of knowledge of museum visitors on the 3D printing process
Q2	Have you ever encountered tangible 3D printed replicas in a museum before?	To determine prior exposure of visitors to 3D printed replicas
Q3	Do you think that handling tangible 3D printed replicas like these could enhance your museum experience?	To determine whether or not visitors considered the replica's an asset or detriment to a visit.
Q4	Do you think that tangible 3D printed replicas like these should be present in more museums?	To determine the visitor's impressions on the acceptability of the technology
Q5	Would the opportunity to handle such 3D printed replicas encourage you to visit museums more or less often?	To determine if the presence of 3D printed replicas would influence visiting behaviour
Q6	Do you feel that interacting with 3D printed replicas like these could help you to achieve what you set out to do at the museum today?	To determine whether or not participants thought that 3D printed replicas would align with their visiting goals

atomic number of the material through which it passes (Ketcham and Carlson, 2001; Flay and Leach, 2012). This creates a grayscale image that is representative of the composition of the material that comprises the object, roughly correlating with density. After a single X-ray radiograph from a single orientation is acquired, the stage and object are rotated and another is acquired, the process repeated until a number of images is acquired through 360° of the object (De Chiffre et al. 2014; Warnett et al. 2015). These images are then converted by the process of reconstruction, typically through filtered-back projection method (Feldkamp et al. 1984; Racicot, 2017), to create a 3D volume consisting of 3D pixels or voxels, each voxel being assigned a value representative of the relative proportion of attenuated X-rays. Denser materials typically attenuate more x-rays and thus have higher attenuation values whereas less dense materials behave in the opposite manner. The spatial resolution of each voxel determines the minimum feature size that can be scanned, ranging from ~300μm down to <1μm, depending upon the type of scanner used, the size of the object and the properties of the source and detector (Copley et al. 1994; Racicot, 2017). The data can then be examined and processed to select regions of interest (ROI) for further use.

The specimen was scanned using a Zeiss XRadia 520 Versa CT scanner at a power value of 160kV and a current value of 63μA, with an exposure of 15s and a Calcium Fluoride (CaF_2) filter of 1mm thickness (HE1). This generated a series of projections with a voxel resolution of 18μm. The resulting volumes were then reconstructed using a Filtered Back Projection Algorithm (FBP) (Feldkamp et al. 1984) and exported as a DICOM stack. This CT

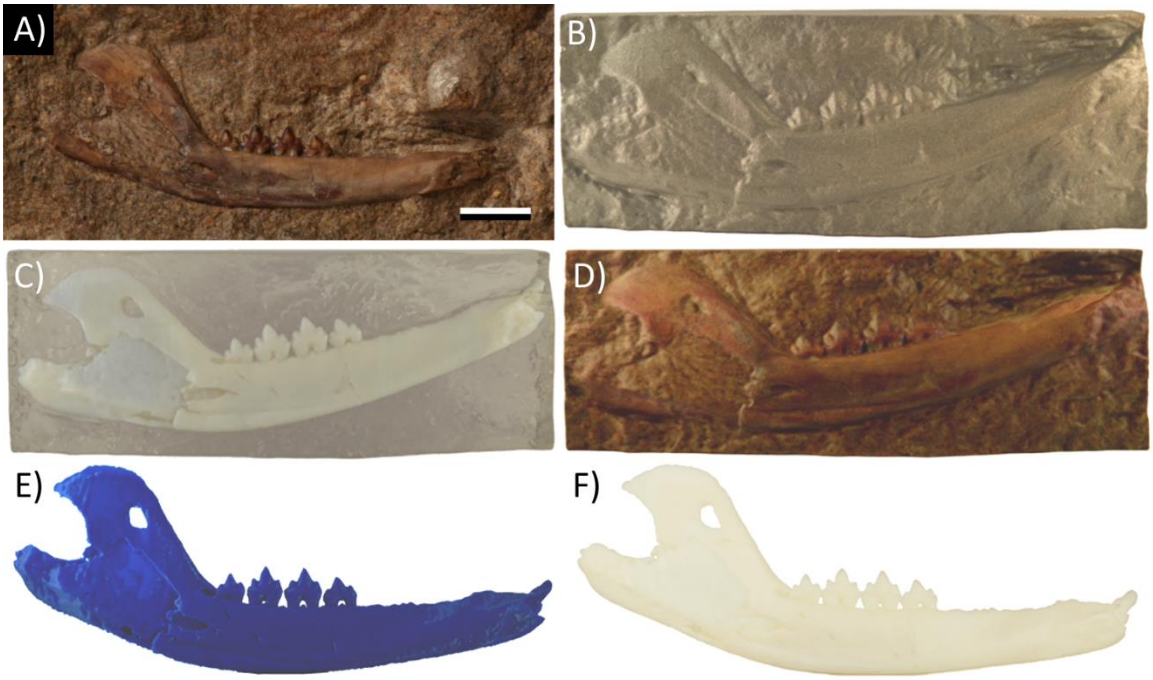


Fig. 4.2*: Phascolotherium bucklandii* and the 3D Prints: A) The paratype dentary of *Phascolotherium bucklandii* (OUMNH J.20077) used in the study. Scale bar is 5mm. B) Stainless steel print (SLS). C) Multimaterial clear and white resin 3D print (MJ). D) 'Colour Sandstone' 3D print (CJP/3DP). E) Blue plastic 3D print (FFF). F) White resin 3D print (MJ).

data was then segmented using Avizo 9.2 (FEI) to separate the jaw bone from the surrounding matrix and then exported as an .stl file for preparation for 3D printing.

A number of 3D prints were created for participants to handle during the process of the interview, derived from the .stl files of a number of different configurations. These were chosen to represent different forms of printing materials, display conditions and treatments. These included; a blue-coloured acrylonitrile butadiene styrene (ABS) print manufactured using fused filament fabrication (FFF) by a private company, a stainless steel print with matrix manufactured using selective laser sintering (SLS) by a private company, a two-material resin, the matrix in clear and the dentary in white, print manufactured using material jetting (MJ) on an Connex3Objet 260 printer at WMG – the University of Warwick, a 'coloured sandstone' 3D print manufactured using powder-based binder jetting (3DP/CJP) of a photo-textured mesh with matrix by a private company and a white, mono-material resin print manufactured using MJ on an Connex3Objet 260 printer at WMG – the University of Warwick (Figure 4.2).

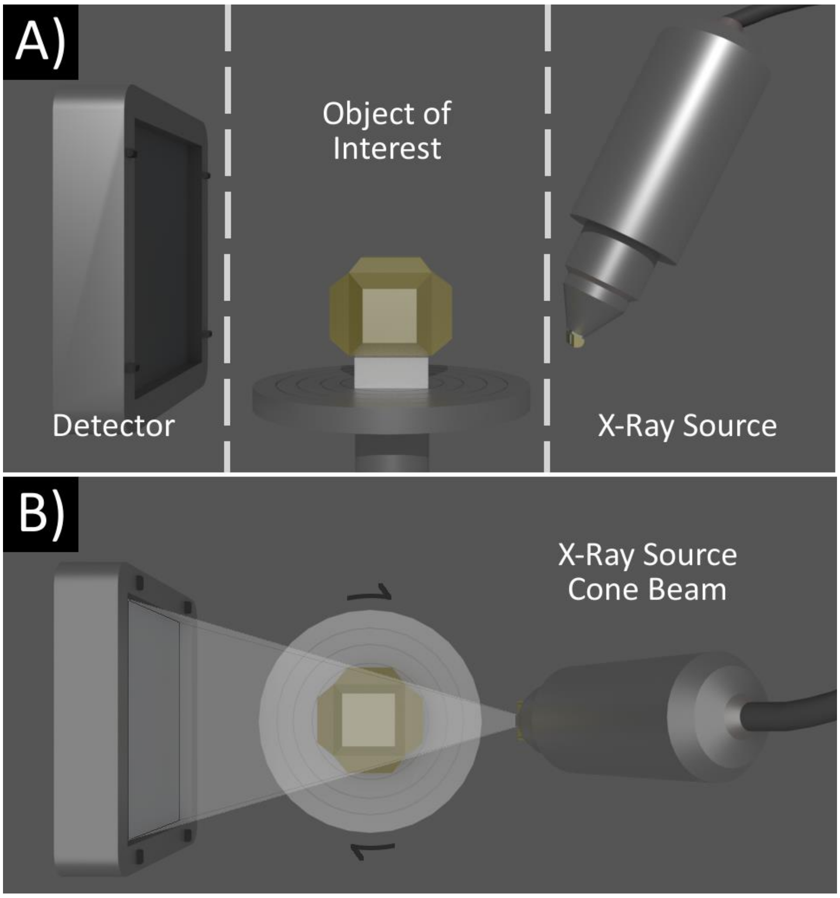


Fig. 4.3: The CT Configuration: A) The default 'third generation' CT configuration. A) The object of interest is placed on a rotary stage between an X-ray source and detector plate. B) During the scan, the X-ray source fires a continuous cone beam of X-rays through the object that are attenuated by the object and then picked up by the detector. After a sufficient amount of exposure, the stage rotates by an increment and the process repeats.

4.3.4 Procedure

Once the recruitment process had been completed, the interview began. The interview schedule is detailed in Appendix 11.A. In the case of single interviews, the participant was asked each question in the order detailed in Table 4.1. In double or triple interviews, the questions were asked to each participant one after the other, the order being randomised for each question to control for answer influence. After the first two questions, depending on the amount of discussion that took place before the interview, the participant was told about the process of 3D printing if they did not understand and about the *Phascolotherium* specimen. Following this, the interview process continued as normal for the final four questions.

The participant's response was probed following each question to better explore the reasons for their answers. Probing continued until the interviewer was satisfied that the participant had provided a sufficient reason for their response. The participant's responses were audio-recorded in all cases and subsequently transcribed manually using an intelligent edited transcription approach for subsequent analysis.

Once the main questions were asked, the participants were thanked for their time and were invited to add further any comments. Once this was done, the participants were dismissed and the process continued for the next participant. The whole process lasted between 5 and 20 minutes.

4.3.5 Analysis

The transcribed interviews were subjected to content analysis. The principal investigator read through each of the transcribed interviews and developed a series of categories for each question through inductive category creation, a common approach in qualitative data analysis known as qualitative coding (Thomas, 2006; Saldaña, 2016). An initial set of categories were created and were then refined in order to create an initial coding scheme for use in content analysis. This process involves dividing a transcript into a number of equal divisible units, in this case each total response to the questions asked during the interview, called units of analysis (Krippendorff, 2013). Each of these units is assigned to a different category or code, each of which must be mutually exclusive from one another so that it could not possibly be assigned mistakenly to another category (Krippendorff 2013). From all this, a Phase 1 coding scheme was created which was then subjected to inter-rater reliability (IRR) assessment, a requirement for the content analysis process (Krippendorff, 2013). Krippendorff's α was used as it is considered to be the truest, most conservative assessment of IRR (Krippendorff, 2009).

IRR was carried out on ~10% of the total sample ($n = 8$). A 1hr training session was conducted and the inter-rater coder was allowed to carry out a trial on one transcript before carrying out the coding properly on the transcripts to be assessed. Both the principal investigator and the inter-rater coder then independently coded the same set of transcripts. The results were then compared using ReCal2 (Freelon, 2013) and manual calculation for corroboration. A Krippendorff's α of 0.584 was calculated, a ratio representing the consistency of the coding between the coders. This fell short of the minimum accepted agreement value of 0.8 (Krippendorff 2009; 2013), although values between 0.7 and 0.85 can be seen as acceptable for minimum agreement for some IRR methods (Taylor and Watkinson, 2007).

In order to improve reliability, both coders discussed the issues of using the coding scheme, discrepancies in interpretation and suggested improvements, which were then implemented and the coding scheme refined in order to improve reliability. From this, a Phase 2 coding scheme was produced. IRR was recalculated for this coding scheme using Krippendorff's α, computing a value of 0.889, exceeding the accepted minimum criteria for a coding scheme to be deemed reliable. The coding system was then applied to all of the interview data, the results of which are described below.

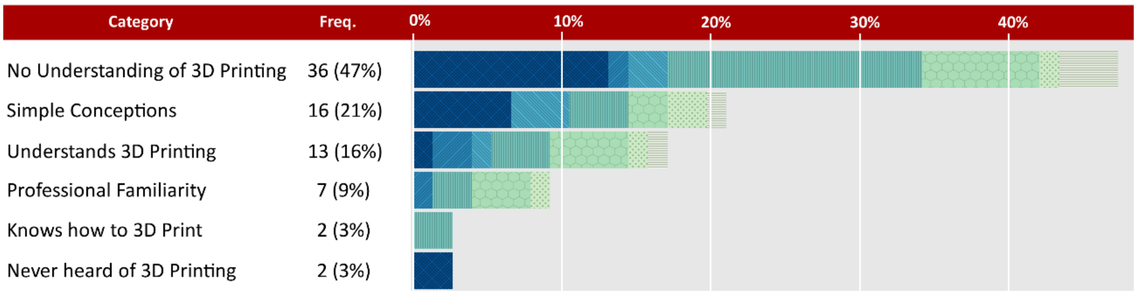


Fig. 4.4: Q1: What do you know about 3D Printing?: Coded responses to the participant's knowledge of 3D printing. Colours represent age categories: Royal Blue (Cross-hatched): 08-17, Blue (Left Diagonal): 18-24, Light Blue (Right Diagonal): 25-34, Turquoise (Vertical): 35-44, Green (Hexes): 45-54, Light Green (Dots): 55-64, Yellow (Horizontal): 65+.

4.4 RESULTS

4.4.1 Q1: What do you know about 3D Printing?

Overall, the vast majority of the participants had heard of 3D printing before (~97%), compared to a small fraction who had never heard of it (3%) (Fig. 4.4). Both participants who had never heard of 3D printing both belonged to the 8-17 age category, which suggests that younger visitors are unlikely to have had much exposure to the technology.

Of those who had heard of 3D printing, around half had heard of it but had little to no understanding of how the technology functioned (47%). 21% were able to provide some form of simple conception about how the technology worked, stating either crude ideas or a naïve interpretation of how 3D printers functioned. In both of these categories, age distribution is rather uniform. By comparison, only 16% of participants showed an understanding of how 3D printing worked, being able to state the basic mechanics of how 3D printers operate. In this group, the proportion of 8-17-year-olds compared to adult groups is much smaller. This suggests that children may need some particular assistance in understanding how 3D printing technologies function. A smaller fraction again exhibited professional familiarity (9%), articulating concepts of how the process of 3D printing functions but having never operated a 3D printer themselves. No 8-17-year-olds exhibited this knowledge. Only 3% of the sampled visitors knew how to operate a 3D printer or had operated one in the past, both belonging to the 35-44 category.

Overall, the data shows that while the overwhelming majority of the sampled visitors had heard of 3D printing, only half had any real understanding of how the technology functions. Of these, even fewer properly understood how the technology works properly or had prior experience.

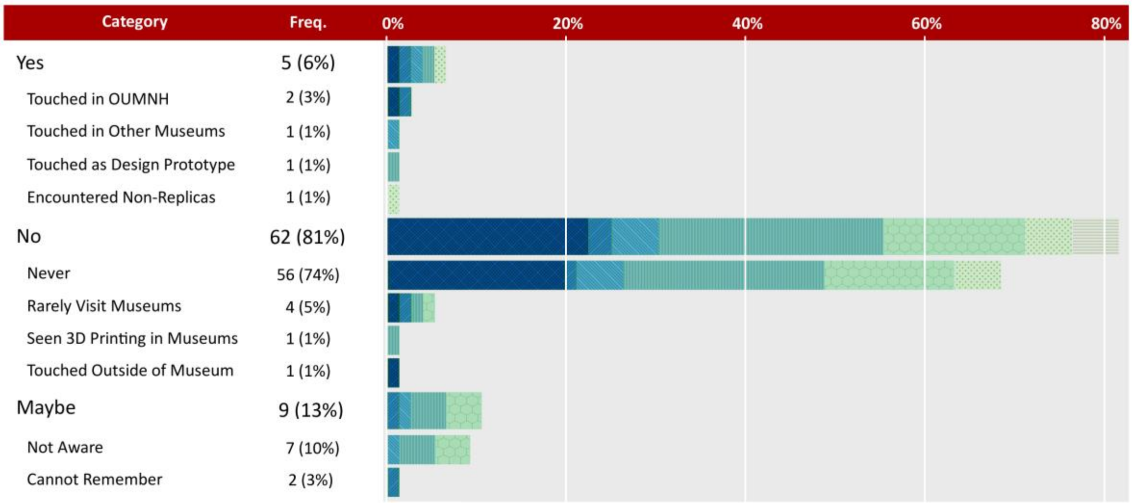


Fig. 4.5: Q2: Have you ever encountered tangible 3D printed replicas in a museum before?: Coded responses to the sampled visitors experience with tangible 3D printed replicas. Colours represent age categories: Royal Blue (Cross-hatched): 08-17, Blue (Left Diagonal): 18-24, Light Blue (Right Diagonal): 25-34, Turquoise (Vertical): 35-44, Green (Hexes): 45-54, Light Green (Dots): 55-64, Yellow (Horizontal): 65+.

The implication is that museum visitors might benefit from a targeted explanation of how 3D printing functions when incorporating replicas into museum exhibitions. This may be particularly beneficial in the case of younger visitors, who appear to be less likely to have an understanding of the technology.

4.4.2 Q2: Have you ever encountered tangible 3D printed replicas in a museum before?

In terms of prior experiences tangible 3D printed replicas (Fig. 4.5), the overwhelming majority of sampled visitors expressed that they had never encountered tangible 3D printed replicas (81%) compared to a considerably smaller proportion who stated that they had (6%). The remaining percentage stated that were not sure, the majority stating that they might not have been aware that they had handled tangible 3D printed replicas (10%) while the remainder stated that they could not remember if they had or not (3%).

Of those who responded yes, only 1% stated that they had encountered tangible 3D printed replicas in other museums, while 3% had encountered them previously within the OUMNH on a previous visit. A further 1% had encountered them as a design prototype for a museum. Another 1% had encountered tangible non-replica 3D prints, simple shapes used to demonstrate the technology.

Of those who responded no, the majority (74%) stated that they had never encountered them in any shape or form while 5% stated that they had never encountered them, but rarely visit museums anyway. A further 1% had only seen 3D printing in a museum while another 1% had only touched replicas outside of a museum.

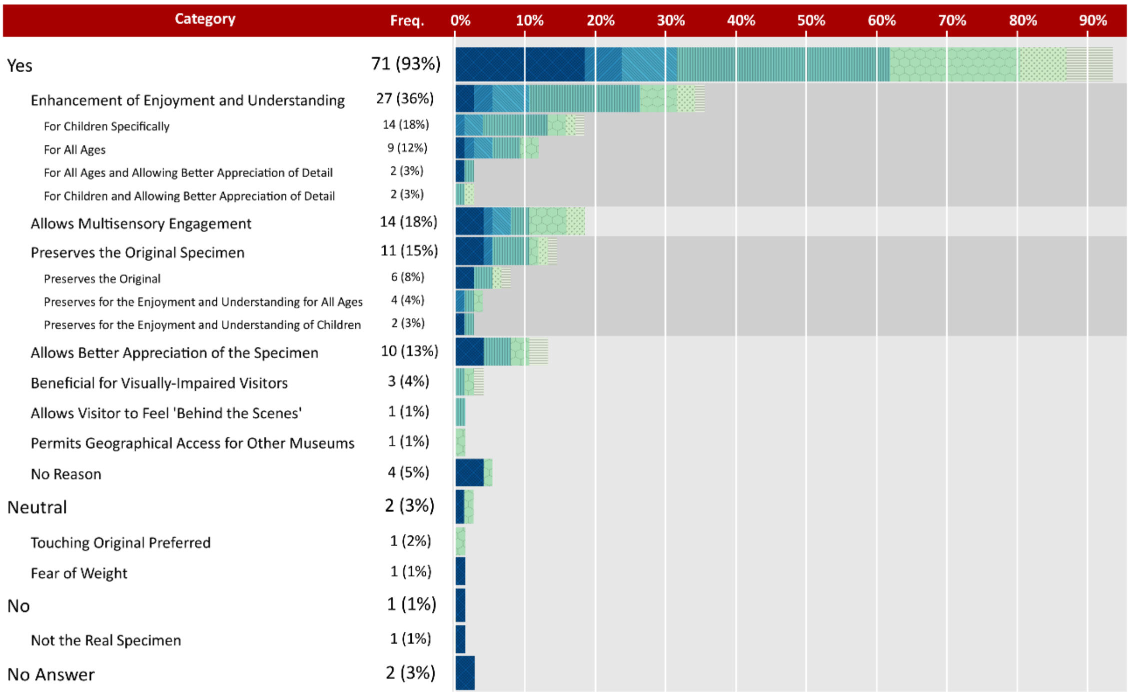


Fig. 4.6: Q3: Do you think that handling tangible 3D printed replicas like these could enhance your museum experience?: Coded responses to visitor's opinions on whether or not tangible 3D prints would enhance their museum experience. Colours represent age categories: Royal Blue (Cross-hatched): 08-17, Blue (Left Diagonal): 18-24, Light Blue (Right Diagonal): 25-34, Turquoise (Vertical): 35-44, Green (Hexes): 45-54, Light Green (Dots): 55-64, Yellow (Horizontal): 65+.

Overall, the vast majority of sampled participants had not encountered tangible 3D printed replicas within a museum before and of those who had, only 60% had encountered them on the exhibition floor. This suggests that, as can be associated with the sparse literature on the topic, that tangible 3D printed replicas have been encountered by few museum visitors so far.

4.4.3 Q3: Do you think that handling tangible 3D printed replicas like these could enhance your museum experience?

The vast majority of sampled participants thought that tangible 3D printed replicas could enhance their museum experience (93%), in comparison to only 1% who thought that they would not. Another 3% responded neutrally, saying that it might but with a caveat. 3% responded with an answer too vague to be categorised (Fig. 4.6).

The most common reason for thinking that tangible 3D printed replicas would enhance their museum experience was that it would enhance both their enjoyment and understanding of exhibition content (36%). This category can be further broken down, most stating that it would enhance the enjoyment and understanding of children only (18%), for all age groups (12%), for all age groups while also allowing better appreciation of detail (3%) and specifically for children whilst also allowing better appreciation of detail (3%). The next most common reason was that it allowed normally banned multisensory engagement with the objects in the museum collection (18%). The next most popular reason was that it would also preserve the original specimen, allowing visitors to interact with the object whilst also avoiding damaging it (15%). This category could also be broken down further, 8% of these respondents simply stating that it preserves the original, 4% stating that it preserves the object while also enhancing visitor's enjoyment and understanding for all age groups and ~3% for children specifically. Another significant portion of participants responded that interacting with a 3D print allowed them to better appreciate the specimen and its normally unobservable detail (13%). A number of other minor reasons were stated for tangible 3D printed replicas enhancing the museum experience, including it being beneficial for blind and partially sighted (BPS) visitors (4%), allowing visitors to feel like they are accessing aspects of the collection not normally in reach or 'behind the scenes' (1%) and permitting geographical access to specimens to other museums and enhancing other museum visitor's experiences (1%). 5% of respondents who replied 'yes' were unable to supply a valid reason.

For neutral respondents, responses fall into only two categories; the first being that while tangible 3D printed replicas might enhance their experience, they'd much prefer to touch the original (2%). The second response was that while they might enhance the visitor's experience, there would be a fear of damaging the print (1%).

Only one participant responded no, citing reasons that because the specimen was not the real one, it was not interesting enough and so would not enhance their experience. This participant belonged to the 8-17 category which could highlight that this might be more of a concern for younger visitors. No notable trends are apparent among age groups.

4.4.4 Q4: Do you think that tangible 3D printed replicas like these should be present in more museums?

As before, the majority of respondents expressed a desire to see tangible 3D prints in more museums, 80% responding yes (Fig. 4.7). 14% responded neutrally, citing concerns over the practicalities associated with introducing such prints but would otherwise welcome them. 4% cited specific concerns that would need to be alleviated in order for them to be implemented in more museums while, again, only 1% of participants did not want to see them in more museum. 1% of visitors did not provide a valid response.

For participants who responded yes, the most common reason cited was, again, that it would enhance their enjoyment and understanding of museum content (32%), 18% of these stating for people of all age groups while 14% stating for children particularly. 11% cited that it would permit multisensory engagement with the museum. 8% stated that it would allow better

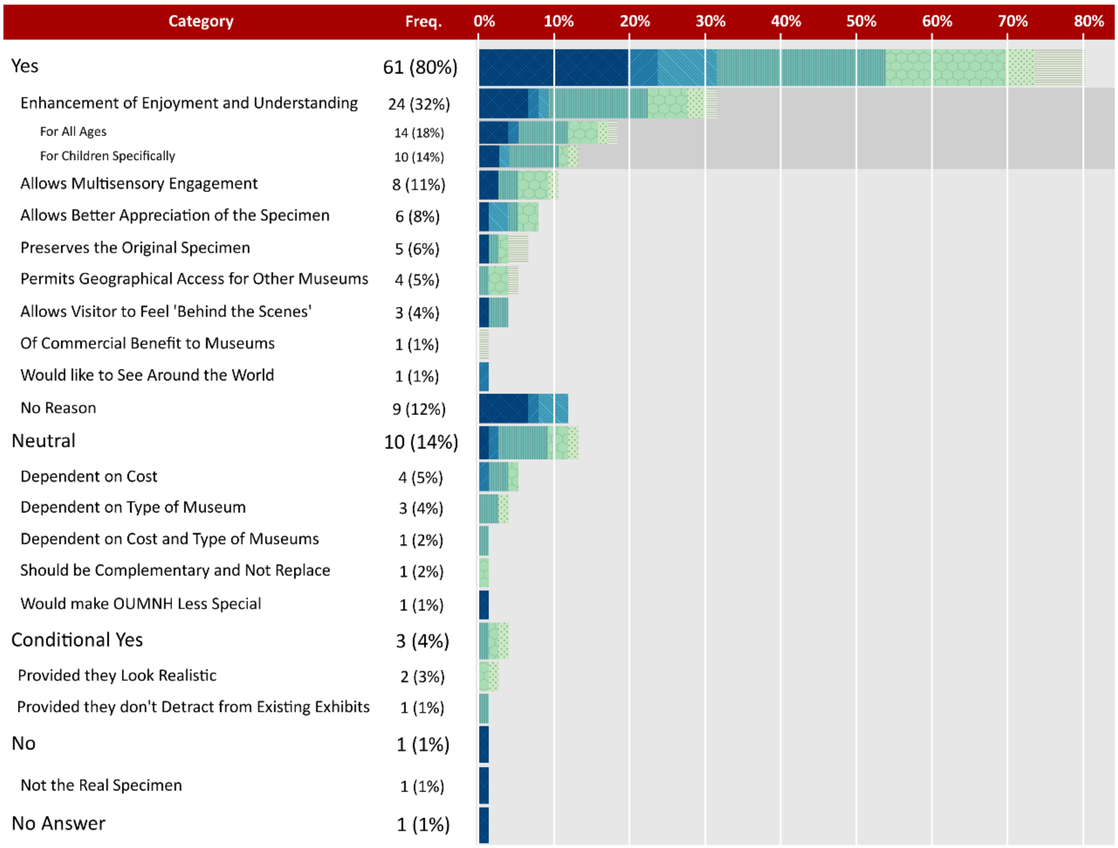


Fig. 4.7: Q4: Do you think that tangible 3D printed replicas like these should be present in more museums?: Coded responses for museum visitors opinions on whether or not they would like to see tangible 3D prints in more museums. Colours represent age categories: Royal Blue (Cross-hatched): 08-17, Blue (Left Diagonal): 18-24, Light Blue (Right Diagonal): 25-34, Turquoise (Vertical): 35-44, Green (Hexes): 45-54, Light Green (Dots): 55-64, Yellow (Horizontal): 65+.

appreciation of the object while another 6% stated that it would help to preserve the original specimen while permitting multisensory interaction. Other reasons included increased geographical access to objects from around the world (5%), allowing visitors to feel ‘behind the scenes’ and interact with collections (4%), potential commercial benefits for museums themselves (1%) and wanting to see such technologies applied around the world (1%). 12% of these participants did not provide a valid reason for stating yes.

For neutral responses, the most commonly cited reason was that of cost concerns, that while they would like to see them in more museums, they might be too expensive for museums to implement (5%). The next most common reason was that of the type of museum, that tangible 3D printed replicas would not be suitable for all types of museums (4%). The next was a combination of these two, that cost concerns and museum type should be taken into consideration (2%). Other reasons included that such tangible 3D printed replicas should never replace the existing exhibits or genuine items (2%) and concerns over the fact that having tangible 3D prints in more museums would make the OUMNH less unique (1%).

For participants who replied yes under certain conditions, the most common reason was that they should look as realistic as is feasibly possible (3%) and that they should not detract from the existing exhibits (1%).

Finally, again only one respondent replied negatively (1%), citing repeated concerns that because the prints were not the real specimen, they were not interesting. This response was again in the 8-17 age category, and no other notable trends are observable in the age groups.

4.4.5 Q5: Would the opportunity to handle such 3D printed replicas encourage you to visit museums more or less often?

Overall, participants responded positively to whether or not tangible 3D printed replicas would change their visiting habits with 62% of visitors responding that they would visit museums more often if they were present, 30% who stated that their visiting habits would not change and only 1% who would visit less often. 7% did not provide a valid answer (Fig. 4.8).

For visitors who stated that they would visit more often, the most commonly cited reason was that it would enhance their enjoyment and understanding of exhibition content (25%), again divided into whether it would benefit all age groups (8%) or benefit children specifically (17%). The next most common reason was that it would allow multisensory engagement with exhibition content and thus would encourage more frequent visits (15%). The ability to better appreciate the specimen (8%) and the preservation of the original specimen (3%) were again both cited as reasons to visit the museum more often. Other minor reasons also included that they would encourage more visits provided they were sufficiently advertised (1%), that they would make visits longer and more worthwhile (1%) and would fuel an active interest in the technology of 3D printing (1%). 8% of participants stated that tangible 3D printed replicas would encourage them to visit more often, but did not provide a specific reason.

A significant proportion of visitors reported that tangible 3D prints would not change their visiting habits, the most commonly cited reason being that while it would enhance the actual visit itself, it would be unlikely to alter their visiting habits (9%). This was tied with the importance of the subject matter of an exhibit being of far more importance for drawing the visitor, rather than the presence of tangible 3D printed replicas alone (9%). Other visitors stated that the presence of tangible 3D printed replicas would influence their choice of museum and where to visit, but not necessarily the frequency of their visits (5%). Others mentioned that they already visited museums a lot and therefore could not visit any more often (3%). Other reasons included the limitations of time on the frequencies of visits and finding

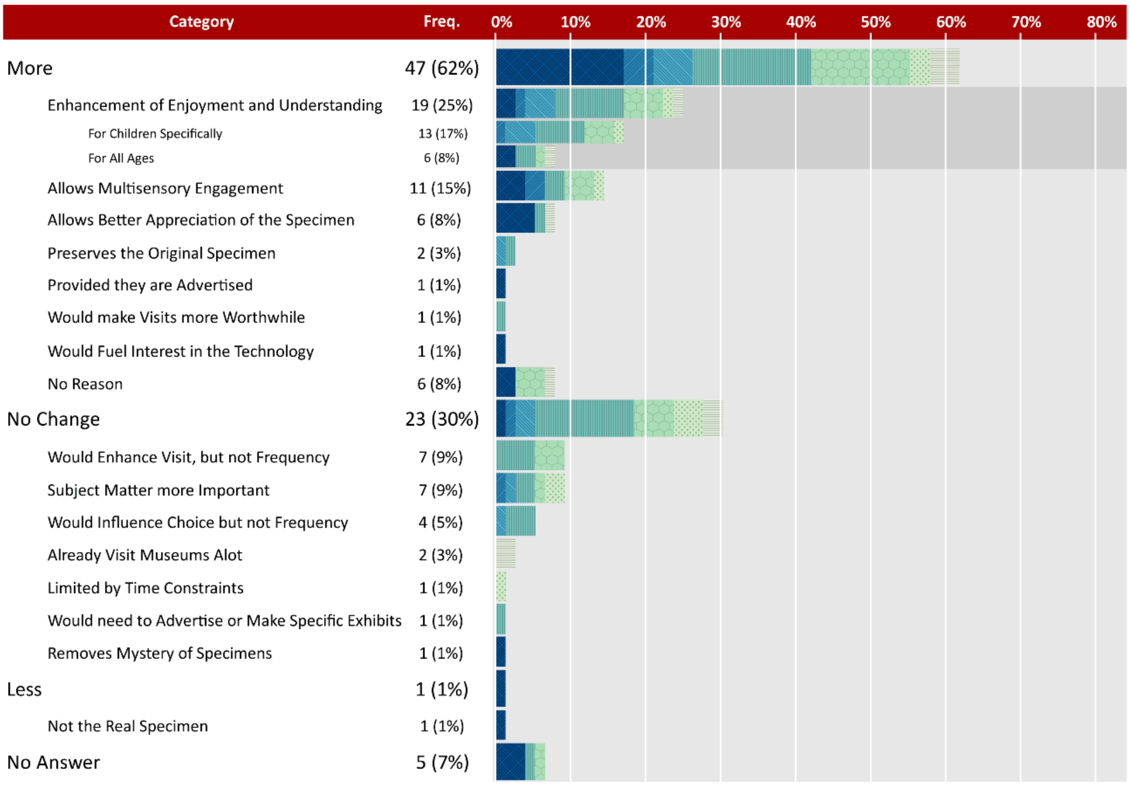


Fig. 4.8: Q5: Would the opportunity to handle such 3D printed replicas encourage you to visit museums more or less often?: Coded responses for visitor's opinions on whether or not tangible 3D printed replicas would influence their visiting habits. Colours represent age categories: Royal Blue (Cross-hatched): 08-17, Blue (Left Diagonal): 18-24, Light Blue (Right Diagonal): 25-34, Turquoise (Vertical): 35-44, Green (Hexes): 45-54, Light Green (Dots): 55-64, Yellow (Horizontal): 65+.

the time to come to the museum (1%), the necessity for advertisement of the creation of specific exhibits incorporating this technology (1%) and the removal of the aura of mystery and interest about certain specimens (1%).

As before, only a single visitor replied that they would visit museums less often (1%), citing reasons that because the tangible 3D prints were not the real specimen, they were less interesting.

Among age groups, the only notable trend was that the majority of younger visitors in the 8-17 age category (72%) expressed that they would be more likely to visit museums if tangible 3D printed replicas were present. However, the only response for visiting less if they were present also in this age category, suggesting that there may be some dissension among younger visitors on the subject of tangible 3D printed replicas.

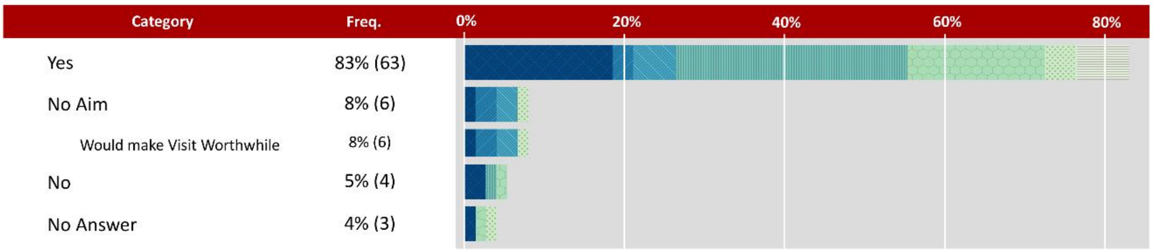


Fig. 4.9: Q6: Do you feel that interacting with 3D printed replicas like these could help you to achieve what you set out to do today?: Coded responses for whether or not museum visitors thought that tangible 3D prints could help them achieve the purpose of their visit. Colours represent age categories: Royal Blue (Cross-hatched): 08-17, Blue (Left Diagonal): 18-24, Light Blue (Right Diagonal): 25-34, Turquoise (Vertical): 35-44, Green (Hexes): 45-54, Light Green (Dots): 55-64, Yellow (Horizontal): 65+.

4.4.6 Q6: Do you feel that interacting with 3D printed replicas like these could help you to achieve what you set out to do today?

When asked if visitors thought that interacting with such tangible 3D printed replicas could help them to achieve the aim of their visit, the overwhelming majority of interviewees responded positively. 83% responded yes, only 5% responding no, 8% responding that they had no real aim or objective for their visit while 4% did not supply a valid response (Fig. 4.9). Of those who responded that they had no real aim, when asked if these replicas would make their visit worthwhile, all (8%) responded that it would while none responded that they would not. No particular trends are notable amongst the age groups.

4.4.7 Summary

In summary, a number of conclusions about museum visitor's thoughts about the subject of tangible 3D printed replicas can be drawn:

- The majority of the sampled museum visitors had heard of 3D printing technology, but more than half had a limited understanding or were able to provide only simple conceptions of how it worked. Only a small fraction had had any proper interaction with the technology. Lack of understanding is notable among younger visitors.
- A very small proportion of the sampled visitors had encountered tangible 3D printed replicas in museums before, suggesting that this approach is not being widely exploited in many British museums at this point in time.
- The sampled museum visitors, in general, proved to be very receptive to the concept of tangible 3D printed replicas in museums. The majority of participants stated that they would enhance their museum experience, would like to see them in more museums and

would be encouraged to visit more frequently. The most common reasons cited were that of enhancing the enjoyment and understanding of the exhibitions, the ability to engage with collections using multisensory interaction, the ability to appreciate the object or specimen in more detail than normal and the ability to interact with an object without risking damaging it. However, nearly a third of visitors responded to Q5 that tangible 3D printed replicas would not change their visiting habits, suggesting that such replicas are unlikely to draw visitors in purely by themselves.

- The majority of sampled visitors thought the tangible 3D prints could help them to achieve the purpose of their visit.

4.5 DISCUSSION

4.5.1 The Multisensory Perspective on Exhibition Practice

Overall, the sampled museum visitors responded positively to the idea of tangible 3D printed replicas and their introduction into the museum. The vast majority thought that they could enhance their museum experience and would indeed like to see them in more museums. Many also thought that they might even encourage them to visit museums more often and help them to achieve the overall aims of their visit. Many of the interviewed participants also provided positive comments and feedback on the concept of tangible 3D printed replicas:

"It's awesome"

Cox (8-17)

"I think it would make it more enjoyable. And, like, it's easier to learn from something that you can physically look at and touch, apart from instead of things behind glass because you wouldn't remember it as much as being able to handle something"

Molly (8-17)

The reasons most commonly cited for this positivity generally converged under a few common themes, typically that they would enhance enjoyment and understanding of exhibition content, as is highlighted by Molly's comment above. The enabling of multisensory interaction was also a common thread, as was the ability to interact with the specimen without risk of damage, to better appreciate the specimen and also, though less common, the sense of feeling 'behind the scenes' and accessing something not normally available for interaction by museum visitors. These reasons, that of unprecedented tangible access to replicas of rare objects, were strongly apparent from the responses of participants:

"Yeah, it's great that you can touch it. So imagine that, under normal circumstances, you wouldn't be able to touch it. Around the museum there's signs everywhere saying don't touch anything"

Nansen (35-44)

They could also increase the attractiveness of specific objects, as in the words of Monid:

"Yeah funnily enough, because we were looking at some of these fossils down the back end weren't we earlier on and looking at that [in reference to the cast], you'd probably just give it a fairly cursory glance, you know, this cast… But you know if you had stuff like this with those there [in reference to the 3D prints] and said this is what it was like, that'd make it much more attractive as an exhibit."

Monid (45-54)

It also brings objects to life, more so than they would be behind a glass case:

"And it just brings it more to life. Because behind a glass sheet its fine to look at but you just want to, I think maybe its human instinct you just, you go 'Well, what does it feel like? I can see it but what's the texture of it? How?'"

Malta (35-44)

Finally, it allows more thorough engagement with an object that can be beneficial for both for adults and for children:

"Yeah, it's more dynamic and appealing, I think. If you get to hold something you make that connection and that's about learning. You are going to learn. More people will have that ability to learn things."

Nina (45-54)

"I'm a childminder so I work a lot with young children and they need to touch things to get an idea of scale and weight and all those kinds of things. It makes a huge difference to their learning."

Skimble (25-34)

All of these comments highlight the 'glass-case paradigm' discussed within the literature review (*2.2.1 The Exile of the Senses*), the prevailing mode of museum display that mandates the presence of a barrier, typically a glass display cabinet or distance to ensure that visitors do not try to touch fragile museum specimens. Some are more psychological than physical, such as forbidding signage placed regularly around exhibition halls mandating that visitors 'Do not

Touch' or museum staff placed as arbiters to prevent unsolicited touch (Dudley, 2012a; Kreps, 2015; Candlin, 2017). Modern museum practice is dominated by this form of display which remains an impassable barrier to the introduction of multisensory interaction into the exhibition hall which is now strongly being supported and forwarded by many practitioners (Dudley, 2015; Levent and McRainey, 2014, Kreps, 2015). The evidence for the benefits of multisensory interaction have already been discussed and these frustrations were echoed by many of the interviewed visitors:

"I think being able to physically handle the object makes it come alive that little bit more. Rather than just being able to look through the glass cabinet like you've got around here doesn't make it real. You don't have the full sensory engagement that you do with stuff like this."

Rosetta (25-34)

"Because for children I think it can be quite boring to just wander around and look at things and I think, depending on the type of child as well, my son was taken to the [Art Gallery] on Friday by my dad, who is an artist. And they came home, both disappointed because [my son] couldn't touch anything. So he was just bored and he complained the whole time and my poor dad thought 'Oh no!'"

Michael (35-44)

Overall, the sampled museum visitors positively embraced the idea of multisensory interaction with 3D printed replicas as an alternative to just looking at a specimen behind a glass case. There was a consistent negative voice however that needs to be addressed. One participant expressed frustration with the 3D prints, stating that:

"This [is] just 3D printed. That's real and this is not. So that's going to make the children upset maybe because they didn't think that they are real. Because I think that things need to be real."

Meryl (8-17)

This participant did not like the 3D prints, namely because they were not the genuine articles and thought that the prints would be less interesting than the real specimen itself. This participant belonged to the 8-17 category, which may suggest that the question of authenticity and what is real may be a concern for younger museum visitors. Visitors below the age of 8 were not sampled, so it is difficult to tell from this study, but could represent a potential future research focus. Psychological experimentation into the perception of reality of younger children shows that the perception of what is real or unreal primarily depends on developmental stage and that younger children do have difficulty in interpreting authenticity which changes longitudinally (Evans, 2002; Bunce and Harris, 2013; Bunce, 2016). Further research may yield important insights into how younger museum visitors consider tangible 3D printed replicas. This question seems to be of wider concern within cultural heritage and is a topic that requires further exploration (Dillon et al. 2016; Land-Zandstra et al. 2018).

However, it must be taken into account that it is unlikely that the introduction of tangible 3D printed replicas is a definitive way to attract visitors. While the majority of visitors stated that they would encourage them to visit more often, a third of the sampled visitors stated that it would not change their visiting patterns, suggesting that tangible 3D prints are not a de facto method of attracting visitors. Visitors thought that while they would enhance their visits, there were other more important considerations that would need to be taken into account, such as time constraints on visits and the subject matter of exhibitions that would be of greater priority.

4.5.2 Presenting Tangible 3D Printed Replicas

The ideas and comments brought up within the interviews also raise a number of concerns over how museum professionals can present tangible 3D printed replicas to visitors. Many visitors articulated specific opinions over preferences in how they would like to see tangible 3D printed replicas displayed and also in terms of their appearance and tangible properties. These need to be taken into account in order to create the best possible experiences, failure to do so risking confusion or displeasure on the part of the visitor.

One prime consideration is the familiarity of visitors with 3D printing and their understanding of the technology. Q1 and Q2 covered the visitor's knowledge of 3D printing and their experience with handling them, finding that most visitors had heard of 3D printing but around half didn't understand it, in addition to relatively few visitors having handled tangible 3D printers in museums previously. In order for visitors to properly understand what they are touching, the fact that these objects are 3D printed must be plainly advertised in order to avoid deception. Exhibitions should declare how the replica is related to the original specimen both in terms of its scaling and how it was made. An explanation of how the technology operates, particularly for younger visitors, may also benefit museum visitors, allowing proper understanding of how it was made alongside learning about the object itself. This might be best articulated in the form of labelling near the replica, incorporating both information about the object and how it was made, to ensure that visitors clearly understand the object, as articulated by Aglioman:

"I think all I would say is if you are then going to be exhibiting things like this for them to touch, I … think you then need to have, just a bit of explanation, or quite a bit of explanation that as adults you can feed in. If this is supposed to be the real size,…, you want to say that and I think even when we look at these here, sometimes if you are not particularly knowledgeable you want to look up and the question is going to be, is this real or is this a cast?"

Aglioman (45-54)

Given the general restriction on touch, museum visitors may also need to be 'trained' to handle such replicas. Even on objects marked 'Please Touch', visitors will often still have reservations about handling objects through a basic fear of damage and blame. Articulating plainly that such tangible objects are in effect 'valueless' should encourage visitors to more readily handle such objects.

Another important consideration apparent from visitor responses was the strength of preference towards specific 3D prints over other ones. Many participants mentioned this topic without provocation during the interview process, often with strong conviction. Some preferred prints that allowed them to clearly see and observe the features of the object:

"I very much visually like this white against the resin but if I were trying to interpret the thing based on not being able to see the white versus the see-through [referring to the Clear Resin print] then the different colours would be good. Oh god. Don't use extrusion. The blue one is bad"

Lucretia (35-44)

Others focussed much more on realism and many thought that the more authentic and realistic looking the 3D prints were, the better, as in the words of Bismark:

"Oh actually, the only thing I would say is with the resins and the plastics, I'm holding the blue one now, I'm not so keen on the ones that look a bit, well not fake, but a different colour. I think they look a bit tacky almost, whereas the ones where you've got the right colour, it might take a bit of touching up and a bit of artistry and artistic license to get people to warm to them, to question whether or not they are fake or real."

Bismark (25-34)

Others forwarded that both the weight and the thermal properties would also be important when handling these objects, again encouraging them to be as close to the real objects as is physically possible:

"It would be really good if you could handle ones that were a similar weight and feel to the original"

Douglas (25-34)

"I also mentioned before the recording was on about the thermal properties of the things you are touching. Because when you get to look at them, you get to look and see if something is definitely made of rock. … being able to look is different from being able to feel it and to be able to just feel that it's cold, is a new and interesting thing and you don't have the fineness that you might get with a plastic print but you do have the feeling of heaviness…"

Lucretia (35-44)

The ramification of this is that the nature of the 3D print matters to the visitor. How the print is made, what it's made of and its finishing may influence the hedonic experience of the museum visitor. As a result, it is important to then provide the material that best complements the object, considering the fact that our interpretations of physical properties based off sight often deviate from the actual tactile properties of an object, as discussed in the literature review (*2.3.1 Multisensory Experiences*). This seems to be congruent with the views of some of the participants above but unfortunately, few studies exist at this point exploring this topic (Neumüller et al. 2014). Candlin (2003) highlights the preference towards verisimilitude in the blind and partially-sighted (BPS) in interviews, in which one interviewee expressed the importance of the physical properties of an object:

"You don't just look at shape and form, you look at the texture of thing's temperature, you are sensing all of it so you know, cold for bronze work maybe if it is inlaid in different grains…"

Candlin (2003)

Contrarily as discussed in the literature review, Di Franco et al. (2015) carried out a comparison between different display media; glass-cases, power wall displays and tangible 3D printed replicas. The authors found that the authenticity of a display medium took a backseat to the opportunity to learn and gain knowledge, representing a contrast to the results found in this study. Lindgren-Streicher and Reich (2007) carried out a similar study, comparing different forms of display methods in two workshop setting, including real artefacts, visitor-made design prototypes, 3D printed replicas, toy replicas and computer simulations. They found that the sampled visitors used the prototypes the most while the 3D printed artefacts were used less than the real artefacts, computer simulations being the least used across both examples. This shows also that 3D prints do not appear to be *de facto* the default choice for interaction. This highlights a lack of research within this subject area which could potentially be extremely informative for helping exhibition designers create desirable experiences with tangible 3D printed replicas and how to best exploit the rapidly emerging field of 3D printing within cultural heritage and the multifaceted considerations when it comes to choosing materials.

4.5.3 Limitations

While this study has explored insights into museum visitor opinion on tangible 3D printed replicas, there are a few issues which need to be accounted for. First and foremost, these findings are not wholly generalizable. An absence of young adult and older visitors in the sampling demographic under-represents these essential parts of the museum audience, who did not appear to be attracted to the workshop format. Some form of random or systematic sampling would overcome these issues, but were not approved in the ethical process.

The sample also represents the opinions of a small proportion of the audience at the OUMNH. A larger scale quantitative study looking into wider opinions of the visiting public could further provide support for the findings of this chapter, providing a more generalizable interpretation of museum visitor opinions on the subject of 3D printed replicas.

Furthermore, the overwhelming positivity could be associated instead with the so-called 'positive evaluation phenomenon' (*2.5.1 Museum Evaluation*), a fear of the interviewees to criticise the work of the interviewer. Thus, the suggested questionnaire-based quantitative study may be able to yield more accurate insights into visitor opinions on the technology.

4.6 CONCLUSIONS

In conclusion, an interview study into the opinions and understanding of tangible 3D printed replicas of museum visitors shows strong support, finding that:

- The vast majority (98%) of sampled visitors had heard of 3D printing but only half had any form of understanding of the technology whatsoever. Few of them had ever encountered tangible 3D printed replicas. Overall, the lack of knowledge and experience with 3D printing and handling such replicas need to be taken into account when designing applications, incorporating information that plainly explains 3D printing and how it was made.
- The sampled museum visitors thought that tangible 3D printed replicas could enhance their museum experience and thought that they should be present in more museums. While a significant proportion (60%) thought that they would encourage them to visit more often, just under a third (30%) thought that they would not and that interest and time considerations are a stronger influence. This could be associated with the positive evaluation phenomenon however.

- The only negative feedback was in the form of a younger visitor who did not like the prints because they were not the real object, indicating that this might be a concern for younger visitors. The majority of visitors, however, thought that the prints would enhance their enjoyment and understanding of exhibition content, would allow them to better appreciate the artefact, preserve the original specimen and allow them to engage using multiple senses.
- The use of tangible 3D printed replicas in museums is relatively understudied, leaving a void in research particularly with regard to the preference of museum visitors with regard to the aesthetics and physical properties.

5.0 VISITOR PREFERENCE FOR THE PHYSICAL PROPERTIES OF TANGIBLE 3D PRINTED REPLICAS

5.1 PUBLICATION RECORD

The results of this chapter have been published in the following peer-reviewed article:

Wilson, PF, Stott, J, Warnett, JM, Attridge, A, Smith, MP, Williams, MA. 2018a. Museum visitor preference for the physical properties of 3D printed replicas. *Journal of Cultural Heritage*, 32: 176-185.

5.2 INTRODUCTION

Thus far, the general implications of museum practice with regard to tangible 3D printed replicas have been discussed. It has been found that the sampled museum visitors were accepting of the permanent provision of tangible 3D printed replicas within museum exhibitions and that they could enhance their museum experience. A number of unexpected research topics emerged from this study as a by-product but albeit crucial to the handling experience. These concerns, if not properly taken into account, could significantly impact the hedonic experience of the visitor with a tangible replica. It could also influence what is learned or cause misconceptions, an occurrence that runs contrary to the educational role of the museum. If a visitor encounters an unfamiliar object in an off-colour, or with print imperfections, they may come away with an impression that these properties are also present in the original. This is highly likely to impact the pedagogical goals of an exhibit and thus undermine the educational role of the museum. This must be taken into account to ensure that handling experiences are both enjoyable and informative.

In the last chapter, the potential considerations of displaying tangible 3D printed replicas to audiences and the potential impact that this could bring were discovered (*4.5.2 Presenting Tangible 3D Printed Replicas*). A major topic that emerged from that discussion was the physical properties of the prints used in the study, namely in terms of the realism of the print itself, its thermal properties and weight. These aspects of the prints made some of the sampled visitors display preference towards one over another, with many of the visitors saying that realistic, more authentic looking 3D prints were preferred. This is a key but poorly explored topic within the wider literature, the aforementioned studies in the literature review yielding relatively little in the way of robust analysis of this phenomenon (Candlin, 2003; Lindgren-Streicher and Reich, 2007; Di Franco et al. 2015; Balletti et al. 2017), least of all directly addressing the subject of 3D printing as has been previously discussed. The implications for practice are severe however as highlighted above and are likely to have a considerable effect on the quality of the handling experience, the desirability of an object for handling and the educational outcomes for visitors who engage with a replica. A negative experience may dissuade handling all together in the future. Thus, this subject needs to be researched in more detail to ascertain what aspects of the physical handling experience are most important to the museum visitor.

This chapter will attempt to do just this, analysing museum visitor's preference towards the physical properties of tangible 3D printed replicas. This is done using a robust mixed-methods approach utilising analysis of variance (ANOVA), correlative analysis, exploratory factor analysis and content analysis to break down the physical properties of tangible 3D printed replicas and evaluate what particular attributes are most important for a desirable handling experience.

5.3 METHODS AND MATERIALS

5.3.1 Research Questions and Design

The purpose of this study was to further explore the issue of the verisimilitude and the physical properties of 3D printed replicas. The study was designed to coax apart this complex multisensory design problem and to determine which properties were most essential to visitor preference. The main research question that this study attempted to answer was:

What design considerations need to be taken into account in order to create user-friendly 3D printed replicas for sighted and BPS audiences?

The study was thus designed around answering a number of sub-research questions on this theme:

- What properties of 3D prints do participants want prioritised in tangible 3D printed replicas?
- Do material preferences change depending on the type of visitor?
- What properties result in undesirable handling experiences for visitors?

In order to study and answer these research questions, a quantitative questionnaire-based approach was adopted in order to identify which physical properties were of greatest importance to museum visitors.

A semantic differential method was employed, allowing the definition of each physical property on an interpretable continuous spectrum between the extreme forms of that property. Semantic scale schemes are typically created in a number of different ways, either from theoretical practice and previous research (Slater and Narver, 2000; Kang and Zhang, 2010), by arbitrary definition based upon the needs of the research project (Wellings et al. 2010; Huang et al. 2012) or via inductive definition from the target audience (Dickson and Albaum, 1977; Hsu et al. 2000; Ding and Ng, 2008), in some cases using multiple approaches (Polizzi, 2003). In this case, given the overall lack of research into physical properties of 3D prints with no strong research background to draw from, inductive creation of categories was chosen.

The adopted approach bears similarities to the primary interview approach of Low and Lamb Jr. (2000) among other authors. Interviews were carried out in the same manner as in the previous chapter, using 15 participants with no demographic information collected. This interview instead asked participants to describe each of the six 3D prints in terms of their physical properties; especially the texture, weight, material properties and aesthetic qualities. These descriptions were recorded, transcribed and subjected to keyword analysis using NVivo 11 (QSR). The most commonly used adjectives, descriptive nouns and verbs were extracted and used to create a shortlist of 20 opposing word pairs for the semantic scales. If a word did not have a counterpart that emerged during the interviews, a logical word was chosen based on antonyms listed in an online dictionary.

This shortlist was then subjected to a pilot testing stage and reliability analysis using Cronbach's alpha to select the most reliable scales for the proper analysis, using participants from colleagues, friends and family (n = 26). All scales met the minimum reliability criteria of 0.7, ranging between 0.7 - 0.8 (Tavakol and Dennick, 2011; Field et al. 2012). Only in the stainless steel print reliability was insufficient (Table 5.1). The twelve most reliable and informative scales were then picked for use in the questionnaire; Good Quality – Bad Quality, Unclear – Clear, Cheap – Expensive, Soft – Hard, Light – Heavy, Weak – Strong, Brittle – Durable, Rough – Smooth, Glossy – Matte, Unrealistic – Realistic, Undetailed – Detailed and Boring – Interesting.

The questionnaire (Appendix 11.B) consisted of six sets of the 12 items listed above, one for each of the six 3D prints highlighted below (*5.3.3 Materials*). The participants were to fill out each of the 12 continuous scales for each print based upon where they thought it sat on the scales relative to the other five. The intent of this was to define the physical properties of each of the 3D prints for correlational and factor analysis.

The questionnaire also asked each participant to fill out another set of semantic differentials consisting of six items, each item being a scale of preference between Not Preferred – Preferred for each of the six 3D prints. They were asked to rate each print based on their preference. The intent of this was to provide information on the order of preference for correlational analysis, mean comparison and interpreting factor scores.

Finally, the participants were also asked to state which prints were their most and least preferred and provide reasons for their choices. The intent of this was to describe which prints were most preferred generally and the reasons why, in order to triangulate with the findings of the semantic scales. This data was analysed using content analysis.

5.3.2 Participants

The sampling method used in this study was similar to that used in the previous study (*4.4.4 Sampling and Data Collection*). A total of 140 visitors to the OUMNH were sampled using a convenience sampling approach using the same method as the previous chapter, taking place within the main exhibition hall as a workshop.

As before, the recruited participants were asked to read an information sheet detailing the questionnaire process and asked to sign a consent form confirming their agreement to take part in the study. A demographic form, collecting age and gender information was also filled out by each participant. As before, this process was approved by the University of Warwick BSREC ethics committee.

The collected demographic information is summarised in Fig. 5.1. Contrary to the last study, despite using an identical sampling method, the sample shows a greater proportion of females (58%; n = 79) relative to males (41%; n = 56). A small proportion chose other as their gender (1%, n = 1) and another small proportion chose not to disclose their gender (2%; n = 2).

The majority of the sampled participant belonged to the 08-16 (25%; n = 36), 35-44 (31%; n = 45) and 25-34 (14%; n = 19) age categories with other age groups making up a much smaller proportion of the sample. 45-54 is the next most represented age group (11%; n=16), with 17-24 (6%; n = 8), 55-64 (6%; n = 9) and 65+ (4%; n = 6) representing far smaller components. One participant chose not to disclose their age (1%; n = 1). As before, these distributions are likely a product of the sampling method used.

5.3.3 Materials and 3D Printing

The materials used in this study were identical to those used in the previous one, using the *Phascolotherium bucklandii* paratype dentary (OUMNH J.20077) and all of the 3D prints derived from the CT data used in that study (*4.3.1 Materials*).

Another print was added, bringing the total number of prints used in the study up to six (Fig. 5.2). This newer print was identical to the white resin 3D print, manufactured again on a Connex3 Objet260 MJ printer. However, this print was painted by the conservator at the OUMNH in order to make the object bear more realistic colouration as another condition for the procedure. As a result, the six prints used in this study were; the blue plastic print (FFF), the stainless steel print (SLS), the multimaterial resin print (MJ), the white resin print (MJ), the painted resin (MJ) and the colour sandstone (CJP/3DP) (Fig. 5.2b). These prints were selected to represent a range of different 3D printing technologies, levels of layer resolution and verisimilitude.

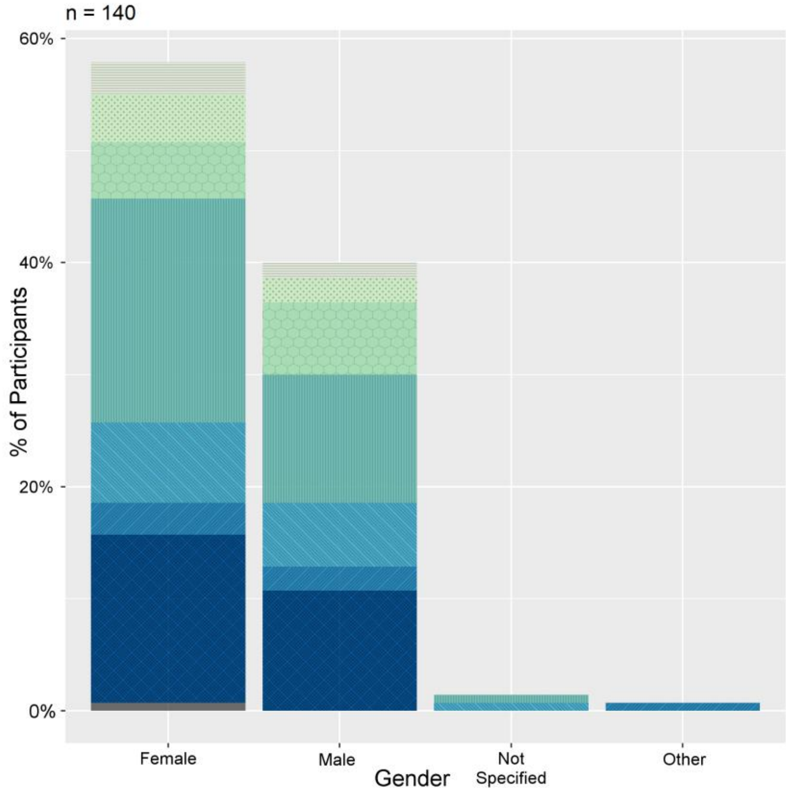


Fig. 5.1: Demographics of Sampled Participants: Gender and Age data for each of the 140 participants sampled in the study. Colours represent age groups: Royal Blue (Cross-hatched): 08-17, Blue (Left Diagonal): 18-24, Light Blue (Right Diagonal): 25-34, Turquoise (Vertical): 35-44, Green (Hexes): 45-54, Light Green (Dots): 55-64, Yellow (Horizontal): 65+.

5.3.4 Procedure

Following the recruitment process, the participants were guided through the questionnaire process. Before filling out the questionnaire, the participant was encouraged to handle each of the six 3D prints as they desired to get a good appreciation for the range of objects and to form their opinions. Once satisfied, they were then given the questionnaire and presented each print in a randomised order (Appendix 11.B). They rated each of the 12 continuous semantic differential scale items for the set corresponding to the print given (Q1). The scale headers were flipped for each scale randomly and they were randomly ordered to minimised order biases. Once they filled out the set, they returned the print and another was randomly assigned and the process repeated until all items for all prints had been filled out.

Next, the participants filled out of the six items of the second set (Q2) scale based on their preference for each print to be incorporated in an exhibition as a tangible component. The participants were also asked to provide which print they most preferred to see and why they preferred it (Q2a) and then their least preferred print and why they did not prefer it (Q2b).

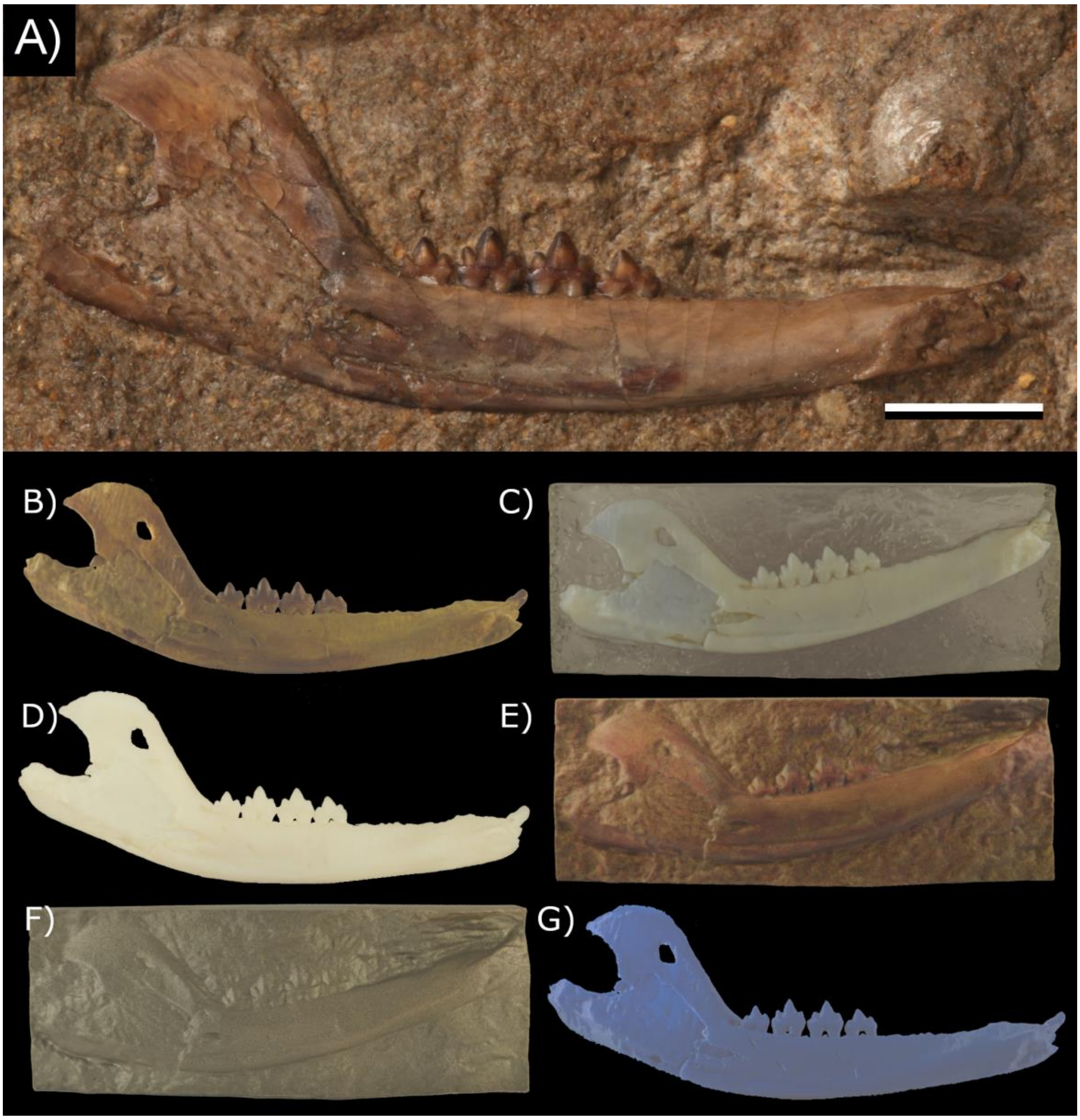


Fig. 5.2: ***Phascolotherium*** **and the 3D Prints:** A) *Phascolotherium bucklandii* paratype dentary, as used in the previous chapter. The six 3D prints used in the study. Five are the same prints used in the last study while another one was added (Painted Resin) to round out the materials. B) Painted Resin; C) Clear Resin; D) White Resin; E) Colour Sandstone; F) Stainless Steel; G) Blue Plastic.

The questionnaires were then manually processed, the scales being de-flipped and normalised for the purpose of consistency and converted into numerical values from the continuous scales, for both physical property scales (Q1) and preference scales (Q2). These scales were then subjected to correlational analysis, factor analysis and mean comparison with ANOVA-based methods. The preference and non-preference reasons were separated by participant and then subjected to content analysis.

Table 5.1: Cronbach's α Reliability of the Raw Semantic Scales

Semantic Scale Set	*Pilot Alpha* (α)*	*Final Alpha* (α)**
Clear Resin	.83	.69
Colour Sandstone	.78	.8
Painted Resin	.82	.72
White Resin	.85	.77
Blue Plastic	.75	.78
Stainless Steel	.68	.71
Average	**.785**	**.745**

* n = 26; ** n = 140 (Smooth – Rough and Glossy – Matte dropped)

5.3.5 Analysis

The data collected as highlighted above were analysed using a number of different qualitative and quantitative approaches. The Shapiro-Wilk normality test carried out across all data sets showed that all data was non-normal, and thus non-parametric methods were mandated. Data transformation was not carried out to achieve normality.

Three forms of statistical analysis were carried out on the different types of data collected. First of all, to ascertain which prints were most popular, raw scale values were examined and compared to their preference values and a Friedmann's ANOVA was carried out to determine if the prints had significantly different preference values from each other and any groupings. Friedmann's ANOVA was selected due to the non-normality of the data and because all participants were used in each of the six conditions, a repeated measures design (Field et al. 2012).

Next, in the physical property semantic scales were compared to the preference values of each participant using Spearman's ρ, again due to the non-parametric nature of the data. This was to identify certain physical properties that correlated highly with preference.

Next, the physical scales were subjected to exploratory factor analysis to determine how the physical scales clustered and to see if there were any underlying factors across the prints that could explain the opinions of visitors. Factor scores were also correlated with preference to identify how they related to preference.

Table 5.2: Mean Preference Values of 3D Printed Replicas

3D Print	*Mean* (x)	*SD* (σ)	*Group*
Painted Resin	80.5 ± 4.0	24.0	A
Clear Resin	78.8 ± 3.5	20.9	A
White Resin	73.3 ± 3.7	22.5	A
Colour Sandstone	49.1 ± 4.7	28.4	B
Stainless Steel	42.2 ± 5.1	30.8	B
Blue Plastic	25.8 ± 4.4	26.8	C

95% Confidence Intervals

Finally, content analysis was carried out on the positive and negative comments for the visitor's most and least preferred 3D print. Positive and negative comments were coded separately. First, the comments for each were examined to create a number of preliminary categories which were then refined to create a first phase coding scheme for both positive and negative comments. These were subjected to interrater reliability analysis using Krippendorff's α once again (Krippendorff, 2013) on 20% of the total responses (n = 29), each coder working independently. An initial α of 0.796 was computed, which could be viewed as an acceptable value based on some author's interpretations, 0.8 being the desired rating (Krippendorff, 2009; 2013). Both raters met up to discuss the issues with the coding scheme and to discuss disagreements found within the coded data and reconcile them. This reconciled data computed a much higher and acceptable α of 0.868, sufficiently matching the requirements of a reliable coding scheme.

5.4 RESULTS

5.4.1 Hedonic Comparison

The raw preference values were examined for each of the six 3D prints (Table 5.2). Each of the semantic scales has been converted into 100 point scales for ease of interpretation. Higher values indicate a tendency towards the right-hand variable. In order, the most preferred 3D print was that the painted resin ($\bar{x}$ = 80.5 ± 4.0), closely followed by the clear resin ($\bar{x}$ = 78.8 ± 3.5) and white resin prints ($\bar{x}$ = 73.3 ± 3.7). Significantly lower than this were the colour sandstone ($\bar{x}$ = 49.1 ± 4.7) and stainless steel prints ($\bar{x}$ = 42.2 ± 5.1) with the blue plastic 3D print being the lowest rated print at a lower value again ($\bar{x}$ = 25.8 ± 4.4). The three resin-based prints appear to have the highest preference ratings. Looking at the raw scale means for each of the 3D prints for each of the 12 physical properties (Fig. 5.3), these three resin prints rate particularly highly on a few scales, namely Bad Quality – Good Quality, Unclear – Clear, Unrealistic – Realistic, Undetailed – Detailed and Boring – Interesting (Table 5.3), these mean values being typically in the 70+ range. On the contrary, these values are much lower for the less popular prints, typically ~ 50, the blue plastic rating particularly lowly on the Unrealistic – Realistic scale. This highlights a few key variables that might potentially explain the preference of the sampled museum visitors. The stainless steel print shows a notable deviation from the other prints, with particularly high scale means on the attributes associated with toughness; Soft – Hard, Light – Heavy, Weak – Strong and Brittle – Durable. Given the stainless steel print's overall lower preference rating, these properties appear to be of lesser importance for the sampled museum visitors.

The differential frequency of most and least preferred prints was also examined (Fig. 5.4). The print with the lowest differential frequency was that of the blue plastic (n = -84), agreeing with mean print preference ratings. The stainless steel was the next with a much lower negative value (n = -23) which was followed by the colour sandstone (n = -8) and white resin with a low positive value (n = +6). The remaining two 3D prints, the painted resin and the clear resin had much higher positive differential frequencies, spaced by just under 50 and with similar values. The painted resin was one lower (n = +54) whereas the clear resin had the highest differential frequency (n = +55).

The raw preference values for each of the six prints were then compared using Friedmann's ANOVA, in order to ascertain to determine whether or not these differences in preference were statistically significant. The raw preference values were first tested using Shapiro-Wilk's test ($W = 0.89$, p = <0.001), which returned a significant result, indicating that the data was non-normal. Levene's test also showed that the data violated the assumption for homogeneity of variance (F (5,834) = 9.17, p = <0.001), that the variances in each group were significantly different from each other. As a result, robust, non-parametric methods were used, hence the selection of Friedmann's ANOVA as discussed in the methods section (*See 5.3.5 Data Analysis*) (McCrum-Gardner, 2008; Field et al. 2012).

Comparison of the preference values of the sampled participants using Friedmann's ANOVA found that there was a significant difference in preference values between the six replicas $\chi^2(5) = 293.4$, $p = < 0.001$. *Post hoc* tests using the Bonferroni correction identified critical differences between the different prints, dividing them into three different groups of clustered preference (Table 5.2 and 5.4) (Fig. 5.5). Group A consists of the three resin-based 3D prints, the painted resin, the clear resin and the white resin. Group B contains the two

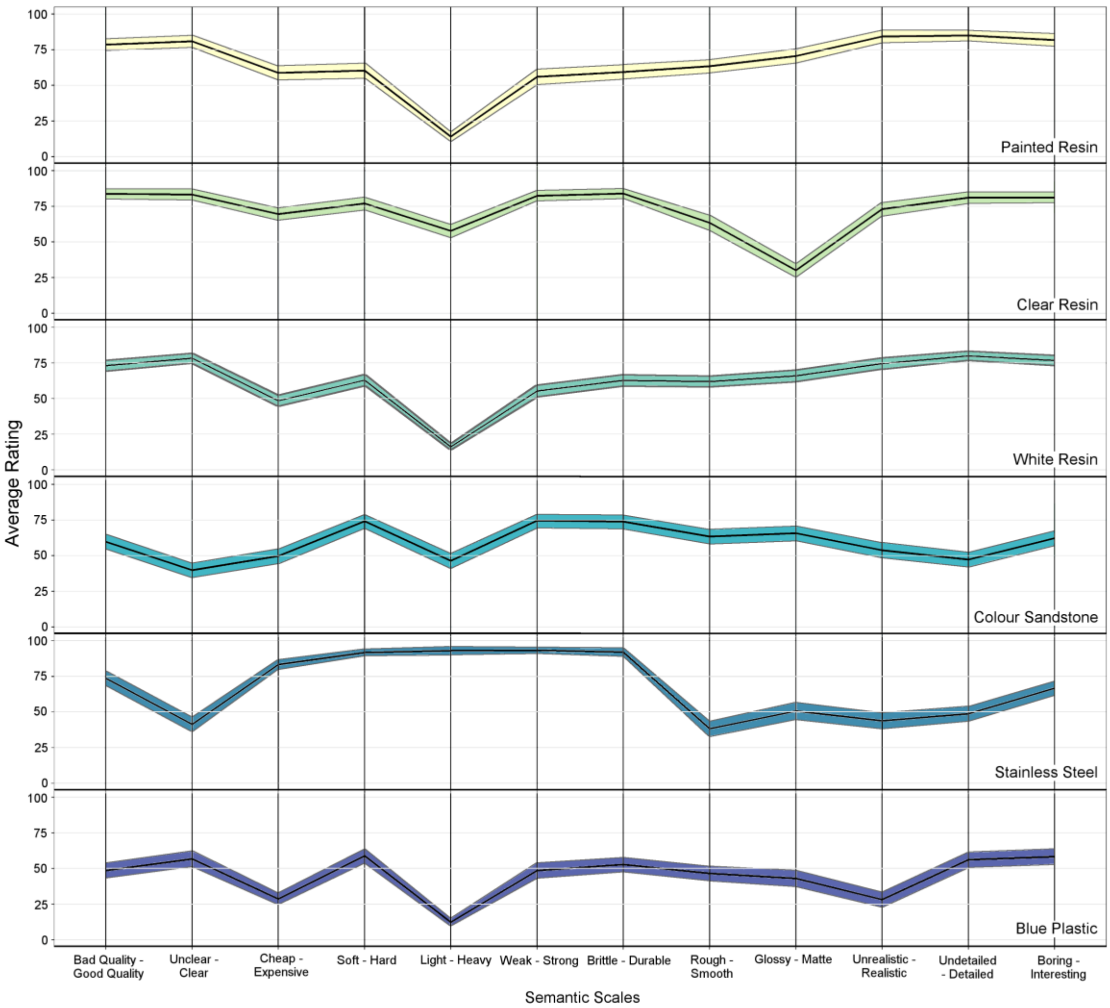


Fig. 5.3: Raw Semantic Scale Data for the Six 3D Printed Replicas: Raw scale means, with 95% confidence intervals supplied, for each scale on each 3D printed replica. Values again converted to 100pt scales for ease of interpretation. Colours represent each print: Yellow = Painted Resin; Green = Clear Resin; Turquoise = White Resin; Teal = Colour Sandstone; Blue = Stainless Steel; Royal Blue = Blue Plastic.

matrix prints, the stainless steel and the colour sandstone. Group C consisted of the blue plastic print alone. This shows that the resin prints were the most preferred, while the blue thermoplastic print was the least preferred. Additionally, a comparison was carried out on two of the underlying conditions of the six 3D prints, whether or not the print was embedded within a ‘rock matrix’ (Clear Resin, Colour Sandstone and Stainless Steel) or not embedded (Painted Resin, White Resin, Blue Plastic). The scores for these two groups of prints were separated for each participant and tested using Shapiro-Wilks normality test, the embedded preference values holding to the assumption of normality (W = 0.99, p = 0.29) while the unembedded prints did not (W= 0.96, p = 0.001). Levene’s test for homogeneity of variance returned a significant

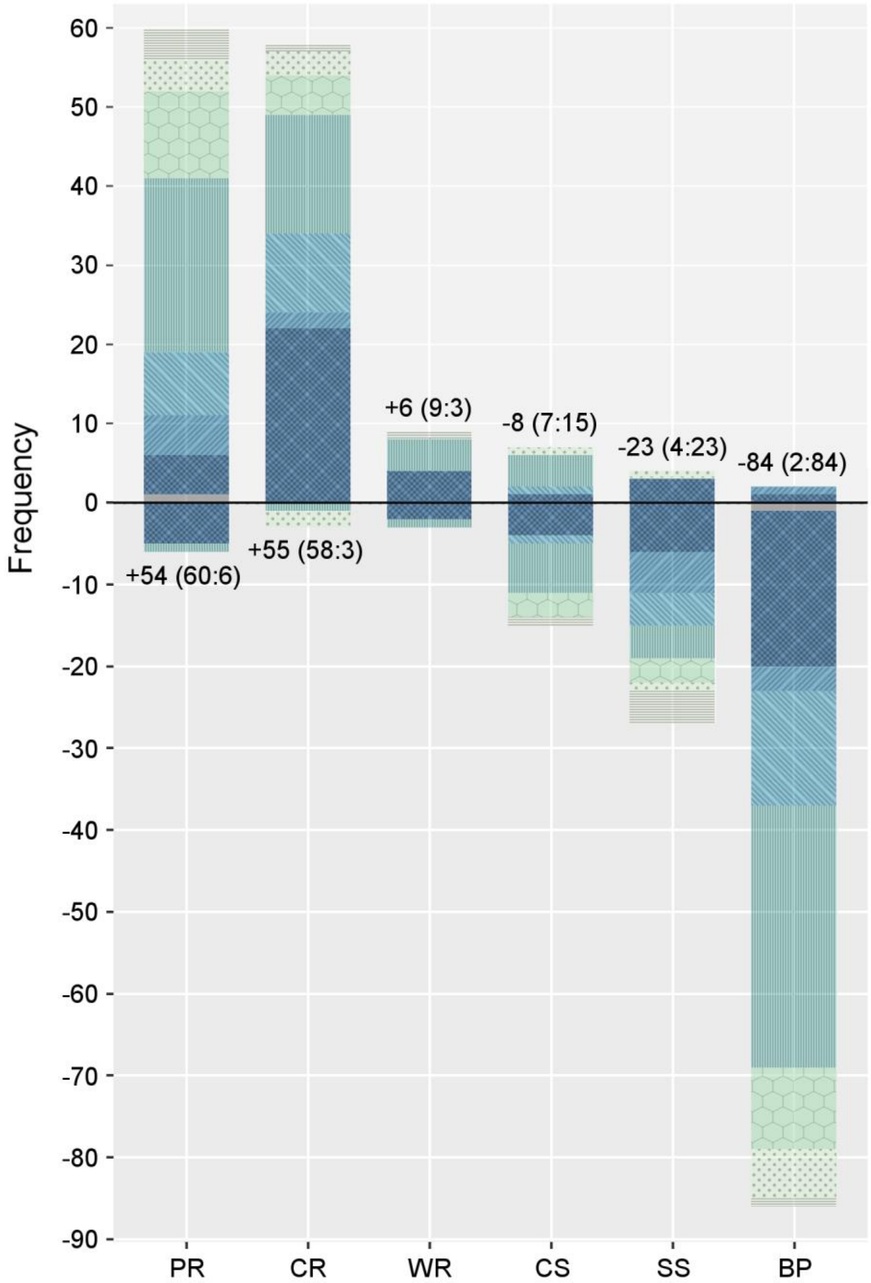


Fig. 5.4: Differential Frequency of each 3D printed replica: Comparison of most preferred prints to least preferred prints by object. Bracketed values represent Most Liked : Least Liked. Colours represent age groups: Royal Blue (Cross-hatched): 08-17, Blue (Left Diagonal): 18-24, Light Blue (Right Diagonal): 25-34, Turquoise (Vertical): 35-44, Green (Hexes): 45-54, Light Green (Dots): 55-64, Yellow (Horizontal): 65+.

result (F = 6.07, p = 0.014) and thus this assumption was violated. As a result, a non-parametric repeated measure method was used, that of the Wilcoxon Signed-Rank test (Field et al. 2012). The test returned a non-significant result between preference for embedded and non-embedded prints ($p = 0.085$), suggesting that there was no preference difference between the two groups.

5.4.2 Correlation between Physical Properties and Preference

As highlighted above, all of the scales violated the assumption of normality as tested using Shapiro-Wilks. Thus in order to test the correlation of this dataset, Spearman's ρ was used as a robust test of correlation between each of the physical attribute scales and the preference values given to the prints by each participant.

Overall, a number of strong, significant correlations can be observed within the semantic scales, in addition to some attributes that correlate weakly or not at all. These are summarised in Table 5.5. For the total group semantic data, Bad Quality – Good Quality, Unclear – Clear, Unrealistic – Realistic, Undetailed – Detailed and Boring – Interesting all strongly correlated with preference. Weaker correlations can be observed between Cheap – Expensive, Rough – Smooth and Light – Heavy, the latter having an extremely weak negative correlation. The remaining variables; Soft – Hard, Weak – Strong, Brittle – Durable and Glossy – Matte, all showed insignificant correlations with preference.

When the physical attribute scale data was divided by age group, somewhat contrasting correlations to preference can be observed. In the 08-16 age bracket, correlation values are lower on the whole compared to the total group. For these younger visitors, strong positive correlations are again found for Bad Quality – Good Quality, Unclear – Clear, Cheap – Expensive, Undetailed – Detailed and Boring – Interesting. Of these, Bad Quality – Good Quality and Boring – Interesting exhibit the strongest positive correlations. Weaker correlations can be found between Brittle – Durable, Unrealistic – Realistic, Weak – Strong, Soft – Hard and Glossy – Matte, the last being a negative correlation. The remaining variables; Light – Heavy and Rough – Smooth show no significant correlation with preference.

By comparison, the 17-34, 35-54 and 55+ age categories converge with the total group. Again, strong, significant positive correlations are found with the variables Bad Quality – Good Quality, Unclear – Clear, Unrealistic – Realistic, Undetailed – Detailed and Boring – Interesting. These correlations are stronger than that in the total group. The remaining variables, those typically associated with robustness are either uncorrelated or weakly negatively correlated, such as Light – Heavy in 17-34 and 35-54, Soft – Hard in 17-34 and 55+. Rough – Smooth is however moderately correlated in 17-34 and 35-54. These negative correlations represent preference towards lighter and softer prints, and the positive correlation towards smoother prints may suggest handling concerns by older visitors associated with more unpleasant experiences.

5.4.3 Factor Analysis of Physical Properties

An exploratory factor analysis was carried out on the semantic scales scale data for physical properties, two scales (Rough – Smooth) and (Glossy – Matte) being dropped to meet minimum

Fig. 5.5: Critical Difference Comparison Chart for the 3D Printed Replicas: Graphical depiction of groupings of preference from *post hoc* Bonferroni correction. The red circle indicates the critical different threshold, above which that print shows a significant difference in preference to the plotted print. Colours represent each print: Yellow = Painted Resin (PR); Green = Clear Resin (CR); Turquoise = White Resin (WR); Teal = Colour Sandstone (CS); Blue = Stainless Steel (SS); Royal Blue = Blue Plastic (BP).

Table 5.3: Raw Scale Means for each Scale for each 3D Printed Replica

Scales	*Painted Resin*	*Clear Resin*	*White Resin*	*Colour Sandstone*	*Stainless Steel*	*Blue Plastic*
B. Quality – G. Quality	**80.0 ±3.2**	**84.3 ±2.6**	**72.9 ±3.7**	61.4 ±4.3	73.7 ±4.4	48.6 ±4.6
Unclear – Clear	**82.4 ±3.3**	**83.8 ±3.0**	**78.3 ±3.4**	41.4 ±4.0	41.3 ±4.5	56.8 ±4.8
Cheap – Expensive	60.2 ±4.0	70.1 ±3.4	48.3 ±3.8	51.3 ±4.2	83.3 ±2.7	28.6 ±3.6
Soft – Hard	60.4 ±4.4	76.9 ±3.6	62.8 ±3.9	74.3 ±3.6	**91.7 ±1.7**	58.9 ±4.3
Light – Heavy	15.6 ±2.2	58.2 ±3.7	16.2 ±2.2	47.9 ±4.1	**93.1 ±2.3**	12.3 ±1.9
Weak – Strong	56.0 ±4.4	82.4 ±2.7	55.3 ±4.2	74.7 ±3.5	**93.2 ±1.5**	48.6 ±4.7
Brittle – Durable	60.9 ±4.1	84.5 ±2.6	62.7 ±4.0	75.5 ±3.6	**92.0 ±2.2**	52.8 ±4.4
Rough – Smooth	64.9 ±3.7	64.0 ±4.4	62.3 ±3.9	65.0 ±4.1	38.2 ±4.6	46.6 ±4.4
Glossy – Matte	70.6 ±4.0	30.2 ±3.8	65.7 ±4.1	65.7 ±4.2	50.7 ±5.4	43.1 ±5.1
Unrealistic – Realistic	**85.8 ±3.5**	**73.5 ±3.9**	**74.4 ±3.9**	55.3 ±4.6	43.8 ±4.8	**28.2 ±4.6**
Undetailed – Detailed	**86.5 ±2.8**	**81.6 ±3.1**	**79.8 ±3.3**	48.8 ±4.2	48.8 ±4.5	56.1 ±4.7
Boring – Interesting	**81.8 ±3.6**	**81.2 ±2.8**	**76.6 ±3.6**	62.3 ±4.2	66.6 ±4.2	58.4 ±4.6

95% Confidence Intervals. Bolded values referred to in the text.

reliability constraints. First, the sampling adequacy of the raw data was evaluated using the Kaiser-Meyer-Olkin (KMO) measure, which resulted in a KMO of .86 (‘Great’ according to Kaiser, 1974). Every item had a KMO of >.8 with the exception of the Cheap –Expensive semantic scale, which had a KMO value of .6 (‘Mediocre’). These all exceeded the minimum threshold of .5 (Kaiser, 1974; Field et al. 2012; Hadi et al. 2016). Next, Bartlett’s test of sphericity (χ^2 (45) = 3953.4, p = < 0.001) indicated that the correlation between the different scales was sufficient for a factor analysis to be carried out (Bartlett, 1954). The analysis was carried out using oblimin factor rotation as the variables are arguably interrelated and the factors were extracted using both eigenvalues and scree plots, three factors being identified as exceeding Kaiser’s criterion (1.0) and scree plots also identifying three factors (Cattell, 1966; Kaiser, 1960; Yong and Pearce, 2013). Together, these three factors explained 72% of the total variance within the dataset (Table 5.7).

The first factor, Factor 1 (Verisimilitude), loaded highly on a number of variables associated with how close the 3D printed replica was to the original specimen and its overall quality, including the attributes Undetailed – Detailed (.88), Unclear – Clear (.84), Unrealistic – Realistic (.79), Boring – Interesting (.76), Bad Quality – Good Quality (.72).

Table 5.4: Critical Differences from *Post Hoc* Bonferroni Correction

Comparison	*Observed Difference*	*Difference*
Clear Resin to Colour Sandstone	231.5	True
Clear Resin to Painted Resin	8.5	False
Clear Resin to White Resin	76	False
Clear Resin to Blue Plastic	402.5	True
Clear Resin to Stainless Steel	288.5	True
Colour Sandstone to Painted Resin	240	True
Colour Sandstone to White Resin	155.5	True
Colour Sandstone to Blue Plastic	171	True
Colour Sandstone to Stainless Steel	57	False
Painted Resin to White Resin	84.5	False
Painted Resin to Blue Plastic	411	True
Painted Resin to Stainless Steel	297	True
White Resin to Blue Plastic	326.5	True
White Resin to Stainless Steel	212.5	True
Blue Plastic to Stainless Steel	114	True

Critical Difference = 91.9

The second factor, Factor 2 (Robustness), loaded highly on factors associated with the overall toughness of the print, including Weak – Strong (.87), Soft-Hard (.83), Brittle – Durable (.78) and Light – Heavy (.52).

The third factor, Factor 3 (Quality), loaded on a number of attributes associated with the general quality of the print and also its felt quality, including Bad Quality – Good Quality (.5), Weak – Strong (.53), Brittle – Durable (.56), Cheap – Expensive (.89) and Light – Heavy (.8).

Reliability analysis using Cronbach's α found all of the extracted factors to be sufficiently reliable, exceeding the minimum threshold of .7 (Kline, 1999). Factor 1 (Verisimilitude) with $\alpha = 0.86$, Factor 2 (Robustness) with $\alpha = 0.79$ and Factor 4 (Quality) with $\alpha = 0.78$.

Next, factor scores were calculated for each participant and correlated using Pearson's *r* to preference values to determine if the factors were related to one another and whether they correlated directly to visitor's preferences (Table 5.8). Factor 1 (Verisimilitude) showed a weak positive correlation with Factor 3 (Quality) ($\rho = .12$, $p = <0.001$) and was strongly positively correlated with preference ($\rho = .68$, $p = <0.001$), confirming the preference of visitors towards verisimilar 3D prints. Factor 2 (Robustness) did not however show a correlation to preference but showed a strong correlation to Factor 3 (Quality) ($\rho = .47$, $p = <0.001$), suggesting that the

Table 5.5: Spearman's ρ Correlation between Preference and Semantic Scales

	Total (ρ)	*08-16 (ρ)*	*17-34 (ρ)*	*35-54 (ρ)*	*55+ (ρ)*
Bad Quality – Good Quality	**.52 *****	**.44 *****	**.48 *****	**.56 *****	**.58 *****
Unclear – Clear	**.55 *****	**.39 *****	**.67 *****	**.57 *****	**.62 *****
Cheap – Expensive	**.29 *****	**.37 *****	**.26 *****	**.25 *****	**.3 ****
Soft – Hard		**.14 ***	**-.24 ****		**-.21 ***
Light – Heavy	**-.07 ***		**-.2 ****	**-.13 ****	
Weak – Strong		**.21** **			
Brittle – Durable		**.27 *****			
Rough – Smooth	**.23 *****		**.42 *****	**.24 *****	
Glossy – Matte		**- .22 ****			
Unrealistic – Realistic	**.60 *****	**.28 *****	**.71 *****	**.73 *****	**.70 *****
Undetailed – Detailed	**.56 *****	**.30 *****	**.71 *****	**.64 *****	**.64 *****
Boring – Interesting	**.55*****	**.46 *****	**.62 *****	**.56 *****	**.57 *****

***** p = < .05   ** p = < .01   *** p = < .001

toughness of a 3D print and its overall quality are associated. Factor 3 (Quality) itself was weakly positively correlated Verisimilitude as discussed above and was also weakly positively correlated with preference (ρ = .19, p = <0.001).

5.4.4 Content Analysis of Positive and Negative Statements

The comments for each visitor's most and least preferred 3D prints were analysed using content analysis to determine underlying reasons for visitor preferences, resulting in frequency counts for provided reasons as displayed in Fig. 5.6 and 5.7.

The comments for visitor's most preferred 3D prints were primarily dominated by the print being realistic, having properties that made them more verisimilar to the original specimen (30%). The next two categories, the detail of the specimen (15%) and the visual and/or tactile clarity of the features present upon it (9%) were also dominant. A long tail of lesser cited reasons exists outside of these three dominant ones. The ability to provide three-dimensional interaction with the specimen in the case of the prints not embedded within a 'rock matrix' was another strongly cited reason (6%), perhaps explaining the popularity of the non-embedded prints (Painted Resin, White Resin, Blue Plastic) compared to the embedded ones (Clear Resin, Colour Sandstone, Stainless Steel), though the fact that blue plastic was the least popular and clear resin the second most popular suggests that there are other complicating factors at work. The interest invested into a replica (6%) and the durability of the print (6%) were tied for the next position, suggesting that durability does have some concern for preference and that creating

Table 5.6: Factor Analysis Structure Matrix of Physical Properties

	Factor 1 (Verisimilitude)	*Factor 2 (Robustness)*	*Factor 3 (Quality)*
Undetailed – Detailed	.88		
Unclear – Clear	.84		
Unrealistic – Realistic	.79		
Boring – Interesting	.76		
Bad Quality – Good Quality	.72		.5
Weak – Strong		.87	.53
Soft – Hard		.83	
Brittle – Durable		.78	.56
Cheap – Expensive			.89
Light – Heavy		.53	.8
Eigenvalues	3.35	2.15	1.75
% of Variance	33.0 (46)	21.0 (29)	18.0 (25)
α	.86	.79	.78

Factor Loadings less than .4 have been discarded. () is the proportion of in-factor variance explained

an object that is captivating to interact with is important. Next, the ease of handling (5%) in terms of the objects weight, surface smoothness and roughness of edges was a commonly cited reason. Notably, no children (8-16) cited this reason, suggesting that it was more of a concern for adults, which may confirm the weaker correlation found between older visitors and physical attributes associated with smoother and lighter prints. This was followed by a number of arbitrary preferences (5%), such as they thought the print was 'cool'. Tactual (4%) and visual appeal (3%) were the next two categories, which suggest that an attractive looking print has some influence. Other reasons included that the print was transparent (2%), informative (2%), shiny (1%), was a good weight (1%) and of good quality (1%). These were followed by a long tail of eclectic reasons cited by few participants. Notably, only younger participants forwarded the transparent and shiny categories as a reason for preference. This may suggest that children have some rather different reasons for preferences that may be associated with how the item looks, rather than its tangible properties. This requires further research to affirm however.

On the other hand, the most common comments for the visitor's least preferred 3D print were dominated by the exact inverse of the positive comments. The primary reason, again with a large majority was that their least preferred print lacked realism and was far away from what the original specimen was like (25%). These were followed by the lack of detail (10%) and the lack of visual or tactile clarity on the print (10%) being major reasons for non-preference.

Table 5.7: Factor Score Correlation Matrix

	Factor 1 (Verisimilitude)	Factor 2 (Robustness)	Factor 3 (Quality)	Preference
Factor 1 (Verisimilitude)	**1**		**.12 *** **	**.68 *** **
Factor 2 (Robustness)		**1**	**.47 *** **	
Factor 3 (Quality)			**1**	**.19 *** **
Preference				**1**

* *p* = < .05 ** *p* = < .01 *** *p* = < .001

Notably, a large portion of 08-16-year-olds cited a lack of clarity as a major reason for not preferring a print, suggesting that being unable to clearly pick out features may be detrimental to children's appreciation for an object. The next most cited reason was that of the apparent cheapness of the replica (8%). This was followed by the print being too heavy for handling (6%) and the print being too artificial and non-natural (4%) being tied with a similar concern of the unnatural nature of the print, that it was too fake-looking (4%). The colour being incorrect was also a concern for some visitors (4%). These reasons, artificiality, fakeness and colour again lend themselves into the idea that realism is a major concern in preference towards 3D prints. The next category, the print not being interesting to interact with (3%), was dominated by younger visitors (8-16) as in the case for the print being interesting in the positive case. This strongly suggests that the ability for a print to generate and hold interest is a massive contributor to the preference of younger visitors with regard to tactile 3D printed replicas. The next most common reasons were a three-way tie between the lack of durability and the ease of a print being damaged (3%), the poor quality of a print (3%) and a lack of tactual appeal for handling (3%). Arbitrary reasons followed (2%) which were tied with printing issues and artifacts produced during the printing process, such as rough edges and ridges (2%) and the print being dull or not shiny (2%). In the case of printing issues, no visitors in the 8-16 age group cited this reason for non-preference, suggesting that children may be less concerned with such artifacts or may simply think them part of the specimen. On the other hand, much like with shiny for the positive comments, dullness was only cited by visitors in the 8-16 age category, again lending towards the idea that children tend to have preferences associated with the visual quality of a print, rather than its tangible properties.

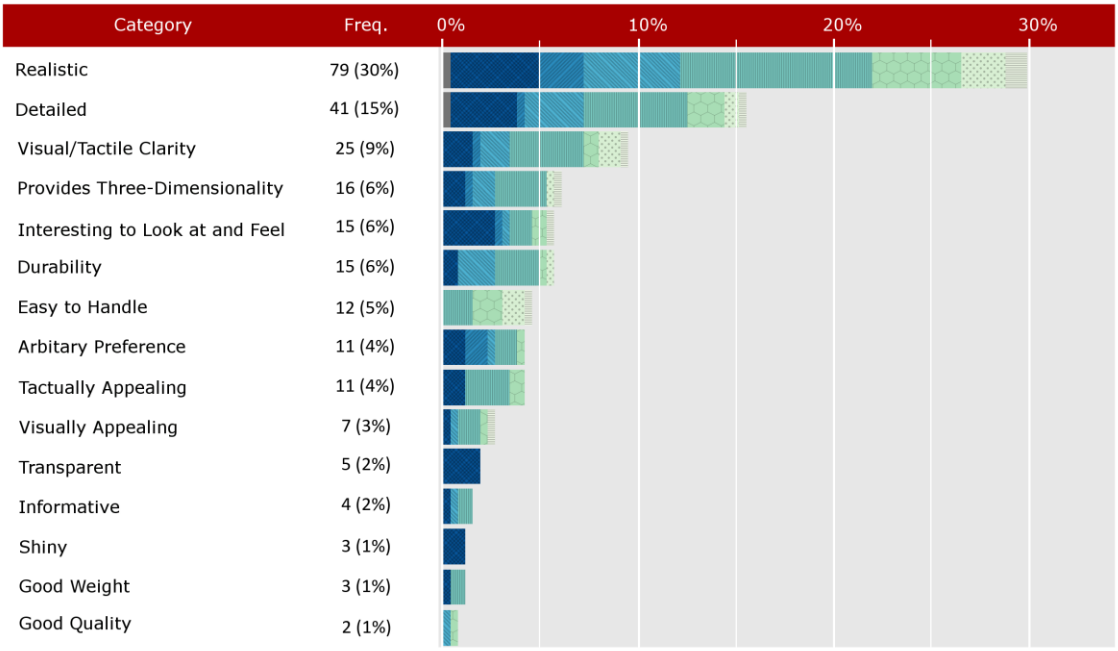


Fig. 5.6: Positive Comments for museum visitor's most preferred 3D Print: Frequency counts of the top fifteen most commonly cited reasons for preferring their most preferred 3D prints. Colours represent age groups: Royal Blue (Cross-hatched): 08-17, Blue (Left Diagonal): 18-24, Light Blue (Right Diagonal): 25-34, Turquoise (Vertical): 35-44, Green (Hexes): 45-54, Light Green (Dots): 55-64, Yellow (Horizontal): 65+.

5.4.5 Summary

Overall, it can be summarised that the most important physical property to visitor preference is that of the verisimilitude, or the similarity to the original object, of a tangible 3D printed replica.

From raw scale values, the most preferred 3D prints rated highly on these scales, there was a strong positive correlation across age groups, less so in younger visitors, towards more realistic, detailed and clear prints that accurately represent the original object. The dominant factor revealed from exploratory factor analysis was also of verisimilitude, loading strongly on scales associated with the accuracy, realism and quality of the piece. Finally, these same reasons were dominant for preference and non-preference of a particular 3D print. This factor also strongly correlated with preference and appears to be the dominant influence on tangible 3D printed experiences with replicas.

The robustness of a tangible 3D printed replica was also a factor in terms of the raw scales, but appeared to be of lesser concern to the sampled visitors and their preferences. While being the second factor in the exploratory factor analysis, the scales with which it loaded heavily showed little correlation with preference, save for weak negative correlations towards lighter prints in adults and the factor being uncorrelated with preference. Durability was cited as a reason for preference however in the content analysis for positive preference while weight and

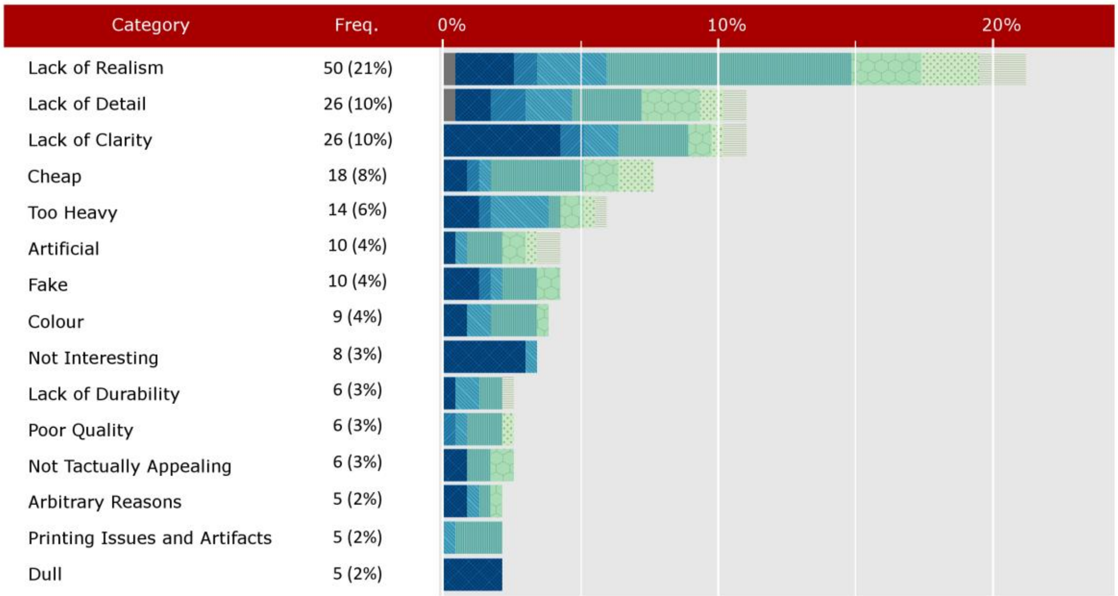


Fig. 5.7: Negative Comments for museum visitor's least preferred 3D Print: frequency counts of the top fifteen most commonly cited reasons for not preferring their least preferred 3D prints. Colours represent age groups: Royal Blue (Cross-hatched): 08-17, Blue (Left Diagonal): 18-24, Light Blue (Right Diagonal): 25-34, Turquoise (Vertical): 35-44, Green (Hexes): 45-54, Light Green (Dots): 55-64, Yellow (Horizontal): 65+.

a lack of durability were both of concern with regard to negative comments, suggesting that in extreme cases these properties could be detrimental to visitor preference.

Finally, the quality of a tangible 3D printed replicas is also important, but to a lesser degree than verisimilitude. This was the third factor and the scales that loaded were indeed highly correlated with preference across age groups, again being weaker in younger visitors. The factor was weakly positively correlated with preference, suggesting it is of lesser concern to museum visitor preference. For positive comments for preference, few quality-related reasons were cited and were more of a concern for negative comments, in which visitors cited poor quality, artificiality, fakeness, cheapness and a lack of durability in addition to printing artifacts as reasons for non-preference of certain replicas. This suggests that quality may be more a concern if a print is below a certain threshold of quality, rather than if a print is the highest quality it possibly can be.

5.5 DISCUSSION

5.5.1 Preference for Physical Properties of 3D Prints

Overall, the analysis carried out in this chapter on the preferences of museum visitors towards tangible 3D printed replicas finds that the key factor is that of the verisimilitude of the print. While arguably intrinsically tied to verisimilitude, the quality of the print appeared to be a lesser factor, perhaps more of a concern when the print is of very low quality and the robustness of a 3D print is of little concern to the museum visitor. This places particular importance on the creation of replicas that accurately encapsulate the details present on the original specimen in a visually and tactually clear manner which being as realistic as possible, both in terms of its visual properties such as colour but also in its tactile properties such as temperature and weight. This topic was discussed briefly in the previous chapter in which some of the interview participants highlighted that they preferred realistic prints. This analysis thus confirms that museum visitors do indeed hold this preference towards verisimilar 3D prints. However, very little research has been carried out into this particular subject area on the subject of preferences towards 3D printed materials and in 3D printing with regard to the museum visitor experience, as discussed in the literature review (*2.4.2.4 User Research into 3D Printed Replicas in Cultural Heritage*). As a result, this study represents the first foray into this particular subject area.

Factor analysis and the correlation of the factors to preference, however, showed that the robustness of tangible 3D printed replicas was of little concern to the preferences of museum visitors. It was only weakly correlated to preference in younger age groups while effectively uncorrelated in older age groups, in some cases, namely Soft – Hard and Light – Heavy. For adults, this can be explained by concerns over handling for older visitors. First and foremost, ease of handling was the 7th most cited reason for preference of a particular print. In the negative comments for least preferred prints, some visitors stated that the print was too heavy for handling, suggesting that the ease that one is able to manipulate and handle a print has some influence on the visitor's handling experiences, which seems to be negative when the object is too heavy. Similarly, older visitors showed a moderate positive correlation towards toward smoother prints, suggesting that better handling experiences do indeed relate to higher preference for a print. Added to this is the durability of the print being brought up in both positive and negative comments for preference, the print being durable in the case of positive and not being durable in the case of negative. This does suggest that robustness is a concern for some museum visitors, but to a lesser degree than the verisimilitude and the quality of the print, although again little research has been carried out looking into this particular issue.

On the subject of the quality of the print, while explaining the least proportion of the variance within the dataset, it correlates weakly positively with preference, suggesting that the quality of a print does have some influence. This scale correlates moderately with preference across all age groups but comments related to preference of the participants most preferred 3D prints are generally lacking, only being the 15th most commonly cited reason for preference of a particular 3D print. On the contrary, comments associated with non-preference of a particular print are much more common, including cheapness, artificiality, fakeness, poor quality and printing artifacts. Overall, this suggests that a print being of insufficient quality may be more of a concern to the museum visitor than a print being of particularly high quality. The connotations for this is that a certain threshold of quality needs to be achieved for a tangible 3D printed replicas, which means that creating a print of the highest quality, and thus raising the costs of printing, may not be necessary. However, as has been plainly expressed thus far throughout this chapter, little research into the perspective of the museum visitors with regard to tangible 3D printed replicas has been carried out to date.

These three major factors may be further characterised by comparison to the Kano Model (Kano et al. 1984; Sauerwein et al. 1996). The Kano model (Fig. 5.8) is a UX design model that expresses the nature of product requirements and how they relate to the satisfaction levels of the consumer during usage. It expresses a number of different types of product requirements:

- *Must-be Requirements*: Those that are mandatory and taken for granted by the user, whose absence will have a large negative influence on user satisfaction but whose presence will not increase satisfaction.
- *One-dimensional Requirements*: Those that scale linearly with user satisfaction, where poor quality will result in lower user satisfaction but better quality will result in a linear increase in user satisfaction.
- *Attractive Requirements*: Those that have a solely positive influence on user satisfaction when present, but will not adversely affect satisfaction if absent.
- *Indifferent Requirements*: Those that do not positively or negatively affect user satisfaction with the product.

The Kano model is explicitly useful because it allows the better conceptualisation of those characteristics that should be prioritised during product development and to better understand the needs of the consumer (Sauerwein et al. 1996; Lin et al. 2017). Thus, it should be useful in the design of tangible 3D printed replicas. Taking from the major factors highlighted in this chapter, verisimilitude, robustness and quality may be mapped onto the Kano model. Verisimilitude, given its strong correlation with preference, is identifiable as a one-dimensional requirement, which increasing verisimilitude of a print will increase the satisfaction of the user with the model. Quality, on the other hand, was deemed less important for positive preference but a driver of negative preference, being a must-be requirement. A poor quality print will result in a less preferred print and lower satisfaction, as in the blue plastic sample, but maximising quality will not increase overall satisfaction. The robustness of the print can be expressed as an indifferent requirement, one that has no influence on overall satisfaction.

These factors do map onto the Kano model well, but it is important to note that they perhaps might not be valid. The measure used for analysis here was that of preference while the Kano model specifically deals with product satisfaction. While these variables are arguably interrelated, they are not explicitly conflatable. While convenient for conceptualising the nature of these key requirements, reanalysis under the Kano model may be necessary to properly identify the nature of these key product requirements.

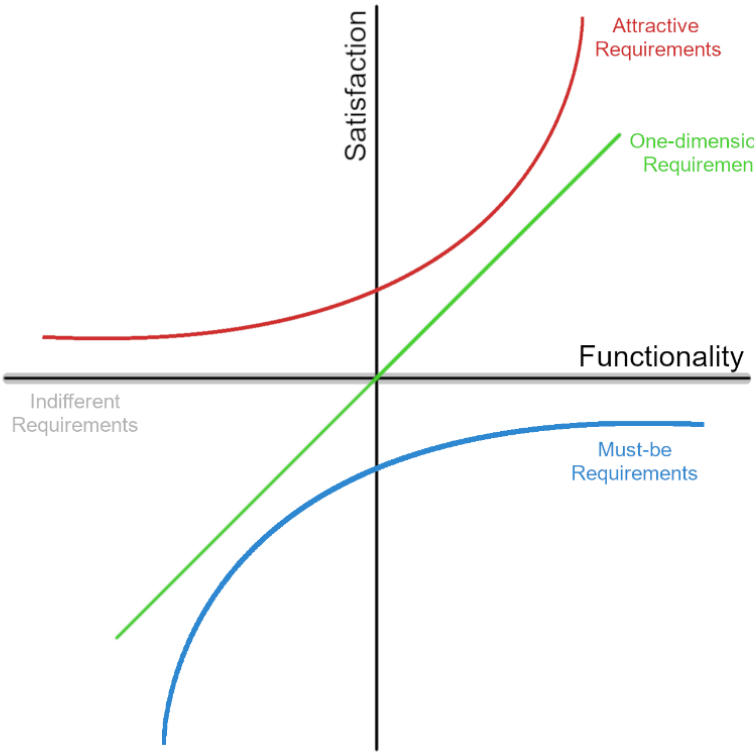


Fig. 5.8 The Kano Model: The Kano model expresses the qualities of a product and how they relate to its functionality and satisfaction potential. Four types of requirements are described. 1) Attractive Requirements (Red); 2) One-dimensional Requirements (Green); 3) Must-be Requirements (Blue); Indifferent Requirements (Grey).

5.5.2 Implications for use in Museums

First and foremost, the implication of cost needs to be addressed. Scopigno et al. (2017) provide a review of cost considerations for the most accessible 3D printing technologies, these costs varying depending primarily on the method of data acquisition and the materials used in addition to a few tricks of the trade (Abate et al. 2011; Abel et al. 2012; Remondino et al. 2013; Scopigno et al. 2014). Material costs primarily depend on the materials used which is determined by the printing method. As a general rule, FFF prints are cheapest, utilising low-cost thermoplastics such as ABS and PLA on affordable printers to create models (Table 5.8) (Mahindru and Mahendru, 2013; Torabi et al. 2015; Gibson et al. 2015; Scopigno et al. 2017). However, these models are typically marred by build problems and relatively coarse layer thicknesses that create unsightly lines on the surface and strange material and optical properties, generally resulting in a poorer quality, more artificial-looking print (Olson et al. 2014; Scopigno et al. 2014; 2017; Baletti et al. 2017). At the other end of the spectrum, SLA 3D printing uses photopolymer resins, those that react to UV light to harden into a solid but somewhat fragile model (Mahindru and Mahendru, 2013; Gibson et al. 2015; Torabi et al. 2015; Scopigno et al. 2017). These prints are capable of much finer layer thicknesses thanks to the printing methodology used and also suffer less from printing artefacts observed in FFF printing, resulting in smoother surfaces generally and less pronounced visual artefacts. This means that they are generally more verisimilar to the original model or design (Scopigno et al. 2014; 2017; Gibson et al. 2015).

However, these prints cost significantly more due to higher machine and material costs and being capable of printing in full-colour and with variable physical properties (Scopigno et al. 2014; 2017; Gibson et al. 2015). This provides a conundrum for museum professionals. In order to create authentic replicas that museum visitors seem to prefer, spending must increase accordingly. For larger national museums this may not be so much of a concern, but the fact remains that for smaller regional museums with already limited budgets, creating truly authentic prints may be out of the question. In the UK, where public museums are frequently subjected to yearly funding cuts the problem is exasperated (Museums Association, 2018). Ideally, the cost of such models is a primary consideration over authenticity and museum professionals need to make important decisions on a case-by-case basis when choosing the type of materials that they want to use. The costs of doing so must be weighed against what the print is needed for and the level of authenticity required for use.

Tied to cost considerations is the issue of toughness and robustness. As the results show above, robustness to be unrelated to preference, but a real concern to the museum professional. Acquiring a durable print is within the museum's interest, mitigating the costs of replacement through handling damage over time. The most durable print in this study, stainless steel, was also the most expensive to print, using powder-based laser sintering (SLS). This machines that utilise this method are expensive to purchase and maintain, which naturally drives up the price of part production (Mahindru and Mahendru, 2013; Gibson et al. 2015; Torabi et al. 2015). Such a durable print may be expensive in the short term but over time will pay for itself by being resistant to wear and damage. However as shown from the results in this chapter toughness is directly traded off against verisimilitude, more robust prints generally being less realistic, less clear and less detailed than more fragile ones. When taking into consideration the overall preference towards the more realistic resin prints, which are also less robust, important decisions need to be made when deciding which materials need to be used for a tangible replica (Scopigno et al. 2017). Purchasing quick-wearing realistic prints may quickly become expensive through replacement by comparison to an initially expensive but durable metallic 3D print.

Another consideration is that of the varied nature of the museum audience. Any museum is frequented by visitors across a huge range of ages, from babies to the elderly. This analysis itself has already revealed a dichotomy between adult visitors and younger visitors, adult visitors seemingly preferring more authentic 3D prints while younger visitors showing more variable preference. It is notable that the strongest correlate to preference in children (08-16) was that of interest and in the content analysis, children were the only visitors to highlight a few key reasons, including transparency (2%) and shininess (1%) and being the majority for interesting 3D prints (6%) for preference comments and not interesting (3%) and dullness (2%) for non-preference comments (Fig. 5.6 and 5.7). All of these traits pertain to how eye-catching a 3D print is and may indicate that younger visitors may be more drawn to a piece that is attractive and visually compelling rather than one that is authentic and representative of the real thing. As was discussed in the last chapter, a further consideration is noted by Evans (2002), who show that young children can become easily confused about what is real and fake, a trend that diminishes up to the age of 10 to 11 (Bunce and Harris, 2013; Bunce, 2016). Providing a 'realistic' print for such age groups may be even more problematic, as even an off-coloured, poor quality print may have the potential to be interpreted as a genuine museum object, seeding misinformation that goes against the grain of the expectations of museum visitors. This is likely variable from child to child and as this study did not fully explore differences in opinion among this age group and further exploration of the preferences of children at younger developmental stages could help further inform best practices for use of tangible 3D printed replicas.

5.5.3 Limitations

While this study has found some key insights into museum visitor preference of tangible 3D printed replicas, there are a number of limitations that should be accounted for. While a strong preference towards verisimilarity was found, this is not complete confirmation that verisimilarity is the ultimate decider on visitor preference. This study did not test this preference within an ecologically-valid environment, such as part of an exhibit. Further empirical testing looking into how verisimilarity actually influences the experience of museum visitors could help to better inform museum professionals of how to design such 3D prints.

As before, the method of participant recruitment used led to a lack of participants in the young adult and older age categories. The relatively limited amount of participants in these groups means that they are relatively underrepresented and they could, in fact, have different preferences that are not properly accounted for here. Random or systematic sampling could alleviate this issue but was not ethically approved.

5.6 CONCLUSIONS

Overall, mixed-methods analysis of the physical preferences of museum visitors towards tangible 3D printed replicas has revealed that:

- Museum visitor's preference of tangible 3D printed replicas is primarily governed by the verisimilitude of the print relative to the original object, being a one-dimensional requirement. The overall quality of the print having a weaker influence on museum visitor preference, likely representing a must-be requirement. The third factor, the robustness of a print showed no correlation to preference, representing an indifferent requirement. Therefore, museum professionals should prioritize making tangible 3D printed replicas as verisimilar to the original as possible.

- The selection of printing materials and methods has a large impact on these physical properties and must be carefully considered and taken into account for the exhibition or scheme for which they are being created. Poorer quality, less verisimilar prints are generally cheaper and more accessible to museum institutions but will be less desired by visitors whereas on the other hand, higher quality, verisimilar 3D prints are more desirable but may be out of the budget constraints of museums. A critical level of quality, below which prints are unacceptable appears to also exist.
- Further research is required to understand a number of research topics that are poorly understood within this research sector. First and foremost, younger children need to be researched in greater detail as they were not covered in this study and the preference of younger visitors appeared to be more variable compared to older visitors. Testing these preferences in an ecologically-valid environment may also be necessary in order to prove that these preferences are observable in a proper museum environment.

6.0 WHAT CAN YOU FEEL?: BPS PERCEPTION OF MUSEUM OBJECTS

6.1 PUBLICATION RECORD

The results of this chapter are in the process of being written up as a peer-reviewed publication, due to be submitted in Late Spring/Early Summer of 2019.

6.2 INTRODUCTION

Thus far only the general needs of the museum audience with regards to tangible 3D printed replicas have been discussed. This however glosses over one key demographic, that of the blind and partially-sighted (BPS) audience. As discussed in the literature review, BPS visitors were not truly considered until a major shift in policy mandated cultural institutions be more inclusive towards marginalised audiences (Candlin, 2010; DDA, 1995; Equality Act, 2010).

Many efforts have been undertaken since then, many providing handling experiences for BPS audiences (Candlin, 2006; 2008; McGlone, 2008; Phillips, 2008; McGee and Rosenberg, 2014). Even then, efforts over the past few decades, while in the best interest, often failed to properly take into account the needs of BPS individuals and the key differences between tactile and visual perception or were poorly thought out solutions to the issue (Hetherington, 2000; 2003; Candlin, 2003; 2010; Chick, 2017). Greater accessibility is now being afforded to BPS individuals in the modern museum in the form of touch tours, handling sessions and braille and audio guides (Mesquita and Carneiro, 2015; Chick, 2017). However, the methods used to assist BPS audiences are often regarded as amelioratory solutions to deeper underlying accessibility issues, temporary or small scale projects that fail to feel the demand of BPS audiences (Partington-Sollinger and Morgan, 2011; Eardley et al. 2016; Chick, 2017). This is a visitor demographic of increasing importance due to UK and international legislation, such as the Equality Act (2010) and the UN Convention of the Rights of People with Disability (United Nations, 2008) (CRPD).

A number of studies express the population of BPS individuals in the UK at somewhere around 2 million in 2018 (RNIB, 2018), growing from around 1.8 million in 2008 (Access Economics, 2009). 82% are over the age of 50 and combined with an ageing population, such as that in the UK, these figures are guaranteed to increase (Small et al. 2012; Office for National Statistics, 2017; Chick, 2017). Forecasts from 2008 expect a BPS population of ~4 million by 2050, meaning that BPS provision must rise accordingly (Access Economics, 2009). However, the situation remains difficult for many BPS museum visitors. Services are typically poorly advertised, limited in their educational depth and are irregular, often one-off events that require pre-booking (Candlin, 2003; 2010; Partington-Sollinger and Morgan, 2011; Eardley et al. 2016; Chick, 2017). Thus, such provisions do little to stem the demand of BPS visitors. There is a propensity towards providing braille also, despite a very small percentage of BPS individuals having the necessary skills to read it. Only <10% of BPS people in the US and ~5% in the UK are thought to be able to read braille, although these figures are somewhat out of date (National Federation of the Blind, 2009; Phillips and Beesley, 2011). The majority of braille readers typically live with severe congenital sight loss, 98% being full-blind and 67% suffering from early-onset of sight loss in the UK (Phillips and Beesley, 2011). Poor staff training is also a frequent issue and opportunities to actually handle objects are restricted to less interesting objects in handling collections (Argyropoulos and Kanari, 2015; Anagnostakis et al. 2016; Mesquita and Carneiro, 2016). Other key accessibility issues are also prevalent, such as physical barriers, wayfinding, difficulty in accessing information both pre- and in-visit and issues with guide dogs (Weisen, 2008; Small et al. 2012; Mesquita and Carneiro, 2016).

Further compounding these issues is the fact that research into how to best provide for BPS individuals are often small scale, ungeneralizable exploratory case studies that do little to inform ongoing museum practice (Mesquita and Carneiro, 2016; Chick, 2017). This does not suggest that nothing is being done however. Many institutions are developing internal frameworks for how to provide for BPS audiences properly, such as the Smithsonian Guidelines for Accessible Exhibition Design among others (National Museums of Scotland, 2002; Smithsonian, 2018b; Anagnostakis et al. 2016). These however typically deal with exhibition design procedures rather than detailed research into the needs of BPS visitors. Efforts to understand and include BPS individuals in the exhibition design process are on the rise however and through inclusive research approaches and Universal Design Theory (UDT), provision is greatly improving (Salgado and Kellokoski, 2005; Mesquita and Carneiro, 2016; Chick, 2017).

Given this overall lack of research into the needs of BPS individuals in museums, unsurprisingly little research has been carried out on how tangible 3D printed replicas can assist BPS audiences. Thus far, the needs of sighted audiences have been discussed and how museum professionals can create desirable handling experiences for them. It could be assumed that these same considerations, prioritizing verisimilitude and quality, could also be adopted for BPS applications. This would be unreasonable to assume however, due to the core differences in how sight and touch operate (Candlin, 2010).

A large corpus of sensory research has highlighted that touch is limited by its spatial resolution and ‘field-of-view’, meaning that interpreting large and complex structures is laborious and cognitively-demanding (Heller and Ballesteros, 2006; Gupta et al. 2017). Touch and sight also typically have different sensory proficiencies, textures often contrasting with their interpretation through sight alone (Lederman and Klatzky, 2004; Heller and Ballesteros, 2006; Spence and Gallace, 2008; Tiballi, 2015). Certain properties, such as glossiness, fail to translate from sight into touch, an issue Candlin (2010) notes in the Tate Modern’s flagship BPS exhibition, *Raised Awareness*. It also deals poorly with complex structures, tangible images often requiring simplification and decluttering to be more easily interpretable by their intended audience (Koch et al. 2013; Furferi et al. 2014; Gupta et al. 2017). Modern sensory research also advocates the multisensory, integrated nature of the senses (Lacey and Sathian, 2014; Ward, 2014; Eardley et al. 2016) and the absence of any single sense has a major influence on total perception. Thus, it cannot be assumed verisimilarity in tangible 3D printed replicas is a key factor for BPS visitors. Greater understanding of what exactly BPS individuals actually perceive from such objects must instead be considered before any judgements on physical properties can be ascertained. What measures can be taken to support BPS interpretation of such objects? Should objects be simplified for the purposes of 3D printing? Do BPS audiences even want objects to be changed to assist them? These are valid questions in need of answering.

In this chapter, the perception of BPS individuals with regard to natural history objects is analysed in order to explore and ascertain a number of different key threads. Firstly, how do BPS individuals utilise their senses when interacting with museum objects. Secondly, how efficiently can BPS individuals identify objects and the materials they are composed of and thirdly, how can their perception of these objects be assisted using 3D printing technology. Using semi-structured interviews paired with content analysis, the key components of BPS interpretation of museum objects and how they identify and interpret such objects is elucidated.

6.3 METHODS AND MATERIALS

6.3.1 Research Questions and Design

The aim of this particular study was that of the exploration of some of the primary design considerations when designing tangible 3D printed replicas for BPS audiences. The overall purpose was to identify what BPS persons could interpret from museum objects, how they did so and how 3D printing could possibly assist them in their interpretation of the object. As a result, this particular study focusses mainly around the research question:

"How can tangible 3D printed replicas assist BPS persons in their interpretation and enjoyment of exhibitions?"

The study was designed based around answering this question, and can be further broken down into a number of sub-research questions:

- How accurately are BPS individuals able to identify museum objects using only their senses?
- How do BPS individuals utilise their senses when exploring such objects?
- How are object and material properties interrelated in BPS interpretation?
- What properties of these objects are integral to their understanding of them?
- What makes an object easier or more difficult to interpret for BPS individuals?
- How can 3D printing assist BPS individuals in their interpretation of objects?

In order to explore these questions, an interview study was designed to pick apart these complex issues in sensory perception. This study asked a number of questions exploring these themes, discerning how the participants explored and interpreted the objects in question. These are summarised in Table 6.1. For Q1, the think-aloud process was used combined with a number of premade probes when the participant struggled to respond. These prompted the participant to describe general aspects of the object without specifically referring to descriptive terms. All of these questions were subsequently analysed using content analysis, save Q1 which is not analysed here due to time limitations. The division of object and material properties was employed to glean understanding into how the properties of the object, such as shape and features, were related to material, such as texture and temperature. These two property categories are key for 3D printing as the object properties reflect the nature of the CAD file and how geometry influences perception while the material properties reflect the printing methods used and how materials, such as resins or plastics, would affect perception.

Additionally, observation was utilised in order to assess how participants utilised their senses. As they interacted with the objects, the principal investigator noted down which senses were engaged. As touch was used in every case, it was not counted. The intent of this was to assess which senses were important to understanding to object interpretation.

6.3.2 Participants

Sampling utilised a snowball sampling approach. The principal researcher contacted a number of BPS support groups across the UK, asking them for assistance in gathering participants for the study. Upon response, the principal researcher discussed potential dates and interest with the organisation and the BPS support group enquired of its members for participants. The principal researcher and the BPS support group then organised a suitable date, or multiple, to come and carry out data collection with the interested participants.

The sampled organisations included Focus Birmingham (9), the OUMNH (2), BirminghamVision (4), the Beacon Trust (3) and BucksVision (3). Thus a total of 21 different BPS individuals from a variety of different backgrounds, ages, sight loss conditions and durations formed the sampled participants.

Prior to the interview, each participant was read the information sheet detailing the nature of the project, its objectives and what to expect. Once the participant had reviewed this information and confirmed their agreement in taking part in the study, consent was acquired. The participant was given the options to provide written or audio consent. In the former, the participant signed their name as required. In the latter, the participant was read a confirmatory statement that asked them if they were willing to take part in the study. This and their response

Table 6.1: Questions used and their Intent

No.	Question	Intent
Q1	Could you please describe this object while thinking aloud, focussing on its features, shape, texture and material properties? (Premade Probes)	To determine what aspects of the object the participant was able to interpret.
Q2	What do you think the object is made of? (Probe) Why?	To determine the accuracy of material judgments and to determine what aspects influenced material judgements
Q3	What do you think the object is? (Probe) Why?	To determine the accuracy of object judgments and to determine what aspects influenced object judgements
Q4	If you could change anything about this object to help you better understand it through 3D printing, what would you change if anything? (Probe) Why?	To determine if participants wanted or needed assistance in their interpretation of the object.
Q5	Which object was easiest for you to perceive and understand? (Probe) Why?	To determine what made certain objects easier to interpret
Q6	Which object was most difficult for you to perceive and understand? (Probe) Why?	To determine what made certain objects harder to interpret

was audio-recorded in lieu of a written record. If audio-recording was rejected here, the process was terminated and the participant dismissed. During this process, the participants also provided demographic details about both their background and the nature of their sight loss. This information is summarised in Table 6.2. This process was ethically approved by the University of Warwick BSREC ethics committee and the OUMNH IRB and complied with their standards of informed consent.

The participants have been anonymised and the names used in this study assigned via a random name generator.

6.3.3 Materials

This study used a number of natural history objects from the Oxford University Museum of Natural History (OUMNH), derived from the teaching collections due to their relative disposability. These five objects were: a tortoise shell (*Manouria emrys*) (OUMNH SR2203); a fossilised scallop shell (*Pseudopecten equivalvis*) (OUMNH SR0409); a brain coral (*Diploporia* sp.) (OUMNH SR0615); the shell (minus appendages and body) of a crab (*Cancer pagurus*)

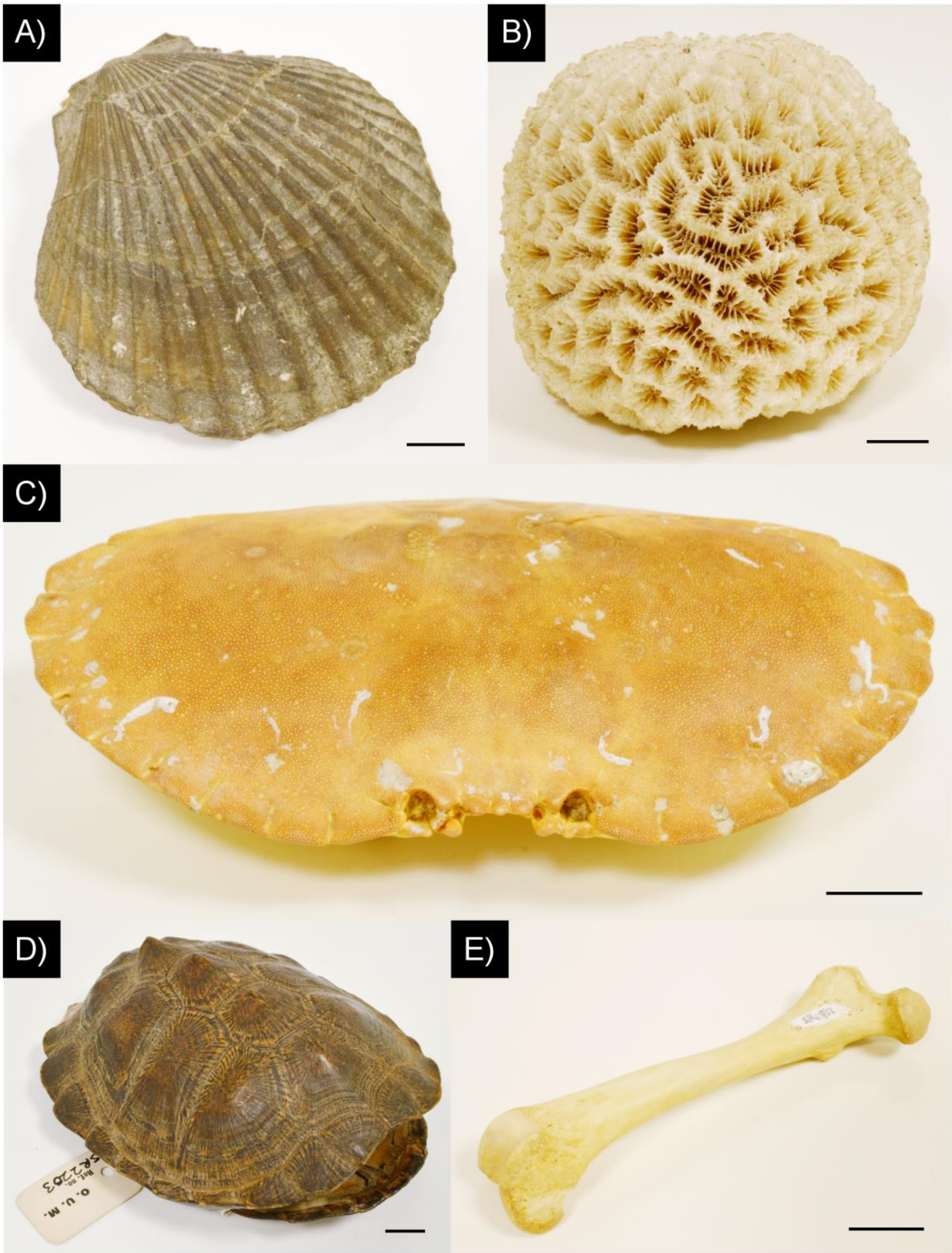


Fig. 6.1: Objects used in the study: The five objects used in the study. A) Scallop Shell. Scale bar equals 1cm, B) Brain Coral. Scale bar equals 1cm C) Crab Shell. Scale bar equals 2cm, D) Tortoise Shell. Scale bar equals 1cm, E) Fox Femur, Scale bar equals 2cm.

(OUMNH SR0671) and the right femur of a fox (*Vulpes vulpes*) (OUMNH SR1812). Each of the five objects was handled by each participant over the course of the interview (Fig. 6.1).

6.3.4 Procedure

Once informed consent was completed, the interview commenced following the schedule detailed in Appendix 11.C. First, the participant was presented with one of the five objects, selected randomly using a pre-made random table. They were then asked to think-aloud whilst interpreting the object, which tasked them with describing the object (Q1). They were asked to describe it based on its features, shape, texture and material properties and were probed with premade probing questions until they had no more to say or the interviewer was satisfied that they had described as much of the object as possible. While describing the object, the principal researcher noted down which senses were used.

After describing the object, they were first asked to try and identify what the material was made of and why they thought so (Q2). Following that, they were asked to identify what they thought the object was and why they thought so (Q3). Following this, the interviewer described the object to the participant in order to give them a full impression of what the object was and the features on it, to clear up any misunderstandings. This was done using a premade written description to minimise variation in interpretation between participants. The participant then had an opportunity to comment and ask questions about the object before proceeding, so that they fully understood the object. Finally, the participant was then asked to suggest how the object could be changed through the medium of 3D printing to assist their understanding (Q4). Once complete, the object was returned and the participant given the next object and the process repeated.

This process was repeated for each of the five objects. Finally, once all objects had been explored they were all placed in front of the participant. They were then asked two questions on how difficult they were to interpret. First, they were asked which of the five objects was easiest to perceive and why they thought so (Q5). Finally, they were then asked which was the hardest to perceive and why they thought so (Q6). Once these questions were asked, the participant was thanked and then given the opportunity to ask any further questions or add any additional comments. After this, the participant was dismissed. No incentives were given for taking part in the study. The whole process lasted between 25 and 50 minutes.

6.3.5 Analysis

In order to quantify the corpus of interview data, content analysis was employed on the interview transcripts to draw out key recurring themes and identify how the participants responded to the questions. As highlighted previous, this particular approach was chosen for its ability to convert complex qualitative data and reduce it to highlight its key themes using a rigorous, repeatable approach (Krippendorff, 2009; 2013; Nili et al. 2017). A total of 10 different coding schemes were used, each designed to address a particular question and categorise the responses to that specific question. These are summarised in Table 6.3, along

Table 6.2: Demographic Information of Participants

Participant	Age	Gender	Sight Loss	Duration	Braille Proficiency	Cause of Blindness
Albert (001)	65+	Male	Minor Visual Impairment	Congenital	Cannot Read	Congenital Macular Degeneration
Devon (002)	65+	Female	Minimal Colour Perception	3 to 5 Years Ago	Cannot Read	Auto-Immune Retinopathy
Roxanne (003)	55-64	Female	Blindness with Light Perception	15+ Years Ago	Cannot Read	Pellucid Marginal Degeneration
Karrey (004)	65+	Male	Total Blindness	Congenital	Fluent	Congenital Optic Atrophy
Guenevere (005)	35-44	Female	Minimal Visual Shape Perception	5 to 10 Years Ago	Cannot Read	Keratoconus
Pamela (006)	65+	Female	Minimal Visual Shape Perception	5 to 10 Years Ago	Cannot Read	Macular Degeneration
Svana (007)	35-44	Female	Blindness with Light Perception	15+ Years Ago	Partial Fluency	Retinitis Pigmentosa
Magdalene (008)	65+	Female	Minor Visual Impairment	5 to 10 Years Ago	Cannot Read	Glaucoma and Optic Nerve Damage
Choux (009)	55-64	Male	Blindness with Light Perception	5 to 10 Years Ago	Cannot Read	Glaucoma
James (010)	45-54	Female	Minor Visual Impairment	15+ Years Ago	Cannot Read	Stargardt's Disease
Ariel (011)	45-54	Female	Total Blindness	15+ Years Ago	Cannot Read	Retinitis Pigmentosa
Robinson (012)	25-34	Female	Minimal Visual Shape Perception	Congenital	Partial Fluency	Septo-optic Displasia
Paulman (013)	55-64	Male	Minimal Colour Perception	Congenital	Fluent	Unspecified Condition
Yvonne (014)	55-64	Female	Total Blindness	15+ Years Ago	Undergoing Training	Retinitis Pigmentosa
Mathus (015)	25-34	Male	Total Blindness	Congenital	Fluent	Retinopathy of Prematurity
Mariah (016)	35-44	Male	Total Blindness	Congenital	Fluent	Unspecified Condition
Auslese (017)	65+	Female	Minimal Colour Perception	15+ Years Ago	Cannot Read	Cataracts and Age-Related Macular Degeneration
Orivea (018)	45-54	Male	Minor Visual Impairment	15+ Years Ago	Cannot Read	Congenital Rubella Syndrome
Dorro (019)	45-54	Male	Minimal Visual Shape Perception	3 to 5 Years Ago	Cannot Read	Stargardt's Disease
Iris (020)	45-54	Male	Minimal Visual Shape Perception	Congenital	Cannot Read	Congenital Cataracts. Detached Retina. Glaucoma
Gainer (021)	45-54	Male	Blindness with Light Perception	15+ Years Ago	Cannot Read	Retinitis Pigmentosa

with inter-rater reliability values and units of analysis.

In order to generate these schemes, inductive category creation was carried out in the same manner as in previous chapters for similar reasons. A P1 scheme was created and subjected to inter-rater reliability analysis using Krippendorff's α. This was carried out with the principal researcher and another inter-rater, who both independently applied the coding scheme on four randomly-selected transcripts (~20% of the data). The results of this first phase can be found in Table 6.2, with α values for each of the schemes ranging from 0.48 to 1 depending on the coding scheme. Afterwards, both raters met and discussed issues with the coding scheme and recommended refinements to the coding scheme and corrected mistakes and errors, producing reconciled α values between 0.51 and 1. Lowest α values were notable in *Scheme 4: Object Changes* (α = 0.65) and *Scheme 6.2: Hard Reasons* (α = 0.51), both below the acceptable limits of Krippendorff's α (0.7-0.8) (Krippendorff, 2009; Nili et al. 2017).

The suggested corrections to the schemes were then applied which was refined to become a second phase coding scheme (P2). The process was repeated with this second scheme, with the same raters independently coding another four randomly selected transcripts. These showed higher α values in almost all of the schemes, between 0.62 and 1 (Table 6.3). The majority of the schemes sufficiently met the standard of Krippendorff's α with the exception of *Scheme 3.2: Object Reasons* (α = .68) and *Scheme 6.2: Hard Reasons* (α = .62). However, both of these exhibited high raw percentage agreement values, 86% and 89% respectively. This issue is associated with a peculiarity of the calculation of Krippendorff's α, where α values are significantly deflated when few categories are coded, resulting in an overestimation of error (Feng, 2015). Regardless, a further stage of reconciliation and error correction was carried out, resulting in largely improved α values of between .84 and 1, all schemes now fulfilling the requirements of reliability for content analysis.

6.4 RESULTS

6.4.1 Sensory Usage Observation

In total, participants used touch in all cases and sight, sound and smell to varying degrees in order to interpret the objects. Taste was not used by any participant. Frequency plots for sensory usage can be found in Fig. 6.2.

Overall, sound (Fig. 6.2a) was heavily utilised, between ~30 to ~60% of participants making use of acoustic properties. Use of sound was greatest when interacting with the crab shell (62%) and the tortoise shell (57%) and was used by over half of the participants. Participants handling the fox femur also used sound to a lesser degree (47%) whilst usage was much lower in the scallop shell (34%) and the brain coral (29%). It would also appear that a large proportion of participants who made use of sound were those who suffered from more severe sight loss, such as those with total blindness or only light perception. This also would appear to be true for those who lived with longer periods of blindness, such as congenital blindness and 15+ years of blindness. This might suggest that participants living with more severe sight loss and great experience in dealing with it were more reliant on their hearing to

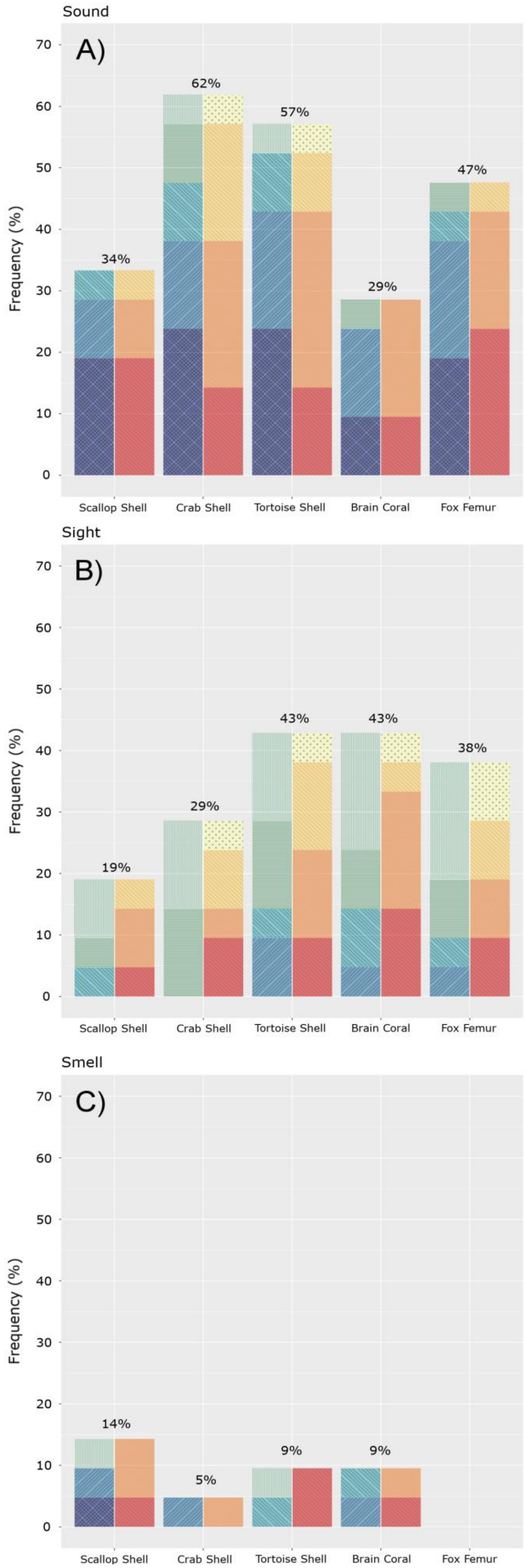
Table 6.3: Interrater Reliability of Content Analysis Schemes

Coding Scheme	Description	Unit of Analysis	Phase 1 IRR (P1) (α)	Phase 2 IRR (P2) (α)
Scheme 1: Object Description	Coding of different features, shapes and textures identified by participants	Logical Clause	.81 (.8)	.92 (.84)
Scheme 2.1: Material Identification	Coding of the material the participant identified the object was made out of.	Whole Answer	.89	.95 (.89)
Scheme 2.2: Material Reasons	Coding of the reasons the participant thought that the object was made of that particular material.	Logical Clause	.79 (.77)	.99 (.92)
Scheme 3.1: Object Identification	Coding of the object the participant identified the object was made out of.	Whole Answer	.89	.89
Scheme 3.2: Object Reasons	Coding of the reasons the participant thought that the object was what they thought it was.	Logical Clause	.73 (.71)	.92 (.68)
Scheme 4: Object Changes	Coding of what changes the participant thought could be made to the object to assist them.	Logical Clause	.65 (.58)	.85 (.82)
Scheme 5.1: Easiest Objects	Coding of which object the participant thought was easiest to understand.	Whole Answer	1	1
Scheme 5.2: Easiest Reason	Coding of why that particular object was easy to understand and interpret for the participant.	Logical Clause	.8	1
Scheme 6.1: Hardest Object	Coding of which object the participant thought was hardest to understand.	Whole Answer	1	1
Scheme 6.2: Hardest Reasons	Coding of why that particular object was easy to understand and interpret for the participant.	Logical Clause	.51 (.48)	.89 (.62)

() values indicate raw α prior to reconciliation and error correction

help understand the objects, although this was not confirmable using statistics due to the limited sample size.

Sight was used by fewer participants, ranging from ~20% to 45% of participants (Fig. 6.2b). Use of sight was greatest when interacting with the tortoise shell (43%) and the brain coral (43%), closely followed by the fox femur (38%). The crab shell was object explored using sight by 29% of participants while the scallop shell (19%) was explored the least using sight. By contrast to sound, it can be observed that the majority of participants who used sight generally suffered from less severe forms of sight loss while the duration of this sight loss appears to have no real impact, although again this could not be confirmed through statistical analysis. Sight levels are likely underestimated however, due to the difficulties in interpreting when the sense was used.



Sound
A)
Frequency (%)
34%
62%
57%
29%
47%
Scallop Shell
Crab Shell
Tortoise Shell
Brain Coral
Fox Femur
Sight
B)
Frequency (%)
19%
29%
43%
43%
38%
Scallop Shell
Crab Shell
Tortoise Shell
Brain Coral
Fox Femur
Smell
C)
Frequency (%)
14%
5%
9%
9%
Scallop Shell
Crab Shell
Tortoise Shell
Brain Coral
Fox Femur

Fig. 6.2: Sensory Usage by BPS Participants in Object Handling: Frequency plots of sensory usage for BPS participants for each of the five objects A) Use of the sense of sound. B) Use of the sense of sight. C) Use of the sense of smell. Colours represent sight loss demographics. The left bar represents the sight loss condition; Mint Green (Vertical) = Minor Visual Impairment, Green (Horizontal) = Minimal Visual Shape Perception, Turquoise (Thick Diagonal Right) = Minimal Colour Perception, Dull Blue (Thick Diagonal Left) = Blindness with Light Perception, Royal Blue (Thick Cross-hatched) = Total Blindness. The right bar represents the duration of sight loss; Yellow (Dots) = 3 to 5 Years Ago, Gold (Thin Diagonal Right) = 5 to 10 Years Ago, Orange (Thin Diagonal Left) = 15+ Years Ago, Red (Thin Cross-hatched) = Congenital.

Scent was used by an extremely small proportion of the sampled participants, ranging between 0% and ~14% (Fig. 6.2c). Smell was used the most when interpreting the scallop shell (14%), relatively similar amounts in the tortoise shell and brain coral (9%), a lower amount in the crab shell (5%) and was absent in the fox femur. It would appear only participants who had congenitally suffered from sight loss or those who had been living with it for greater than 15 years used their sense of smell to engage with the objects, but again the sample size limited any meaningful statistical analysis.

Overall, all blind and partially sighted participants used all of their senses, with the exception of taste, to varying degrees while interacting with the objects. Sound and sight were most commonly used with smell being used by few participants.

6.4.2 Material and Object Definition

6.4.2.1 Material Definition

After describing the object, participants were asked to identify what they thought the object was made of and were able to do so with reasonable accuracy, ranging between ~60% up to ~85% (Fig. 6.3).

The scallop shell (Fig. 6.3a) showed the lowest accuracy, with only 58% of visitors stating that it was made of a rock-like material, such as fossilised shell (10%) or material (5%), minerals (5%) while the majority that it was stone or rock (38%). This represented a good proportion of participants and a reasonable level of accuracy. Other interpretations included clay (5%), cement (5%) and natural material (5%) while the majority identified it as shell (29%). This last interpretation reflects that participants were unable to differentiate between rock and shell, suggesting that they were inferring that it was made of shell based on their interpretation of the object rather than its material properties. This is further discussed below.

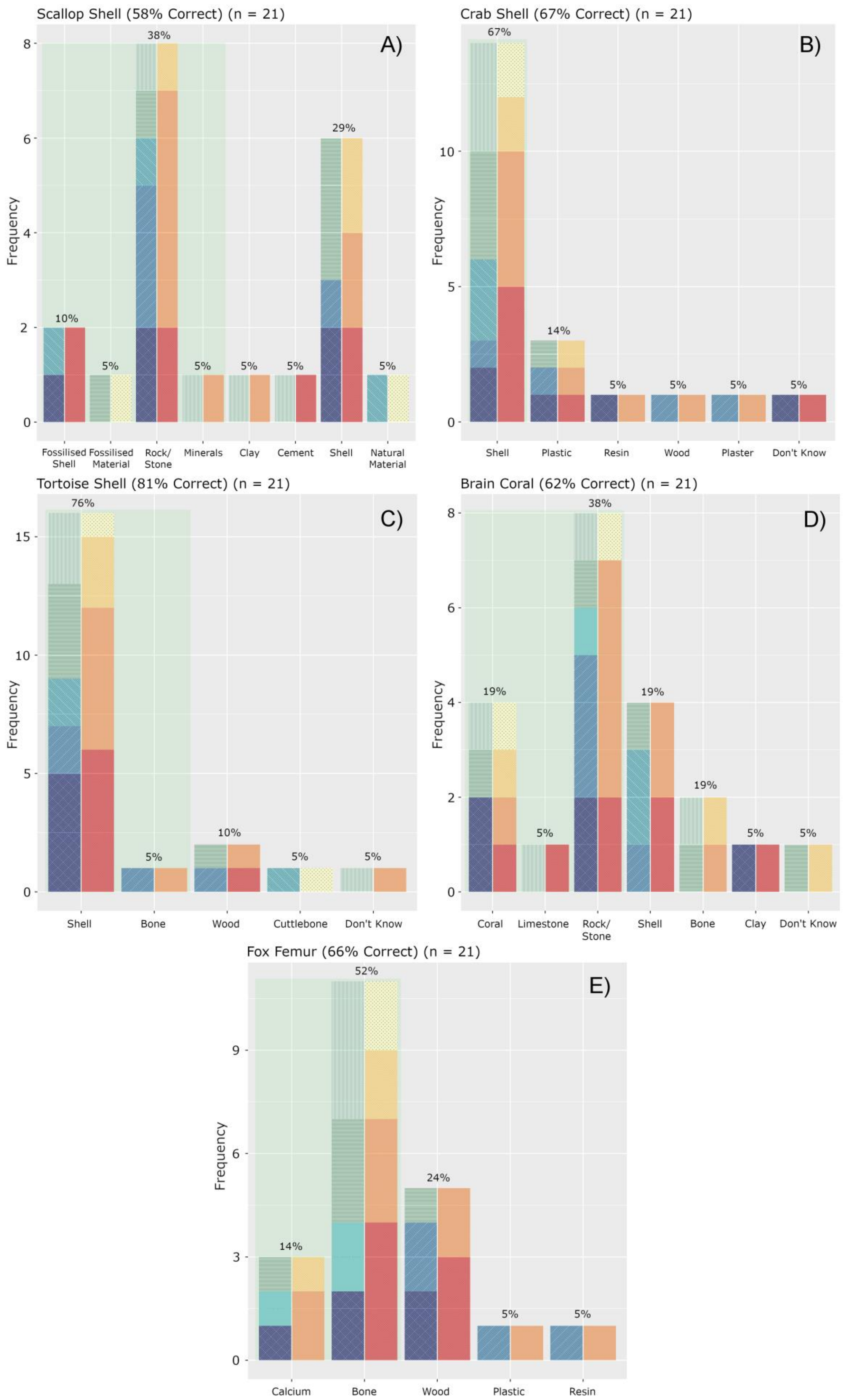
For the crab shell (Fig. 6.3b), participants showed reasonable accuracy of material identification, with 67% of participants identifying it as being made of shell alone. Incorrect responses were varied, including plastic (14%), resin (5%), wood (5%) and plaster (5%). These errors suggest that chitinous shell material can be easily mistaken for multiple different materials.

The tortoise shell (Fig. 6.3c) showed the highest accuracy (81%), with 76% of the participants easily interpreting it as shell and 5% identifying it as bone. Incorrect responses make up a small proportion, such as wood (10%) and cuttlebone (5%), with one participant being unable to identify it (5%). Again, the misinterpretation of the shell material as wood suggests again that some BPS individuals have difficulty in differentiating certain materials.

The brain coral (Fig. 6.3d) showed a reasonable level of accuracy (62%), with 19% identifying the object as being made of coral, 5% as limestone and 36% as stone or rock. For incorrect responses, 19% of participants mistook the object as made of some form of shell, 10% as being made of bone, 5% being made of clay while 5% were unable to identify what the object was made of. As above, the misinterpretation of the object as shell could be related to object interpretation as a shell (see 6.4.2.2 Object Definition). This again might suggest that material judgements are influenced by object judgements.

Finally, the fox femur (Fig. 6.3e) also showed a reasonable level of accuracy (66%), with 14% of the participants identifying the object from being made of calcium (14%) and the majority identifying it as bone (52%). For incorrect responses, wood was the most common response (24%), with plastic (5%) and resin (5%). Misinterpretation as plastic suggests again that some materials may be difficult to differentiate from each other.

Next, participants were asked to provide reasons why they thought the object was made of their chosen material (Fig. 6.4). The most dominant contributor to material identification was that of the texture of the object (16%), composed of a number of more specific categories. These included the general ‘texture’ (5%) of the object and its roughness (5%), which were the greatest contributors alongside its smoothness (4%) and its graininess (2%). Next, the shape of an object (13%) was a major contributor to identifying the material, matching the idea that material judgements are in some way integrated with object judgements. Next, the weight of the object was a major contributor (9%) alongside the specific features the object had (9%) and the general ‘feel’ of the object (9%), its unqualifiable textural properties. An objects specific features are traits that define the object which appeared to have been utilised to interpret the material. The ‘feel’ and weight are however tied to material, the weight being informative of density and it’s relative ‘feel’ defining a complex suite of textural and physical properties. Next, the robustness of the object (6%) was also key, nesting within it toughness (2%), hardness (2%), fragility (1%) and rigidity (<1%). Interestingly, residual sight (5%) supports the idea of the prevalent use of sight in the interpretation of the objects noted above. Following this is a long



Scallop Shell (58% Correct) (n = 21)
A)
Frequency
10%
5%
38%
5%
5%
5%
29%
5%
Fossilised Shell
Fossilised Material
Rock/ Stone
Minerals
Clay
Cement
Shell
Natural Material
Crab Shell (67% Correct) (n = 21)
B)
Frequency
67%
14%
5%
5%
5%
5%
Shell
Plastic
Resin
Wood
Plaster
Don't Know
Tortoise Shell (81% Correct) (n = 21)
C)
Frequency
76%
5%
10%
5%
5%
Shell
Bone
Wood
Cuttlebone
Don't Know
Brain Coral (62% Correct) (n = 21)
D)
Frequency
19%
5%
38%
19%
19%
5%
5%
Coral
Limestone
Rock/ Stone
Shell
Bone
Clay
Don't Know
Fox Femur (66% Correct) (n = 21)
E)
Frequency
14%
52%
24%
5%
5%
Calcium
Bone
Wood
Plastic
Resin

Fig. 6.3: Material Judgements by BPS Participants: (Previous Page) Frequency plots of participant's interpretations of the materials of the five objects. Green box indicates field of 'correct' responses. A) Scallop Shell, B) Crab Shell, C) Tortoise Shell, D) Brain Coral, E) Fox Femur. Colours represent sight loss demographics. The left bar represents the sight loss condition; Mint Green (Vertical) = Minor Visual Impairment, Green (Horizontal) = Minimal Visual Shape Perception, Turquoise (Thick Diagonal Right) = Minimal Colour Perception, Dull Blue (Thick Diagonal Left) = Blindness with Light Perception, Royal Blue (Thick Cross-hatched) = Total Blindness. The right bar represents the duration of sight loss; Yellow (Dots) = 3 to 5 Years Ago, Gold (Thin Diagonal Right) = 5 to 10 Years Ago, Orange (Thin Diagonal Left) = 15+ Years Ago, Red (Thin Cross-hatched) = Congenital.

tail of more minor reasons, some of which are particularly notable. Prior experience (4%) was a minor reason, suggesting that a participant's prior experience with an object is key to their interpretation as well as the use of sound (4%), again suggesting that acoustic properties are indeed useful for the interpretation of material. The internal structure (3%), the size (2%) and object association (2%) suggest again that properties of the object that are independent of material can inform such judgments. The object's colour (2%) again advocates the idea of optical properties being useful for interpretation.

6.4.2.2 Object Definition

After being asked about the material of the object, participants were then asked to identify what the object was and why they thought so (Fig. 6.5). Overall, participants were less accurate at identifying the objects, with correctness ranging between ~20% and ~50%.

For the scallop shell (Fig. 6.5a), accuracy was low (19%), with 5% identifying the object as specifically a fossilised mollusc whereas 14% were able to identify the object as some form of generic fossilised shell. The majority of responses can be deemed partially correct (67%), including as a fossilised animal (5%), as a non-fossilised mollusc shell (24%), as a sea shell (5%) and as some form of shell (33%). This large number of partially correct responses shows that despite having difficulties in object identification, most participants were able to glean a general mental image of the object. Some participants misinterpreted the object as a leaf (5%), as an axe part (5%) and one was unable to identify the object (5%).

For the crab shell (Fig. 6.5b), accuracy was much higher with 52% of participants identifying it as a crab shell. A large amount of partially correct responses can be noted, including as a lobster shell (5%), a sea shell (5%) or a shell in general (19%). Again this suggests that participants partially understood what the object was. More spurious answers included identification as a tortoise shell (5%), a bowl (5%), a boat (5%) and finally, 5% could not identify what the object was.

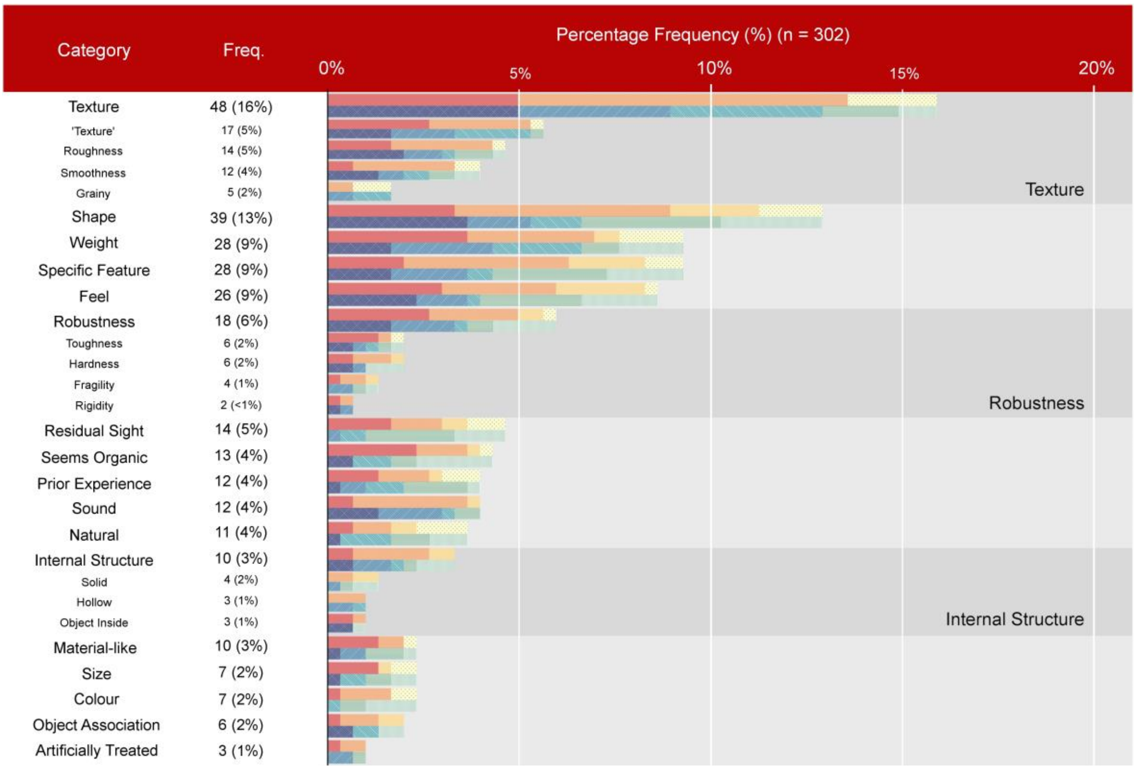


Fig. 6.4: Reasons for Identifying Materials by BPS Participants: Frequency plots for reasons for identifying the material the object is made of. Values below 3 have been removed. Colours represent sight loss demographics. The top bar represents duration of sight loss; Yellow (Dots) = 3 to 5 Years Ago, Gold (Thin Diagonal Right) = 5 to 10 Years Ago, Orange (Thin Diagonal Left) = 15+ Years Ago, Red (Thin Cross-hatched) = Congenital. The bottom bar represents the sight loss condition; Mint Green (Vertical) = Minor Visual Impairment, Green (Horizontal) = Minimal Visual Shape Perception, Turquoise (Thick Diagonal Right) = Minimal Colour Perception, Dull Blue (Thick Diagonal Left) = Blindness with Light Perception, Royal Blue (Thick Cross-hatched) = Total Blindness.

The tortoise shell (Fig. 6.5c) exhibited similar levels of correctness (58%). The majority of participants described the object as a tortoise, turtle or terrapin (53%) while one participant (5%) described it as a baby tortoise. Outside of this again, partially correct categories make up the majority of the remaining responses, 10% identifying it as an animal shell while a further 21% identified it as some form of marine creature. 10% were unable to identify what the object was.

The brain coral (Fig. 6.5d) exhibited much lower accuracy (19%), with a large disparity in responses. 19% all identified the object as a coral of some sort while again, a large number of partially correct responses can be noted. 10% identified the object as a sea urchin, 5% as a sea anemone and 5% as a barnacle, 10% identified the object as a generic sea creature and 5% as a generic sea shell. Many participants also identified the object as a fossil of some sort, 5% stating it was a fossil sea urchin, another 5% as a fossil in general and 10% as some sort of plant or part of a plant fossil. This may be in part due to the interpretation of the material of the object as rock or stone, suggesting again that material and object judgement were interrelated. Interpretation as some form of plant was also evident, another 14% identifying the object as some part of a non-fossilised plant. A further 14% of the participants were unable to identify the object, the highest amount in all the objects. This suggests that the brain coral was by far the most problematic objects to identify in the set.

Finally, the fox femur (Fig. 6.5e) showed similarly low levels of accuracy, with 24% of participants being able to identify it as a leg bone or femur. 5% were able to identify it as a femur belonging to a specific animal, 5% as an animal femur in general and a further 14% as a general leg bone. The remainder represent partially correct responses. 10% identified the object as some form of limb bone, be it arm or leg, while a further 5% identified it as a bone belonging to a specific animal. Half of the respondents identified the object as an animal bone in general (52%) and a further 5% were unable to identify the object.

For object justifications (Fig. 6.6), the dominant reason for identifying an object was its shape (20%). Next, the specific features of the object (14%) were used alongside the texture (11%), itself being composed of the general 'texture' of the object (8%), its roughness (3%) and its smoothness (1%). These top three reasons are notable in that they are also among the top reasons supplied for material identification noted above (Fig. 6.4), which certainly adds to the suggestion that both material and object interpretation is interrelated. Next, prior experience (10%), a lesser contributor in material judgements, was key in object judgements which suggests that previous experience of handling something similar allowed identification. The size of the object was also important (8%). Again, a long tail of more minor reasons can be found, of which there are a few of pertinent interest. The 'feel' of the object (5%), again a prominent contributor in material judgements suggests the integrated nature of interpretation while optical properties, including the colour (3%) and the residual sight (3%) of the participant, were again used to identify the object.

6.4.3 Enhancing Interpretability

Participants were asked to provide ways in which objects could be improved to better enhance their interpretation of the object (Fig. 6.7). For the most part, a significant proportion stated that no changes should be made to the objects (44%), showing fairly equal representation across all demographic categories. This is surprising given the general difficulty that participants had in identifying the objects but suggests that participants may have a preference towards handling objects with minimal alterations. Audio description (16%) was the most common response for change, the process of simply adding a complementary description of the object to aid their

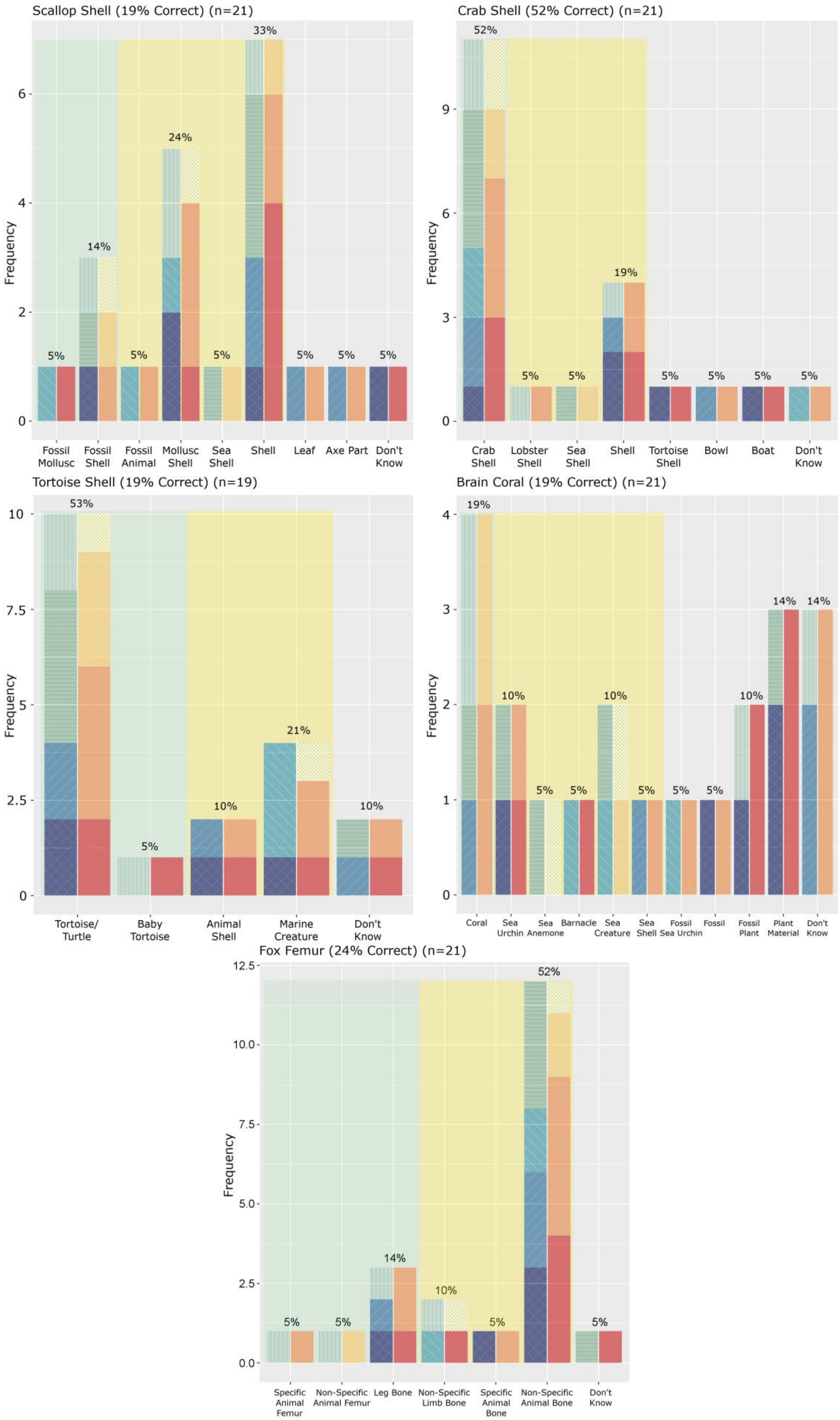

Scallop Shell (19% Correct) (n=21)
Frequency
Fossil Mollusc
Fossil Shell
Fossil Animal
Mollusc Shell
Sea Shell
Shell
Leaf
Axe Part
Don't Know
Crab Shell (52% Correct) (n=21)
Crab Shell
Lobster Shell
Sea Shell
Shell
Tortoise Shell
Bowl
Boat
Don't Know
Tortoise Shell (19% Correct) (n=19)
Tortoise/ Turtle
Baby Tortoise
Animal Shell
Marine Creature
Don't Know
Brain Coral (19% Correct) (n=21)
Coral
Sea Urchin
Sea Anemone
Barnacle
Sea Creature
Sea Shell
Fossil Sea Urchin
Fossil
Fossil Plant
Plant Material
Don't Know
Fox Femur (24% Correct) (n=21)
Specific Animal Femur
Non-Specific Animal Femur
Leg Bone
Non-Specific Limb Bone
Specific Animal Bone
Non-Specific Animal Bone
Don't Know

Fig. 6.5: Object Judgements by BPS Participants: (Previous Page) Frequency plots of participants interpretations of the five objects. Green box indicates field of 'correct' responses and yellow box indicates those deemed partially correct. A) Scallop Shell, B) Crab Shell, C) Tortoise Shell, D) Brain Coral, E) Fox Femur. Colours represent sight loss demographics. The left bar represents the sight loss condition; Mint Green (Vertical) = Minor Visual Impairment, Green (Horizontal) = Minimal Visual Shape Perception, Turquoise (Thick Diagonal Right) = Minimal Colour Perception, Dull Blue (Thick Diagonal Left) = Blindness with Light Perception, Royal Blue (Thick Cross-hatched) = Total Blindness. The right bar represents the duration of sight loss; Yellow (Dots) = 3 to 5 Years Ago, Gold (Thin Diagonal Right) = 5 to 10 Years Ago, Orange (Thin Diagonal Left) = 15+ Years Ago, Red (Thin Cross-hatched) = Congenital.

interpretation as they handled it. Some also stated that increasing the size of the object (11%) to aid the interpretation of smaller features could be useful followed by the addition of in-life features to the object (7%). This included adding limbs or bodies into objects, such as the crab shell, to better represent the creature as it should be. Other cited changes included internal access (4%), such as allowing parts to open or slide apart, exaggerating textural features (3%) to make them easier to interpret, altering colours (3%) to increase contrast and counter limited colour perception (3%), removing coatings and previous treatments for a truer feel of the object (2%), preserving damage on the object for a more realistic interpretation (2%) and enlarging specific parts of the object (2%).

6.4.4 Ease of Interpretation

Participants were also asked to choose which objects were easiest and hardest to interpret and to justify their response (Fig. 6.8). Overall, the most difficult to interpret object was the brain coral by a large margin (n = -11), with no participants choosing it as easiest to interpret. This was followed by the tortoise shell which showed an even number of easiest and hardest judgements (n = 0) followed by the crab shell (n = 1) and scallop shell (n = 2) which were deemed to be slightly easier to interpret whilst the fox femur (n = 8) was deemed to be the easiest, with no participants choosing it as the hardest to interpret. Overall, the fox femur was the easiest object to interpret whilst the brain coral was the hardest.

The order of interpretational difficulty of these objects could be associated with how much exposure one would have to such objects in daily life. The bone was likely easier interpret as it is a fairly common object, contrasted with a brain coral which few people are ever likely to have encountered in person. This suggests that perhaps prior experience could be an important factor, which is further corroborated below.

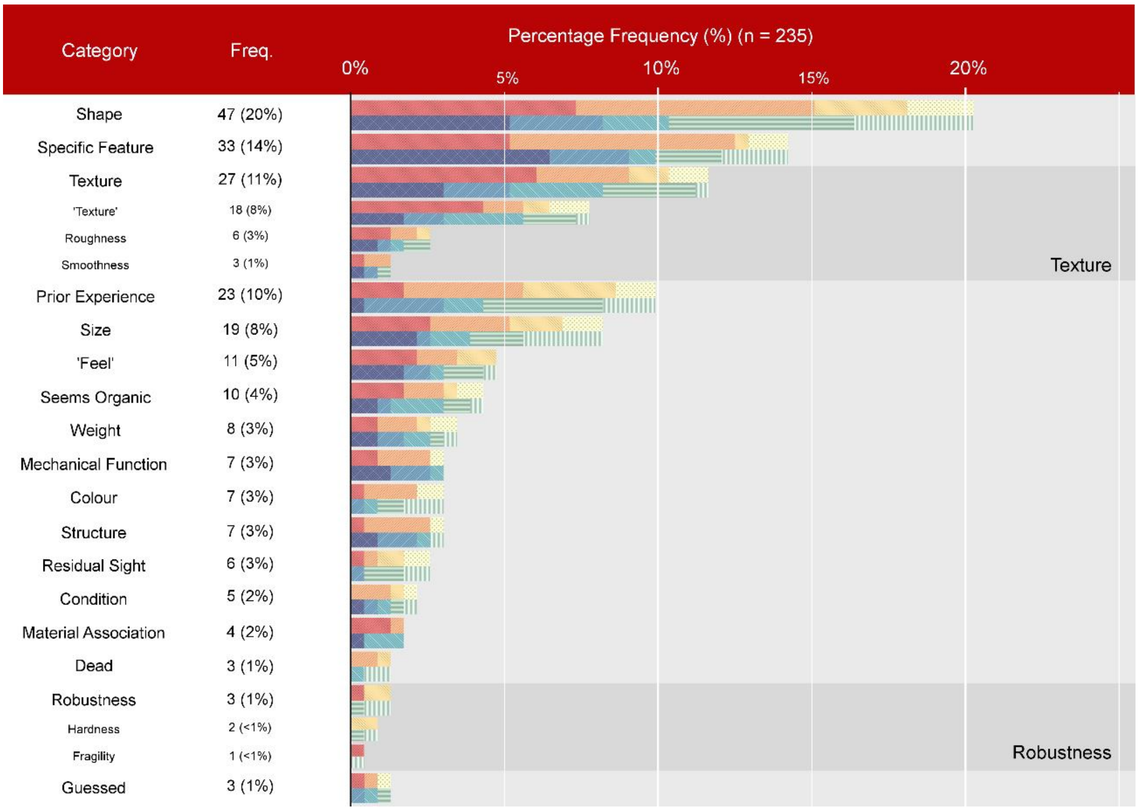


Fig. 6.6: Reasons for Identifying Objects by BPS Participants: Frequency plots for reasons for identifying objects. Values below 3 have been removed. Colours represent sight loss demographics. The top bar represents duration of sight loss; Yellow (Dots) = 3 to 5 Years Ago, Gold (Thin Diagonal Right) = 5 to 10 Years Ago, Orange (Thin Diagonal Left) = 15+ Years Ago, Red (Thin Cross-hatched) = Congenital. The bottom bar represents the sight loss condition; Mint Green (Vertical) = Minor Visual Impairment, Green (Horizontal) = Minimal Visual Shape Perception, Turquoise (Thick Diagonal Right) = Minimal Colour Perception, Dull Blue (Thick Diagonal Left) = Blindness with Light Perception, Royal Blue (Thick Cross-hatched) = Total Blindness.

6.4.4.1 Reasons for Easiest Object

Participants were asked to provide reasons why they considered the object easy to interpret (Fig. 6.9). The most commonly cited reason for finding an object easy to understand was the shape of the object (23%) and that it was a distinctive object (23%), both suggesting that shapes that are common and well known were easier to interpret that objects that were less distinctive. Tying into this is the participant's previous experiences (19%), with similar objects in the past which contributed to their ease of understanding. These three reasons lend credence to the idea that prior experience is essential to the interpretation of these objects and that familiarity will aid a participant's interpretation. Other cited reasons included the 'feel' of an object (9%), it's weight (5%), texture (5%), the simplicity of its structure (2%), the fact that it felt organic (2%) and the visual features it possessed (2%).

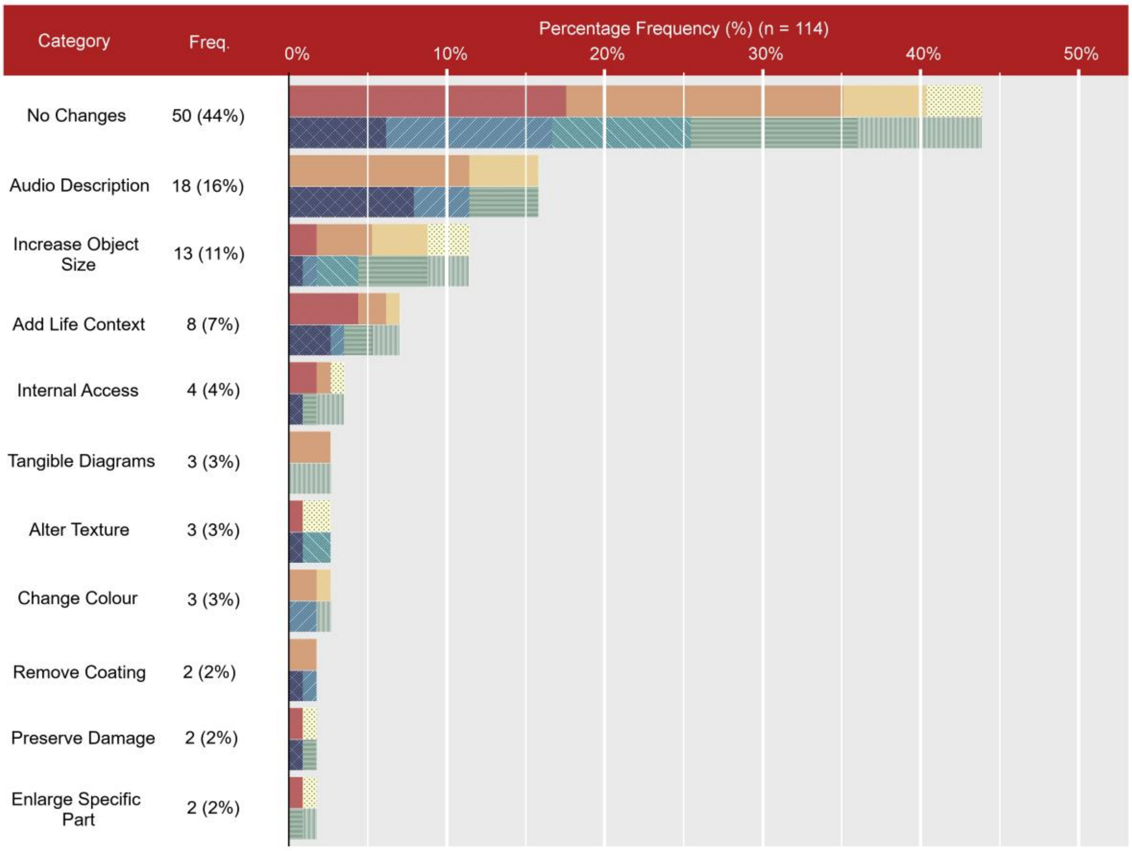


Fig. 6.7: Suggested Changes for Objects via 3D Printing: Frequency plot for reasons provided by BPS participants as to how their interpretations of the objects could have been assisted. Values below 2 have been removed. Colours represent sight loss demographics. The top bar represents duration of sight loss; Yellow = 3 to 5 Years Ago, Gold = 5 to 10 Years Ago, Orange = 15+ Years Ago, Red = Congenital. The bottom bar represents the sight loss condition; Mint Green = Minor Visual Impairment, Green = Minimal Visual Shape Perception, Turquoise = Minimal Colour Perception, Dull Blue = Blindness with Light Perception, Royal Blue = Total Blindness.

6.4.4.2 Reasons for Hardest Object

On the converse, participants were also asked to provide reasons why the object was difficult to understand (Fig. 6.10). The most common response was that the participant had no previous experience of the object or similar objects (21%), again supporting the idea of the necessity of prior experience in understanding and interpreting objects. The second most cited reason was that they simply misidentified the object (15%) and thought it was something completely different. Next, the texture was misleading (12%) for some found the object too complex to understand (9%) while others simply could not identify the object at all (9%). Some were confused by the size of the object (6%) while some were only able to identify the object in general terms (6%).

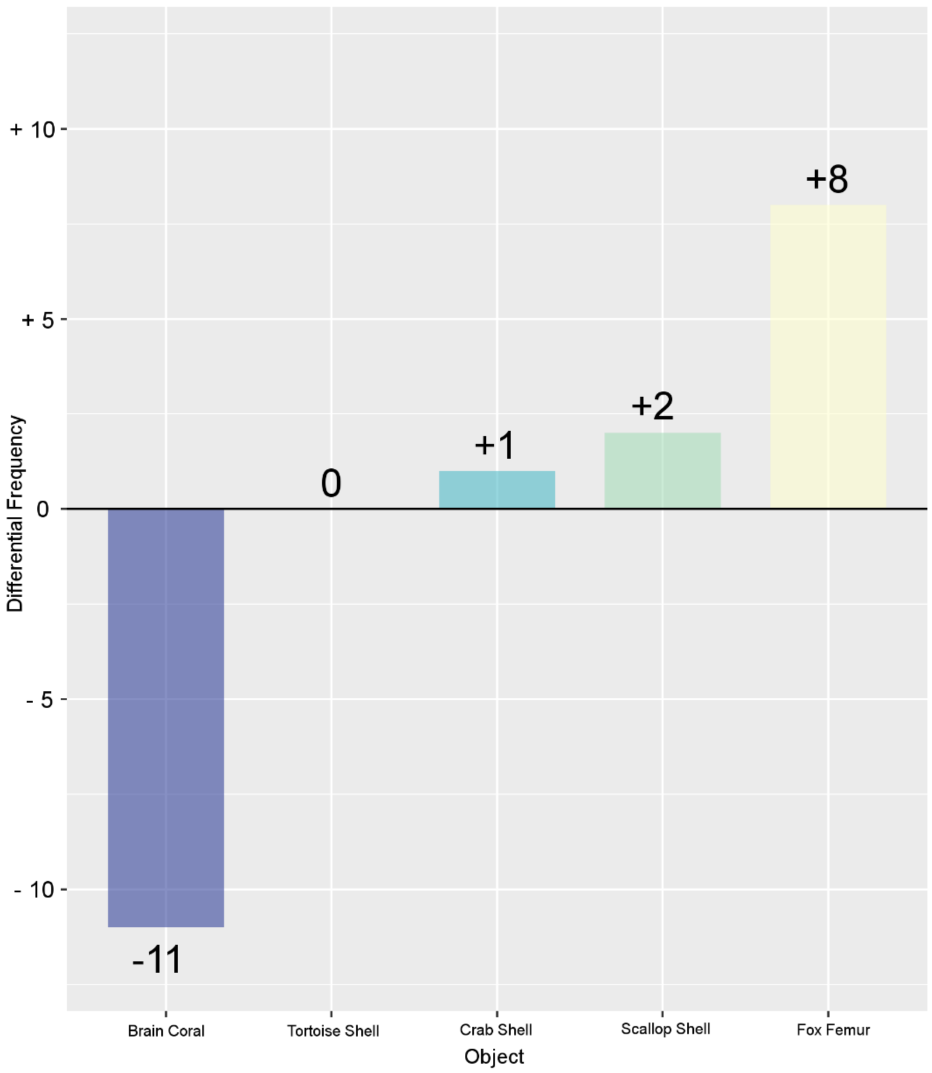


Fig. 6.8: Differential Frequency in Object Interpretational Difficulty: Differential frequency between which objects were easiest and hardest to interpret for each of the five objects. Negative values denote objects that more people found hard to interpret while positive values denote objects that were easier to interpret.

Other more minor reasons included that the object was too similar in shape to others (3%), misinterpretation of key features (3%), a lack of colour contrast (3%), the indistinctiveness of the shape of the object (3%), interpreting the object in the wrong orientation (3%), unexpected structures (3%) and thinking that the object was artificial (3%).

6.4.5 Summary

Overall, a number of key interpretations can be drawn from this analysis. First and foremost, BPS individuals do not solely rely on touch to interpret objects and use acoustic, optical and in some case, olfactory, object properties to interpret them. This exemplifies the multisensory

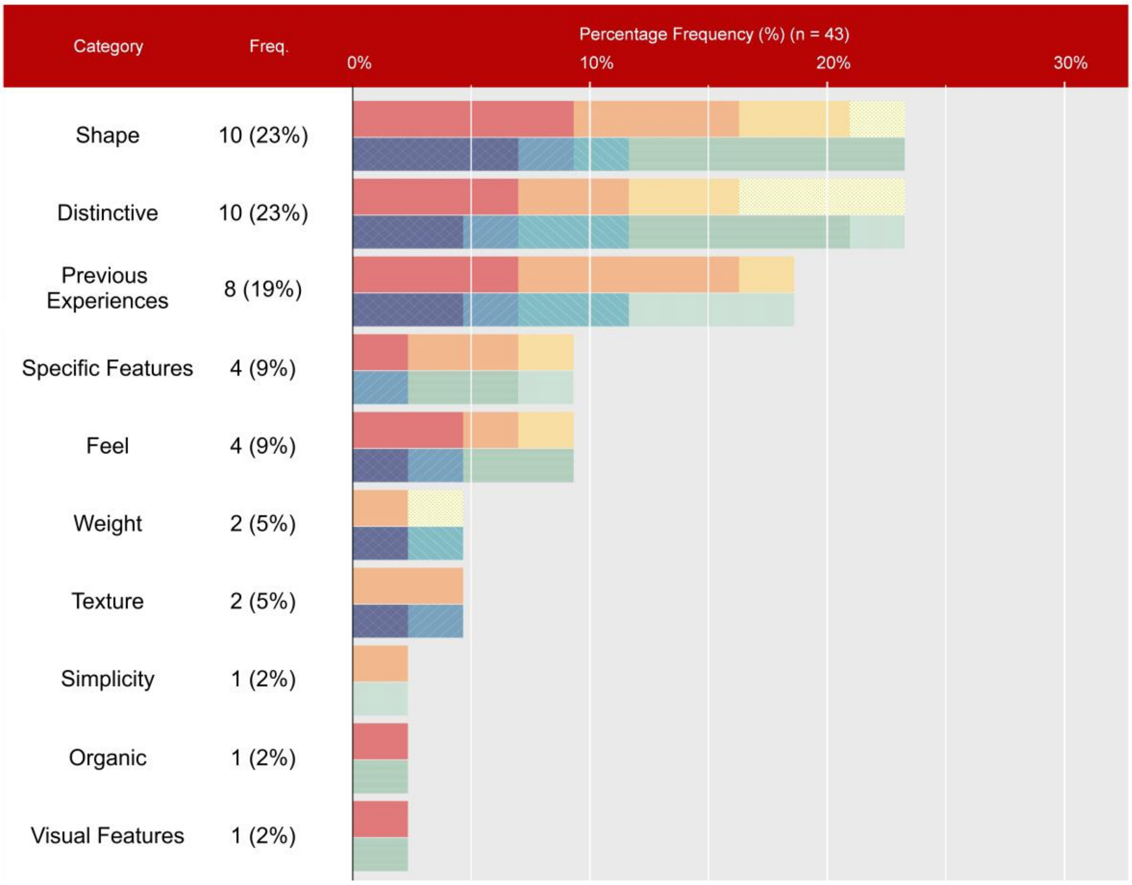


Fig. 6.9: Reasons for Easy Identification: Frequency plots for reasons for provided by participants for why they found their chosen object easiest to interpret. Colours represent sight loss demographics. The top bar represents duration of sight loss; Yellow (Dots) = 3 to 5 Years Ago, Gold (Thin Diagonal Right) = 5 to 10 Years Ago, Orange (Thin Diagonal Left) = 15+ Years Ago, Red (Thin Cross-hatched) = Congenital. The bottom bar represents the sight loss condition; Mint Green (Vertical) = Minor Visual Impairment, Green (Horizontal) = Minimal Visual Shape Perception, Turquoise (Thick Diagonal Right) = Minimal Colour Perception, Dull Blue (Thick Diagonal Left) = Blindness with Light Perception, Royal Blue (Thick Cross-hatched) = Total Blindness.

nature of BPS object interaction. Use of sound and sight could potentially depend on sight loss condition but although this could not be corroborated using statistical analysis.

For judgements of materials and object, material judgments showed greater accuracy than object judgements, although some evidence showed that the two were co-dependent. Both exhibited overlapping reasons for identification, suggesting that material properties inform the interpretation of an object and vice versa. Key for understanding these were the shape, specific features, texture, weight, size and optical properties. While object identification accuracy was poor among participants, the majority exhibited a partial understanding of what the object might have been. This suggests that objects may not be definitively understood through tangible

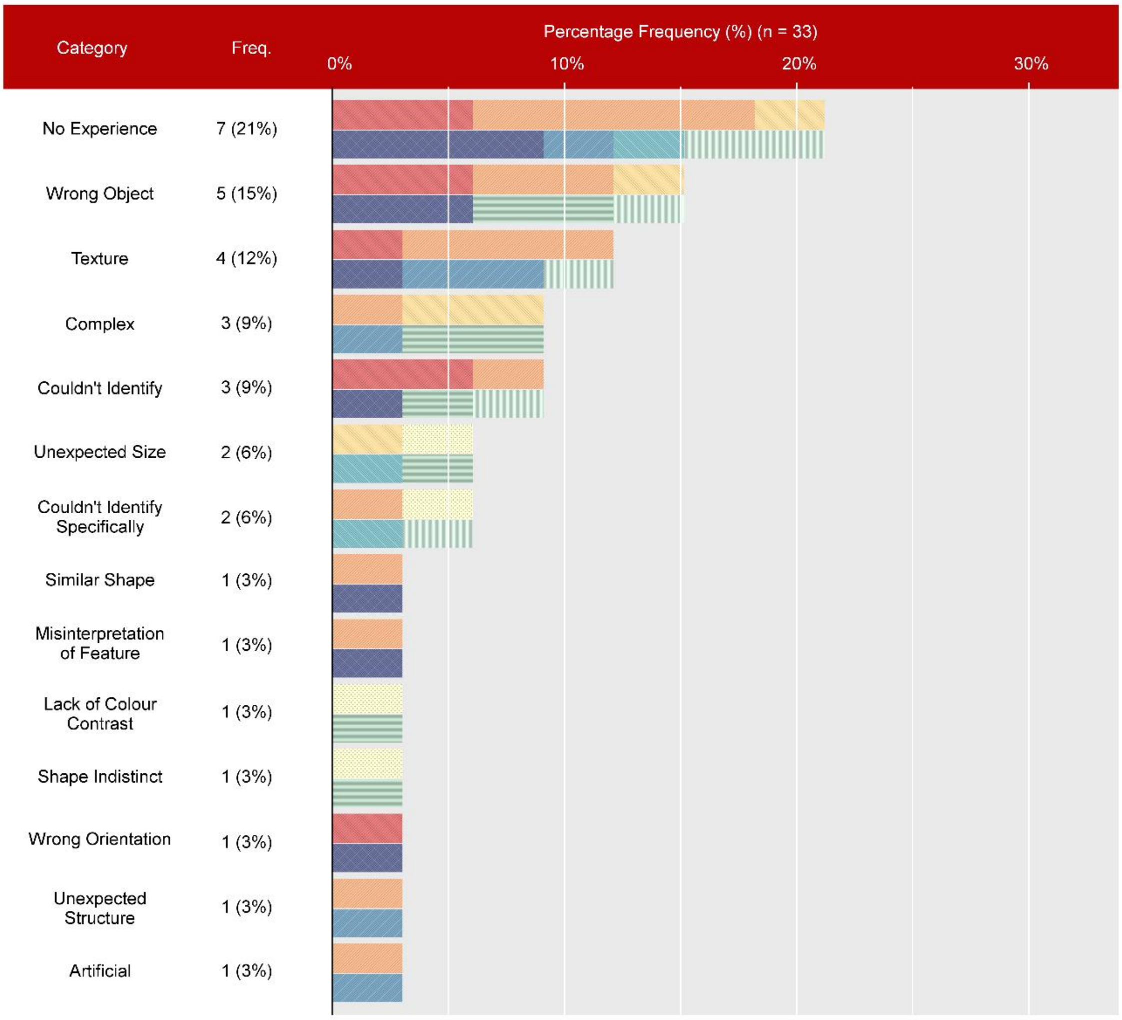


Fig. 6.10: Reasons for Hard Identification: Frequency plots for reasons for provided by participants for why they found their chosen object hardest to interpret. Colours represent sight loss demographics. The top bar represents duration of sight loss; Yellow (Dots) = 3 to 5 Years Ago, Gold (Thin Diagonal Right) = 5 to 10 Years Ago, Orange (Thin Diagonal Left) = 15+ Years Ago, Red (Thin Cross-hatched) = Congenital. The bottom bar represents the sight loss condition; Mint Green (Vertical) = Minor Visual Impairment, Green (Horizontal) = Minimal Visual Shape Perception, Turquoise (Thick Diagonal Right) = Minimal Colour Perception, Dull Blue (Thick Diagonal Left) = Blindness with Light Perception, Royal Blue (Thick Cross-hatched) = Total Blindness.

interaction and must be assisted.

The majority of participants did not want the objects to be changed in any way, but some advocated that the addition of audio description to assist interpretations, increasing the size of the objects for easier interpretation and adding life context to the object could assist their interpretation.

Finally, prior experience played a key role in whether or not an object was easy to or hard to interpret, common objects that were distinctive in features and shape being easier to interpret.

6.5 DISCUSSION

Overall, participants were able to identify the five natural history objects to a reasonable degree, although not without difficulty. The majority of participants were able to glean a general understanding of what the objects were without any assistance, which suggests that with appropriate presentation within a museum environment, accurate interpretation should be feasible. Another notable trend was the multisensory nature of object interaction, many participants utilising tangible, optical, acoustic and olfactory properties in their interpretations. Prior experience and a number of other key object properties were also important for understanding what objects were, all of which have a number of implications for the fabrication of 3D printed replicas.

6.5.1 BPS Object Interpretation

The first major consideration that must be accounted for is that of the integration of multiple senses in the interpretation of the objects. While tangible properties were dominant in participant's reasonings for object and material identification, the use of optical and acoustic properties also implies that perception of these objects is multisensory. This, of course, is fairly well documented in research in sensory studies, which have vindicated touch from being a 'second citizen' inferior to the other senses as it was historically viewed (Lederman and Klatsky, 1987; 2004; Heller, 1989; Heller and Ballesteros, 2006). The idea of the multisensory nature of human perception has since proliferated from a large number of studies carried out in the latter half of the 20th century, which typically found that different senses were more adept at interpreting different kinds of information, such as touch for texture and vision for shape and that they can complement one another, leading to perceptual redundancy and a clearer interpretation (Lederman and Klatzky, 2004; Millar, 2006; Gallace and Spence, 2014). These typically took the form of quantitative clinical experiments but more recent developments in visualising brain activity *in vivo* have confirmed these ideas, using methods including Positron Emission Tomography (PET) or Transcranial Magnetic Stimulation (TMS) (Sathian, 2005; Lacey and Sathian, 2014). Many of these experiments show multisensory recruitment of different parts of the cortex, the visual cortex being recruited into use in tangible interaction, particularly of note in BPS tangible interaction with braille (Sathian, 2005; Lacey and Sathian, 2014; Voss et al. 2016). For example, the lateral occipital complex (LOC) has been shown to be responsible for shape recognition in both sight and touch, but can also be trained to respond to sound (Grill-Spector et al. 2001; Lacey and Sathian, 2014). Many of these studies however historically have used rather simple objects that are easy to quantify, such as sandpaper (Spence and Gallace, 2008; Etzi et al. 2014), so confirming such sensory integration using more ecologically valid objects is useful, as other authors have (Baumgartner et al. 2015). The overall implication of this is that all senses must be accounted for when considering the design of 3D printed replicas. For example, making a monotone, thermoplastic print will have markedly different optical, acoustic and olfactory properties compared to the original and could actively serve to deceive the holder, rather than inform them.

Further complicating this issue is the general perception of the BPS population. Typically only the 'typical' condition of congenitally totally blind individuals is considered for many BPS applications. This generally means a focus on tactility to the exclusion of the other senses and a propensity towards braille. In reality however, the BPS audience is composed of a variegated population of different people with different backgrounds, experiences, sensory proficiencies and lifestyles. As mentioned earlier, there are 2 million BPS persons in the UK but only 14% are diagnosed as legally blind along with the rather limited proportion of BPS individuals who are capable of reading braille (Mesquita and Carneiro, 2016; RNIB, 2018). This means that many of these provisions in museum environments are only really useful to a small proportion of BPS visitors. The varied nature of sight loss is often ignored, which ranges from patchy vision or blurring, down to reduced colour, light perception and finally, total blindness (Fig. 6.11) (Bourne et al. 2013; WHO, 2018). Naturally, these life experiences have an impact on tactile proficiency, a trend noticed by a number of authors (Koch et al. 2013).

Another complicating factor is that of the 'sensory compensation hypothesis', a somewhat controversial hypothesis that states that sensory deprivation in the blind leads to increased sensitivity in other senses. Thus the absence of sight leads to more acute hearing and tactual clarity (Grant et al. 2000; Alary et al. 2009; Voss, 2011; Baumgartner et al. 2015). The evidence is conflicting, but generally findings have concluded that prior visual experience to becoming blind is irrelevant, as many studies have shown that congenitally blind and late-blind participants show similar performances on a variety of different tactile tasks (Heller, 1989; Heller and Ballesteros, 2006; Sathian and Stilla, 2010; Baumgartner et al. 2015) and that practice with tangible interaction is more important, more experience leading to greater performances in these studies (Grant et al. 2000; Alary et al. 2009). Interesting, even sighted participants who have been blindfolded show rapid acclimatisation and increase in accuracy over the course of a study, which is subsequently lost (Sathian, 2005). Given that participants will have different levels of experience with tactile interaction depending on how long they have been suffering from sight loss, this further complicates how easy it is for a single BPS person to interpret and understand an object. All of these complicating factors lead to a more complex BPS population with a variety of different levels of residual sight, tactile experience and prior knowledge that need to be accounted for when designing 3D printed replicas. For example, Callieri et al. (2015) created a 3D printed replica of an artwork called *Alchemy* by Jackson

Pollock, a highly-textured painting incorporating a wide variety of materials from industrial enamels to sand and wooden sticks. However, the final 3D printed replica did not include the colour of the original, potentially removing informative information for BPS persons with residual colour vision which would assist in the interpretation of the piece. Thus, considering the varied needs and sensory proficiencies of the BPS audience is a vital consideration to the design of 3D printed replicas (Guarini, 2015).

Prior experience is also an important factor. It is well-documented in museum literature, as highlighted in the literature review (*See 2.3.1 Multisensory Experiences*), that inherent in the museum learning experience is the person's prior experiences. This has a strong influence on what museum content is attended to and what is learned (Falk and Dierking, 2000; 2012; Hooper-Greenhill, 2007; Smith, 2015). This was evident the participants provided reasons for object interpretation difficulty and appears to be also important in BPS individuals. Tangible interaction is laborious and cognitively demanding, meaning that identifying a novel object is a more demanding task. The tortoise shell and brain coral in particular were divisive objects for such reasons. Many participants were unable to identify the brain coral in any capacity, mostly due to never having interacted with such an object before, as in the words of Karrey:

"Well I'd never recognise that, I've never felt any coral before so it's not right."

Karrey (Congenital Total Blindness)

In this case, the participant was congenitally full-blind, having no visual experience of such creatures. This visual experience did appear to have a strong impact on object identification. For example, some participants were instantly able to identify the tortoise shell due to having owned a pet tortoise in the past, as in the words of Iris:

"I actually owned a tortoise so I remember what it felt like you know."

Iris (Congenital Minimal Visual Shape Perception)

Another identified the crab shell as a shell quickly, again because they had an active interest in shells, in the words of Roxanne:

"I collect shells. I've got several of them. Real ones."

Roxanne (15+ Years Blindness with Light Perception)

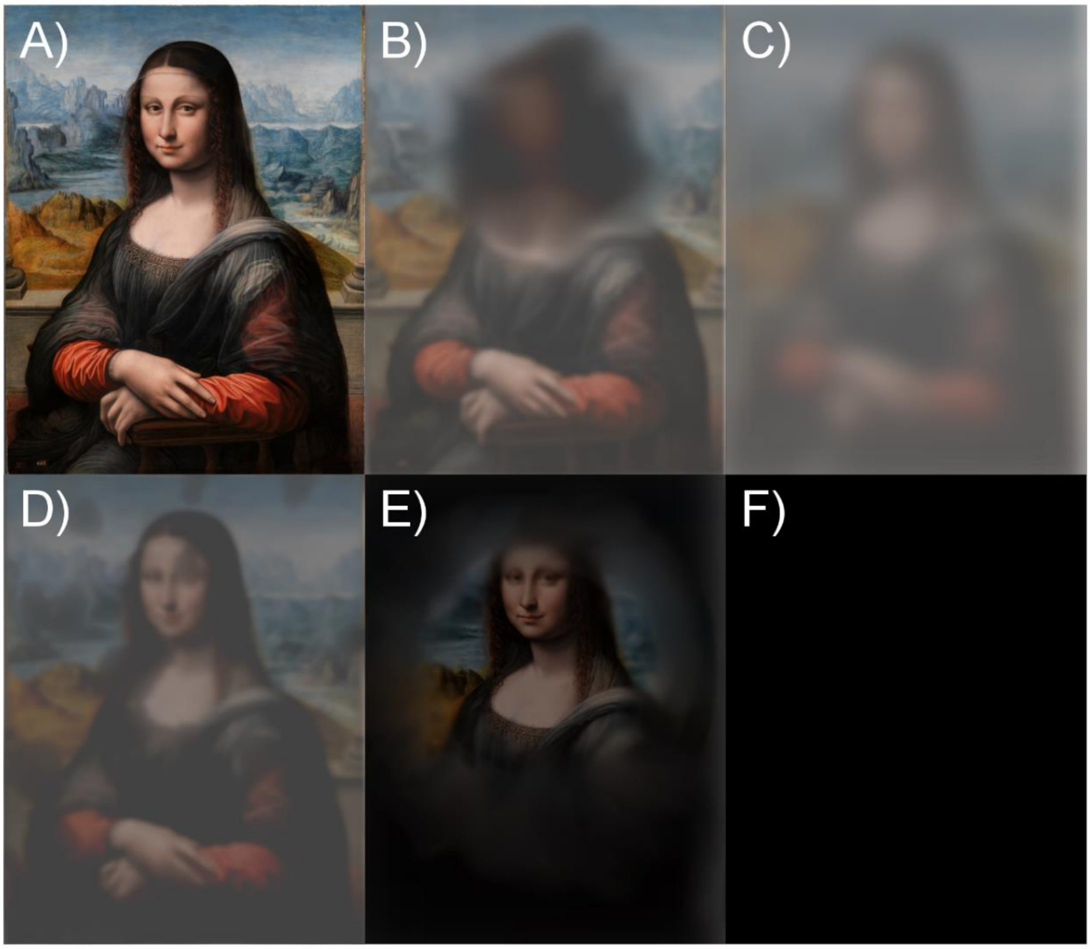


Fig. 6.11: The Varied Nature of Sight Loss: Sight loss varies immensely from person to person based on the conditions they are suffering from. Common sight loss conditions are shown here. A) Perfect Vision, B) Central Vision Loss, typical of Age-related Macular Degeneration (AMD), C) Blurring of vision, typical of Cataracts, D) Patchy vision loss, typical of Diabetic Retinopathy, E) Peripheral vision loss, typical of Glaucoma, F) Total blindness.

Overall, this suggests that the prior life experiences of the participants were integral to their interpretations. This brings up some interesting connotations for those who incur blindness early in their lives. These individuals are likely to have far less breadth of experience with exotic and unusual objects compared to the late-blind. Unfortunately, museums are typically repositories for rare and unfamiliar objects and aim to educate participants about them. This creates a challenge in presenting unusual objects to those who have limited experience with such objects, especially when touch is their dominant interpretative sense. This also highlights one final point, that participants were unable to obtain complete understanding through touch alone. Given the poor object identification rates, many of the participants in this study gleaned a general understanding of the objects, but were unable to specifically identify it. The overall implication of this is that simply giving or offering up tangible content for BPS visitors is insufficient for true understanding, and complementary content is required in order to facilitate learning and understanding. This can be done through a variety of means, most commonly through audio guides. This principle of truly multisensory interaction is demonstrated effectively by Eardley et al. (2016) at the National Tile Museum (Lisbon) and the Community Museum of Batalha, who incorporated detailed object descriptions into these audio guides to guide and accompany object handling. These recommendations were indeed forwarded by the participants here, who also emphatically advised such practice:

So, you know that if they did these in museums. Would there be an audio with it to have a description of what these objects would be in Oxford? (…) That would be fantastic to be able to do that.

Guenevere (5 to 10 Minimal Visual Shape Perception)

Another suggested that such approaches could be useful priming tools for BPS visitors, giving them useful information that tailors their expectations or could even warn handlers if the object may be undesirable to handle or of a sensitive nature:

"So audio would be better to start with like, explaining like what you are actually going through like and if it's a certain person, he might want to feel something, he might not want to feel something, he could be a vegetarian.(…) He might not like touching meat. So they might think it's an offence. And if it's on audio there, that will give them the mind of saying yes or no. Shall I go and touch it."

Choux (5 to 10 Blindness with Light Perception)

Fortunately, given the widespread integration of audio devices in the modern museum, incorporating focussed content for BPS should be of little difficulty and many institutions worldwide currently offer such support for BPS visitors.

6.5.2 Creating 3D Prints for BPS Individuals

With the perceptual requirements of BPS individuals in mind, design philosophies for the creation of tangible 3D printed replicas for handling can now be considered. First and foremost, the implication of multisensory exploration of the objects used in this study implies that optical, acoustic and olfactory properties of an object are important to BPS understanding and interpretation. Using the example of a sea shell, the smell of salt, the 'clack' it makes when placed on a hard surface or high contrast colouration on its surface could all be potentially informative traits in understanding the nature of the object. The issue with fabrication via 3D printing is that replicas of such objects will lack these authentic traits due to the nature of their creation and the materials used, an issue highlighted by Albert:

"The thing about 3D printing, that my perception of it, which is probably incorrect, but anyway, is that it can reproduce certain aspects of an object but other aspects which are very important to blind people in terms of identification aren't reproduced: smell, weight and the feel of it."

Albert (Congenital Minor Visual Impairment)

This subject is further discussed in the Discussion chapter (*8.2.3 Technical Design Considerations*), but is of note as the majority of modern 3D printing machines will create objects that lack these defining multisensory traits.

Another design consideration is potentially altering the geometry of 3D prints, such as enlarging small objects to make them more readily interpretable. However as this analysis has shown, a significant portion of participants thought that no major changes should be made to the objects. The reasons for this varied somewhat, some simply being unable to suggest any changes and some emphasizing that touching the truest representation of the object is more important, as in the words of Paulman:

"It's a perfect example of what it is. You couldn't. How could you possibly change it? If you printed it in 3D or had the real article, you may as well have the real article. There's nothing you could improve on that in any way."

Paulman (Congenital Minimal Colour Perception)

Whilst this was the overall general opinion, as noted above there were a few specific ways which participants thought that the object could be enhanced. Audio description is fairly self-explanatory, a commonly adopted methodology that as discussed above could provide useful descriptions for participants during the process of object interaction and appreciated by BPS users (Eardley et al. 2016; 2017; Lombardi, 2018). Increasing the size of the object was also favoured by many participants, as highlighted by Albert:

"Because it's too small to feel the textures properly, to interpret them properly. You actually needed to magnify the size of them."

Albert (Congenital Minor Visual Impairment)

This represents a way tackling the issues of scale and is an approach suggested by many other authors as a way of presenting typically small objects, such as algae or microstructures, to BPS individuals (Teshima et al. 2010; Jafri and Ali, 2015; Hegna and Johnson, 2016). However, this does bring in a few concerns. The size of the object was the fourth most dominant reason for identifying objects in this study, which suggests that changing the scale of the object may influence interpretations of the object's true nature. This certainly seemed to be the case with the tortoise shell, where a few participants had some difficulty in differentiating between whether it was a juvenile or adult. Similarly, the size was important to understanding which animal the fox femur was from which the majority of participants were unable to achieve, as in the words of Guenevere:

"I suppose the question you would ask is a bone of what? To what? So I suppose if you had the context to know where this bone came from, then it would make a bit more sense to know what is it or what size is it and that."

Guenevere (5 to 10 Years Minimal Visual Shape Perception)

This raises concerns over altering the size or geometry of the object. In some cases, as with microscopic objects, it may be beneficial to do so as there is no alternative, but to change aspects of their geometry has the potential to hinder the interpretations of BPS object handlers. Alternatively, it could create a false interpretation of the object, an error that is difficult to correct in memory (Roschelle, 1995). As an example, participants during the first research chapter (*4.0 Evaluation of Tangible 3D Printed Replicas in Museums*) commonly misinterpreted the *Phascolotherium* jawbone as belonging to a pig or dog, due primarily to the fact that it had been scaled up. Even when the author stated it had been scaled up, participants still regularly referred to it as a large animal, suggesting that it can be difficult to get around the immediacy of a physical replica and its own scale. Similarly, Ballarin et al. (2018) created a replica of a small Palaeolithic engraved slab, choosing to enhance the depth of the engraving for that BPS handlers could properly perceive them, impossible to perceive through tactual interaction. Lombardi et al. (2018) similarly used 3D printing to convert flat pottery images into pseudo bas-reliefs, aiding interpretability through the use of high-colour contrast and the exaggeration of certain features. These well-meaning interventions may permit the perception of complex geometry, but exaggerating such features could lead to their misinterpretation and a false impression of the nature of the object.

Thus the situation remains complex and minimally invasive solutions that alter geometry, scale and shape may be more favourable over more extreme alterations. Such prints could even be presented alongside the original object as a way to focus in on features of interest, as suggested by a few participants. This could be implemented in the form of internal access to specimens, like opening up the tortoise's shell to be touched inside, or enlarging specific features of parts of the specimen so that their geometry and texture can be more readily perceived. Thus again, museum practitioners must carefully assess what alterations they are making to objects and be sure that such measures have minimal impact on the handler's interpretation of the object.

Finally, materials used for the process of 3D printing must be carefully considered. The overlap of reasons between material and object judgement suggests that they are integrated, and interpretation of material can partially dictate the interpretation of what the object actually is and vice versa. The ramification of this is that the chosen material used for 3D printing can influence the perception of the handler, throwing off their overall interpretation of the object and vice versa. The magnitude of this effect is at this stage somewhat uncertain and again, little research has been carried out to see the extremity of this relationship between object and material-related judgements (Baumgartner et al. 2015). Nevertheless, museum practitioners are advised to be cautious and carefully select the materials they use for BPS handling applications to ensure they do not throw off the interpretations of their visitors.

6.5.3 Limitations

As before, some insights have been yielded into the nature of BPS interpretation of museum objects that should be generally informative into how museum professionals can create 3D printed replicas that can assist the interpretations of BPS individuals. However, this study does have a few shortcomings that must be accounted for.

First is the issue of sample size, a problem that plagues most research into BPS phenomena. Access to BPS participants is notoriously difficult and usually gated by blind institutions who will voluntarily lend assistance, as in this study, or charge for use of participants and facilities. As there was insufficient financial backing to pursue the latter, the former was the only path that could be taken. Ideally, a larger sample would provide the opportunity to use statistics to determine trends in the data related to sight condition and duration. This was unfortunately not possible as a result.

This study also does not examine the phenomenon within a proper museum environment and rather represents a preliminary foray into what aspects of museum objects were most significant for BPS understanding of objects. A more ecologically valid study exploring this phenomenon in the exhibition gallery would thus be useful and represent a potential future research avenue.

6.6 CONCLUSIONS

In conclusion, this study has looked into the perception of BPS individuals with regard to their interpretation of natural history objects, in order to best ascertain what design considerations should be taken into account when creating tangible 3D printed replicas. A number of preliminary design considerations have been highlighted. These include:

- The multisensory nature of BPS interpretation. The participants used acoustic, optical and in some cases, olfactory properties, to understand the objects. Thus, the nature of perception is multisensory and to ignore other senses when designed tangible 3D printed replicas means missing out key information that may be informative to BPS perception.
- Participants were able to identify both the material and object with some difficulty. Overall participants had more difficulty with identifying what the object was but in

most cases were able to get a general impression, with a ‘halo’ of partially correct answers around the correct responses. Reasons for choices were partially shared for both object and material judgements, expressing that interpretation of objects is a complex multisensory process. Dominant reasons for identification included texture, shape, specific features, weight, size, ‘feel’, prior experience and optical properties.

- BPS individuals are not a homogeneous mass. Many have different levels of sight loss and different experiences with dealing with sight loss, in addition to their own experiences which have an impact on their interpretations of objects. Thus, solutions should take into account different levels of object handling experience, different background knowledge and different levels of residual sight.
- Participants, in general, did not want significant alterations made to the objects to assist their understanding, although some participants advocated that accompanying audio descriptions, scaling the object up and adding more life context to the object could assist their interpretations of them. Choices to alter the geometry of an object to make it more interpretable and material choice could potentially influence BPS interpretation.

7.0 ADDITIONAL BENEFITS OF DIGITIZING MUSEUM OBJECTS: *MEGALOSAURUS BUCKLANDII*

7.1 PUBLICATION RECORD

The results of this chapter have been published in the following two separate peer-reviewed articles:

Wilson, P, Williams, MA, Warnett, JM, Attridge, A, Ketchum, H, Hay, J and Smith, MP. (2017a) Utilizing X-Ray Computed Tomography for heritage conservation: the case of *Megalosaurus bucklandii*. I2MTC 2017 IEEE International Instrumentation and Measurement Technology Conference, Torino, Italy, 22-25 May, 2017. (Conference Paper).

Wilson, PF, Smith, MP, Hay, J, Warnett, JM, Attridge, A and Williams, MA. 2018b. X-ray computed tomography (XCT) and chemical analysis (EDX and XRF) used in conjunction for cultural conservation: the case of the earliest described dinosaur *Megalosaurus bucklandii*. *Heritage Science*, 6: 58.

7.2 INTRODUCTION

For the rarest and most precious of all museum objects, the need to preserve often outweighs the potential benefits of digitizing them. Acquiring permission to carry out procedures on extremely rare, one-of-a-kind objects is a long process and a high level of trust is required between the hosting institution and the researcher. The fragile nature of such objects or their rarity are often dissuading factors in carrying out work upon them, especially procedures that would risk further damage or degradation. Even non-invasive procedures, such as x-ray computed tomography (XCT), laser scanning and photogrammetry, incur minor-destructive risks involving the transportation of the object between facilities, partial movement during acquisition and other logistical concerns. The ramification of this is that such objects may never be explored and invaluable insights into the object may remain undiscovered.

However, the process of scanning and digitizing such objects for the purposes of creating tangible 3D printed replicas may provide a reason to pursue such an avenue. Many authors have advocated the use of scanning and 3D printing for creating permanent records of fragile and rare artefacts, whether for public engagement, record-making or tracking changes in condition (Laycock et al. 2015; Scopigno et al. 2017). These applications have the potential to yield surprising insights and lead to exciting new research opportunities where none were thought to previously exist. It is often from the mundane that exciting, ground-breaking discoveries are made. The discovery of the body of Richard III under a Tesco car park is one such example (King et al. 2014), but the Roman town of Herculaneum, itself accidentally discovered by a farmer, also yielded precious insights into life in the distant past (Seales et al.

2010). Carbonised scrolls found in a mansion were inspected using XCT, revealing a sufficient enough density contrast to allow the scrolls to be read from the data. Today, efforts are being continued by researchers to 'digitally unwrap' these scrolls so as to read them without having to risk damage to them (Seales et al. 2010; Bukreeva et al. 2016). Such examination has the potential to open up new research avenues that may have far-reaching ramifications for their disciplines.

Thus far, only the immediate considerations of the museum audience and tangible 3D print approaches in exhibition galleries have been addressed. In this chapter the benefits provided by the digitisation process of key museum objects are explored and how even in objects thought to be completely understood, the unexpected can still emerge. This chapter will focus on the lectotype dentary of *Megalosaurus bucklandii*, Mantell, 1827. This specimen is of particular importance as it represents one of the earliest dinosaur taxa discovered and one of the founding members of the Dinosauria. The specimen was first formally described by William Buckland in 1824 (Buckland, 1824) which immediately sparked intense scientific debate between famous 'Age of Enlightenment' figures including Richard Owen and Georges Cuvier (Howlett et al. 2017). It was formally described in 1842 by Richard Owen (Owen, 1842) along with *Iguanodon* and *Hylaeosaurus* in the first scientific description of Dinosauria. The first Victorian 'Dinosaur craze' triggered by the publication of this work has cemented *Megalosaurus* as one of the progenitors of the popularity of the dinosaurs. A testament to this can still be seen today in the Crystal Palace park in the form of statues of Owen's original interpretations. Since then, the species and *Megalosaurus* became a *nomen dubium* and recent efforts to refine the taxon have removed much of the poorly classified material and validated the species (Benson et al. 2008; Benson, 2010), although the fossil material itself has never been digitised.

The most iconic of the specimens attributed to *Megalosaurus bucklandii,* the lectotype right dentary (Fig. 7.1a), is currently kept at the Oxford University Museum of Natural History along with the majority of the original material. The specimen was CT-scanned for the purposes of replication using 3D printing but the process of segmentation, the extraction of desired features from the background in CT data, revealed several undocumented features, namely a complex labyrinth of mandibular canals nested within the jawbone in addition to a significant amount of plaster restoration that had never been extensively documented in the past. Museum records, in fact, detailed little of these restoration phases, when they were carried out, or what materials were used. This presented an opportunity to fully document the state of restoration of the *Megalosaurus* dentary, an unexpected direction that emerged from what was to be a straightforward exercise in the fabrication of a 3D printed replica.

The insights provided by this were of use to the museum and the overall conservation of the specimen. The process of conservation is defined by the International Council of Museums Conservation Council (ICOM – CC) as:

"All measures and actions aimed at safeguarding tangible cultural heritage while ensuring its accessibility to present and future generations."

Sully (2015)

The process of conservation itself lies at the crossroads between protecting objects and ensuring their accessibility. Museums need to protect and conserve the objects in their collection. To do this, conservators need to be able to apply reversible, temporally and conditionally-stable conservational solutions to an object. Without a solid understanding of what conservation attempts have been made on an object before, it can be difficult to select the correct materials and solutions to ensure that the object remains chemically-stable over time (Pye, 2001). In the case of the *M. bucklandii* lectotype, no such records exist and so the process of exploring its conservational history provided a basis upon which new records could be created. This will be used to inform future conservational efforts that may be applied to the specimen.

In this chapter, the details of this procedure are covered and the insights gleaned from inspecting the *Megalosaurus bucklandii* lectotype dentary using XCT are summarised. This represents an additional avenue of unexpected research opened up by scanning the object for the purposes of replication through 3D printing. It will cover particularly the proper documentation of its conservational history and also other potential insights into its palaeobiological significance.

7.3 BACKGROUND, MATERIALS AND METHODS

7.3.1 Research Design

The purpose of this chapter is to explore the additional benefits that the digitisation and replication of rare museum objects that would never normally be worked on due to their need to be conserved. Thus, it falls neatly into the following research question:

What benefits can the replication of museum objects have in wider museum practice?

This study represents a purely quantitative research project rather than one based within the social sciences and as such, does not utilise typical research methods. Instead, to explore the nature of the object's conservation and palaeontological significance, XCT and chemical analysis methods are employed.

7.3.2 Background of the Specimen

The lectotype dentary of *Megalosaurus bucklandii* has been kept at the Oxford University Museum of Natural History (OUMNH) for more than 200 years, since before its formal description in Buckland (1824). Archival records at the OUMNH suggest that the specimen first arrived in the museum from a private purchase in 1797, costing just 10s 6d, the equivalent of about £50 today (Howlett et al. 2017). The specimen was first kept at the Christ Church Anatomy School in Oxford before being transferred to the collection of the OUMNH, presumably when the museum first opened in mid-19th Century.

As highlighted above, the specimen was first described in 1824 by Buckland (1824) and then formally used in the classification of Dinosauria by Owen (1842), although the species was not formally named until Mantell (1827) gave it the specific name '*bucklandii'* in reference to the man who first described the creature.

7.3.3 Materials

The *M. bucklandii* lectotype right dentary is accessioned in the OUMNH (J.12505) and is the sole specimen used within this study (Fig. 7.1a). The specimen is also associated with two thin slabs of limestone that remain within the collections (J.13505b and J13505c), each of which bear a small amount of fossilised bone from the main jawbone which were probably broken off during the extraction of the specimen.

The specimen is known to be from the local Stonesfield slate, quarried from a prominent quarry in Stonesfield, about 14km NW of Oxford itself. This quarry was commonly used for the production of roofing (Howlett et al. 2017) and contains rocks from the 'Stonesfield Slate', a sandy-limestone of Middle Jurassic age.

7.3.4 Methods

7.3.4.1 X-Ray Computed Tomography

The lectotype dentary was transported to WMG – The University of Warwick and was scanned at CIMAT using a Nikon (Xtek) 320LC micro CT scanner.

A 225KV reflection target head was used to scan the specimen. The fossil was scanned at a voltage of 225KV, a beam current of 418μA and an exposure of 1s using a 2mm tin filter. The specimen was too large to fit into a single CT scan and so it was instead scanned as a stacked volume, three separate scans being carried out in sequence with the same settings and alignment used. These were then compiled into a single volume at a later point.

Each volume was separately reconstructed using the standard Filtered Back Projection method (FBP) (Feldkamp et al. 1984), creating three volumes with a voxel resolution of 94μm. Next, the three volumes were aligned in VGStudioMAX 2.2 (Volume Graphics) were they were first roughly registered by manual alignment and then automatically aligned using a grey-level dependant best-fit method. This manual to automatic approach increases the accuracy of the automatic alignment and increases the quality of the final volume. The aligned volumes were then exported as a single volume in the DICOM format for manual segmentation in Avizo 9.2 (FEI).

The process of segmentation was carried out in order to separate the jawbone from the matrix material infilling the jaw and to identify structures inside the specimen that could be of further interest. Due to the low x-ray contrast of the jawbone relative to the matrix (calcium phosphate compared to calcium carbonate), manual segmentation had to be adopted as standard-thresholding techniques were unable to extract any useful geometry from the CT data.

From the segmented data, volumes were exported for visualisation using Drishti 2.6 to visualise repair materials and for museum purposes (Limaye, 2012) and the meshes exported for 3D printing for use by the museum (Fig. 7.1bc). Two prints were then produced using a Stratasys Fortus J750 printer. The first was a multi-material print with the dentary printed in a transparent resin to reveal the growth of the teeth and internal canals (Fig. 7.1b). The second was a fully-coloured 3D print produced with a texture-mapped mesh derived from photographs captured using a Nikon D3200 with an AF-S Micro NIKKOR 40mm (Fig. 7.1c).

7.3.4.2 Chemical Analysis (EDS and XRF)

In order to identify and further characterise the repair materials found through the above CT scanning method, further chemical sampling and analysis was undertaken. First of all, Energy Dispersive X-Ray Spectroscopy (EDS) was carried out. In order to do this, destructive sampling was carried out using several samples were taken from both of the two plaster materials (P1 and P2) identified from the CT data (*7.4.1 XCT Inspection of Dentary*), numbering seven in total. Five samples were taken from P1 from the ventral-posterior portion of the specimen and the lateral-posterior surface and two were taken from P2 on the lateral surface of the prominent tooth crown replacement (Fig. 7.3). A limited number of samples were taken from P2 due to conservational concerns. The samples were affixed to an SEM stub via carbon tape and gold-coated to a thickness of 5nm. The samples were then examined via SEM and the composition mapped using EDS using a Zeiss Sigma SEM at AMMC at WMG – The University of Warwick.

In order to further explore the findings of the EDS analysis, a larger sample was taken from the posterior of the specimen for analysis using X-Ray Fluorescence (XRF). This sample was affixed to a microscopy slide for examination using both plain and cross-polarised light microscopy in addition to mapping its chemical composition using XRF. XRF was carried out using a Bruker M4 Tornado at AMMC at WMG – The University of Warwick and the slide was examined under normal and cross-polarised light using a petrological microscope at the OUMNH.

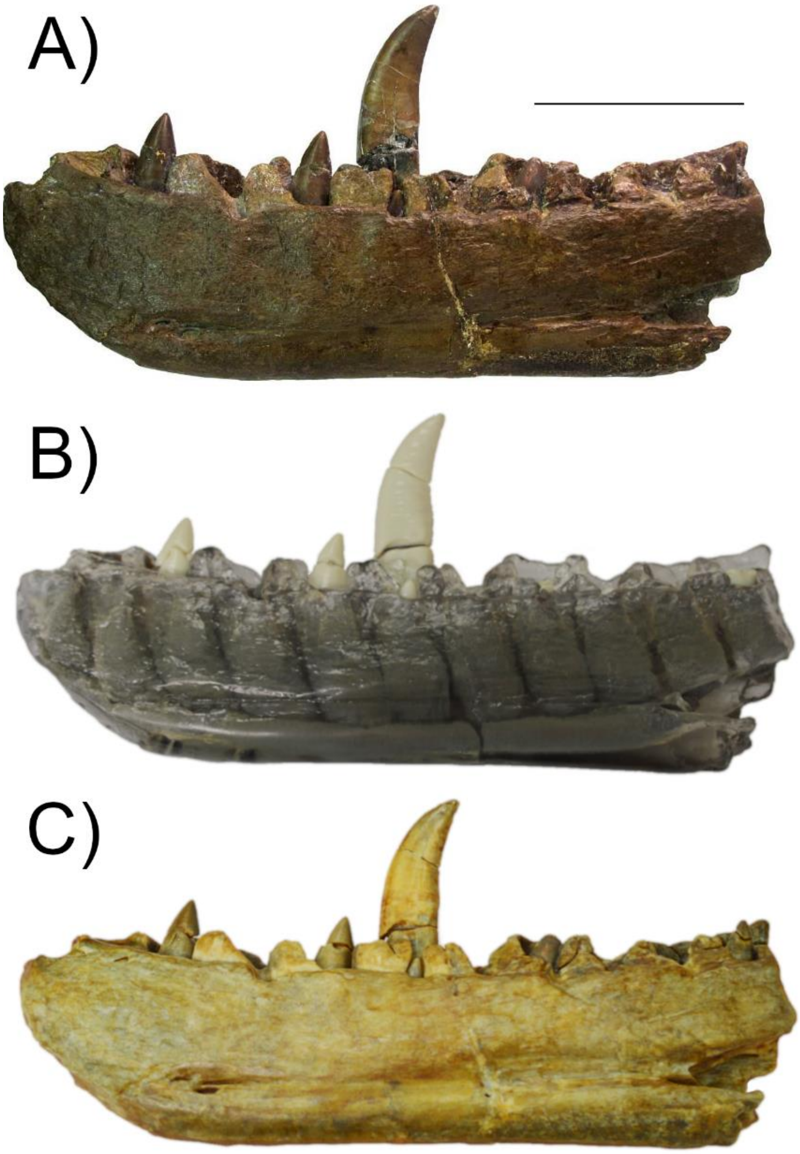


Fig. 7.1: ***Megalosaurus bucklandii*** **and its 3D Printed Replicas**: A) The original lectotype dentary of *Megalosaurus bucklandii.* Scale bar is 10cm; B) Two material resin print (MJ), revealing the internal structure of the jaw; C) Textured resin print (MJ) with colour textures derived from photos of the original specimen.

7.4 PREVIOUS UNDERSTANDING OF REPAIR HISTORY

The *M. bucklandii* lectotype dentary has had a long and storied history within the collections at the OUMNH but despite this, very little is currently known about its conservational history, both by current staff and in the limited documentation at the museum. The timing of its current repair is uncertain, but thought to have occurred between 1927 and 1931, when the specimen was first put on display at the OUMNH. Some minor repair has been undertaken by the current conservator, fixing the prominent tooth with a Paraloid B72 resin.

A rough window of when this restoration took place can be provided by examining images of the specimen through time (Fig. 7.2). The specimen is first figured in Buckland (1824), where it has a markedly different outline and completely lacks all of the repair that can be noted in the modern specimen (Fig. 7.2b) (Plate XLI in Buckland, 1824). The specimen shows very little damage, with the exception of a single dorso-ventral crack on the medial surface running across the surface of the dentary, rather than penetrating through the specimen as it currently does. It seems reasonable to assume that this crack was the catalyst along which the modern breakage and subsequent repair occurred. A horizontal fracture on the lateral surface of the prominent, mature tooth suggests that damage in this area has persisted since the specimen was first found. The strange shape of the jaw compared to now can probably be attributed to the difficulties of lithograph printing and represent inaccuracies in its representation, rather than meaningful information about its prior condition. The same figure is depicted in Owen (1842). A more crude, lower quality but similar lithograph appears in Buckland (1836) (Plate 23) that appears to represent a similar condition, the same medial dorso-ventral crack being present and the same a horizontal fracture along the prominent, mature tooth. It also appears to more accurately resemble the modern shape of the specimen, but still holds many inaccuracies (Fig. 7.2c).

The specimen is next depicted in a J. Erxleben illustration in Owen (1849) (Plate 33) (Fig. 7.2d), where it resembles the modern specimen more accurately. The crack noted above is now missing however, casting the accuracy of the original lithograph into doubt, though it may have simply been omitted to more clearly depict the morphology of the specimen. The lateral crack on the prominent, mature tooth is again present in this diagram. The interdental plates in both the Buckland (1824; 1836) and Owen (1842; 1849) diagrams appear to be more triangular compared to the modern specimen, particularly the plate on the immediately posterior to the large, mature tooth which appears to have lost its top. This is the last clear historical depiction of the specimen in antiquity, as Phillips (1871) only depicts the jawbone in an undetailed, diagnostic manner but does contain a diagram of the mature, prominent tooth, minus the horizontal crack (Fig. 7.2e). Given however its earlier appearances in Buckland (1836) and Owen (1849), it may be that it was simply excluded for the purposes of more accurately displaying its anatomy rather than an accurate figure.

This is the last figured appearance of the specimen until the modern day and has only been extensively documented in Benson et al. (2008) and Benson (2010), in an effort to further refine the species and remove falsely assigned material from the taxon. In Benson et al. (2008), the authors review the conservation of the specimen from surface inspection (Fig. 7.3). They detail the areas which are suspected to have been replaced by plaster, which are mainly concentrated on the posterior portions of the specimen, particularly on the lateral surface. On the lateral surface (Fig. 7.3b), repair is concentrated around the central dorso-ventral crack (1) and

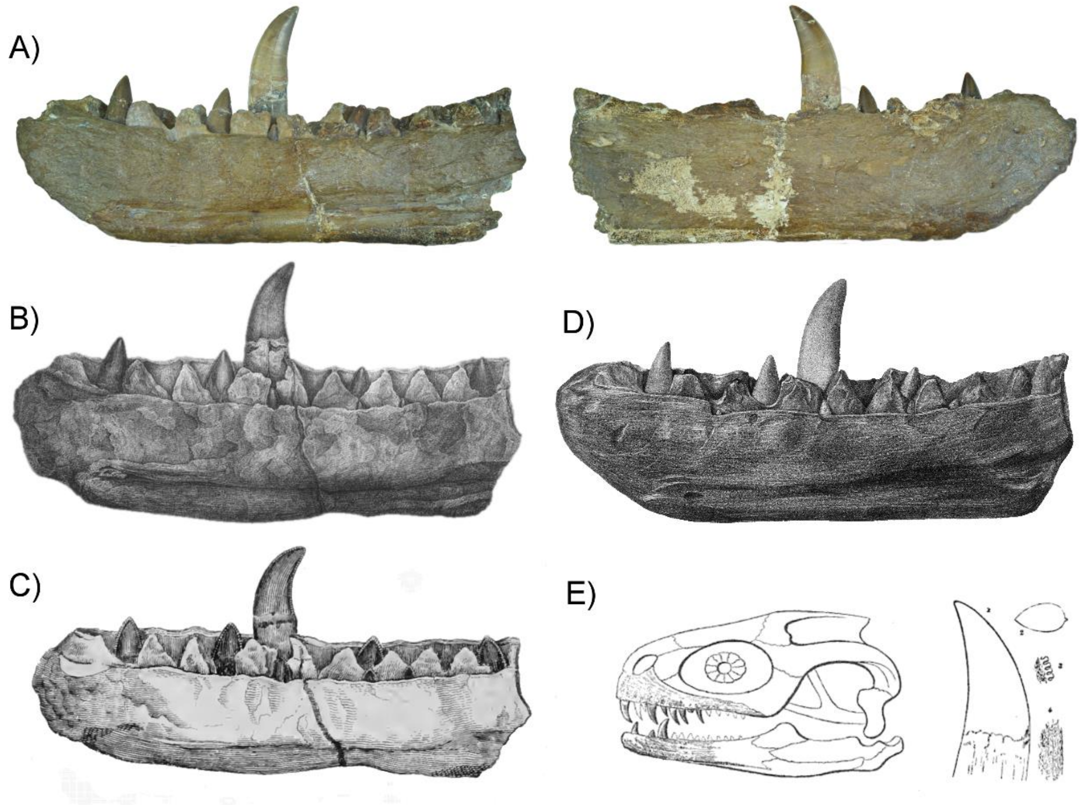


Fig. 7.2: The Condition of *Megalosaurus bucklandii* in antiquity. Images depicting the *M. bucklandii* lectotype dentary are few and far between, but its condition through time can be traced by its appearance in publications. A) Medial (left) and lateral (right) modern photographs of the dentary. B) First appearance in Buckland (1824) as a lithograph. Pl. XLI. C) Less detailed lithograph in Buckland (1836). Pl. 23. D) Extremely detailed lithograph from Owen (1849). Pl. 33. E) Diagnostic representations of the jaw and prominent mature tooth. Diagrams XVI and XVII.

along the ventero-posterior portion of the jawbone (2), in addition to along the lateral side of the tooth margin (3). This entire large zone of repair connects to a large replacement on the side of the lateral surface (4). Another small zone is found towards the anterior end of the lateral surface, along the side of the tooth row (5). On the medial surface (Fig. 7.3a), there is significantly less repair which is again focussed along the dorso-ventral crack just behind the mature, prominent tooth (6) and along the ventero-posterior portion of the specimen (7). Minor repair has also been carried out on the teeth on both sides (8, 9).

7.5 RESULTS

7.5.1 XCT Inspection of Dentary

XCT scanning of the dentary revealed a number of insights into the scope of restoration undertaken on the *M. bucklandii* lectotype dentary (Fig. 7.4). The findings of Benson et al. (2008) are broadly supported by the analysis, with a few notable exceptions. First, plaster replacement is mostly found on the ventrolateral and dorsolateral surfaces in the areas noted in the previous section. However, a notable difference is that these areas appear to be less extensive on the whole compared to the interpretation of Benson et al. (2008). In the case of the larger replacement on the lateral surface towards the posterior of the specimen (1), which does not connect to the other to the central crack (2) and ventral replacement (3) on the lateral surface. There are also a number of fragments of the original fossil material that appear to be embedded inside the plaster replacements, three along the dorsoposterior lateral replacement (4,5,6) and another in the dorsolateral, anterior replacement (7). This reflects an unusually conservative form of restoration whereas much of the original specimen was preserved in situ as possible, despite the seemingly large amount of damage that the specimen has incurred over its lifetime. Another small, previously undocumented, plaster replacement can be found on the ventral surface of the specimen (8). Substantial tooth replacement is also found along the tooth row, both replacing missing crowns and damaged portions of the teeth and also small portions of missing dentary material (9,10,11,12,13). Most notable is that this replacement along the tooth row appears to be of a different composition compared to that of the rest of the dentary, as can be observed directly from the CT data (Fig. 7.5).

These two materials, dubbed Plaster 1 (P1) and Plaster 2 (P2), can be differentiated via their properties within the CT data:

- Plaster 1 (P1): Replaces damaged proportions along the medial and lateral surfaces of the jaw (Red in Fig. 7.4). P1 makes up approximately 3.5% of the total volume of the specimen and has a slightly higher density than P2 and thus brighter grey values. The most distinctive feature of this plaster however is the presence of high-density particles sizes <1mm which are distributed evenly throughout the plaster. This distribution lends suggests that they are inclusions within the plaster rather than a secondary mineral growth such as pyrite, which would typically cluster around specific recrystallization sites.
- Plaster 2 (P2): Replaces damaged and broken teeth and small portions along the tooth row only and makes up only 0.3% of the total volume of the specimen (Green in Fig. 7.4). It is fairly homogeneous and is slightly less dense than P1, exhibited by its slighter darker grey values. It lacks any form of dense mineral inclusions, making it easy to distinguish from P1. On some teeth, it completely replaces the tooth crown and is occasionally set at an off-angle.

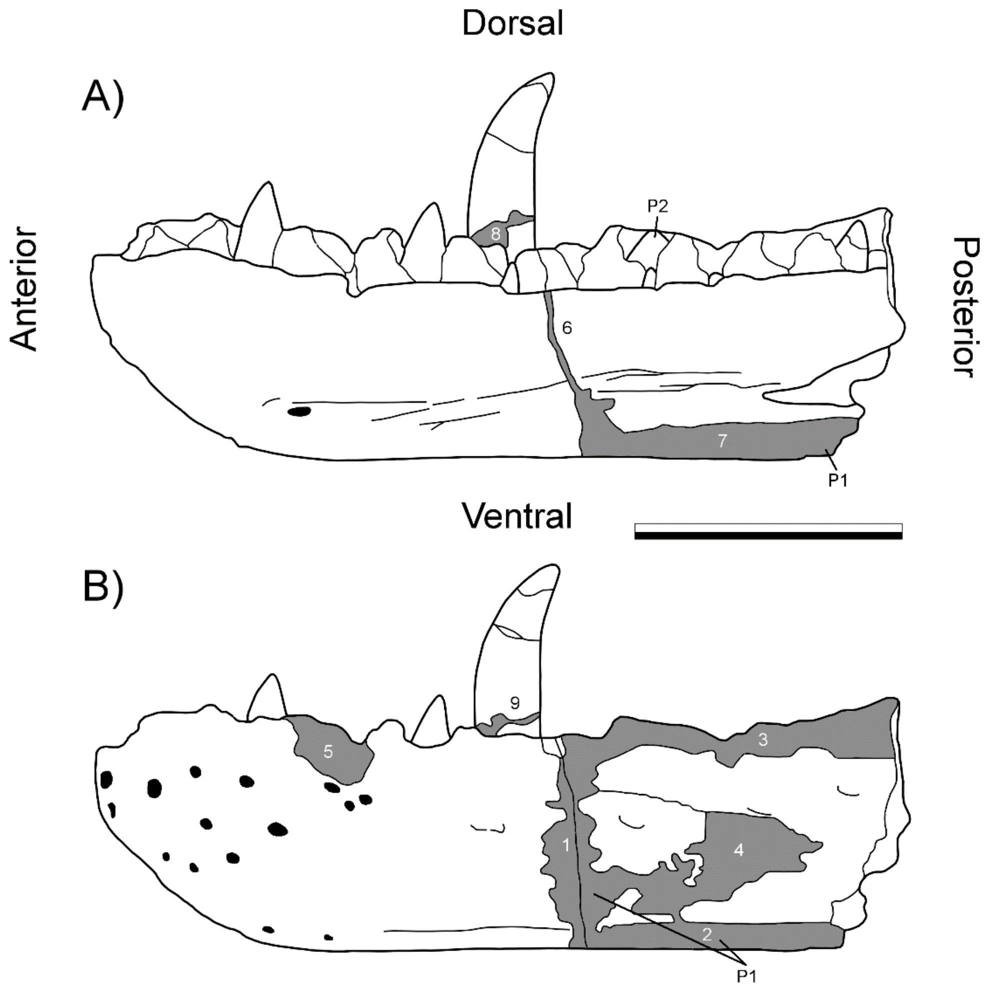


Fig. 7.3: Previous Knowledge of Repair: Previous distribution of suspected repair from Benson et al. (2008). A) Medial surface of the dentary. B) Lateral surface of the dentary. Grey areas indicate areas where the specimen has repaired. Numbers indicate zones of repair mentioned in the text. Scale bar equals 10cm.

Overall, XCT analysis has revealed that the plaster replacement on the *Megalosaurus bucklandii* lectotype dentary is less extensive than previously thought and conserves a surprising amount of the original material of the specimen. Two different plasters have been used in the conservation of the specimen, P1 which replaces the bulk of the total replacement within the jawbone on the lateral and medial surfaces while P2 only replaces material along the tooth row. Both have discrete characteristics within the CT data, P1 being denser and containing high-density particles evenly disseminated throughout and P2 being less dense and more homogeneous. The different composition of these suggests that there were likely two different phases of repair in the specimen’s life, though the relative timing of these cannot be determined.

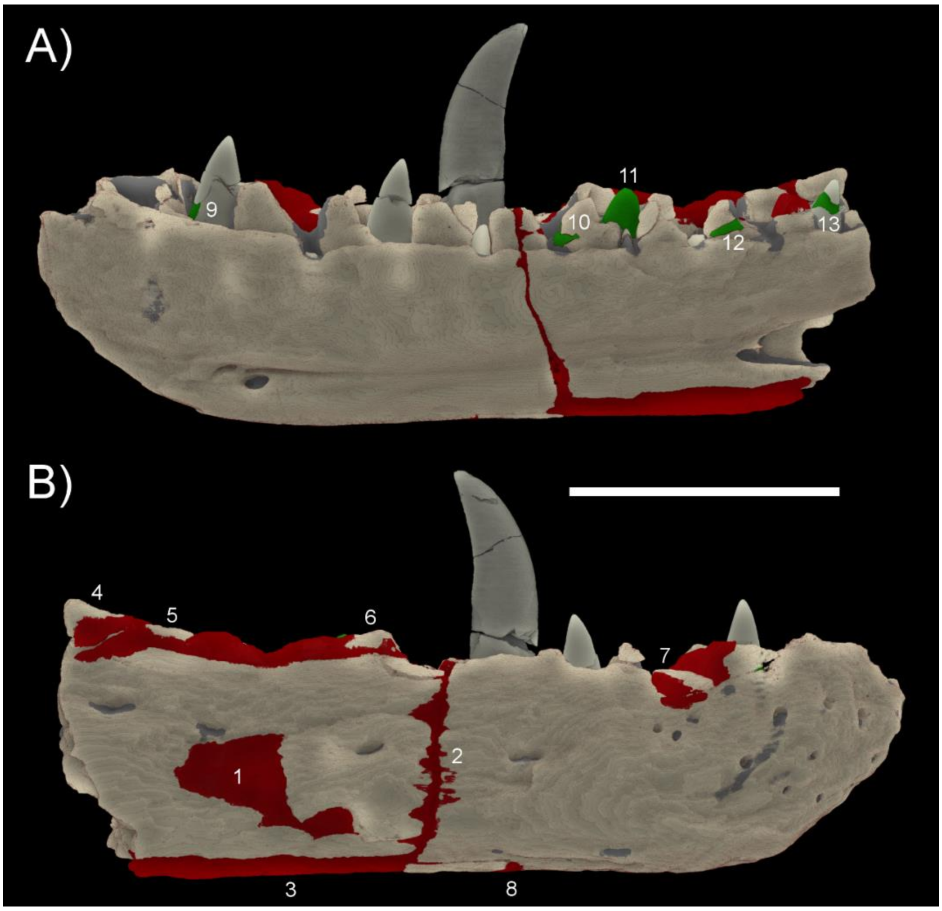


Fig. 7.4: XCT Scanning of the *M. bucklandii* lectotype dentary: Two different types of plaster can be found distributed across the specimen; P1 (Red) and P2 (Green). A) Medial surface. B) Lateral surface. Numbers refer to references within the main text. Scale bar is 10 cm.

7.5.2 Chemical Analysis (EDS/XRF) of Dentary

Next, the chemical composition of these two plaster materials was ascertained, using both Energy Dispersive X-Ray Spectroscopy (EDS) and X-Ray Fluorescence (XRF).

The sampled plaster from P1 and P2 were examined using EDS. The broad composition of both P1 and P2 is similar, with a few exceptions. The elemental spectra of the samples (Fig. 7.6) shows that the plaster is dominantly composed of oxygen (O), calcium (Ca) and sulphur (S), which lends itself to interpretation as gypsum plaster ($CaSO_4{\cdot}2H_2O$) rather than a lime-based plaster ($CaCO_3$ dominated) (Fig. 7.6ab). It appears to be impure, with a number of other elements included that may not be accounted for by a pure gypsum composition. Silicon (Si) is also very common and is probably present in the form of quartz (SiO_2) or sand, which is confirmed by the appearance of fine, reddish grains (<0.5mm) on the exposed surfaces of the plaster. Carbon (C) also occurs frequently throughout the samples, but is probably representative of the leaching of a surface coating of shellac ($C_{30}H_{50}O_{11}$), a natural resin

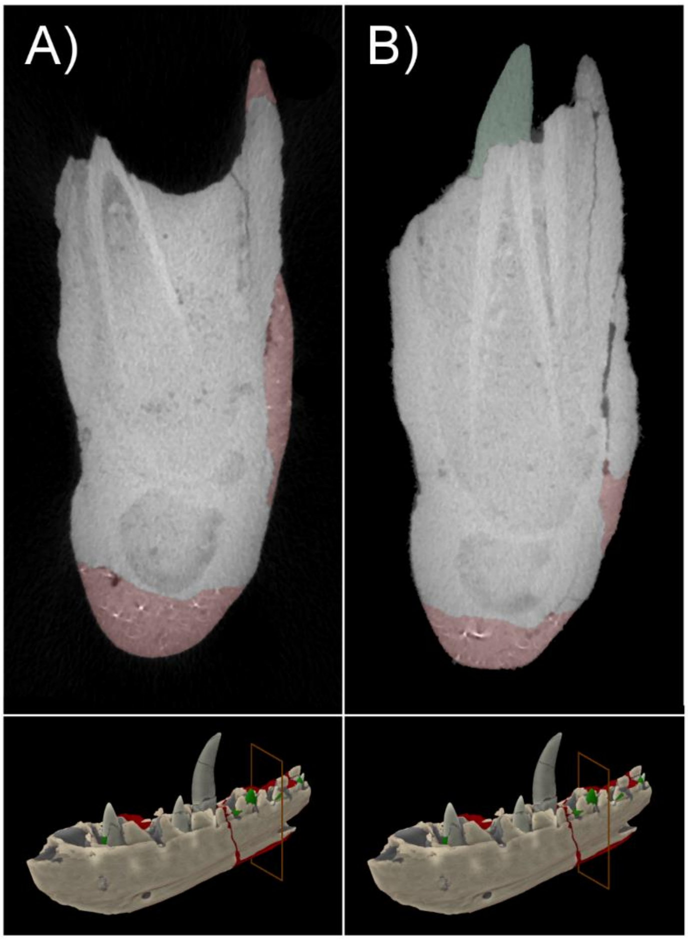


Fig. 7.5: Cross-section through CT data for *M. bucklandii*. A) Cross-sectional slice showing the internal structure of P1, containing high-density grains that cause imaging artefacts. B) P1 and P2, P2 lacking the high-density grains and repairing the teeth exclusively. Tooth replacement of P2 is offset from the actual tooth. Inset figures show slice location within the CT volume.

probably used as a sealant for the plaster (Wilson et al. 2018b). It could also represent the presence of grains of calcium carbonate ($CaCO_3$), which is further confirmed below. Also notable is a trace amount of chlorine across all samples (Fig. 7.6c), which could represent either atmospheric contamination, the leaching of cleaning agents applied or handling over the specimen's lifetime. Iron (Fe) is also present in trace amounts and is likely derived a natural coating of iron oxide on the reddish sand grains present within the plaster. The composition of the dense grains from the CT scans could not be identified using EDS, as they were not able to be sampled.

P2, as mentioned earlier, is of a slightly different composition. One sample contained barium (Ba) (Fig. 7.6d) but likely represents the compound barium hydroxide ($Ba(OH)_2$). Barium hydroxide is often used as a consolidant for coating plasters and thus is most likely the source for the barium found within this sample. Other than this, the composition of the plaster is identical, saving the lack of the high-density particles, whose composition is determined below. This difference in composition seems to suggest that both of these replacements likely took place at different times, but still may have been carried out contemporaneously if the conservator needed plasters with different physical properties, though this seems unlikely.

As the dense particles of P1 could not be identified, micro-XRF was used to identify the composition of these grains and to further understand the composition of P1. The elemental spectral maps show the overall composition of the sample taken (Fig. 7.7). The background material of the specimen is confirmed to consist of gypsum, containing high concentrations of S and Ca. Embedded within this matrix are a number of particles 0.3-0.4mm in diameter. These are of two types; sub-angular to sub-rounded Si-rich grains which represent grains of quartz sand and sub-rounded to rounded Ca-rich grains, which likely represent calcium carbonate grains. Both of these appear to be evenly mixed throughout the sample. Also present are small (<0.1-0.2mm) lead-rich (Pb) particles that are widely disseminated throughout the samples. Under a light microscope, these have a reddish-orange colour, which likely represents the lead ore minium (Pb_3O_4) mixed in with the samples. These minium grains likely represent the dense grains found in P1, especially given the high-density of minium ($8.3 g/cm^3$) compared to the overall gypsum and the calcium phosphate of the jawbone, which would account for their appearance within the scan data.

In summary, both plasters have a similar composition with a number of discrete differences:

- Plaster 1 (P1): P1 is composed of approximately ~15-20% quartz, ~20-30% calcite and minium <10% while the remaining fraction is that of the gypsum. The presence of minium may be explained by two different hypotheses; 1) it was used to add more weight to the specimen and make the plaster feel like a more authentic part of the specimen or 2) as a pigment, to match the colour of the plaster towards the reddish-brown colour of the jawbone itself (Aze et al. 2008). The quartz and calcite found within the sample may be derived from the matrix of the Stonesfield Slate, a sandy-limestone (Dineley and Metcalf, 1999) that was added in for similar reasons, to bulk and add weight to the plaster and for the purposes of a more verisimilar colour. A shellac coating and trace amounts of chlorine contamination are also present.
- Plaster 2 (P2): The composition of P2 was explored in lesser detail due to the inability to sample further and is of a similar composition. It lacks the dense minium grains of P1 and is coated in barium hydroxide that was likely used as a sealant to prevent the percolation of moisture through the plaster. Given the differential composition of these two plasters, it is safe to assume that they were

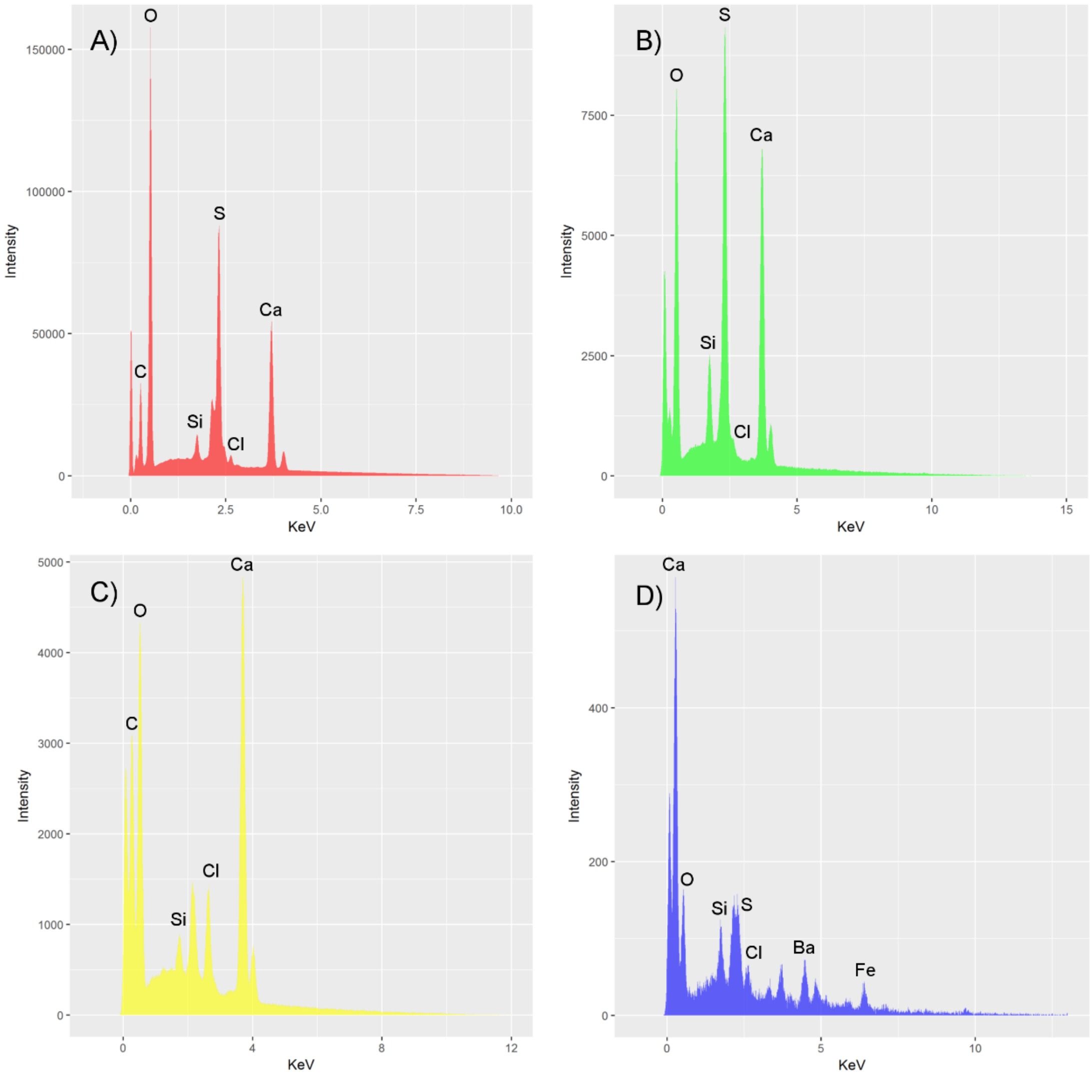


Fig. 7.6: Elemental plots from EDS analysis. Repair in the *M. bucklandii* dentary is in plaster of two types. A) Typical elemental composition of P1 repair material. B) Typical elemental composition of P2 repair material. C) Chlorine-rich sample of P1. D) Barium-rich sample of P2.

carried out at different times, though the timing of these cannot be determined from the CT data.

This interpretation agrees with an unusually conservative mode of restoration whereas much effort as possible has been put into making the plaster replacements as close to the original specimen in weight and colour as possible.

7.5.3 New Insights into M. bucklandii

Also revealed from the CT data were a number of structures previously unknown in *Megalosaurus bucklandii*, despite how long it has been exposed to palaeontologists. Among these are the presence of growing teeth, both the roots of the exposed teeth and several previously unknown teeth embedded within the matrix, in addition to some other structures of potential palaeontological significance.

The teeth can be divided into a number of discrete generations, as depicted in Fig. 7.8a. The first generation is that of the adult teeth, consisting of the large, prominent tooth (T1) and three, partially-resorbed tooth fragments offset towards the lateral margin behind T2-4. The second generation consists of four partially-developed teeth (T2-4), lacking the elongate shape of the first generation tooth and in the case of the posterior-most two, are partially replaced by plaster (T4-5). The third generation teeth are mostly obscured by the matrix. One is more well-developed and resembles the second generation teeth closely (T6), while the others are poorly developed crowns at the first stage of tooth germination (T7). This form of tooth replacement is well-known in reptiles in general and also in dinosaur taxa, known as the 'Zahnreihen hypothesis' (Owen, 1845; Erickson, 1996; Rieppel, 2001; D'Emic et al. 2013; Wu et al. 2013; Erickson et al. 2017) and is also well documented in *M. bucklandii* specimens by both Buckland (1824) himself (Owen, 1845), by surface inspection from a number of *M. bucklandii* specimens (Benson, 2008; Benson et al. 2010) and also in the lost specimen of the Duke of Marlborough during the 19th Century (Owen, 1849). Characterisation in 3D allows the acquisition of more information however, such as the lateral growth of its teeth, which germinate in shallow lingual crypts beneath the medial surface of the jaw which then migrate labially towards the lateral surface, resorbing the previous tooth generation. Notably, this is also accompanied by minor labialward rotation of the tooth by approximately 1-2° towards the lateral margin (Fig. 7.9). The significance of this relative to other theropod taxa is unclear at this stage, this field being rather poorly understood within dinosaur taxa. This form of tooth replacement agrees with the limited number of taxa which have been explored fully, including *Coelophysis*, *Gorgosaurus* and *Allosaurus* (Le Blanc et al. 2017). The same authors suggest that this method of tooth replacement was common to all theropods, although do not specifically refer to rotation of growing generations.

Also present within the scan data was a complex network of vascular canals beneath the medial and lateral surface (Fig. 7.8b). Many of these are exposed on the lateral surface, their terminations being associated with the side slabs that contain a thin sliver of bone from the surface of the jaw (J.13505b and c). These structures are well known in archosaur taxa but are rarely properly described. However, recent publications are beginning to explore the palaeobiological significance of these structures, being only properly described in spinosaurids, allosauroids and tyrannosaurids to date (Barker et al. 2017; Carr et al. 2017).

7.6 DISCUSSION

7.6.1 Making the most of 3D Datasets

Overall, it has been demonstrated that the act of replicating an object for the purposes of 3D printing can result in surprising insights into the object that may not have been previously

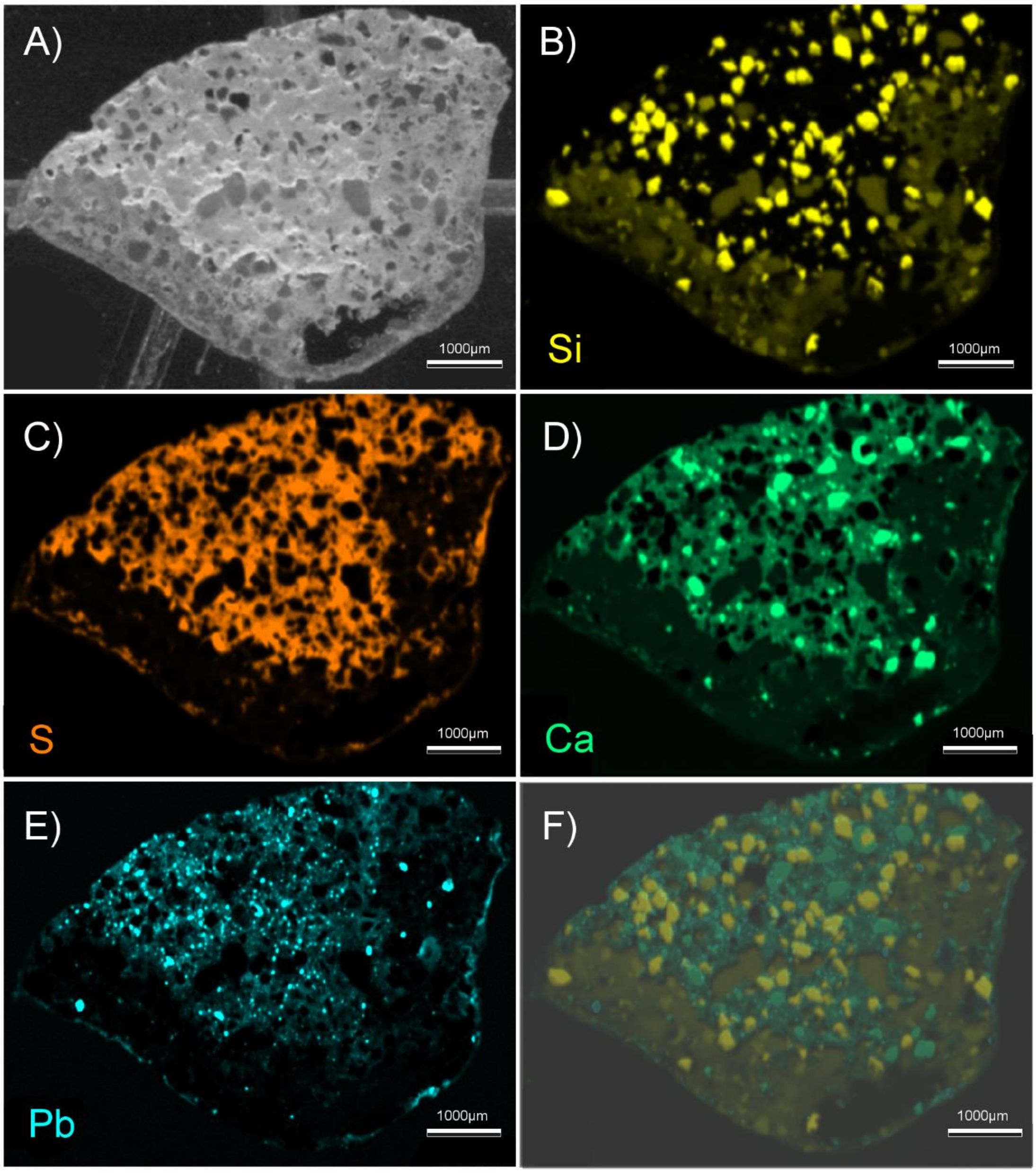


Fig. 7.7: XRF Analysis of Sampled Plaster: Another sample of P1 was analysed using Micro XRF to better ascertain its chemical composition. A) SEM Micrograph of sampled plaster fragment. B) Distribution of silicon (Si). Fainter yellow shapes reflect holes in the sample, which represent the glass of the mounting slide. C) Distribution of sulphur (S). D) Distribution of calcium (Ca). E) Distribution of lead (Pb). F) All four chemical maps overlaid to show locations of different particles.

considered or understood. Here, XCT scanning of the *M. bucklandii* lectotype specimen for the purposes of exhibition and display has revealed the unusual and complicated conservational history of *M. bucklandii*, alongside a number of other palaeontological findings. Their significance is uncertain at this stage, although could potentially be informative for understanding the species in the future. This exemplifies the benefits of scanning and digitisation for more general museum purposes and a single application can have

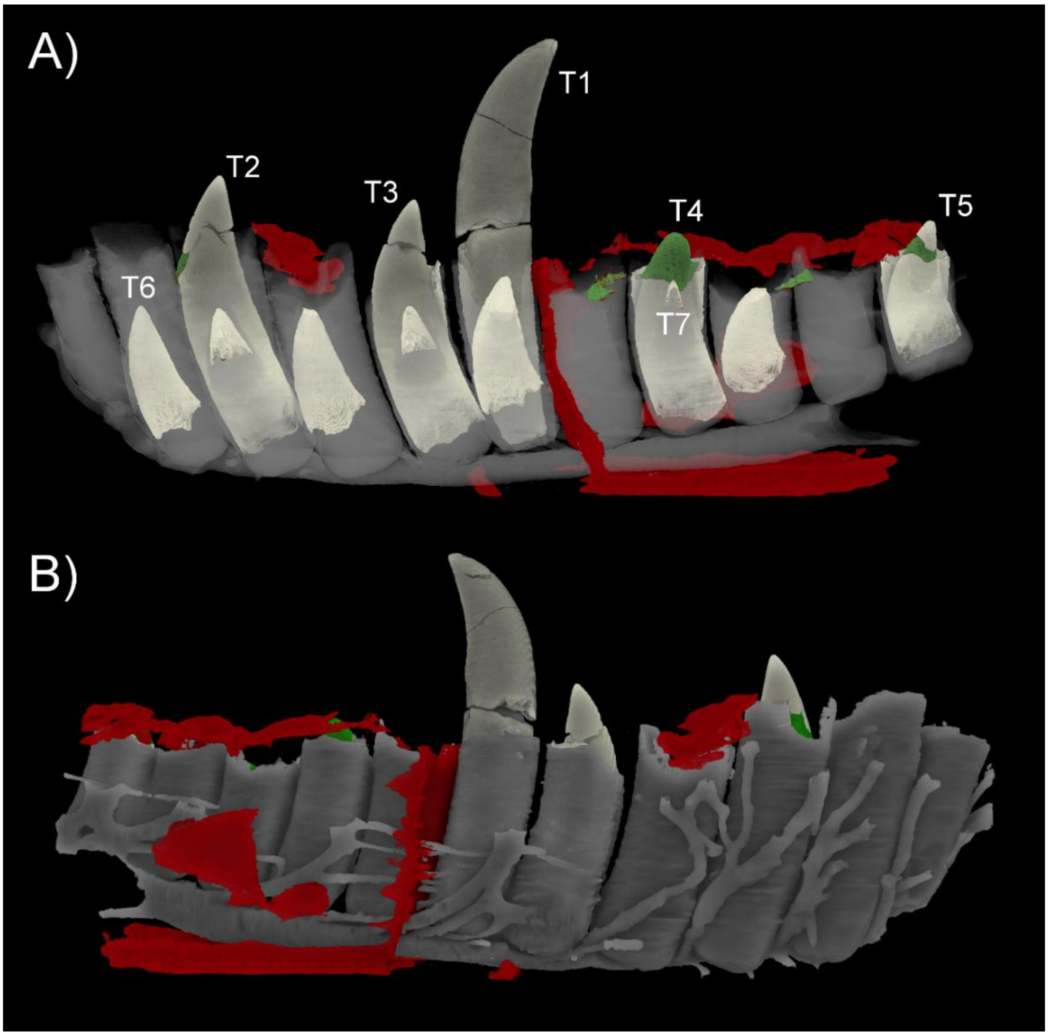


Fig. 7.8: Subsurface structures in *M. bucklandii*. A) Teeth embedded within the matrix represent a number of different generations. B) Vascular canals previous undocumented in the specimen have been mapped out. T numbers represent references within the text. Red and green areas reflect P1 and P2 repair materials.

wider benefits than initially expected.

Within cultural heritage, the past decade has seen a sharp rise in the use of digitisation technologies like these for museum practice. A number of different scanning methodologies are currently being exploited for a wide variety of purposes within cultural heritage, including XCT, laser scanning, structured light scanning and photogrammetry (SfM), although photogrammetry and laser-scanning are by far the most widely exploited methodologies due to their ease of use and cost considerations (Santagati et al. 2013ab; McCarthy, 2014). A large quantity of data has been collected across all of cultural heritage on objects of a variety of scales, from entire buildings or sites, such as Pompeii and Herculaneum, to individual museum artefacts and objects, such as cuneiform tablets and a disparate variety of other objects (Ch'ng et al. 2013;

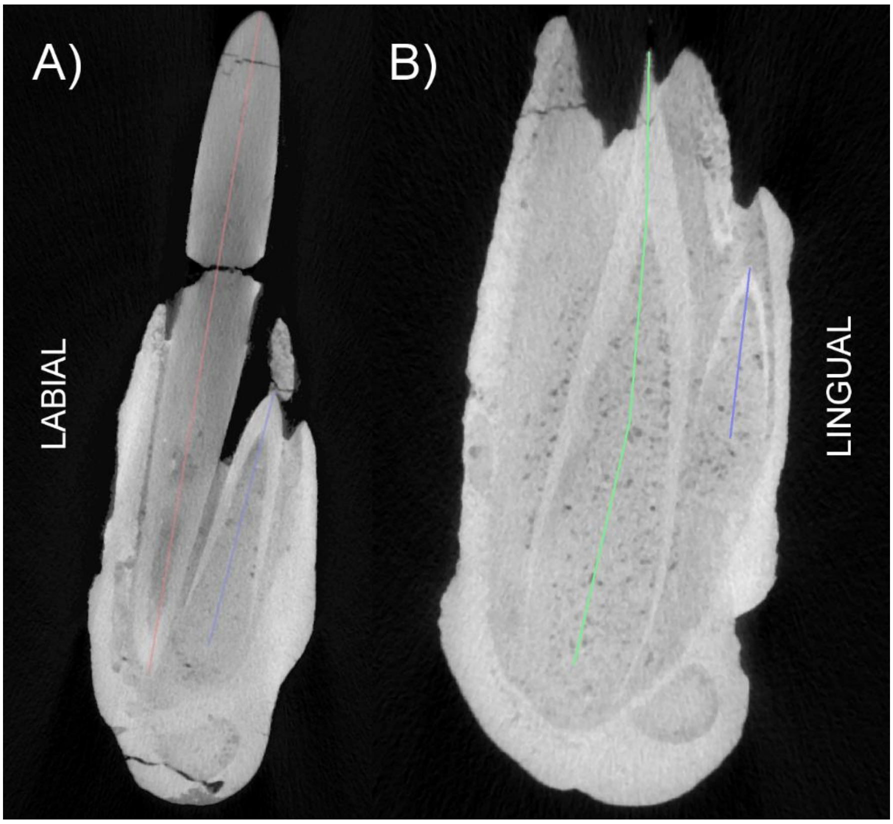


Fig. 7.9: Tooth growth in the *M. bucklandii* dentary: A) XCT slice showing mature first generation (Red) and growing third generation tooth (Blue). There is a slight rotation (~5º) between both of these generations. B) XCT slice showing semi-mature second generation tooth (Green) and immature third generation tooth.

Jocks et al. 2015; Greenop and Landorf, 2017). Factoring in that the regular scanning of museum objects has been an ongoing process since the mid 00's and earlier in cultural heritage, the corpus of scan data across all institutions globally at this stage is likely to be immense (Arias et al. 2005; English Heritage, 2011). Given this body of 3D data, very little seems to have been done with it beyond its initial application, a condition disparaged by Haddad (2012) who state that such data could be used for educational applications rather than just being sequestered in a database to moulder. The author discusses, as has been emphasised in this chapter thus far, that cultural heritage data goes hand-in-hand with public engagement and education and that such data needs to be further exploited.

Thus, the potential of 3D data within cultural heritage is key to cultural heritage practice, and many authors do advocate the potential of 3D data for educational means, although little is usually done with data (White, 2013; Laycock et al. 2015; Jocks et al. 2015). Many workers advocate and have developed digital databases to act as repositories for such data derived from photogrammetry and laser scanning to attempt to share data to the public for visualisation and 3D printing, such as the Smithsonian X 3D database or the British Museum's Sketchfab page, among others. However, it is as of yet unclear how effective these databases are in terms of actual public engagement and whether or not they justify their costs of maintenance (Abate et al. 2011; Mitsopolou et al. 2015; Smithsonian Website, 2018a; Sketchfab, 2018). Others have seen use within the sphere of so-called ‘serious games’, whose usefulness has been heavily studied over the past two decades (Kontogianni and Georgopoulos, 2015; Kontogianni et al. 2017). In other words, as has been discussed in the past three chapters there is a general lack of robust inquiry into the effectiveness of how these datasets are exploited on a larger scale within cultural heritage and whether or not they are particularly useful facets of museum practice. Research should ideally begin to focus on how museums can exploit 3D scanning technologies beyond their initial use and examine how museums can make efficient use of the data for the purposes of public engagement.

7.6.2 Benefits to Conservation Practice

Many applications in conservation have directly exploited 3D digitization in order to characterise archaeological sites and objects and assess their condition and conservation, both at the time of scanning how their geometry changes over time (Lerma et al. 2010; Chapman et al. 2013; Payne, 2013; Quagliarini et al. 2017). XCT, in particular, has been used in many different contexts as an effective method of exploring the subsurface structure of fragile artefacts, a feat which photogrammetry and laser-scanning cannot achieve (Payne, 2013; De Chiffre et al. 2014). For example, the Enhanced Digital Unwrapping for Conservation and Exploration (EDUCE) project at the University of Maryland has carried out major conservation work of the legendary scroll cache of Herculaneum, extremely fragile carbonised Greek scrolls which under normal circumstances, cannot be read without destroying them. Seales et al. (2010), Mocella et al. (2015) and Bukreeva et al. (2016) have used the non-invasive and hands-free advantages methodology provided by XCT to image the scrolls in 3D to assess the internal structure of the scrolls, whether or not there is any internal derangement of the sheets and most recently, begun to read them by ‘digitally unwrapping’ them, a venture made possible by the presence of high-density inks that permit individual letters to be extracted from the scan data. There are many other examples of XCT being exploited for the purposes of exploring the conservation of items in detail, including; the ‘Doppio Corpo’ at the Quirinale Palace (Re et al. 2014), high-quality stringed instruments (Sirr and Waddle, 1999; Sodini et al. 2012), evaluating treatments for stone and buildings (Cnudde et al. 2009; Dewanckele et al. 2014), for sculpture (Badde and Illerhaus, 2008), statuary (Morigi et al. 2010; Bettuzi et al. 2015), for identifying embedded artefacts (Stelzner et al. 2010; Schilling et al. 2013), investigating subsurface structure beneath corrosion crusts (Haneca et al. 2012; Mearns et al. 2016) and the subsurface structure of weaponry (Mannes et al. 2014), among many others across the field.

Chemical analysis using either XRF, EDS or both is also an approach that is commonly exploited within cultural heritage, being used to characterise the composition of pigments, chemical agents and alteration products developed over time (Lutterotti et al. 2016; Liss and

Stout, 2017; Walter et al. 2018). These approaches are typically non-contact where the object is either small enough to fit in an SEM vacuum chamber for EDS or if macroscopic XRF (MA-XRF) will provide sufficient spatial resolution to properly characterise the chemistry of the specimen (Legrand et al. 2014). If neither of these hold true, destructive sampling will need to be carried out which is less desirable (Janssens et al. 2010), but even a small sample can provide extremely valuable information about the chemical make-up of a specimen. Overall, both XCT and chemical analysis approaches are widely applied and commonly used within the field of conservation in cultural heritage.

Rarer however is the combination of these two approaches, with far fewer studies that combine both XCT and chemical analysis together. Paintings are among the most common applications of twin usage of the technologies and are objects typically used for XRF due to their thinness, usually not requiring extensive 3D analysis. For example, Janssens et al. (2010) discuss the combination of radiography, XRF and EDS among a wide variety of other chemical techniques for investigating the subsurface structure and chemical composition of paintings, in which the stratigraphy of the paint lying beneath the surface needs to be understood for any form of conservation to be carried out. Similarly, Van der Snickt et al. (2016) demonstrate the combination of XCT and MA-XRF in the unveiling of another painting beneath the surface of René Magritte's *Le portrait*, identified using XCT and then the pigments of both the original and underlying portrait's chemically mapped using MA-XRF.

Others utilise these technologies in tandem to explore 3D dimensional objects. Dewanckele et al. (2009) for example utilise this approach in building stones using XCT. Given that XCT is unable to acquire compositional information beyond the relative density of the object, they used XRF on the external surface of the object in order to identify weathering products and other geological parameters of interest to conservators of stonework. de Kock et al. (2012) describe a similar application to examine gypsum crusts on Lede stone, utilising XCT and XRF to characterise the weathering patterns of the gothic building material. Vavřik et al. (2017), Senesi et al. (2017) and Mikolajska et al. (2012) all describe similar applications of statuary, again utilising this combined approach to better characterise damage and weathering for the purposes of conservation. Other examples include investigating the imaging of papyrus phantoms (Gibson et al. 2018), characterising pigments in furniture (Burgio et al. 2018), characterisation of historic building stone (Lanzón et al. 2014) and the characterisation of historic glass beads (Ngan-Tillard et al. 2018). The direct integration of XCT and XRF systems, known as cXRF systems, also appear to provide extreme potential in evading destructive sampling, allowing 3D compositional scanning in the same process (Laforce et al. 2017). These solutions are arguably far from commercial viability at this stage however. The increasing usage of combined XCT and XRF thus proves to overall be promising for conservation practice.

7.6.3 Confirming Authenticity

Another avenue that this technology could be extremely beneficial for is that of fraud detection within museum practice. The risk of fraud from malicious fakes passed off as genuine objects is a major threat to institutions, resulting in a damaged reputation from being unable to ascertain the true provenance of an item. Frauds and fakes, such as the infamous ‘Piltdown Man’ or the deception of Johann Beringer by his colleagues through the ‘Lying Stones’, can be purported for financial or reputational gain which can, on occasion, fool even the most astute of subject experts. Thus, the threat they present not only to cultural institutions but also the integrity of science and academia is severe (Ruffell et al. 2012). Digitisation technologies, particularly XCT, can provide a way of being able to reverse-engineer spurious objects and properly characterise how the forgery was composed, as has been demonstrated in this chapter. This use is exemplified by Sirr and Waddle (1999), who demonstrate the use of XCT on high-quality, stringed instruments, from a number of expert crafters to detect internal repairs that, from surface examination, may not be detected even by a subject expert. These repairs can strongly influence the quality of an instrument and the sounds that it produces and thus the value of the instrument. Sirr and Waddle (1999) show that XCT can be used to easily detect glues and resins used to repair cracks and damage, woodworms tunnels within the body of the instrument and filler materials which have been expertly applied to fool even the most astute of experts.

Another example is that of ‘Archaeoraptor liaoningensis’, a high-profile case of a fraudulent fossil specimen being clearly debunked using XCT technology. The fossil beds of China are currently producing a number of paradigm-breaking palaeontological finds and there is a growing problem with fraudsters attempting to exploit this niche (Stone, 2000; Wang, 2013). The sudden appearance of a ‘missing-link’ between dinosaurs and birds was one example and the purchaser worked with National Geographic to publish the animal under the name ‘Archaeoraptor liaoningensis’, while submitting papers to Nature and Science for formal classification. These were rejected (Ruffell et al. 2012; Tembe and Siddiqi, 2014). The description of the species in a non-peer-reviewed publication created a backlash which threw the nature of the specimen into question (Dalton, 2000; Tembe and Siddiqi, 2014). While the specimen initially passed expert scrutiny, a reanalysis using XCT demonstrated that the specimen was actually a master-crafted composite of two to five different specimens. The fossil material was attached to an underlying slab of shale using grout while a number of false ‘shims’ of rock were used to fill in the gaps between the different parts of the composite specimen (Rowe et al. 2001). Through using XCT, this fraudulent specimen was revealed and the material composing it went on to be separately described as two different species, adding much to the scientific understanding of the relationship between birds and dinosaurs. Thus such scanning approaches can be invaluable for examining the nature of items and uncovering the true nature of objects of dubious authenticity.

7.7 CONCLUSIONS

In conclusion, there is great potential for the use of XCT and chemical analysis techniques within the field of cultural heritage, particularly for conservation. Combination of both approaches can be exploited to reverse engineer the conservational history of museum objects with a dubious or unknown conservational history, as has here been demonstrated with the example of *Megalosaurus bucklandii*:

- XCT analysis has revealed the distribution and extent of the plaster found in *M. bucklandii* is less than was previously thought, though still extensive throughout the specimen. Two different forms of plaster appear to have been used in the repair of the specimen, one used mainly on the dentary itself and the other exclusively on the teeth and the tooth row, suggesting that two phases of repair had been carried out on the specimen. The first, P1 was denser and contained disseminated grains of a high-density material that could not be recognised from the scan data. The second, P2 was more homogeneous and less dense on the whole.
- Subsequent chemical analysis of both P1 and P2 using EDS and XRF revealed and overall similar compositions, consisting of gypsum mixed with sand and calcium carbonate, possibly originating from the original specimen, a shellac coating and chlorine contamination. P1 however contained dense grains of minium, a lead pigment that likely had been added for colour and/or weight while P2 lacked the minium grains, instead having a potential coating of barium hydroxide as a consolidant.
- The study overall demonstrates the potential of both techniques applied in tandem but also that the process of digitizing a specimen can be a fruitful endeavour for museum practice. From a simple application looking into digitizing and 3D printing a copy for use in object handling for museum visitors, invaluable information was also found about the conservation of the object. This highlights that projects utilising digitisation technologies can have greater value than that which they were initially carried out and that both conservation and education within museum can benefit each other.
- Digitisation of older, thought to be understood specimens can also provide new, valuable information into them, as evidenced by the presence of poorly understood dentary vascular canals and tooth replacements of relevance to palaeontological applications and its potential for foiling hoaxes and frauds that put museums at risk.

8.0 DISCUSSION

Overall, the four major research studies detailed in the previous four chapters have revealed a number of insights into how museum visitors and BPS individuals respond to 3D printed replicas, their opinions on the technology and how these views intersect with core design principles. The further ramifications that the simple act of digitisation can have in extending the value of museum objects and research has also been elucidated. The findings of these studies speak for themselves, but at this stage do not directly address the research questions detailed earlier in the thesis. It is now time to reconcile these studies with these research questions to answer the dominant themes raised during the literature review. This section will summarise the major findings forthcoming from the research detailed in this thesis in an attempt to determine how tangible 3D printed replicas can influence the experience of the museum visitor.

8.1 Answering the Research Questions

The research questions, last outlined at the end of chapter 3, are here reiterated:

- How do museum visitors regard 3D printed replicas and how might they influence their expectations of museum content?
- What design considerations need to be taken into account in order to create user-friendly 3D printed replicas for sighted and BPS audiences?
- How can 3D printed replicas benefit museum audiences and enhance their experiences?
- How can tangible 3D printed replicas assist BPS museum visitors in their interpretation and enjoyment of exhibitions?
- What benefits can the replication of museum objects have in wider museum practice?
- Are user experience methodologies applicable and informative in understanding the needs of museum audiences?

Each of these will be now be addressed in turn and how the findings of the main chapters of this thesis contribute to expanding knowledge with regard to that particular topic.

8.1.1 How do museum visitors regard 3D printed replicas and how might they influence their expectations of museum content?

This question is primarily addressed by chapter 4, which looked specifically at visitor perception and acceptance of tangible 3D printed replicas. First and foremost, a major finding was of the low exposure and understanding of the technology by museum visitors. Only a relatively small proportion had any accurate conception of how 3D printing actually worked and exposure to tangible 3D printed replicas was low. This suggests that these concepts need to be clearly articulated to museum visitors to avoid misconceptions of what the replicas are and how they were made.

Additionally, museum visitors strongly articulated that they thought that such replicas would enhance their museum experience and agreed that such replicas should be present in more museums. However, a significant finding was nearly a third of the sampled visitors would not be encouraged to visit museums more often, many suggesting it would only draw them if it was a special exhibition or event. Reasons for such positivity in opinions towards this approach centred around its ability to enable multisensory interaction, potential educational benefits and a better appreciation of the details of a specimen beyond that enabled by the glass-case paradigm.

Overall, these results do show that museum visitors did regard the technology positively, but a consistent young negative voice expressed displeasure over handling a replica. As a result, further research may be necessary to understand the impressions of more specific audiences, a shortcoming which this particular study failed to take into account.

Chapter 6 also elucidated minor insights into BPS perception of such technologies, where participants were interested to know when such replicas might be introduced to museums. However, as these participants were not primarily sourced from the museum audience, it is difficult to reconcile this positivity with that of the visiting public.

8.1.2 What design considerations need to be taken into account in order to create user-friendly 3D printed replicas for sighted and BPS audiences?

The initial insights into answering this question were first uncovered in chapter 4, where many participants discussed the thermal and tactile properties of the different *Phascolotherium* 3D prints and their own preferences. These participants seemed to favour more accurate replicas, showing some disdain for the less realistic and lower quality prints that they were shown. This in part encouraged further exploration of this particular area of interest in chapter 5.

The results in chapter 5 confirmed this idea, using a mixed-methods approach that elucidated that participants strongly favoured those prints that were verisimilar to the original specimen. This was found to be the dominant factor in sampled visitor preference, while the second factor, that of the robustness of the object, was found to have no correlation to preference. The overall quality of the print was also key, but exhibited a weaker positive correlation to visitor preference. Both represent requirements as per the Kano model, verisimilitude being a one-dimensional requirement while quality being a must-be requirement. Overall, this study advocated the importance of verisimilitude and the quality of 3D prints, while highlighting the natural difficulties with cost and time that come with attempting to prioritize a high degree of verisimilitude. A number of minor findings, such as the difference in preferences between older and younger visitors and some younger participants citing eye-catching characteristics as reasons for preference suggest that different museum demographics have different preferences, mandating experiences be tailored around their target audience.

Similar ideas in BPS audiences were not adequately explored due to time limitations, a further study looking into this phenomenon being planned but not implemented. In chapter 6, some BPS participants did articulate that they would prefer handling objects that were unaltered and as true to the original as possible, which would suggest that verisimilitude would also be favoured by BPS museum-goers. Unfortunately, as above, a similar restriction in that the sampled participants were not sourced from the visiting public means that such conclusions are erroneous and, furthermore, this aspect was not studied with any rigour.

8.1.3 How can 3D printed replicas benefit museum audiences and enhance their experiences?

This particular question was covered in less detail by the major studies and as a result, a definitive answer is not forthcoming. The participants in chapter 4 suggested strongly that such technology would certainly enhance their experience in museums and encourage their understanding of museum content. However, the study provided no empirical evidence or observations of tangible 3D printed replicas actually enhancing said experiences, so it would be unreasonable to claim this to be true.

The same can be said for chapter 6, where BPS many participants again stated that such handling experiences would be highly desirable. These are only the opinions of the participants however, rather than any kind of empirical proof of the enhancement of their experience.

Thus, this question may not be adequately answered by the findings of this thesis. Further work exploring the impact of tangible 3D printed replicas on the museum visitor experience is thus required.

8.1.4 How can tangible 3D printed replicas assist BPS persons in their interpretation and enjoyment of exhibitions?

Chapter 6, covered this topic quite comprehensively, looking into how BPS individuals perceive objects and what they can interpret from them. This study elucidated many key insights, the first being that perception of the object was predominately multisensory, participants utilizing optical, olfactory, tangible and acoustic properties to understand what the objects were. This suggests that these properties need to be conserved and added to tangible 3D printed replicas to maximize understanding.

Participants were also more accurate at identifying materials rather than objects, the main reasons for both object and material judgements being interrelated and predominantly focused around the texture, shape, ‘feel’, weight, optical properties and their prior experience with similar objects. Thus care needs to be taken when altering such properties and in the choice of 3D printing materials, both of which could influence the interpretations of BPS individuals. Participants also did not wish objects to be altered heavily through 3D printing, rather preferring assistive solutions like audio description, providing the object in-life context and accompanying scaled models that enhance certain features. Further discussion encouraged taking into account the variegated nature of blindness and that the ability to create truly verisimilar replicas is at this stage limited.

However, this study did not address the influence on BPS museum experiences or enjoyment and while there was some positive feedback from participants, yet again no empirical evidence of increased enjoyment was pursued. Thus as above, further research is required.

8.1.5 What benefits can the replication of museum objects have in wider museum practice?

The major findings from chapter 7 address this particular research question. The act of digitizing a valuable object, that of the *Megalosaurus bucklandii* lectotype dentary, resulted in a number of findings that proved beneficial beyond simply creating a replica for handling applications. XCT scanning yielded valuable information that resulting in a research project investigating the conservational history of the valuable historic object, resulting in the reverse engineering of prior restoration treatments that will help to inform and guide future conservation efforts. The very same process also yielded some insights into the palaeobiology of the species, a series of complex alveolar canals that are relatively understudied within palaeontology and its tooth replacement. These structures could have important ramifications in interpreting the ecology of the animal and potentially the evolutionary history of the Dinosauria.

Thus, the act of replicating an object or specimen for tangible interaction by the public can certainly lead to joint applications that have a wider-reaching impact within museum practice. The data used in cultural heritage applications could also be better utilised for museum practice, rather than merely being sequestered in museum databases.

8.1.6 Are user experience methodologies applicable and informative in understanding the needs of museum audiences?

The major findings of chapters 4, 5 and 6 all adequately address this particular research question. In chapter 4, the views and knowledge of museum visitors were explored to ascertain if 3D printed replicas would be welcomed, uncovering an overwhelming positivity towards the concept and some initial insights into how to create such replicas, including a low level of understanding of the technology and an unprecedented preference towards verisimilar prints. This verisimilarity was the subject of chapter 5, in which robust mixed-methods analysis of semantic differential scales revealed which characteristics of 3D printed replicas were most important to museums visitor preference of 3D printed replicas. The most important factor was that of the verisimilarity of the print to the original object, followed by the overall quality of the print. These both represented one-dimensional and must-be qualities under the Kano model respectively, while the robustness of the print was unrelated to preference. Finally, chapter 6 explored the design constraints of producing 3D printed tangible replicas for BPS applications.

This study advocated the multisensory nature of BPS interaction with the natural history objects used and the integration of object and material characteristics, which both contributed to the overall interpretation of the object. The study also elucidated a number of important characteristics of concern when designing such replicas to take into account, such as the role of prior experience, properties to prioritize and design considerations to take into account when fabricating replicas.

As a result, it can be determined that the UX methodologies used were extremely informative for museum practice and that UX research could be extremely useful for research into exhibition design and in wider museum practice.

8.1.7 Summarizing the Research Questions

In summary, this thesis has provided valuable insights into a number of these research topics, namely that 3D printed replicas are indeed welcome in museums, verisimilitude is key to making desirable handling experiences with 3D printed replicas and that BPS perception of museum object is dominantly multisensory. Designing such prints for handling is thus a complicated process and needs to take into account the complex nature of object interpretation and interaction. Additionally, the mere act of replicating previous museum objects can have wide and diverse benefits for museum practice beyond simply public engagement, including education, conservation and research.

However, unanswered aspects of these questions are typically associated with actual implementation in museum applications, such as whether or not 3D printed replicas would enhance enjoyment and learning in both sighted and BPS museum audience. This reflects a number of key research areas that mandate future exploration (*8.4 Future Research Approaches*).

8.2 Making 3D Prints for Museum Audiences

Overall then it can be concluded that tangible 3D printed replicas are indeed welcome and even desired by museum visitors, with a few caveats. A major theme in responses across the chapters that emerged was that of the verisimilitude of the replicas, being an emergent topic in chapter 4, the overriding factor for preference in chapter 5 and the importance of multisensory properties that are unlikely to be present within a replica in chapter 6. This represents an interesting discussion as to the current limitations of 3D printing technology with regards to its accuracy and ability to replicate the hallmarks of an ‘authentic replica’. Additionally, the findings of this research have yielded a number of important insights into how such replicas can be presented and how different audiences respond to and consider such replicas. It is these major themes that will now be discussed, and how these feed back into the key decisions that the museum professional will need to consider when creating tangible 3D printed replicas for multisensory experiences.

8.2.1 Impact for Visitors and Museum Practice

Worthy of consideration is the impact that using such tangible 3D printed replicas would have on the interactions of museum visitors with exhibition content and how exhibition designers should design and utilise such replicas. For example in chapter 5 (*5.4.1 Hedonic Comparison of Prints: Friedman's ANOVA*), the 'matrix-less' and 'matrix' prints of *Phascolotherium* were compared to see if there were any differences in preference. This returned an insignificant result, suggesting that this condition had no effect on print preferences. This brings up an interesting question about how to present objects on a conceptual level. In this particular example, printing outside of the matrix allows visitors to understand the specimen in three dimensions and appreciate the complete geometry of the jawbone, but removes the object from the context of being fossilised. This may prevent the object from being treated as a replica of fossil material and more as an ageless, modern object of lesser interest. On the other hand, printing an object inside a matrix will inhibit the clear interpretation of the shape of the fossil, even if a clear material is used in the case of the Clear Resin print. The trade-off is that it provides more of a context for the original fossil or object and stronger association to genuine fossil material. Given that preferences did not differ between both of these modes of presentation, decisions over how objects should be presented need to be given due consideration by museum professionals and how they converge with the educational objectives of the application. This could include the demonstration of anatomy, certain features of the object or just the ability to allow people to handle and manipulate something that represents the original specimen. This is only one such example of key decisions that need to made and there is no simple answer to such questions without further detailed research examining the minutiae of such questions with robust research. A number of such simple insights have been revealed over the course of the studies detailed in this thesis, which will now be expounded upon.

One such concern is that of relevance. In chapter 4, a number of participants who were neutral on the topic of introducing tangible 3D printed replicas into more museums highlighted that it perhaps might be more useful in natural history museums, where the very physicality of a specimen is more important to the visitor than in a science museum:

> *"It's also maybe more on a physical specimen point of view because animals and things are there just like [Unintelligible] the dinosaurs that the bones of things that are here are kind of, they've got more of a physical presence so say like in the, maybe in the science museum you wouldn't be thinking 'Okay, I need a 3D print to show, I don't know, a planet or something' but you might do for like an anatomical thing…"*
>
> *Anne (35-44)*

Thus, such replicas lend themselves to some form of display over others. Creating tangible 3D printed replicas of sculpture would help visitors to appreciate the form of artwork, but would be much less useful for a painting with little three-dimensional form. Likewise, printing a physical object that may have some form of emotive or historical aura to it, like the sword of a famous king, will be much more appreciated than something more abstract and less steeped in history. Objects to be fabricated should really be those which otherwise would never have any access to tangible handling rather than those that are more diagnostic or valueless. Thus, exhibition designers should be cautious of not creating superfluous value-free models that serve as merely a means of enabling tangible access. Objects need to be chosen carefully on a basis of whether or not touch would enable the acquisition of information that would be missed otherwise and, as was articulated by many of the participants in chapter 4, allow greater appreciation of the details and nature of the object in question.

Another primary concern is that of cost. In chapter 4, a portion of the sampled visitors cited concerns over seeing tangible 3D printed replicas in more museums, that 3D printing and the prints themselves could be costly and thus compromise other aspects of museum practice. 3D printing, while certainly becoming increasingly accessible to museums by the year, is still fairly expensive to invest into unless lower-end machines are purchased. This naturally leads to the compromise of model quality and the creation of 'toy-like' replicas. For institutions who create their own replicas, creating a model sufficient for professional use such as handling applications can be an expensive affair (Jung and Tom Dieck, 2017; Scopigno et al. 2017). The more tempting, affordable lower cost 3D printers typically produce poorer quality prints while higher quality materials, such as resins which boast finer layer thickness and better material properties, are also more fragile, easily breaking under prolonged use in handling over their less detailed but more robust cousins (Gibson et al. 2015; Chua and Leong, 2017). Considering that the entire point behind these prints is to provide a disposable surrogate for the original specimen, purchasing expensive models that are liable to break only after a short amount of manual handling could be a potential financial drain should the approach be undertaken. Overall then a balance must be struck for museums between how the amount of funding that is available to create a replica and the choice of key materials which will naturally have an impact on the durability, aesthetic appearance and verisimilitude of the final piece.

Another potential issue is that of a changing visitor profile in response to the permanent provision of tangible 3D printed replicas. For example, Davidson et al. (1999) (Table 2.2) highlight an application of a multisensory experience at the Boston Museum of Science, expressing that the addition of multisensory components shifted the demographics of audiences visiting the gallery, attracting a larger proportion of family groups and a smaller proportion of older and solo visitors. They stated increased noise and disruption as a potential cause. Such preference can be readily observed in science and children's museums today, where family groups are the dominant visiting demographic due to the prevalence of multisensory engagement with interactives encouraging active learning through play (Witcomb, 2006). While it is as of yet uncertain whether widespread implementation of tangible 3D printed replicas would incur a similar change, these concerns are certainly worth taking into account when exploiting multisensory experiences and is a cost that should be weighed prior to implementation. Some museums which typically attract older visitors, like art or cultural museums, may suffer adversely from such introduction and a loss of their core market demographic.

Finally, it is worth considering the needs of the Blind and Partially-Sighted (BPS) audience. This particular demographic has been historically marginalised within the museum environment as has been discussed previously, with minimal, temporary and amelioratory approaches being carried out in museums to provide support for BPS visitors under duress from government legislation passed some time ago (DDA, 1995; Equality Act, 2010; Mesquita and Carneiro, 2016). Tangible 3D printed replicas could provide a way for BPS visitors to properly engage of their own free will with exhibition content, rather than merely having information spoon-fed through audio alone. Some authors have addressed this subject of the preference of BPS visitors in handling the objects provided by museums. Candlin (2003) for example found that many participants took issue with the simplicity of drop-in events and their sometimes condescending nature. The author highlights one particular example of a touch tour at Tate Liverpool where the BPS participants were not permitted to touch the sculpture, only a small limestone block of the same material. The author stated that this represents material without context, almost entirely unrelated to the actual sculpture itself. Similarly, Candlin (2010) again documents a museum application at the V&A designed for BPS interaction with furniture, where audiences were permitted to handle a small cube of representative material. However, as the cube had also been lacquered to protect it, the objects lacked textural information that effectively negated the purpose of providing such objects. These two approaches highlight that efforts to protect these objects can inhibit interpretation and tactile interaction with 3D printed replicas should only be beneficial to BPS audiences.

A number of design considerations in light of the analysis in chapter 6 have already been discussed, namely the risks of altering the geometry of an object and its seemingly complex relationship with material and object judgements and the potential impact of material choice, which is further discussed below. Another important subject was the integration of the prior experience of BPS individuals, an important ramification in individuals living with long term sight-loss are less likely to have experienced rarer and stranger objects and concepts, precisely the objects that make up the majority of museum collections. Museums are thus challenged to create scaffolded experiences that allow BPS individuals with narrower experiences to understand and interpret more complex, alien objects. A major focus however is still the creation of the verisimilar replica, one that accurately represents the material characters of the original object so as not to mislead the handler. The technical considerations of this are also discussed further below. Not explored further however was the question of what physical properties do BPS visitors consider to be most important and how exactly do their preferences compare to that of sighted visitors. The needs of BPS audiences are thus key in the design of tangible 3D printed replicas and museum professionals should consider in-depth the ramifications of material choice, geometry alteration and the prior experiences of their audience and how best to tackle these issues.

8.2.2 Technical Design Constraints

Overall, the potential positive benefits of tangible 3D printed replicas have been explored and the major impact that the technology might have on museum practice ascertained. However, it is also worth considering the current modern limitations of the technology, a key factor in the replication of verisimilar 3D printed replicas. These shortcomings need to be taken into account when creating tangible 3D printed replicas and understanding the limits of the technology will temper expectations of what can be achieved in exhibition content creation.

8.2.2.1 Verisimilitude

The first major key theme is the creation of verisimilar replicas that represent the original object accurately. This aspect was significant for preference in chapter 5 and chapter 6 showed multisensory properties that are potentially informative for BPS individuals and need to be retained. In terms of optical verisimilitude, the vast majority of 3D printing machines on the market today typically print using a single-material at a time by design, with the exception of multi-jetting (MJ), binder jetting (BJ) and laminated object manufacturing (LOM) approaches. Fused filament fabrication approaches (FFF) typically print in a single colour filament, although full-colour FFF methods are now reaching the market (Gibson et al. 2015; Chua and Leong, 2017; Chen et al. 2016; XYZ Printing, 2018). Colour 3D printing typically utilizes the CMYK colour format, with some printers, such as the Spectrum Z510 (CJP/3DP), using 24-bit colour (‘True Colour’) which results in reasonable colour quality (Vanderploeg et al. 2016; Chen et al. 2016). However, colour 3D printing is limited in its spatial resolution and the range of colours it can produce, limiting the verisimilitude of colour to the original object (Fig. 8.1abcd). The quality of the colour can also further impacted by the materials used, the surface characteristics, the printer used, the finishing and post-processing used and the layer thickness, meaning the final model may not accurately replicate the colour of the original object or capture the details of the original mesh (Fig. 8.1ef) (Klein et al. 2014; Chen et al. 2016). Overall, this means that the finished piece is unlikely to be particularly verisimilar without significant post-processing, as such printers certainly cannot replicate more complex optical effects, such as glossiness, at this stage. The situation will improve as the technology develops, the recent Mimaki 3DUJ-553 (Mimaki) being capable of producing 10 million colours, with impressive near-photorealistic results (Fig. 8.1c) (Mimaki, 2018). In terms of olfactory verisimilitude, current 3D printing devices on the market as it stands would be unable to replicate this feature without some form of additional post-processing of a suitable scent, as carried out by Harley et al. (2016) in replicas of prayer nuts. Some materials, such as ABS, even have their own undesirable scents that could actively throw off sensory interpretations exploiting smell (Ngo et al. 2018).

Acoustic verisimilitude is also of major concern, as unless the replica is made of a suitable material and accurately replicates its physical characteristics and structure, the sounds produced may be inaccurate or misleading. Considering the current limitations in the mechanical properties of 3D printing materials, this is unlikely to be the case for some time, mainly owing to the anisotropy of such materials due to the method of their layer-by-layer manufacture (Ngo et al. 2018). A study by Kong et al. (2018) articulates this point, comparing the mechanical properties under compression of gypsum-rock cylinder prints to that of common rock types, finding that their strength was only comparable to the weakest sandstones and schists. This relative weakness is one symptom of the inability of 3D printing to accurately replicate rock samples but the authors also found that gypsum printing methods (3DP/CJP) did not have sufficient layer thickness to accurately replicate pore structures, leading to further mechanical inaccuracy. These traits, while perhaps less important to ‘visual verisimilitude’, arguably still influence tangible verisimilitude of texture and thermal properties, substantially altering tactile experiences with the object and potentially deceiving the handler if these properties are not entirely accurate. For example, printing a historic ceramic in a thermoplastic filament, often regarded as having a strange ‘fabric-like texture’, would be markedly different tangible experience than handling the original, with differing weight, texture and thermal properties despite being derived from highly accurate CAD data.

These considerations are important for sighted individuals, as an absence of such properties, as shown in chapter 5, could lead to a less desirable handling experience and cause confusion, as described by Nofal et al. (2018) by some visitors in their study. These properties are even more important to BPS individuals, to whom the omission of potential informative auxiliary sensory properties would be detrimental. All of these issues are tied together under the lack of development of 3D printing technology as it stands. The technology is still rather young as methods old and new have diversified and the range of materials on offer is still at this stage rather limited (Ngo et al. 2018). There is a general lack of methods that permit the creation of

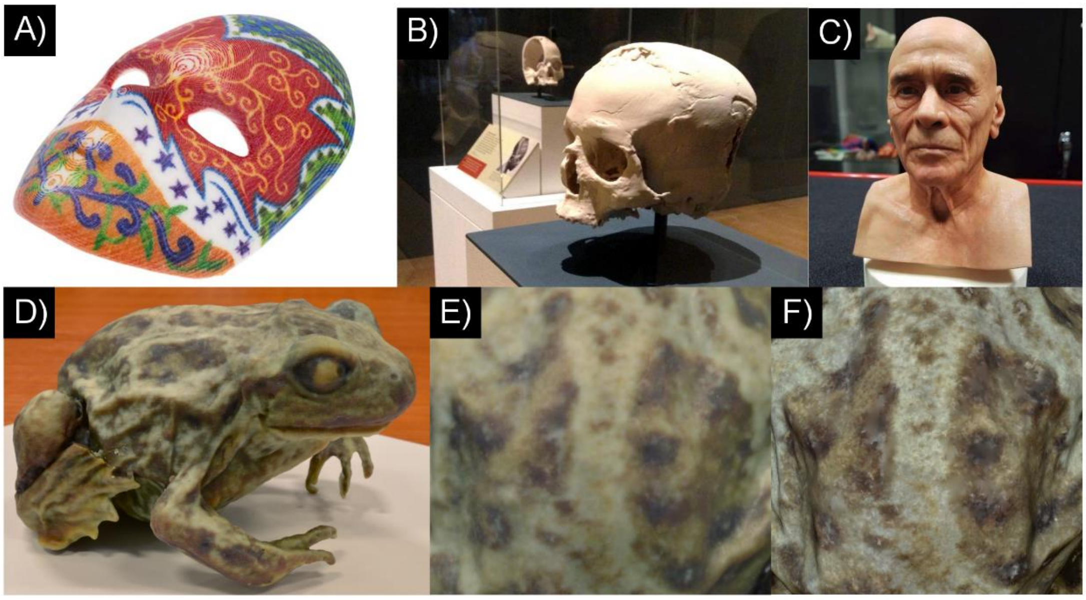


Fig. 8.1: The State of the Art of Colour 3D printing: A) Printed part from Da Vinci Colour (FFF) 3D printer. B) Display at British Museum featuring the Jericho skull printed using a CJP/3DP method. C) Test example of part from Mimaki's 3DUJ printer. D) Example full-colour part from Stratasys J750 (MJ). E) Close up detail from the same print as in D. Colours are blurred and not as sharp as original mesh. F) Original mesh, with sharper detail and different colour gamut than 3D printed model.

verisimilar replicas at this point beyond low-resolution colour, although MJ technology does have the ability to synthesize different materials in full-colour and print them at the same time, as exhibited by the Stratasys J750/J735 (MJ) among other multi-material, full-colour printers. However, these printers are typically more expensive, the da Vinci Color (FFF) retailing in the region of ~£700 for the micro version and ~£3000 for the macro version. This is arguably the affordable solution, as the high-quality Projet CJP 660Pro (3D Systems) (CJP/3DP) retails for >£25,000 and the high-end Mimaki 3DUJ (MJ) and Stratasys J750/735 (MJ) both retail for >£150,000, all of these being well outside the affordability of the majority of museum institutions. This means that mono-material, non-colour printers are typically more affordable, typically utilising thermoplastics and FFF technology such as the MakerBot line among others (Chen et al. 2016; Vanderploeg et al. 2016). Naturally, the expense of such machines is well outside the price range of many museum institutions, although private services such as Cambridge-based ThinkSee3D and online printing companies, either as a dedicated manufacturer such as Shapeways or hub services such as 3D Hubs, provide museum professionals access to these high-fidelity printers for a modest price.

Thus, museum professionals should broadly be aware that the creation of truly accurate replicas is not an easy or inexpensive task, with rather limited results relative to more traditional methods, adding such details associated with colour and physical properties during the post-processing stage, as is commonly done with 3D printed props and models for movies and in fashion (Vanderploeg et al. 2016; Zhou et al. 2018). Such approaches are sometimes adopted in the creation of more ‘authentic’ replicas for exhibition purposes, as exemplified by Amico et al. (2018) with the ‘Kazaphani Boat’ replicated for display in the Smithsonian. Fabrication involved extensive post-processing and painting to create a more verisimilar model. However as in this example, this adds another lengthy stage of post-processing that undermines the initial reasons for using 3D printing in the first place, its rapidity and ease of use. It also is accompanied by increased labour costs through the need for skilled workers to carry this out. Thus, careful decisions will need to be made by museum professionals as to what materials should be used for the purpose of creating 3D printed replicas for handling purposes, to minimise the influence that false properties will have on the interpretations of BPS visitors and mitigate the costs inherent in pursuing truly verisimilar replicas.

8.2.2.2 Quality Trade-offs

Another question is that of the quality required for a 3D print. Chapter 5 showed that quality was weakly correlated to preference towards any particular print. Additionally, few positive comments for preference of a particular print were found whereas the opposite was true of the negative comments, which were dominated by concerns associated with cheap, artificial and fake looking prints. Identification as a ‘must-be requirement’ suggests that perhaps there is a minimum threshold of quality necessary for the visiting public’s acceptance of a particular print. In other words, having a print of an acceptable quality is far more preferable than a bad quality print but there are, in effect, diminishing returns for higher quality prints. This critical threshold is unclear from the results of this research project but has ramifications on exhibition design considerations.

Choice of materials is key, as this generally has a strong impact on the layer thickness, the optical and tactile properties of the final product, and most importantly, its cost, as has been discussed above. For instance, FFF methods are cheaper compared to SLA methods but will generally result in a poorer quality print due to the limitations of its coarser-layer thickness and the nature of the thermoplastics typically used. FFF, due to the need to lay out a consistent stream of heated material through an injection head is limited to a minimum filament thickness whereas the mechanism behind SLA can achieve much finer layer thicknesses, down to <10μm in some cases, due to the precision afforded by utilising UV curing. In terms of the entry costs of buying a simple desktop variant of each of these technologies, FFF is however more affordable with lower end, DIY assembly kits costing between £100-300 whilst more expensive printers, such as those from Makerbot or Ultimaker, can range into the >£1000 region, with greater reliability and accuracy afforded by them. SLA printers, by contrast, have a much higher cost entry point, the popular Formlabs Form 2 (Formlabs), a small desktop variant, retailing for

~£2500, with other similar machines ranging between £2000-3000 such as the Nobel (XYZ Printing). Naturally as a result, greater accuracy mandates greater expenditure.

The ramification of this, as above, is that museum professionals need to carefully consider whether or not the methods that produce the highest quality models are needed for the application to which it will be applied. Assessing at what level this critical threshold of quality exists is key, to mitigate the costs to museum institutions while also providing desirable handling experiences for museum visitors.

8.2.2.3 Robustness

Directly tied to this discussion of cost is that of print durability. In chapter 5, whilst robustness was a supported factor, it was one of little concern to preferences of the museum visitor. However, the question of how long a model will survive extensive handling is more of a concern to the museum professional. Unfortunately, there is no easy solution to this as the complex interactions of cost and material complicate durability considerations. Resin prints, while accurate, are typically brittle, the cured resin polymers being extremely susceptible to breakage during handling. Indeed, over the course of chapter 4 and 5 studies, the painted resin model was snapped twice in two different places and required immediate repair, a testament to the fragility of SLA prints. The reduced accuracy of FFF prints comes with the advantage of the increased physical resistance of ABS and PLA and such prints are unlikely to be affected by all but the most rigorous handling by museum visitors.

Even in the case of breakage, their low price and accessibility means that replicas would be easily replaceable. At the opposite end of the scale comes metallic 3D printing, most commonly manufactured by SLS. Such prints as should be expected are incredibly durable and would be desirable by professionals for handling purposes. However, a lack of verisimilitude to most museum objects would likely result in undesirable handling experience and their expense, ~£500 in the case of the *Phascolotherium* model used in chapter 4 and 5, is a dissuading factor. Cleanliness is a more minor factor, but the white-coloured resin print required repeated cleaning as oils from object handling built up on the surface, even with the total number of participants who handled the objects numbering around 200. If exposed to more regular handling, such as that within a museum exhibition, such items would require extensive daily cleaning. Naturally, these concerns over durability tie in with considerations over cost and verisimilitude, weaker prints being those that are capable of greater similarity to the original while tougher materials are less capable of exhibiting verisimilar properties but would survive much more extensive handling. Thus, museum professionals must carefully decide the trade-offs between how realistic their models need to be and how durable they are, a combination of the two as being yet impossible.

Overall then, there are a number of major design decisions for tangible 3D printed replicas that museums professionals must account for when fabricating such models. True verisimilitude at this stage is limited within 3D printing, colour printing being as of yet underdeveloped and expensive and while more traditional approaches in painting could be utilised, these will incur the same long post-processing stages as traditional cast replication. Print quality is tied directly to price, with more accurate technology being less affordable while durability is generally inversely proportional to verisimilitude, meaning that prints designed for preferable verisimilarity will be more prone to degradation.

8.3 A New Approach to Exhibition Design

The overall lack of research within this particular field further highlights an underlying issue in how museums design their content. In the literature review (*2.5.1 Methods of Cultural Heritage Evaluation*) the history of evaluation within historic museum practice was briefly discussed along with the benefits that UX methodologies bring, as employed by other industries. This thesis has shown the value that UX research methods bring in generating insights into the UX of visitors and in informing design for future applications. UX itself fits within a wider framework of practice, that of User-Centred Design (UCD). Where UX holistically regards the experience of the user with a product, UCD holistically regards all of the needs of the user. It incorporates both UX and usability and other aspects of product design to create a holistic design philosophy.

8.3.1 Utilising User-Centred Design

User-Centred Design (UCD), alternatively referred to as human-centred design (HCD) (Norman, 2013; Rosenzweig, 2015) is a design philosophy rooted predominantly in the work of Norman and Draper (1986) and has since become widely incorporated within design principles in a number of consumer industries to tailor products towards target audiences. It has been shown to vastly improve the final quality of products and services, including in web and application design (Vredenberg et al. 2002) and product development (Rosenzweig, 2015) among others. It was more formally defined by the ISO in ISO 13507 (1999) as:

> *"Human-centered design is characterised by: the active involvement of users and a clear understanding of user and task requirements; an appropriate allocation of function between users and technology; the iteration of design solutions; multi-disciplinary design"*
>
> *ISO 13507 (1999)*

The UCD approach puts the major focus of design solely on creating an end product that is built around the needs and desires of the user and was dominantly a method born from a need to design competitive products in human-computer interaction (HCI) and web design during the boom of computer usage and the internet in the late 90's and early 00's (Vredenberg et al. 2002;

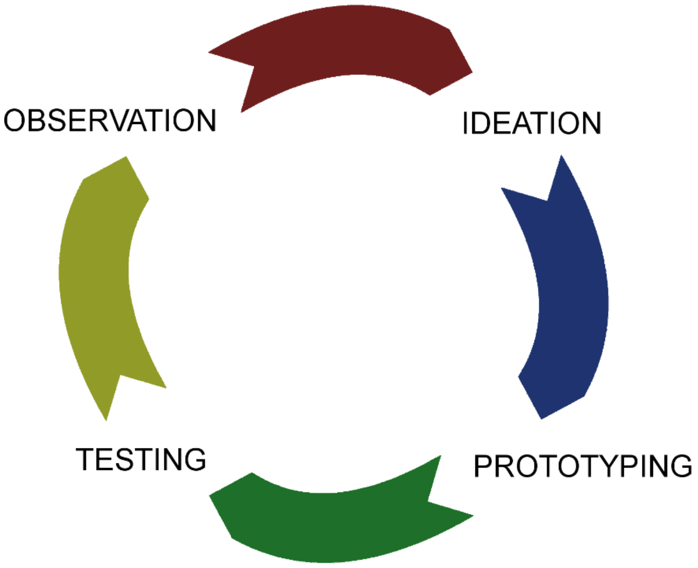


Fig. 8.2: The Iterative Loop of User-Centred Design (UCD): As envisaged by Norman (2013), UCD should employ an iterative approach of four stages. 1) Observation; the audience is observed to ascertain major design flaws. 2) Ideation; the design team generates a number of potential solutions to these flaws. 3) Prototyping; create a mock-up or testable solution to the flaw; 4) Testing; implement the prototype and see how it works. The process cycles back to observation and then repeats again.

Rosenzweig, 2015). It incorporates multidisciplinary practice with in-depth iterative assessment of the needs of the end-user to inform design and create a product or experience that is functional, un-frustrating and enjoyable (Vredenberg et al. 2002; Norman, 2013). The process is ultimately iterative over the course of developing a product and involves multiple stages of ideation, prototyping, testing and observation to create an ultimately superior end-product (Fig. 8.2) (Norman, 2013).

In a museum context, this refers to the creation of exhibition experiences that have been informed by direct analysis of the experiences their users have with them. The major trends within museum practice with regards to evaluative and generative research have already been explored (*2.5.3 User Experience and Museums: Unravelling the Needs of the Visiting Public*), the implication being that museum professionals actively carry out evaluative research, but prevalence towards generative research, that looking into deep, generalizable insights into practice, is more restricted. Widespread adoption of UX research approaches and of UCD would lead to the creation of a stronger research base of visitor insights. This would, in turn, assist the creation of exhibits and programs that lead to more pleasurable and desirable museum experiences. As an unenjoyable visit is unlikely to attract visitors back or promote recommendation to friends and family, tailoring museum content to the needs and desires of visitors should thus be at the forefront of museum practice, so as to minimise those aforementioned frustrations and create an enjoyable museum experience.

Thus, the onus is on museums to actively incorporate UCD design approaches, such as those carried out over the course of this thesis, to inform their exhibition practice carried out when designing content and more importantly, disseminate this information into the public domain so that institutions worldwide can benefit from the insights gleaned from visitors. To do any less than this is to risk falling behind competitive industries that already integrate such approaches within their practice and to ensure that the museums remain a desirable attraction to visitors, rather than dusty tombs for precious but forgotten objects.

8.3.2 Bettering Practice through Universal Design (UD)

Married with the concept of the need to properly incorporate in UCD practice within museums is the impending need to incorporate the principles of Universal Design (UD). UD, sometimes referred to as Universal Design Theory (UDT), is a similar set of design principles that can be defined as:

> *"… a strategy that aims to make the design and composition of different environments and products useable for everyone. It attempts to do this in the most independent and natural manner possible, without the need for adaptation or specialised design solutions. The intent of the universal design concept is to simplify life for everyone by making the built environment, products, and communications equally accessible, useable, and understandable at little or no extra cost. The universal design concept emphasizes user-centered design by following a holistic approach to accommodate the needs of people of all ages, sizes, and abilities. It provides for the changes that all people experience throughout their lives."*
>
> *Null et al. (2014)*

The approach has its origins mainly in the field of housing development and design, particularly to provide usable housing for the elderly and is a subject becoming of ever greater interest with many developed countries trending towards ageing populations (Null et al. 2014). The major facet of this design philosophy is not just focussing on marginalised audiences, such as persons who are BPS, but creating an ultimate solution that is equally usable by all members of the target audience regardless of their condition, age and lifestyle (Story, 1998; Bringolf, 2008; Null et al. 2014). This particular facet is key above all as advocated by the original champion of the approach, Ron Mace (Bringolf, 2008; Null et al. 2014). This philosophy takes the position that all individuals at some point will deviate from what is considered to be 'normal' and 'fit for purpose', whether it be through temporary disability through injury, contracting debilitating conditions later in life or just through the natural process of ageing. Thus, UD goes beyond designing strictly for 'disabled minorities' and instead concerns all potential users.

Given the typically broad demographics that are attracted to museums, from the very youngest to the oldest, the needs of museum audiences are diverse and should be attended to by all exhibitions, especially when providing support for more marginalised audience such as BPS persons. Earlier highlighted were the many difficulties in provision for BPS audiences that museums currently suffer from, predominantly the limited nature of access to rare events and the lack of engagement for BPS audiences without needing supervision by museum staff (Partington-Sollinger and Morgan, 2011; Small et al. 2012; Mesquita and Carneiro, 2016). The integration of such UD design principles in museum practice has been suggested by a number of authors within the heritage sector (Partington-Sollinger and Morgan, 2011; Eardley et al. 2016) and other similar sectors (Udo and Fels, 2010) to help develop more inclusive solutions for assisting BPS visitors within.

8.3.3 Integrating UCD and UD

Both UDT and UD design philosophies have strong synergies with one another (Astbrink and Beekhuyzen, 2003) and with the integration of both approaches, museums could begin to design, create and evaluate exhibitions that are ultimately valuable to all visitors equally. This reduces the need to provide tailored content to specific audiences and most importantly, create museum experiences where all visitors can enjoy the content exhibition without having to rely on limited, irregular services (Chick, 2017). Utilising both UCD and UD, Chick (2017) presents the co-creation of a multisensory exhibit at the National Centre for Craft and Design (Sleaford) on the theme of 3D printing, where BPS individuals were brought on board to help design the temporary exhibit. This resulted in the creation of an exhibit entitled '3D Printing: The Good, the Bad, and the Beautiful' which incorporated many solutions to assist BPS visitors in navigating around the exhibit. Applications such as this should arguably be the ultimate goal of exhibition design, the integration of accessible solutions into exhibition practice rather than as tacked on additions. Tangible 3D replicas, as evaluated in this thesis, are but one small part of this overriding aim and the proper consideration of both UD and UCD design philosophies could revolutionise the way museum visitors interact with museum content.

8.4 Future Research Approaches

A major focus of this thesis has been on the void of research on 3D Printing and the museum visitor experience within the field of cultural heritage and museology. Despite the research efforts detailed here, this represents only a starting point for research into museum visitor experience with 3D printed replicas. Asking questions only begets more and the studies detailed in this thesis are no exception. As discussed in the relevant discussion sections for each of the main chapters, this work has been primarily exploratory and as a result, many unresolved threads have been brought to attention that are in dire need of resolution. It is these that will now be highlighted in an effort to pave the way forward for future research efforts within this sector in the remainder of the discussion.

8.4.1 General Practice

A prominent issue with the research carried out in this thesis is that the samples used represent a skewed view of the museum audience. These findings represent the views of the visitors to a natural history museum in the south of England, which will inevitably be biased by the world-views of a dominantly white ‘middle-class’ audience. One might expect museum audiences in different parts of the UK, or around the world, to have different preferences and views on 3D printing technology and its potential in the museum space. Naturally, this requires more research projects addressing similar themes presented here in other museums across the country, to confirm or disconfirm by weight of evidence what these ‘best-practices’ actually are.

Similarly for other museum types, concerns raised in Chapter 4 by some participants, these findings may not be so applicable. Is verisimilarity so important in an art gallery, where content is more open for interpretation? Would 3D printed pieces be jarring in a country house museum? For natural history museums or archaeological museums, such replicas could work well because the objects are precious and restricted from handling. For a science museum, where the concepts are abstract and demonstrative, do these prints have value as a tool for exhibitioners? These questions have not yet been addressed in the literature, but are worth further exploring in a similar manner as carried out here. Doing so will highlight the broader potential of the technology and ascertain its effectiveness in other museum settings.

Similarly to above, thie studies in this thesis were typically dominated by families with much smaller representation from other age groups. In chapter 4, responses sampled among all age groups show similar levels of positivity, with the notable exception of a younger participant who did not like the idea of handling 3D printed replicas and simply found them boring. This reflects a need to further explore the needs of younger audiences, particularly as the studies that sampled the general museum audience limited the age of participants to 8. Children naturally have different learning needs due to a far narrower worldview that is only gained through experience, so there is a valid question of whether or not 3D prints are really a beneficial learning mode. As discussed in *5.5.2 Implications for Use in Museums*, young children do have some difficulty in discerning real from unreal, so understanding how children use 3D printed replicas to learn should be essential.

At the other end of the scale is the subject of technology acceptance among older audience groups. Older participants were noticeably lacking from the samples in both of the studies looking at the general museum audience, possibly a sign of a lack of interest in such technologies. Wider sampling is needed to properly corroborate the opinions of these groups in order to ensure that their views have been accurately represented and that the same positivity towards the idea is shared across all visitors, to avoid marginalising whole visitor groups that use museums regularly.

Also in need of further exploration is that of the pedagogical effectiveness of tangible interactions with 3D printed replicas. As discussed in the literature review, object-based learning (OBL) seems to be an effective way of encouraging learning in some settings, but does lack some definitive evidence of success in informal learning environments. 3D printed replicas in the same vein are considered good pedagogical tools but the actual empirical evidence for this is remarkably limited. Thus, further evaluation of learning from tangible 3D printed replicas is mandated.

Another topic of interest, as mentioned above, is that of how 3D prints compare in accuracy and desirability to plaster cast replicas and in terms of their affordability. If existing approaches are effective and fulfil the requirements of being desirable tangible objects while retaining cost-effectiveness, then there is little need to invest in what is arguably an expensive, fast-moving technology. There is a lack of research into this topic which will require significant exploration to ascertain which approach is both preferred by museum visitors, if at all, or which is more cost-effective. As a result, further evaluation of the potential of 3D printing is thus required.

8.4.2 3D Print Creation

First of all, a number of findings need to be corroborated, namely that verisimilitude to the original is indeed the dominant factor in museum visitor preference. This can be further explored by carrying out a study in an ecologically valid environment, namely with museum visitors within the exhibition gallery. This study was strictly limited to an out-of-context, guided questionnaire which may have skewed visitor preferences. Thus, further exploration within a proper museum context could confirm, or disconfirm, the findings of these studies and justify the focus on creating models that are truly verisimilar.

Another interesting topic to pursue would be that of the preferences of younger museum visitors. As discussed above, the minimum age constraint placed upon participants was that of 8. Given the differences in the perception of realism of museum objects changing as a child develops, it would be useful to understand the preferences of younger museum visitors and evaluate how the preferences of younger children differ from that of older children and adults. This is important, as producing prints that are understandable and interpretable by younger visitors will be key to their learning and understanding.

8.4.3 Blind and Partially Sighted Audiences

First and foremost, a further exploration of ways of assisting BPS visitors in their interpretation of objects and measures that can be used in the CAD stage prior to printing and assistive approaches once the piece is installed or ready to be used for tangible interaction. Here, the participants only suggested ways in which they might like the objects to be presented. Therefore empirical testing of such procedures, such as object enlargement of assistive audio description, could be carried out to observe how much such assistive measures enhance the interpretations of BPS visitors.

Next, as specified above, it is worth exploring in greater detail how the choice of material can influence perception and further unpicking the above-noted overlap between object and material interpretations and their integrated nature. Questions such as how the choice of printing material influences the handler’s interpretation of the object, or how objects could be treated so that they appeal to multiple different senses, such as with scent treatments or pure touch applications, compare to unisensory replicas. These are but a few examples of what research questions would be of core interest for further exploration to better understand the nature BPS perception of objects and how museum practitioners can assist their interpretations.

Finally, the needs of the BPS visitors must be addressed as discussed above. It has been ascertained what the standard museum visitor’s preferences towards tangible 3D printed replicas are but how does that of the BPS audience compare? The results of Candlin (2003) certainly suggest that this may be the case, but how verisimilar do prints need to be made? Are surface texture, weight or handling properties more important to BPS visitors or are their other factors at work within their preference of tangible 3D printed replicas? This also begs the questions as to how 3D printing can be used to enhance the understanding and perception of BPS visitors. Would BPS visitors welcome the alteration of objects to aid understanding or should the object be left as intact as possible? These research questions need to be addressed so that the needs of both sighted and partially sighted audiences can be understood, so that a convergent solution can be developed that produces museum experiences that naturally fall in line with principles of inclusive design (Udo and Fels, 2010; Chick, 2017).

9.0 CONCLUSIONS

In conclusion, over the course of this thesis the theme of how museums can better leverage 3D printing technology to engage museum audiences using tangible 3D printed replicas has been explored. This solution could capitalise on the advantages of multisensory interaction on learning and engagement, circumvent curatory restrictions on object handling of rare and precious museum objects and provide engagement opportunities for BPS audiences. Throughout the literature review, these themes were explored in detail and a review of usage of 3D printing in cultural heritage revealed that while many organisation and institutions are indeed utilising these technologies for visitor engagement. The manner in which these are being carried out was deemed to be *ad-hoc* with little introspective evaluation or establishment of best practice for their fabrication. The use of UX methodologies however showed some potential for exploring this lack of research over more traditional museum evaluation approaches.

In order to provide the first essential insights into this relatively underexplored field of research in cultural heritage, a number of key research questions were drawn up:

- How do museum visitors regard 3D printed replicas and how might they influence their expectations of museum content?
- What design considerations need to be taken into account in order to create user-friendly 3D printed replicas for sighted and BPS audiences?
- How can 3D printed replicas benefit museum audiences and enhance their experiences?
- How can tangible 3D printed replicas assist BPS persons in their interpretation and enjoyment of exhibitions?
- What benefits can the replication of museum objects have in wider museum practice?
- Are user experience methodologies applicable and informative in understanding the needs of museum audiences?

These research questions were subsequently explored over the next four chapters. The first concerned the theme of visitor opinions, understanding of 3D printing technology and whether or not it is welcome within the heritage sector. The second explored museum visitor preference for the physical properties of 3D printed replicas. The third concerned BPS perception of objects to inform the design of 3D printed replicas. The final chapter confirmed the further impact that digitization and printing technologies can have on other aspects of museum practice.

9.1 Answering the Research Questions

The major findings of each of these chapters were then summarised with regards to the research questions to draw out the main conclusions:

- *Q1: How do museum visitors regard 3D printed replicas and how might they influence their expectations of museum content?*: Museum visitors enthusiastically responded to the idea of tangible 3D printed replicas and wished to see them in more museums. They thought they would enhance their museum experience, but would not necessarily change their visiting habits. Few museum visitors had ever had exposure to such replicas however and understanding of the technology was poor. Visitors thought that such prints would enable better multisensory interaction, improve learning and enjoyment and allow better appreciation of objects. BPS visitors were also interested in seeing the approach implemented in museums.
- *Q2: What design considerations need to be taken into account in order to create user-friendly 3D printed replicas for sighted and BPS audiences?*: Overall, the most important property identified across the main research chapters was that of verisimilitude, highlighted by participants in chapter 4 and further explored in chapter 5. In chapter 5, verisimilitude was strongly correlated to museum visitor preference, the overall quality of the print also being important to preference while the robustness of the print was of little concern. BPS participants in chapter 6 appeared to rely on multisensory cues to interpret objects, again advocating the importance of verisimilitude to the original in 3D printed replicas but this was not explored in further detail.
- *Q3: How can 3D printed replicas benefit museum audiences and enhance their experiences?*: This question was not properly explored over the course of the thesis beyond a superficial level, other than general comments from sighted participants in chapter 4 and BPS participants in chapter 6 that suggested that they would enjoy handling such replicas.
- *Q4: How can tangible 3D printed replicas assist blind and partially sighted persons in their interpretation and enjoyment of exhibitions?*: Chapter 6 showed that BPS audiences relied on all their senses, with the exception of taste, to interpret natural history objects, mandating the need for olfactory, optical and acoustic properties to be included in tangible 3D printed replicas. Material and object identification was interrelated, with material judgements being more accurate than object judgements. This means that changes to shapes and material choice should be carefully considered. BPS participants did not want the objects to be altered by 3D printing, although assistive solutions presented alongside the object, such as audio description were recommended. The theme of enjoyment, as above was not explored in-depth in this chapter.
- *Q5: What benefits can the replication of museum objects have in wider museum practice?*: In chapter 7, analysis of the conservational history of *Megalosaurus bucklandii* showed that the act of digitizing venerable museum objects can reveal further insights into them that can be informative in wider museum practice, such as conservation and research.

- *Q6: Are user experience methodologies applicable and informative in understanding the needs of museum audiences?*: In chapters 4, 5 and 6, each of these major chapters used UX methodologies to pick apart complex research issues with difficult to resolve design constraints. Forthcoming were many different insights into how museum professionals can design tangible 3D printed replicas around both sighted and BPS audiences, suggesting that UX research methods can indeed be instrumental in solving complex design problems.

Further discussion of the main design considerations emerging from these findings explored the theme of the limitations of 3D printing technology at this juncture, particularly with regards to the limitations in creating both accurate and verisimilar prints and how more accurate solutions typically are burdened with increased operating costs and expertise requirements. Further discussed is how User-Centred Design (UCD) and Universal Design (UD) can benefit wider museum practice and should be incorporated into standard exhibition design practice.

9.2 Best Practices for Fabrication of 3D Printed Replicas for Museum Audiences

Overall from these findings, a number of key considerations that need to be taken into account by museum professionals with regards to utilising, designing and presenting 3D printed replicas to their audiences. These are as follows:

1) Museum visitors are unlikely to have much experience with 3D printing technology or with 3D printed replicas. The onus is on exhibition designers wishing to utilise these replicas to provide sufficient information for visitors to both understand that the replicas are fabricated replicas and how they were created.
2) 3D printed replicas show some potential as tools for enhancing museum experience by enhancing their learning, enjoyment, engagement and allowing greater appreciation of museum objects while helping visitors to achieve their visiting goals. However further exploration is required to confirm whether or not this is truly the case and whether or not these opinions are shared at a more generalizable level.
3) Museum visitors showed a strong preference towards the verisimilitude of 3D printed replicas. This aspect of 3D print creation should be prioritised by museum professionals for creating handling experiences and can be regarded as a ‘one-dimensional requirement’, one that results in increased satisfaction as verisimilitude increases. However, 3D prints typically trade verisimilitude for robustness which must be accounted for when choosing materials. Verisimilarity could be key for creating 3D prints for BPS audiences to ensure multisensory interpretability, but this was not explored in-depth in this thesis.

4) The quality of the prints can be considered a ‘must-be requirement’, one that results in decreased satisfaction if quality is poor but does not increase satisfaction if the base standard is met. Museum professionals need to ensure a base-line of quality is reached, although exactly what this is uncertain at this juncture.
5) Print robustness is an ‘indifferent requirement’, one that has little to no effect on visitor satisfaction. Museum professionals must carefully consider what materials they wish to use and how robust the final print must be, especially as robust prints tend to be less verisimilar.
6) When creating 3D prints for BPS audiences, care should be taken to account for all of the senses. Tactile accuracy is not only key, but also the optical, acoustic and olfactory properties which are utilised by many partially-sighted individuals. All of these factors contribute to a multisensory understanding of the object, especially where sight is diminished or absent.
7) The properties of an object (its shape and features) and its materials (its texture and physicality) are interrelated and affect each other during BPS interpretation with objects. Presenting strange materials or altering geometry could adversely influence a BPS individual’s perception of an object. In particular, the texture, shape, specific features, weight, size, ‘feel’ and optical properties were important characteristics of note, and should be conserved during replica production.
8) Significant alteration to the shape and structure of objects were not desired by BPS participants. Rather, assistive provisions and alterations would be preferred, such as audio description, the addition of features that would add more in-life context to the object, or object scaling. Interpretive dangers are associated with altering the geometry of an object to assist interpretation.

These guidelines do not reflect the be all and end all however. They merely represent the earliest forays into an as yet immature field which requires greater exploration to truly understand how 3D printed replicas impact museum visitor engagement and how museum professionals can best design them to suit. They are likely to shift as new research emerges and therefore cannot be deemed as static.

9.3 Future Research Objectives

Throughout the course of this thesis, a number of potential future research themes were also identified. These represent a variety of topics that both need to be explored to further identify the significance of the results here stated and new threads of potential interest. These are as follows:

- Younger audiences were not explored in-depth as part of this study, and their needs, opinions and preferences should be analysed to better understand a major proportion of the visiting population. Older audiences should also be explored in a similar manner.

- The influence of tangible 3D printed replicas on museum learning should be further explored, to ascertain any further positive impact on practice that could be had when implementing such technologies.
- Comparison to traditional casting methods and which approaches are preferable to museums visitor and how they impact practicality in general museum practice.
- Ecologically valid testing of the preferences found in chapter 5 within a real exhibition setting to confirm the results of the study.
- Empirical testing of assistive technologies and alterations to geometry and their impact on BPS perception of objects. Furthermore, evaluation of their preferences towards materials, particularly if verisimilitude is also favoured by BPS audiences is necessary to align the design of tangible 3D printed replicas to be favourable by both sighted and BPS audiences.
- Exploration of how material choices can influence perception should be further explored in BPS audiences to ascertain how material choice and other properties influence perception of objects.

Thus, it can be concluded that tangible 3D printed replicas could be of great potential use to museum institutions around the world. Much research is yet required however in order to properly identify the best practices for museum professionals to utilise this technology in the competitive and ever-changing realm of cultural heritage. Proper mastery of this cutting edge technology promises to revolutionise wider museum practice and forever change the way that museum visitors, regardless of their life experiences, age or sight condition, interact with and engage with history, art and the forgotten legacy of the world.

10.0 REFERENCE LIST

Abate, RL, Ciavarella, R, Furini, G, Guarnieri, G, Migliori, S and Pierattini, S. 2011. 3D modelling and remote rendering technique of a high definition cultural heritage artefact. *Procedia Computer Science*, 3: 848-852. https://doi.org/10.1016/j.procs.2010.12.139

Abel, RL, Laurinin, CR and Richter, M. 2012. A palaeobiologist's guide to 'virtual' micro-CT preparation. *Palaeontologia Electronica*, 15: 15.26T. https://doi.org/10.26879/284

Abt, J. 2006. The Origins of the Public Museum. In: S MacDonald (ed.). A Companion to Museum Studies. Blackwell Publishing Ltd.: Oxford. 115-134.

Access Economics. 2009. Future sight loss UK (1): The economic impact of partial sight and blindness in the UK adult population. Full Report. RNIB: London.

Alary, F, Duquette, M, Goldstein, R, Chapman, CE, Voss, P, La Buissonnière-Ariza, V and Lepore, F. 2009. Tactile acuity in the blind: A closer look reveals superiority over the sighted in some but not all cutaneous tasks. *Neuropsychologia*, 47: 2037-2043. https://doi.org/10.1016/j.neuropsychologia.2009.03.014

Alemanno, G, Cignoni, P, Pietroni, N, Ponchio, F and Scopigno R. 2014. Interlocking pieces for printing tangible cultural heritage replicas. In: R Klein, P Santos (eds.). Proceedings of the Eurographics Workshop on Graphics and Cultural Heritage. Eurographics Association: Switzerland. 145-154.

AllAboutUX. 2018. All About UX: Information for User Experience Professionals. Available at: https://www.allaboutux.org/. [Last Accessed: 04/03/2019].

Amico, N, Ronzino, P, Vassallo, V, Miltiadous, N, Hermon, S and Niccolucci, F. 2018. Theorizing Authenticity – practicing reality: the 3D replica of the Kazaphani boat. In: PDG Di Franco, F Galeazzi, V Vassallo (eds.) Authenticity and cultural heritage in the age of 3D digital reproductions. University of Cambridge: Cambridge. 111-122.

Anagnostakis, G, Antoniao, M, Kardamitsi, E, Sachinidis, T, Koutsabasis, P, Stavrakis, M, Vosinakis, S and Zissis, D. 2016. Accessible Museum Collections for the Visually Impaired: Combining Tactile Exploration, Audio Descriptions and Mobile Gestures. MobileHCI'16 Adjunct, Florence, Italy, 6th – 9th September, 2016. https://doi.org/10.1145/2957265.2963118

Anastasiadou, C and Vettese, S. 2019. "From souvenirs to 3D Printed souvenirs". Exploring the capabilities of additive manufacturing technologies in (re)-framing tourist souvenirs. *Tourism Management*, 71: 428-442. https://doi.org/10.1016/j.tourman.2018.10.032

Ander, EE, Thomson, LJM, Blair, K, Noble, G, Menon, U, Lanceley, A and Chatterjee, HJ. 2013. Using museum objects to improve wellbeing in mental health service users and neurological rehabilitation clients. *British Journal of Occupational Therapy*, 76: 208-216. https://doi.org/10.4276/030802213X13679275042645

Anderson, D. 1997. A Common Wealth: Museums and Learning in the United Kingdom. A Report to the Department of National Heritage, London.

Anderson, D. 1999. A Common Wealth: Museums in the Learning Age. A Report to the Department for Culture, Media and Sport, London.

Antlej, K, Erič, M, Šavnik, M, Županek, B, Slabe, J and Battestin, B. 2011. Combining 3D technologies in the field of cultural heritage: three case studies. In: M Dellepiane, F Niccolucci, S Pena Serna, H Rushmeier, L van Fool (eds.) VAST: International Symposium on Virtual Reality, Archaeology and Intelligent Cultural Heritage – Short and Project Papers. Eurographics Association: Pisa. 1-4.

Arias, P, Herráez, J, Lorenzo, H and Ordóñez, C. 2005. Control of structural problems in cultural heritage monuments using close-range photogrammetry and computer methods. *Computers and Structures*, 83: 1754-1766. https://doi.org/10.1016/j.compstruc.2005.02.018

Argyropoulos, VS and Kanari, C. 2015. Re-imagining the museum through 'touch': Reflections of individuals with visual disability on their experience of museum-visiting in Greece. *ALTER, European Journal of Disability Research*, 9: 130-143. https://doi.org/10.1016/j.alter.2014.12.005

Astbrink, G and Beekhuyzen, J. 2003. The Synergies between Universal Design and User-Centred Design. 10th International Conference on Human-Computer Interaction. Crete, Greece, 22-27 June, 2003.

Aze, S, Vallet, JM, Detalle, V, Grauby, O and Baronnet, A. 2008. Chromatic alterations of red lead pigments in artworks: a review. *Phase Transitions*, 81: 145-154. https://doi.org/10.1080/01411590701514326

Bacci, F and Pavani, F. 2014. "First Hand," not "First Eye" Knowledge: Bodily Experience in Museums. In: N Levent, A Pascual-Leone (eds.). The Multisensory Museum: Cross-disciplinary Perspectives on Touch, Sound, Smell, Memory and Space. Rowman and Littlefield: Plymouth. 17-28.

Badde, A and Illerhaus, B. 2008. Three Dimensional Computerised Microtomography in the Analysis of Sculpture. *Scanning*, 30: 16-26. https://doi.org/10.1002/sca.20080

Bain, R and Ellenbogen, KM. 2002. Placing Objects Within Disciplinary Perspectives: Examples from History and Science. In: SG Paris (ed.). Perspectives on Object-Centered Learning in Museums. Lawrence Erlbaum Associates: London. 153-170.

Baker, J. 2015. Anarchical Artifacts: Museums as Sites for Radical Otherness. In: A Witcomb, K Message (eds.). The International Handbook of Museum Studies: Museum Theory. John Wiley & Sons: Chichester. 63-78. https://doi.org/10.1002/9781118829059.wbihms104

Ballarin, M, Balletti, C and Vernier, P. 2018. Replicas in Cultural Heritage: 3D Printing and the Museum Experience. In: F Remondino, I Toschi, T Fuse (eds.). ISPRS TC II Mid-term Symposium 'Towards Photogrammetry 2020, Volume XLII-2. ISPRS: Hannover. 55-62. https://doi.org/10.5194/isprs-archives-XLII-2-55-2018

Balletti, C, Ballarin, M and Guerra, F. 2017. 3D printing: State of the art and future perspectives. *Journal of Cultural Heritage*, 26: 172-182. https://doi.org/10.1016/j.culher.2017.02.010

Barker, CT, Naish, D, Newham, E, Katsamenis, OL and Dyke G. 2017. Complex neuroanatomy in the rostrum of the Isle of Wight theropod *Neovenator salerii*. *Nature: Science Reports*, 7: 3749.

Bartlett, MS. 1954. A note on the multiplying factors for various chi square approximation. *Journal of Royal Statistical Society*, 16: 296-298. https://doi.org/10.1038/s41598-017-03671-3

Baumgartner, E, Wiebel, CB and Gegenfurtner, KR. 2015. A comparison of haptic material perception in blind and sighted individuals. *Vision Research*, 115: 238-245. https://doi.org/10.1016/j.visres.2015.02.006

Bearman, D. 2011. 3D Representations in Museums. *Curator: The Museum Journal*, 54: 55-61. https://doi.org/10.1111/j.2151-6952.2010.00066.x

Belz, A and Kow, E. 2011. Discrete vs. Continuous Rating Scales for Language Evaluation in NLP. In: D Lin (ed.). Proceedings of the 49th Annual Meeting of the Association for Computational Linguistics Vol 2. Association for Computational Linguistics: Pennsylvania. 230-235.

Benson, RBJ, Barrett, PM, Powell, HP, Norman, DB. 2008. The taxonomic status of *Megalosaurus bucklandii* (Dinosauria, Theropoda) from the Middle Jurassic of Oxfordshire, UK. *Palaeontology*, 51: 419-424. https://doi.org/10.1111/j.1475-4983.2008.00751.x

Benson, RBJ. 2010. A description of *Megalosaurus bucklandii* (Dinosauria: Theropoda) from the Bathonian of the UK and the relationships of Middle Jurassic theropods. *Zoological Journal of the Linnean Society*, 158: 882-935. https://doi.org/10.1111/j.1096-3642.2009.00569.x

Bernhaupt, R. 2010. Evaluating User Experience in Games: Concepts as Methods. Springer: Switzerland. https://doi.org/10.1007/978-1-84882-963-3

Bettuzi, M, Casali, F, Morigi, MP, Brancaccio, R, Carson, D, Chiari, G, Maish, J. 2015. Computed tomography of a medium size Roman bronze statue of Cupid. *Applied Physics A: Materials Science & Processing*, 118: 1161-1169. https://doi.org/10.1007/s00339-014-8799-z

Bieber, R and Rae, J. 2013. From the Mind's Eye: Museum and Art Gallery Appreciation for the Blind – Canadian Perspectives. *Disability Studies Quarterly*, 33: 31-31. https://doi.org/10.18061/dsq.v33i3.3754

Bitgood, S and Loomis, RJ. 2012. Chan Screven's Contributions to Visitor Studies. *Curator: the Museum Journal*, 55: 107-111. https://doi.org/10.1111/j.2151-6952.2012.00133.x

Bohn, JW. 1999. Museums and the Culture of Autograph. *The Journal of Aesthetics and Art Criticism*, 57: 55-65. https://doi.org/10.2307/432064

Boodle, C. 1992. A New Decade: Museums and Education in the 1990's. National Heritage. London.

Bose, S, Vahabzadeh, S and Badyopadhyay, A. 2013. Bone tissue engineering using 3D printing. *Materials Today*, 16: 496-504. https://doi.org/10.1016/j.mattod.2013.11.017

Bourne, RRA, Stevens, GA, White, RA, Smith, JL, Flaxman, SR, Price, H, Jonas, JB, Keeffe, J, Leasher, J, Naidoo, K, Pesidovs, K, Resnikoff, S and Taylor, HR. 2013. Causes of vision loss worldwide, 1990-2010: a systematic analysis. *The Lancet Global Health*, 1: e339-349. https://doi.org/10.1016/S2214-109X(13)70113-X

Bringolf, J. 2008. Universal Design: Is it Accessible? *Multi: The RIT Journal of Plurality and Diversity in Design*, 1: 45-52.

Buckland, W. 1824. Notice on the *Megalosaurus* or great fossil lizard of Stonesfield. *Transactions of the Geological Society of London*, 21: 390-397. https://doi.org/10.1144/transgslb.1.2.390

Buckland, W. 1836. Geology and Mineralogy Considered with Reference to Natural Theology. Vol. II. William Pickering: London. https://doi.org/10.5962/bhl.title.125523

Bukreeva, I, Mittone, A, Bravin, A Festa, G, Alessandrelli, M, Coan, P, Formoso, V, Agostino, RG, Giocondo, M, Ciuchi, F, Fratini, M, Massimi, L, Lamarra, A, Andreani, C, Bartolino, R, Gigli, G, Ranocchia, G, and Cedola A. 2015. Virtual unrolling and deciphering of Herculaneum papyri by X-ray phase-contrast tomography. *Nature: Scientific Reports*, 6: 27227. https://doi.org/10.1038/srep30364

Bunce, L. 2016. Dead Ringer? Visitors' Understanding of Taxidermy as Authentic and Educational Museum Exhibits. *Visitor Studies*, 19: 178-192. https://doi.org/10.1080/10645578.2016.1220189

Bunce, L and Harris, M. 2013. 'He hasn't got the real toolkit!' Young children's reasoning about real/not-real status. *Developmental Psychology*, 49: 1494-1504. https://doi.org/10.1037/a0030608

Burgio, L, Melchar, D, Strekopytov, S, Peggie, DA, Di Crescemzo, MM, Keneghan, B, Najorka, J, Goral, T, Garbout, A and Clark, BL. 2018. Identification, characterisation and mapping of calomel as 'mercury white', a previously undocumented pigment from South America, and its use on a *barniz de Pasto* cabinet at the Victoria and Albert Museum. *Microchemical Journal*, 143: 220-227. https://doi.org/10.1016/j.microc.2018.08.010

Callieri, M, Pingi, P, Potenziani, M, Dellepiane, M, Pavoni, G, Lureau, M and Scopigno, R. 2015. Alchemy in 3D: A Digitization for a Journey through Matter. In: NJ Piscataway (ed.). Proceedings of 2015 Digital Heritage International Congress – Vol. 1. IEEE: Granada. 223-231. https://doi.org/10.1109/DigitalHeritage.2015.7413875

Candlin, F. 2003. Blindness, Art and Exclusion in Museums and Galleries. *The International Journal of Art and Design Education*, 22: 100-110. https://doi.org/10.1111/1468-5949.00343

Candlin, F. 2006. The Dubious Inheritance of Touch: Art History and Museum Access. *Journal of Visual Culture*, 5: 137-154. https://doi.org/10.1177/1470412906066906

Candlin, F. 2008. Don't Touch, Hands Off! Art, Blindness, and the Conservation of Expertise. In: E Pye (ed.). The Power of Touch: Handling Objects in Museum and Heritage Contexts. Left Coast Press: Walnut Creek. 89-106.

Candlin, F. 2010. Art, Museums and Touch. Manchester University Press: Manchester.

Candlin, F. 2017. Rehabilitating unauthorised touch or why museum visitors touch the exhibits. *The Senses and Society*, 12: 251-266. https://doi.org/10.1080/17458927.2017.1367485

Cantoni, V, Lombardi, L, Porta, M and Setti, A. 2016. Interactive, Tangible and Multi-sensory Technology for a Cultural Heritage Exhibition: The Battle of Pavia. In: S Margenov, G Angelova, G Agre (eds.). Innovative Approaches and Solutions in Advanced Intelligent Systems. Springer International: Switzerland. 77-94. https://doi.org/10.1007/978-3-319-32207-0_6

Capurro, C, Mollet, D and Pletincx, D. 2015. Tangible interfaces for digital museum applications: The Virtex and Virtex Light systems in the Keys to Rome exhibition. In: NJ Piscataway (ed.). Proceedings of 2015 Digital Heritage International Congress – Vol. 1. IEEE: Granada. 271-276. https://doi.org/10.1109/DigitalHeritage.2015.7413881

Carr, TD, Varricchio, DJ, Sedlmayr, JC, Roberts, EM, Moore, JR. 2017. A new tyrannosaur with evidence for anagenesis and crocodile-like facial sensory system. *Nature: Scientific Reports*, 7: 44942. https://doi.org/10.1038/srep44942

Cassim, J. 2008. The Touch Experience in Museums in the UK and Japan. In: E Pye (ed.). The Power of Touch: Handling Objects in Museum and Heritage Contexts. Left Coast Press: Walnut Creek. 163-182.

Catell, RB. 1966. The Scree Test for the Number of Factors. *Multivariate Behavioural Research*, 1: 245-2786. https://doi.org/10.1207/s15327906mbr0102_10

Celani, G and Piccoli, V. 2010. The roles of a model. *Arquiteturarevista*, 6: 50-62. https://doi.org/10.4013/arq.2010.61.05

Celani, G, Pupo, R and Piccoli, V. 2008. Digital fabrication and art-exhibition design: a case study. In: J Al-Qawasmi, MA Chiuini, S El-Hakim (eds.). Digital Media and its Applications in Cultural Heritage. CSAAR Press: Jordan. 413-429.

Ch'ng, E, Lewis, A, Gelhken, RE and Woolley, SI. 2013. A Theoretical Framework for Stigmergetic Reconstruction of Ancient Text. In: E Ch'ng, V Gaffney, H Chapman (eds.). Visual heritage in the Digital Age. Springer-Verlag: London. 43-66. https://doi.org/10.1007/978-1-4471-5535-5_4

Chapman, H, Baldwin, E, Moulden, H, Lobb, M. 2013. More Than Just a Sum of the Points: Re-Thinking the Value of Laser Scanning Data. In: E Ch'ng, V Gaffney, Chapman (eds.). Visual Heritage in the Digital Age. Springer: London. 15-32. https://doi.org/10.1007/978-1-4471-5535-5_2

Chatterjee, HJ 2008. Touch in Museums: Policy and Practice in Object Handling. Berg: Oxford.

Chatterjee, HJ. 2009. Staying Essential: Articulating the Value of Object Based Learning. In: S MacDonald, N Nyst, C Weber (eds.). Proceedings of the 9th Conference of the International Committee of ICOM for University Museums and Collections (UMAC), Berkeley, USA. ICOM: Berlin.

Chatterjee, HJ. 2010. Object-based learning in higher education: The pedagogical power of museums. *University Museums and Collection Journal*, 3, 179-181.

Chatterjee, HJ and Hannan, L. 2015. Engaging the Senses: Object-Based Learning in Higher Education. Ashgate Publishing: Surrey. https://doi.org/10.4324/9781315579641

Chen, G, Chen, C, Yu, Z, Yin, H, He, L and Yuan, J. 2016. Color 3D Printing: Theory, Method, and Application. *IntechOpen*, doi: 10.5772/63944. https://doi.org/10.5772/63944

Chick, A. 2017. Co-creating an accessible, Multisensory Exhibition with the National Centre for Craft & Design and Blind and Partially Sighted Participants. In: REDO: 2017 Cumulus International Conference. Kolding, Denmark, 30 May-2 June, 2017.

Christidou, D and Pierroux, P. 2018. Art, touch and meaning making: an analysis of multisensory interpretation in the museum. *Museum Management and Curatorship*, doi: 10.1080/09647775.2018.1516561. https://doi.org/10.1080/09647775.2018.1516561

Chu, HJ and Mazaleki, A. 2019. Embodied Engagement with Narrative: A Design Framework for Presenting Cultural Heritage Artifacts. *Multimodal Technologies and Interaction*, 3, doi: 10.3390/mti3010001. https://doi.org/10.3390/mti3010001

Chua, CK and Leong, KF. 2017. 3D Printing and Additive Manufacturing: Principles and Applications. World Scientific Publishing: Singapore. 5th Edition. https://doi.org/10.1142/10200

Claisse, C, Petrelli, D, Dulake, N, Marshall, M and Ciolfi, L. 2016. Multisensory interactive storytelling to augment the visit of a historical house museum. DigitalHeritage2018. New Realities: Authenticity & Automation in the Digital Age. 3rd International Congress and Expo. San Francisco, USA, 26-30 Oct, 2018.

Classen, C and Howes, D. 2006. The Museum as Sensecape: Western Sensibilities and Indigenous Artifacts. In: E Edwards, C Gosden, RB Phillips (eds.). Sensible objects: Colonialism, Museums and Material Culture. Berg: Oxford: 199-222.

Cnudde, V, Dubruel, P, de Winne, K, de Witte, I, Massschaele, B, Jacobs, P, Schacht, E. 2009. The use of X-ray tomography in the study of water repellents and consolidants. *Engineering Geology*, 103: 84-92. https://doi.org/10.1016/j.enggeo.2008.06.013

Consumer Reports. 2012. Why the MyFord Touch Control System stinks. Available at: https://www.consumerreports.org/cro/news/2012/08/why-the-myford-touch-control-system-stinks/index.htm. [Last Accessed: 04/03/2019].

Copley, DC, Eberhard, JW and Mohr, GA. 1994. Computed Tomography Part 1: Introduction and Industrial Applications. *The Journal of the Minerals, Metals and Materials Society*, 1: 14-26. https://doi.org/10.1016/0963-8695(94)90319-0

Creswell, JW. 2013. Qualitative Inquiry and Research Design. Sage: California. 3rd Edition.

Creswell, JW. 2014. Research Design: Qualitative, Quantitative and Mixed-methods Approaches. Sage: California. 4th Edition.

Creswell, JW and Plano Clark, VL. 2018. Designing and Conducting Mixed-methods Research. Sage: California. 3nd Edition.

D'Agnano, D, Balletti, C, Guerra, F and Vernier, P. 2015. Tooteko: a case study of augmented reality for an accessible cultural heritage. Digitization, 3D Printing and Sensors for an Audio-Tactile Experience. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, XL-5/W4: 207-213. https://doi.org/10.5194/isprsarchives-XL-5-W4-207-2015

D'Emic, MD, Whitlock, JA, Smith, KM, Fisher, DC, Wilson, JA. 2013. Evolution of High Tooth Replacement Rates in Sauropod Dinosaurs. *Proceedings of the National Academy of Sciences*, 110: 8775-8776.

Dalton, R. 2000. Fake bird fossil highlights the problem of illegal trading. *Nature*, 404: 696. https://doi.org/10.1038/35008237

Damala, A, van der Vaart, M, Clarke, L, Hornecker, E, Avram, G, Kockelkorn, H and Ruthven, I. 2016. Evaluating tangible and multisensory museum visiting experiences: Lessons learned from the meSch project. MW2016: Museums and the Web 2016. Los Angeles, California, 6 -9 April, 2016.

Davidson, B, Heald, CL and Hein, GE. 1999. Increased exhibit accessibility through multisensory interaction. In: E Hooper-Greenhill (ed.). The Educational Role of the Museum. Routledge: London. 223-238. 2nd Edition.

Davies, M and Heath, C. 2013. Evaluating Evaluation: Increasing the Impact of Summative Evaluation in Museums and Galleries. Available at: http://visitors.org.uk/wp-content/uploads/2004/01/EvaluatingEvaluation_November2013.pdf [Last Accessed: 16/02/2018].

Davies, M and Heath, C. 2014. "Good" organizational reasons for "ineffectual" research: Evaluating summative evaluation of museums and galleries. *Cultural Trends*, 23: 57-69. https://doi.org/10.1080/09548963.2014.862002

DDA. 1995. Disability Discrimination Act: 1995. UK Government. Available at: http://www.legislation.gov.uk/ukpga/1995/50/pdfs/ukpga_19950050_en.pdf [Last Accessed: 24/7/2018].

De Chiffre, L, Carmingnato, S, Kruth, JP, Schmitt, R and Weckenmann, A. 2014. Industrial application of computed tomography. *CIRP Annals – Manufacturing Technology*, 63: 655-677. https://doi.org/10.1016/j.cirp.2014.05.011

de Kock, T, Dewanckele, J, Boone, M, Vincze, L, Fronteau, G and Van Hoorebeke, L. 2012. Multidisciplinary characterization of gypsum crust on Lede stone (Belgium). 12th International Congress on the Deterioration and Conservation of Stone. Columbia University, New York, 21-25 Oct, 2012.

Dewanckele, J, Cnudde, V, Boone, M, Van Loo, D, De Witte, Y, Pieters, K, Vlassenbroeck, J, Dierick, M, Masschaele, B, Van Hoorebeke, L and Jacobs, P. 2009. Integration of X-ray microtomography and fluorescence for applications on natural building stones. *Journal of Physics: Conference Series*, 186: 012082. https://doi.org/10.1088/1742-6596/186/1/012082

Dewanckele, J, de Kock, T, Fronteau, G, Derluyn, H, Vontobel, P, Dierick, M, van Hoorebeke, L, Jacobs, P, Cnudde, V. 2014. Neutron radiography and X-ray computed tomography for quantifying weathering and water uptake processed inside porous limestone used as building material. *Materials Characterisation*, 88: 86-99. https://doi.org/10.1016/j.matchar.2013.12.007

Diamond, J, Horn, M, Uttal, DH. 2016. Practical Evaluation Guide: Tools for Museums and Other Informal Educational Settings. Rowman and Littlefield: Maryland.

Dickson, J and Albaum, G. 1977. A Method for Developing Tailor-made Semantic Differentials for Specific Marketing Content Areas. *Journal of Marketing Research*, 14: 87-91. https://doi.org/10.1177/002224377701400110

Di Franco, PDG, Camporesi, C, Galeazzi, F and Kallmann, M. 2015. 3D Printing and Immersive Visualization for Improved Perception of Ancient Artifacts. *Presence*, 24: 243-264. https://doi.org/10.1162/PRES_a_00229

Di Franco, PDG, Matthews, JL and Matlock, T. 2016. Framing the past: How virtual experience affects bodily description of artefacts. *Journal of Cultural Heritage*, 17: 179-187. https://doi.org/10.1016/j.culher.2015.04.006

Dillon, J, DeWitt, J, Pegram, E, Irwin, B, Crowley, K, Haydon, R, King, H, Knutson, K, Veall, D and Xanthoudaki, M. 2016. A Learning Research Agenda for Natural History Institutions. Natural History Museum: London.

Dima, M, Hurcombe, L and Wright, M. 2014. Touching the past: Haptic Augmented Reality for Museum Artefacts. In: R Shumaker, S Lackey (eds.). Virtual, Augmented and Mixed Reality. Applications of Virtual and Augmented Reality VAMR 2014. Lecture Notes in Computer Science. Springer: Cham. 3-14. https://doi.org/10.1007/978-3-319-07464-1_1

Dineley, D and Metcalf, S. 1999. Fossil Fishes of Great Britain. Geological Conservation Review Series No. 16. Joint Nature Conservation Committee: Peterborough.

Ding, Z and Ng, F. 2008. A new way of developing semantic differential scales with personal construct theory. *Construction Management and Economics*, 26: 1213-1226. https://doi.org/10.1080/01446190802527522

Dudley, SH. 2010a. Museum Materialities: Objects, Engagements, Interpretations. Routledge: Oxon.

Dudley, SH. 2010b. Museum Materialities: Objects, Sense and Feeling. In: SH Dudley (ed.). Museum Materialities: Objects, Engagements, Interpretations. Routledge: Oxon.

Dudley, SH. 2012a. Materiality Matters: Experiencing the displayed Object. *UM Working Papers in Museum Studies*, 8, Available at: https://deepblue.lib.umich.edu/handle/2027.42/102520. [Last Accessed: 25/07/2018].

Dudley, S.H. 2012b. Museum Objects: Experiencing the Properties of Things. Routledge: London.

Dudley, SH. 2015. What, or Where, Is the (Museum) Object?: Colonial Encounters in Displayed Worlds of Things. In: A Witcomb, K Message (eds.). The International Handbook of Museum Studies: Museum Theory. John Wiley & Sons: Chichester. 41-62. https://doi.org/10.1002/9781118829059.wbihms991

Duhs, R. 2010. Learning from university museums and collection in higher education: University College London (UCL). *University Museums and Collection Journal*, 3: 179-181.

Du Plessis, A, Slabbert, R, Swanepoel, LC, Els, J, Booysen, GJ, Ikram, S and Cornelius, I. 2015. Three-dimensional model of an ancient Egyptian falcon mummy skeleton. *Rapid Prototyping Journal*, 21: 368-372. https://doi.org/10.1108/RPJ-09-2013-0089

Eardley, AF, Mineiro, C, Neves, J and Ride, P. 2016. Redefining Access: Embracing multimodality, memorability and shared experience in Museums. *Curator: The Museum Journal*, 59: 263-286. https://doi.org/10.1111/cura.12163

Eardley, AF, Fryer, L, Hutchinson, R, Cock, M, Ride, P, Neves, J. 2017. Enriched Audio Description: Working Towards and Inclusive Museum Experience. In: S Halder, LC Assaf (eds.). Inclusion, Disability and Culture, Inclusive Learning and Educational Equity. Berlin/Heidelberg: Springer. https://doi.org/10.1007/978-3-319-55224-8_13

Eardley, AF, Dobbin, C, Neves, J and Ride, P. 2018. Hand-On, Shoes-Off: Multisensory tools enhance family Engagement Within and Art Museum. *Visitor Studies*, 21: 79-97. https://doi.org/10.1080/10645578.2018.1503873

Eccles, DW and Arsal, G. 2017. The think aloud method: what is it and how do I use it? *Qualitative Research in Sport, Exercise and Health*, 9: 514-531. https://doi.org/10.1080/2159676X.2017.1331501

English Heritage. 2011. 3D Laser Scanning for Heritage: Advice and guidance to users on laser scanning in archaeology and architecture. English Heritage: Swindon. 2nd Edition.

Equality Act. 2010. Equality Act: 2010. UK Government. Available at: https://www.legislation.gov.uk/ukpga/2010/15/pdfs/ukpga_20100015_en.pdf [Last Accessed: 24/7/2018].

Erickson, GM. 1996. Incremental lines of von Ebner in dinosaurs and the assessment of tooth replacement rates using growth line counts. *Proceedings of the National Academy of Sciences,* 93: 14623-14627. https://doi.org/10.1073/pnas.93.25.14623

Erickson, GM, Zelenitsky, DK, Kay, DI and Norell, MA. 2017. Dinosaur incubation periods directly determined from growth-line counts in embryonic teeth show reptilian-grade development. *Proceedings of the National Academy of Sciences,* 114: 540-545. https://doi.org/10.1073/pnas.1613716114

Etzi, R, Spence, C and Gallace, A. 2014. Textures that we like to touch: An experimental study of aesthetic preferences for tactile stimuli. *Consciousness and Cognition*, 29: 178-188. https://doi.org/10.1016/j.concog.2014.08.011

Evans, EM. 2002. The Authentic Object? A Child's-Eye View. In: SG Paris (ed.). Perspectives on Object-Centered Learning in Museums. Lawrence Erlbaum Associates: London. 55-78.

Falk, JH and Dierking, LD. 1992. The Museum Experience. Whalesback Books: Washington DC.

Falk, JH and Dierking, LD. 2000. Learning from Museums: Visitor experiences and the Making of Meaning. Altamira Press: Plymouth.

Falk, JH and Dierking, LD. 2012. The Museum Experience Revisited. Routledge: Oxon.

Falk, JH, Scott, C, Dierking, L, Rennie, L and Jones, MC. 2004. Interactives and Visitor Learning. *Curator: The Museum Journal*, 47: 171-198. https://doi.org/10.1111/j.2151-6952.2004.tb00116.x

Feilzer, M. 2009. Doing Mixed-methods Research Pragmatically: Implications for the Rediscover of Pragmatism as a Research Paradigm. *Journal of Mixed-methods Research*, 4: 1-11. https://doi.org/10.1177/1558689809349691

Feldkamp, LA, Davis, LC and Kress, KW. 1984. Practical cone-beam algorithm. *Journal of the Optical Society of America A*, 1: 612-619. https://doi.org/10.1364/JOSAA.1.000612

Feng, GC. 2015. Mistakes and how to avoid mistakes in using Intercoder reliability indices. *Methodology: European Journal of Research Methods for the Behavioural and Social Sciences,* 11: 11-22. https://doi.org/10.1027/1614-2241/a000086

Field, A, and Miles, J and Field, Z. 2012. Discovering Statistics using R. Sage: California.

Findlen, P. 2004. The Museum: Its Classical Etymology and Renaissance Genealogy. In: B Carbonell (ed.). Museum Studies: An Anthology of Contexts. Blackwell Publishing: Oxford. 23-50.

Flay, N and Leach, RK. 2012. Application of the optical transfer function in X-ray computed tomography –a review. NPL Report ENG 41. Queen's Printer and Controller: Teddington.

Freelon, D. 2013. ReCal OIR: Ordinal, Interval, and ratio Intercoder reliability as a web service. *International Journal of Internet Science*, 8: 10-16.

Funke, F. 2012. Why semantic differentials in web-based research should be made from visual analogue scales and not from 5 point scales. *Field Methods*, 24: 310-327. https://doi.org/10.1177/1525822X12444061

Furferi, R, Governi, L, Vanni, N and Volpe, Y. 2014. Tactile 3D Bas-relief from Single-point Perspective Paintings: A Computer Based Method. *Journal of Information & Computational Science*, 11: 5667-5680. https://doi.org/10.12733/jics20104135

Gallace, A and Spence, C. 2014. In touch with the future: The sense of touch from cognitive neuroscience to virtual reality. Oxford University Press: Oxford. https://doi.org/10.1093/acprof:oso/9780199644469.001.0001

Galeazzo, L. 2017. Mapping change and motion in the Lagoon: The Island of San Secondo. In: KL Huffman, A Giordano (eds.). Visualizing Venice: Mapping and Modeling Time and Change in a City. Routledge: Oxon. 43-50. https://doi.org/10.4324/9781315100685-7

Garrett, JJ. 2010. The Elements of User Experience: User-Centred Design for the Web and Beyond. New Riders: California. 2nd Edition.

Gaskell, I. 2015. The Life of Things. In: M Hennig (ed.). The International Handbooks of Museum Studies: Museum Media. John Wiley and Sons: Chichester. 167-190. https://doi.org/10.1002/9781118829059.wbihms308

Gerber, LC, Kim, H and Riedel-Kruse, IH. 2015. Microfluidic assembly kit based on laser-cut building blocks for education and fast prototyping. *Biomicrofluidics*, 9: 064105. https://doi.org/10.1063/1.4935593

Gibson, I, Rosen, D and Stucker, B. 2015. Additive Manufacturing Technologies: 3D Printing, Rapid Prototyping, and Direct Digital Manufacturing. New York: Springer. https://doi.org/10.1007/978-1-4939-2113-3

Gibson, A, Piquette, KE, Bergman, U, Christens-Barry, W, Davis, G and Endrizzi, M. 2018. An assessment of multimodal imaging of subsurface text in mummy cartonnage using surrogate papyrus phantoms. *Heritage Science*, 6: 7. https://doi.org/10.1186/s40494-018-0175-4

Gilman, BI. 1916. Museum Fatigue. *Scientific Monthly*, 12: 62-74.

Gkouskos, D and Chen, F. 2012. The use of affective interaction design in car user interfaces. Work: 41: 5057-5061.

Gkouskos, D, Pettersson, I, Karlsson, M and Chen, F. 2015. Exploring User Experience in the Wild: Facets of the Modern Car. In: A Marcus (ed.). DUXU 2015: Design, User Experience, and Usability: Interactive Experience Design. Springer: Switzerland. 450-461. https://doi.org/10.1007/978-3-319-20889-3_42

Golding, V. 2010. Dreams and Wishes: The multi-sensory museum space. In: SH Dudley (ed.). Museum Materialities: Objects, Engagements, Interpretations. Routledge: Oxon. 224-240.

Goldman, LW. 2007. Principles of CT and CT Technology. *Journal of Nuclear Medicine Technology*, 35: 115-128. https://doi.org/10.2967/jnmt.107.042978

Gómez-Corona, C, Chollet, S, Escalona-Buendia, HB and Valentin, D. 2017. Measuring the drinking experience of beer in real context situations. The impact of affects, senses, and cognition. *Food Quality and Preference*, 60: 113-122. https://doi.org/10.1016/j.foodqual.2017.04.002

Goodwin, MB and Chaney DS. 1995. Molding, Casting, and Painting: Molding and casting: techniques and materials. In: P Leiggi, P May (eds.). Vertebrate Paleontological Techniques. Cambridge University Press: Cambridge. 235-284.

Götzelmann, T. 2017. 3D-Druck für blinde Menschen. *Informatik Spektrum*, 40: 511-515. https://doi.org/10.1007/s00287-017-1068-8

Grant, AC, Thiagarajah, MC and Sathian, K. 2000. Tactile perception in blind braille readers: A psychophysical study of acuity and hyperacuity using gratings and dot patterns. *Perception and Psychophysics*, 62: 301-312. https://doi.org/10.3758/BF03205550

Greenop, K and Landorf, C. 2017. Grave-to-cradle: a paradigm shift for heritage conservation and interpretation in the era of 3D laser scanning. *Historic Environment*, 29: 45-55.

Grill-Spector, K, Kourtzi, Z and Kanwisher, N. 2001. The alteral occipital complex and its role in object recognition. *Vision Research*, 41: 1409-1422. https://doi.org/10.1016/S0042-6989(01)00073-6

Guarini, BF. 2015. Beyond Braille on Toilet Doors: Museum Curators and Audiences with Vision Impairment. *M/C Journal*, 18: 1.

Guba, GG and Lincoln, YS. 2005. Paradigmatic Controversies, Contradictions, and Emerging Confluences. In: NK Denzin, YS Lincoln (eds.). The Sage Handbook of Qualitative Research. Sage: California. 191-215. 3rd Edition.

Gupta, R, Balakrishnan, M and Rao, PVM. 2017. Tactile diagrams for the visually impaired. *IEEE Potentials*, 36: 14-18. https://doi.org/10.1109/MPOT.2016.2614754

Haddad, NA. 2012. Educational Multimedia Entertainement (EME) and Childhood Heritage Awareness. Proceedings of the 1st International Conference on Best Practices in World Heritage: Archaeology. Menorca, Spain, 9-13th April, 2012.

Hadi, NU, Abdullah, N. and Sentosa, I. 2016. An Easy Approach to Exploratory Factor Analysis: Marketing Perspective. *Journal of Educational and Social Research*, 6: 215-223.

Hampp, C and Schwan, S. 2015. The Role of Authentic Objects in Museums of the History of Science and Technology: Findings from a visitor study. *International Journal of Science Education Part B,* 5: 161-181. https://doi.org/10.1080/21548455.2013.875238

Hancock, M. 2015. Museums and 3D Printing: More Than a Workshop Novelty, Connecting to Collections and the Classroom. *Bulletin of the Association for Information Science and Technology*, 42: 32-35.

Haneca, K, Deforce, K, Boone, MN, van Loo, D, Dierick, M, van Acker, J and Van den Bulcke, J. 2012. X-ray sub-micron tomography as a tool for the study of archaeological wood preserved through the corrosion of metal objects. *Archaeometry*, 54: 893-905. https://doi.org/10.1111/j.1475-4754.2011.00640.x

Hardie, K. 2015. Engaging Learners through Engaging Designs that Enrich and Energise Learning and Teaching. In: HJ Chatterjee, L Hannan (eds.) Engaging the Senses: Object-Based Learning in Higher Education. Ashgate Publishing: Surrey. 21-42.

Hassenzahl, M. 2003. The Thing and I: Understanding the Relationship between User and Product. In: MA Blythe, AF Monk, K Overbeek, PC Wright (eds.). Funology: From Usability to Enjoyment. Kluwer Academic Publishers: Netherlands. 31-42. https://doi.org/10.1007/1-4020-2967-5_4

Hassenzahl, M and Tractinsky, N. 2006. User Experience – a Research Agenda. *Behaviour & Information Technology*. 25: 91-97. https://doi.org/10.1080/01449290500330331

Hassenzahl, M, Law, ELC and Hvannberg, ET. 2006. User Experience – Towards a unified view. In: ELC Law, EB Hvannberg, M Hassenzahl (eds.). User Experience Towards a unified view. European Cooperation in the field of Scientific and Technical Research: Belgium. 1-3.

Hassenzahl, M. 2008. User Experience (UX): Towards an experiential perspective on product quality. In: E Brangier, G Michel, JMC Bastien, N Carbonell (eds.). IHM ’08 Proceedings of the 20th Conference on l’Interaction Homme-Machine. ACM: New York. 11-15. https://doi.org/10.1145/1512714.1512717

Harley, D, McBride, M, Chu, JH, Kwan, J, Nolan, J and Mazalek, A. 2016. Sensing Context: Reflexive design principles for the intersensory museums interactions. Available at: https://mw2016.museumsandtheweb.com/paper/sensing-context-reflexive-design-principles-for-inter-sensory-museum-interactions/. [Last Accessed: 07/01/2019].

Harvey, ML, Loomis, RJ, Bell, PA, Marino, M. 1998. The Influence of Museum Exhibit Design on Immersion and Psychological Flow. *Environment and Behaviour,* 30: 601-627. https://doi.org/10.1177/001391659803000502

Hegna, TA and Johnson, RE. 2016. Preparation of Fossil and Osteological 3D-Printable Models form Freely Available CT-Scan Movies. *Journal of Paleontological Techniques*, 16: 1-10.

Hein, GE. 1998. Learning in the Museum. Routledge, London.

Hess, M and Robson, S. 2013. Re-engineering Watt: a case study and best practice recommendations for 3D colour laser scans and 3D printing in museum artefact documentation. In: S Saunders, M Strlic, C Kronen, K Birholzerberg, N Luxford (eds.). Lasers in the Conservation of Artworks IX. Archetype Publications: London. 154-162

Hetherington, K. 2000. Museums and the visually impaired: the spatial politics of access. *The Sociological Review*, 48: 444-463. https://doi.org/10.1111/1467-954X.00225

Hetherington, K. 2003. Accountability and Disposal: Visual Impairment and the Museum. *Museum and Society*, 1: 104-115. https://doi.org/10.29311/mas.v1i2.18

Heller, MA. 1989. Texture perception in sighted and blind observers. *Perception & Psychophysics*, 45: 49-54. https://doi.org/10.3758/BF03208032

Heller, MA and Ballesteros, S. 2006. Introduction: Approaches to Touch and Blindness. In: MA Heller, S Ballesteros (eds.). Touch and Blindness: Psychology and Neuroscience. Lawrence Erlbaum Associates: New Jersey. 1-24. https://doi.org/10.4324/9781410615671

Hofman, M. 2014. 3D Printing gets a boost and opportunities with polymer materials. *ACS Macro Letters*, 3: 382-386. https://doi.org/10.1021/mz4006556

Hollinger, RE, John, E, Jacobs, H, Moran-Collins, L, Thome, C, Zastrow, J, Metallo, A, Waibel, G and Rossi, V. 2013. Tlingit-Smithsonian Collaborations with 3D Digitization of Cultural Objects. *Museum Anthropology Review*, 7: 201-253.

Hooper-Greenhill, E. 1992. Museums and the Shaping of Knowledge. Routledge: London. https://doi.org/10.4324/9780203415825

Hooper-Greenhill, E. 1999. Education, communication and interpretation: towards a critical pedagogy in museums. In: E Hooper-Greenhill (ed.). The Educational Role of the Museum. Routledge: London. 3-27. 2nd Edition.

Hooper-Greenhill, E. 2000a. Changing Values in the Art Museum: rethinking communication and learning. *International Journal of Heritage Studies,* **6**: 9-31. https://doi.org/10.1080/135272500363715

Hooper-Greenhill, E. 2000b. Museums and the Interpretation of Visual Culture. Routledge: London.

Hooper-Greenhill, E. 2006. Studying Visitors. In: S MacDonald (ed.). A Companion to Museum Studies. Blackwell Publishing ltd: Oxford. 362-376. https://doi.org/10.1002/9780470996836.ch22

Hooper-Greenhill, E. 2007. Museums and Education. Routledge: Oxon. https://doi.org/10.4324/9780203937525

Hornbæk, K and Hertzum, M. 2017. Technology Acceptance and User Experience: A Review of the Experiential Component in HCI. *ACM Transactions on Computer-Human Interaction*, 24: 1-30. https://doi.org/10.1145/3127358

Howes, D and Classen, C. 2014. Ways of Sensing: Understanding the Senses in Society. London: Routledge. https://doi.org/10.4324/9781315856032

Howlett, EA, Kennedy, WJ, Powell, HP, Torrens, HS. 2017. New light on the history of *Megalosaurus*, the great lizard of Stonesfield. *Archives of Natural History,* 44.1: 82-102. https://doi.org/10.3366/anh.2017.0416

Hsu, SH, Chuang, MC and Chang, CC. 2000. A semantic differential study of designer's and user's product form perception. *International Journal of Industrial Ergonomics*, 25: 375-391. https://doi.org/10.1016/S0169-8141(99)00026-8

Huang, Y, Chen, CH and Khoo, LP. 2012. Products classification in emotional design using a basic-emotion based sematic differential. *International Journal of Industrial Ergonomics*, 42: 569-580. https://doi.org/10.1016/j.ergon.2012.09.002

Ingle, M. 1999. Pupils' perceptions of museum education sessions. In: E Hooper-Greenhill (ed.). *The Educational Role of the Museum*. Routledge: London. 312-319. 2nd Edition.

Isaac, G. 2015. Preclusive Alliances: Digital 3D, Museums, and the Reconciling of Culturally Diverse Knowledges. *Current Anthropology,* 56: 286-296. https://doi.org/10.1086/683296

ISO. 1999. 13.180 13407: Human-centred design processes for interactive systems. Available at: https://www.iso.org/standard/21197.html. [Last Accessed: 04/03/2019].

Jafri, R and Ali, AA. 2015. Utilizing 3D Printing to Assist the Blind. HIMS'15 International Conference on Informatics and Medical Systems. Las Vegas, USA, 27 - 30 July, 2015.

Jakobsen, LS. 2016. Flip-flopping museum objects from physical to digital – and back again. *Nordisk Museologi*, 1: 121-137. https://doi.org/10.5617/nm.3068

Janssens, K, Dik, J, Cotte, M, Susini, J. 2010. Photon-Based Techniques for Non-destructive Subsurface Analysis of Painted Cultural Heritage Artifacts. *Accounts of Chemical Research*, 43: 814-825. https://doi.org/10.1021/ar900248e

Jant, EA, Haden, CA, Uttal, DH and Babcock, E. 2014. Conversation and Object Manipulation Influence Children's Learning in a Museum. *Child Development*, 85: 2029-2045. https://doi.org/10.1111/cdev.12252

JD Power and Associates. 2011. J.D. Power and Associates Reports: Initial Quality of Recent Vehicle Launches is Considerably Lower than in 2010, While Carryover Model Quality is Better than Ever. Available at: https://www.jdpower.com/sites/default/files/2011089-uiqs.pdf. [Last Accessed: 04/03/2019].

Jocks, I, Livingstone, D and Rea, PM. 2015. An Investigation to examine the most appropriate methodology to capture historical and modern preserved anatomical specimens for use in the digital age to improve access – a pilot study. In: LG Chova, AL Martínez, IC Torres (eds.). INTED2015 Proceedings: 9th International Technology, Education and Development Conference. March 2nd-4th, 2015 – Madrid, Spain. IATED Academy: Valencia. 6377-6386.

Johanson, K and Glow, H. 2015. A virtuous circle: The positive evaluation phenomenon in arts audience research. *Participations: Journal of Audience and Reception Studies*, 12: 254-270.

Johnson, RB and Onwuegbuzie, AJ. 2004. Mixed-methods Research: A Research Paradigm Whose Time Has Come. *Educational Researcher*, 33: 14-26. https://doi.org/10.3102/0013189X033007014

Jung, ME, Sirkin, D, Gür, TM and Steinert, M. 2015. Displayed Uncertainty Improves Driving Experience and Behaviour: The Case of Range Anxiety in an Electric Car. In: B Begole, J Kim, K Inkpen, W Woo (eds.). Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems. ACM: New York. 2201-2210. https://doi.org/10.1145/2702123.2702479

Jung, TH and tom Dieck, MC. 2017. Augmented reality, virtual reality and 3D printing for the co-creation of value for the visitor experience at cultural heritage places, *Journal of Place Management and Development.* 10: 140-151. https://doi.org/10.1108/JPMD-07-2016-0045

Jung, TH, tom Dieck, MC, Lee, H and Chung, N. 2016. Effects of Virtual Reality and Augmented Reality on Visitor Experiences in Museums. In: A Inversini, R Schegg (eds.). Information and Communication Technologies in Tourism 2016. Springer: Switzerland. 621-635. https://doi.org/10.1007/978-3-319-28231-2_45

Kador, T, Hannan, L, Nyhan, J, Terras, M, Chatterjee, HJ and Carnall, M. 2018. Object-based learning and research-based education: Case studies from the UCL curricula. In: JP Davies, N Pachler (eds.). Teaching and Learning in Higher Education: Perspectives from UCL. UCL Institute of Education Press: London. 157-206.

Kaiser, HF. 1960. The Application of Electronic Computers to Factor Analysis. *Educational and Psychological Measurement*, 20: 141-151. https://doi.org/10.1177/001316446002000116

Kaiser, HF. 1974. An Index of Factorial Simplicity. *Psychometrika*, 39: 31-36. https://doi.org/10.1007/BF02291575

Kang, J and Zhang, M. 2010. Semantic differential analysis of the soundscape in urban open public spaces. *Building and Environment*, 45: 150-157. https://doi.org/10.1016/j.buildenv.2009.05.014

Kano, N, Seraku, N, Takahashi, F and Tsuji, S. 1984. Attractive Quality and Must-be Quality. *Journal of the Japanese Society for Quality Control*, 41: 39-48.

Karnapke, M and Baker, B. 2018. Digital Heritage and 3D Printing: Trans-media Analysis and the Display of Prehistoric Rock Art from Valcamonica. In M Ioannides (ed.). Digital Cultural Heritage. Springer: Switzerland. 227-238. https://doi.org/10.1007/978-3-319-75826-8_19

Ketcham, RA and Carlson, WD. 2001. Acquisition, optimization and interpretation of X-ray computed tomographic imagery: applications to the geosciences. *Computers and Geosciences*, 27: 381-400. https://doi.org/10.1016/S0098-3004(00)00116-3

Khayami, S. 2008. Touching Art, Touching You: BlindArt, Sense and Sensuality. In: E Pye (ed.). The Power of Touch: Handling Objects in Museum and Heritage Contexts. Left Coast Press: Walnut Creek. 183-190.

King, TE, Fortes, GG, Balaresque, P, Thomas, MG, Balding, D, Delser, PM, Neumann, R, Parson, W, Knapp, M, Walsh, S, Tonasso, L, Holt, J, Kayser, M, Appleby, J, Forster, P, Ekserdijian, D, Hofreiter, M and Schürer, K. 2014. Identification of the remains of King Richard III. *Nature Communications,* 5: 5631. https://doi.org/10.1038/ncomms6631

Klein, S, Avery, M, Adams, G, Pollard, S and Simske, S. 2014. From Scan to Print: 3D printing as a Means for Replication. Available at: http://labs.hp.com/techreports/2014/HPL-2014-30.html. [Last Accessed: 07/01/2019].

Kline, P. 1999. The handbook of psychological testing. London, Routledge: UK. 2nd Edition.

Koch, V, Lückert, A, Schwarz, T, Both, P and Diziol, P. 2013. Using rapid prototyping technologies to grant visually impaired persons access to paintings, sculptures, graphics and architecture. In: H Achten, J Pavliček, J Hulín, D Matějovská (eds.). 30th eCAADe Conference

Prague 2012 Czech Technical University in Prague, Czech Republic. Vol. 2. Physical Digitality. eCAADe: Brussels. 501-508.

Kolb, DA. 2015. Experiential Learning: Experience as the Source of Learning and Development. Pearson Education Ltd.: Upper Saddle River. 2nd Edition.

Kong, L, Ostadhassan, M, Li, C and Tamimi, N. 2018. Can 3-D Printed Gypsum Samples Replicate Natural Rocks? An Experimental Study. *Rock Mechanics and Rock Engineering*, 51: 3061-3074. https://doi.org/10.1007/s00603-018-1520-3

Kontogianni, G and Georgopoulos, A. 2015. Exploiting textured 3D models for developing serious games. In: YN Yen, KH Weng, HM Cheng. 25th International CIPA Symposium 2015. XL-5/W7. International Society of Photogrammetry, Remote Sensing and Spatial Information Sciences: Germany. 249-255. https://doi.org/10.5194/isprsarchives-XL-5-W7-249-2015

Kontogianni, G, Koutsaftis, C, Skamantzari, M, Chrysanthopoulou, C and Georgopoulos, A. 2017. Utilising 3D realistic models in serious games for cultural heritage. *International Journal of Computations Methods in Heritage Science*, 1: 21-46. https://doi.org/10.4018/IJCMHS.2017070102

Körber, M, Eichinger, A, Bengler, K and Olaverri-Monreal C. 2013. User Experience Evaluation in an Automotive Context. 2013 IEEE Intelligent Vehicles Symposium. Gold Coast, Australia, 23rd-26th June, 2013. https://doi.org/10.1109/IVWorkshops.2013.6615219

Koutsabasis, P and Vosinakis, S. 2018. Kinaesthetic interactions in museums: conveying cultural heritage by making use of ancient tools and (re-)constructing artworks. *Virtual Reality*, 22: 103-118. https://doi.org/10.1007/s10055-017-0325-0

Kreps, C. 2015. University Museums as Laboratories for Experiential Learning and Engaged Practice. *Museum Anthropology*, 38: 96-111. https://doi.org/10.1111/muan.12086

Krippendorff, K. 2009. Testing the Reliability of Content Analysis Data: What is involved and why. In: K Krippendorff, MA Bock (eds.). The Content Analysis Reader. Sage: California. 350-357.

Krippendorff, K. 2013. Content Analysis: An Introduction to its Methodology. Sage: California.

Krosnick, JA and Fabriger, LR. 1997. Designing Rating Scales for Effective Measurement in Surveys. In: L Lyberg, P Biemer, M Collins, E de Leeuw, C Dippo, N Schwarz, D Trewin (eds.). Survey Measurement and Process Quality. New York: John Wiley. 141-164. https://doi.org/10.1002/9781118490013.ch6

Kruth, JP, Bartscher, M, Carmignato, S, Schmitt, R, De Chiffre, L and Weckenmann, A. 2011. Computed tomography for dimensional metrology. *CIRP Annals – Manufacturing Technology*, 60: 821-842. https://doi.org/10.1016/j.cirp.2011.05.006

Kuo, CW, Lin, C and Wang, MC. 2016. New Media Display Technology and Exhibition Experience. *ACSIJ Advances in Computer Science: an International Journal*, 5: 103-109.

Labbe, D, Ferrage, A, Rytz, A, Pace, J and Martin, N. 2015. Pleasantness, emotions and perceptions induced by coffee beverage experience depend on the consumption motivation (hedonic or utilitarian). *Food Quality and Preference*, 44: 56-61. https://doi.org/10.1016/j.foodqual.2015.03.017

Lacey, S and Sathian, K. 2014. Please DO Touch the Exhibits! Interactions between Visual Imagery and Haptic Perception. In: N Levent, A Pascual-Leone (eds.). The Multisensory Museum: Cross-disciplinary Perspectives on Touch, Sound, Smell, Memory and Space. Rowman and Littlefield: Plymouth. 3-16.

Laforce, B, Massschaele, B, Boone, MN, Schaubroeck, D, Dierick, M, Vekemans, B, Walgraeve, C, Jansses, C, Cnudde, V, Van Hoorbeke, L and Vincze, L. 2017. Integrated Three-Dimensional Microanalysis Combining X-Ray Microtomography and X-Ray Fluorescence Methodologies. *Analytic Chemistry*, 89: 10617-10624. https://doi.org/10.1021/acs.analchem.7b03205

Lallemand, C, Gronier, G and Koenig, V. 2015. User Experience: A concept without consensus? Exploring practitioner's perspectives through an international survey. *Computers in Human Behaviour*, 43: 35-48. https://doi.org/10.1016/j.chb.2014.10.048

Land-Zandstra, AM, van Gerven, DJJ and Damsma W. 2018. Is it real? How visitors interpret authenticity in a natural history museum. *Spokes*, 37. Available at: https://www.ecsite.eu/activities-and-services/news-and-publications/digital-spokes/issue-37#section=section-indepth&href=/feature/depth/it-real [Last Accessed: 03/07/2018].

Lanzón, M, Cnudde, V, De Kock, T, Dewanckele, J and Piñero, A. 2014. X-ray tomography and chemical-physical study of the calcarenite extracted from a Roman quarry in Cartagena (Spain). *Engineering Geology*, 171: 21-30. https://doi.org/10.1016/j.enggeo.2013.12.007

Lautenschlager, S and Rücklin, M. 2014. Beyond the Print – Virtual Paleontology in Science Publishing, Outreach, and Education. *Journal of Palaeontology*, 88: 727-734. https://doi.org/10.1666/13-085

Laycock, SD, Bell, GD, Mortimore, DB, Greco, MK, Corps, N and Finkle, I. 2012. Combining X-Ray Micro-CT Technology and 3D Printing for the Digital Preservation and Study of a 19th

Century Cantonese Chess Piece with Intricate Internal Structure. *ACM Journal on Computing and Cultural Heritage*, 5: 13.

Laycock, SD, Bell, GD, Corps, N, Mortimore, DB, Cox, G, May, S and Finkel, I. 2015. Using a Combination of Micro-Computed Tomography, CAD and 3D Printing Techniques to Reconstruct Incomplete 19th-Century Cantonese Chess Pieces. *ACM Journal on Computing and Cultural Heritage*, 7: 25.

Leakey, L and Dzamabova, T. 2013. Prehistoric collections and 3D printing for Education: In: E Canessa, C Fonda, M Zennaro (eds.). Low-Cost 3D Printing for Science, Education and Sustainable Development. The Abdus Salam International Centre for Theoretical Physics: Trieste. 159-162.

Le Cabec, A and Toussaint, M. 2017. Impacts of curatorial and research practices on the preservation of fossil hominid remains. *Journal of Anthropological Sciences*, 95: 1-28.

Lederman, SJ and Klatzky, RL. 1987. Hand Movements: A Window into Haptic Object Recognition. *Cognitive Psychology*, 19: 342-368. https://doi.org/10.1016/0010-0285(87)90008-9

Lederman, SJ and Klatzky, RL. 2004. Multisensory Texture Perception. In: GA Calvert, C Spence, BE Stein (eds.). The Handbook of Multisensory Processes. MIT Press: Cambridge. 107-122.

Legrand, S, Vanmeert, F, Van der Snickt, G, Alfeld, M, de Nolf, W, Dik, J and Janssens, K. 2014. Examination of historical paintings by state-if-the-art hyperspectral imaging methods: from scanning infra-red spectroscopy to computed X-ray laminography. *Heritage Science*, 2: 13. https://doi.org/10.1186/2050-7445-2-13

Leinhardt, G. and Crowley, K. 2002. Objects of Learning, Objects of Talk: Changing Minds in Museums. In: SG Paris (ed.). Perspectives on Object-Centered Learning in Museums. Lawrence Erlbaum Associates: London. 301-324.

Lerma, JL, Navarro, S, Cabrelles, M and Villaverde, V. 2010. Terrestrial laser scanning and close range photogrammetry for 3D archaeological documentation: the Upper Palaeolithic Cave of Parpalló as a case study. *Journal of Archaeological Science*, 37: 499-507. https://doi.org/10.1016/j.jas.2009.10.011

Levent, N and McRainey, DL. 2014. Touch and Narrative in Art and History Museums. In: N Levent, A Pascual-Leone (eds.). The Multisensory Museum: Cross-disciplinary Perspectives on Touch, Sound, Smell, Memory and Space. Rowman and Littlefield: Plymouth. 61-81.

Levent, N and Pascual-Leone, A. 2014. The Multisensory Museum: Cross-disciplinary Perspectives on Touch, Sound, Smell, Memory and Space. Rowman and Littlefield: Plymouth.

Limaye, A. 2012. Drishti: a volume exploration and presentation tool. In: SR Stocks (ed.), Developments in X-Ray Tomography VIII. Proceedings Volume 8506. SPIE Optical Engineering + Applications. 12th-16th August 2012 – San Diego, California. SPIE Digital Library: Washington DC. 85060X. https://doi.org/10.1117/12.935640

Lin, FH, Tasi, SB, Lee, YC, Hsiao, CF, Zhou, J, Wang, J and Shang, Z. 2017. Empirical research on Kano's model and customer satisfaction. *PlosOne*, 12: e0183888. https://doi.org/10.1371/journal.pone.0183888

Lindauer, M. 2005. What to ask and how to answer: a comparative analysis of methodologies and philosophies of summative evaluation. *Museum and Society*, 3: 137-152.

Lindgren-Streicher, A and Reich, CA. 2007. Visitor Usage of Digital and Physical Artifacts in Two Museum Programs. *Visitor Studies*, 10: 152-167. https://doi.org/10.1080/10645570701603666

Lindsay, W, Larkin, N and Smith, N. 1996. Displaying Dinosaurs at The Natural History Museum, London. *Curator: The Museum Journal*, 39: 262-279. https://doi.org/10.1111/j.2151-6952.1996.tb01102.x

Lipson, H and Kurman, M. 2013. Fabricated: the New World of 3D Printing. John Wiley & Sons: Indianapolis.

Liss, B and Stout, S. 2017. Materials Characterization for Cultural Heritage: XRF Case Studies in Archaeology and Art. In: ML Vincent, VM López-Menchero Bendicho, M Ioannadis, TE Levy (eds.). Heritage and Archaeology in the Digital Age: Acquisition, Curation, and Dissemination of Spatial Cultural Heritage Data. Springer: London. 49-65. https://doi.org/10.1007/978-3-319-65370-9_3

Liu, Z, Zhang, M, Bhandari, B and Wang, Y. 2017. 3D printing: printing precision and application in food sector. *Trends in Food Science & Technology*, 69: 83-94. https://doi.org/10.1016/j.tifs.2017.08.018

Lombardi, M. 2018. 3D Modeling and "Relief-Printing" for a More Inclusive Fruition of Cultural Heritage. In: M Koui, F Zezza, D Kouis (eds.). 10th International Symposium on the Conservation of Monuments in the Mediterranean Basin. Springer International Publishing: Berlin. 555-559. https://doi.org/10.1007/978-3-319-78093-1_60

Low, GS and Lamb Jr. CW. 2000. The measurement and dimensionality of brand association. *Journal of Product & Brand Management*, 9: 350-368. https://doi.org/10.1108/10610420010356966

Lutterotti, L, Dell'Amore, F, Angelucci, DE, carrer, F and Gialanella, S. 2016. Combined X-ray diffraction and fluorescence analysis in the cultural heritage field. *Microchemical Journal*, 126: 423-430. https://doi.org/10.1016/j.microc.2015.12.031

MacDonald, S. 2008. Exploring the Role of Touch in Connoisseurship and the Identification of Objects. In E Pye (ed.). The Power of Touch: Handling Objects in Museum and heritage Contexts. Left Coast Press: Walnut Creek. 107-120.

Macaluso, E and Driver, D. 2005. Multisensory spatial interactions: a window onto functional integration in the human brain. *TRENDS in Neuroscience*, 28: 264-271. https://doi.org/10.1016/j.tins.2005.03.008

Mahindru, DV and Mahendru, P. 2013. Review of Rapid Prototyping-Technology for the Future. *Global Journal of Computer Science and Technology Graphics & Vision*, 13: 27-37.

Mahmoud, A and Bennett, M. 2015. Introducing 3-Dimensional Printing of a Human Anatomic Pathology Specimen: Potential Benefits for Undergraduate and Postgraduate Education and Anatomic Pathology Practice. *Archives of Pathology and Laboratory Medicine*, 139: 1048-1051. https://doi.org/10.5858/arpa.2014-0408-OA

Malenka, S. 2000. The ritual around replica: From replicated works of art to art as a replica (part 1). In: V Greene, JS Johnson (eds.). Objects Specialty Group Postprints, Volume Seven, 2000. The American Institute for Conservation of Historic and Artistic Works: Washington DC. 21-28.

Mannes, D, Schmid, F, Frey, J, Schmidt-Ott, K and Lehmann, E. 2014. Combined Neutron and X-Ray imaging for non-invasive investigations of cultural heritage objects. *Physics Procedia*, 69: 653-660. https://doi.org/10.1016/j.phpro.2015.07.092

Marchietti, E. 2013. Playful Learning Culture in the Museum: MicroCulture and Guided Tour Practice. In MJ Kirkeback, XY Du, AA Jensen (eds.). Teaching and Learning Culture: Negotiating the Context. Sense Publishers: Netherlands. 129-144. https://doi.org/10.1007/978-94-6209-440-6_9

Markon, KE, Chmielewski, M and Miller, CJ. 2011. The Reliability and Validity of Discrete and Continuous Measures of Psychopathology: A Quantitative Review. *Psychological Bulletin*, 137: 856-879. https://doi.org/10.1037/a0023678

Marshall, MT, Dulake, N, Ciolfi, L, Duranti, D, Kockelkorn, H and Petrelli, D. 2016. Using Tangible Smart Replicas as Controls for an Interactive Museum Exhibition. In: S Bakker, C Hummels, B Ullmer, L Geurts, B Hengeveld, D Saakes, M Broekhuijsen (eds.). Proceedings of the TEI '16: Tenth International Conference on Tangible, Embedded, and Embodied Interaction 14-17 Feb. ACM: New York. 159-167. https://doi.org/10.1145/2839462.2839493

Maxwell, M, Gray, J and Goldberg, M. 2015. The Interplay of Digital and Traditional Craft: re-creating an Authentic Pictish Drinking Horn Fitting. In: S Campana, R Scopigno, G Carpentiero, M Cirillo (eds.). CAA 2015 Keep the Revolution Going: Proceedings of the 43rd Annual Conference on Computer Applications and Quantitative Methods in Archaeology. Archaeopress Publishing Ltd: Oxford. 35-40.

McCarthy, J. 2014. Multi-image photogrammetry as a practical tool for cultural heritage survey and community engagement. *Journal of Archaeological Science*, 43: 175-185. https://doi.org/10.1016/j.jas.2014.01.010

McCrum-Gardner, E. 2008. Which is the correct statistical test to use? *British Journal of Oral and Maxillofacial Surgery*, 46: 38-41. https://doi.org/10.1016/j.bjoms.2007.09.002

McGee, C. and F. Rosenberg. 2014. "Art Making as Multisensory Engagement". In: N Levent, A Pascual-Leone (eds.) The Multisensory Museum: Cross-disciplinary Perspectives on Touch, Sound, Smell, Memory and Space. Rowman and Littlefield: Plymouth. 29-44.

McGlone, F. 2008. The Two Sides of Touch. In: HJ Chatterjee (ed.) Touch in Museums: Policy and Practice in Object Handling. Berg: Oxford. 41-60.

McKnight, LM, Adams, JE, Chamberlain, A, Atherton-Woolham, SD and Bibb, R. 2015. Application of clinical imaging and 3D printing to the identification of anomalies in an ancient Egyptian animal mummy. *Journal of Archaeological Science: Reports*, 3: 328-332.

McManus, PM. 2015. Museums. In: R Gunstone (ed.). Encyclopedia of Science Education. Springer: Netherlands. 682-685. https://doi.org/10.1007/978-94-007-2150-0_301

Mearns, DL, Parham, D and Frohlich, B. 2016. A Portuguese East Indiaman from the 1502-1503 Fleet of Vasco da Gama off Al Hallaniyah Island, Oman: an interim report. *International Journal of Nautical Archaeology*, 45: 331-350. https://doi.org/10.1111/1095-9270.12175

Meecham, P. 2015. Talking about Things: Internationalisation of the Curriculum through Object-Based Learning. In: HJ Chatterjee, L Hannan (eds.). Engaging the Senses: Object-Based Learning in Higher Education. Ashgate Publishing: Surrey. 77-94.

Melton, AW. 1936. Measuring Museum Based Learning: Experimental Studies of the Education of Children in a Museum of Science. American Association of Museums: Washington DC.

Mesquita, S and Carneiro, MJ. 2016. Accessibility of European museums to visitors with visual impairments. *Disability & Society*, 31: 373-388. https://doi.org/10.1080/09687599.2016.1167671

Mikolajska, A, Walczak, M, Kaszowska, Z, Zawadzka, MU and Banyś, RP. 2012. X-ray techniques in the investigation of a Gothic sculpture: *The Risen Christ*. *Nukleonika*, 57: 627-31.

Millar, S. 2006. Processing Spatial Information from Touch and Movement: Implications from and for Neuroscience. In: MA Heller, S Ballesteros (eds.). Touch and Blindness: Psychology and Neuroscience. Lawrence Erlbaum Associates: New Jersey. 49-73.

Miles, R and Tout, A. 1994. Impact of Research on the approach to the visiting public at the Natural History Museum, London. In: E Hooper-Greenhill (ed.). The Educational Role of the Museum. Routledge: London. 101-106.

Miles, RS, Alt, MB, Gosling, DC, Lewis, BN and Tout, AF. 1988. The Design of Educational Exhibits. Unwin Hyman ltd.: London. 2nd Edition.

Miles, J, Mavrogordato, M, Sinclair, I, Hinton, D, Boardman, RP and Earl, G. 2015. The use of computed tomography for the study of archaeological coins. *Journal of Archaeological Science*, 6: 35-41. https://doi.org/10.1016/j.jasrep.2016.01.019

Mimaki. 2018. Mimaki Global. 3DUJ-553. Available at: https://mimaki.com/product/3d/3d-flat/3duj-553/ [Last Accessed: 19/10/2018].

Mitsopolou, V, Michailidism D, Theodorou, E, Isidorou, S, Roussiakis, S, Vasilopoulos, T, Polydoras, S, Kaisarlis, G, Spitas, V, Stathopoulou, E, Provatidis, C and Theodorou, G. 2015. Digitizing, modelling and 3D printing of skeletal digital models of *Palaeoloxodon tiliensis* (Tilos, Dodecanese, Greece). *Quaternary International*, 379: 4-13. https://doi.org/10.1016/j.quaint.2015.06.068

MLA. 2006. Museum Learning Survey 2006. Museums, Libraries and Archives Council: London.

Mocella, V, Brum, E, Ferrero, C and Delattre, D. 2015. Revealing letters in rolled Herculaneum papyri by x-ray phase-contrast imaging. *Nature Communications*, 6: 5895. https://doi.org/10.1038/ncomms6895

Monge, JM and Mann, AE. 2004. Ethical issues in the Molding and Casting of Fossil Specimens. In: R Turner (ed.). Biological Anthropology and Ethics: From Repatriation to Genetic Identity. State University of New York Press: New York. 91-110.

Monti, F and Keene, S. 2013. Museums and Silent Objects: Designing Effective Exhibitions. Taylor & Francis: Didcot.

Morgan, DL. 2007. Paradigms Lost and Pragmatism Regained: Methodological Implications of Combining Qualitative and Quantitative Methods. *Journal of Mixed-Methods Research*, 1: 48-76. https://doi.org/10.1177/2345678906292462

Morgan, J. 2011. The Multisensory Museum. *Journal of the Ethnographic Institute (Serbia)*, 60: 65-77. https://doi.org/10.2298/GEI1201065M

Morgan, DL. 2014a. Pragmatism as a Paradigm for Social Research. *Qualitative Inquiry*, 20: 1045-1053. https://doi.org/10.1177/1077800413513733

Morgan, DL. 2014b. Integrating Qualitative and Quantitative Methods: A Pragmatic Approach. Sage: California. https://doi.org/10.4135/9781544304533

Morigi, MP, Casali, F, Bettuzzi, M, Brancaccio, R and D'Errico V. Application of X-ray Computed Tomography to Cultural Heritage diagnostics. Applied Physics A: Material Science and Processing, 100: 653-661. https://doi.org/10.1007/s00339-010-5648-6

Müller, K. 2002. Museums and Virtuality. *Curator: the Museum Journal*, 45: 21-33. https://doi.org/10.1111/j.2151-6952.2002.tb00047.x

Murphy, SV and Atala, A. 2014. 3D bioprinting of tissues and organs. *Nature Biotechnology*, 32: 773-785. https://doi.org/10.1038/nbt.2958

Museums Association. 2015. Cuts Survey 2015: December 2015. Museums Association: London. Available at: https://www.museumsassociation.org/download?id=1155642 [Last Accessed: 19/08/2016].

Museums Association. 2018. Museums in the UK: 2018 report. Museums Association: London. Available at: https://www.museumsassociation.org/download?id=1244881 [Accessed: 21/02/2018].

National Federation of the Blind. 2009. The Braille Literacy Crisis in America: Facing the Truth, Reversing the Trend, Empowering the Blind. A Report to the Nation by the National Federation of the Blind. NFB: Baltimore.

National Museums of Scotland. 2002. Exhibitions for All: A practical guide to designing inclusive exhibitions. Edinburgh: NMS Publishing.

Neely, L and Langer, M. 2013. Please Feel the Museum: The Emergence of 3D Printing and Scanning. In: N Proctor, R Cherry (eds.). Museums and the Web 2013. Silver Spring: Maryland. Available at: https://mw2013.museumsandtheweb.com/paper/please-feel-the-museum-the-emergence-of-3d-printing-and-scanning/ [Last Accessed: 21/02/2016].

Neumüller, M and Reichinger, A. 2013. From Stereoscopy to Tactile Photography. *PhotoResearcher*: 19: 59-63.

Neumüller, M, Reichinger, A, Rist, F and Kern, C. 2014. 3D Printing for Cultural Heritage: Preservation, Accessibility, Research and Education. In: M Ioannides, E Quak (eds.). 3D Research Challenges. Springer-Verlag: Berlin/Heidelberg. 119-134. https://doi.org/10.1007/978-3-662-44630-0_9

Ngan-Tillard, DJM, Huisman, DJ, Corbella, F and Van Nass, A. 2018. Over the rainbow? Micro-CT scanning to non-destructively study Roman and early medieval glass bead manufacture. *Journal of Archaeological Science*, 98:7-21. https://doi.org/10.1016/j.jas.2018.07.007

Ngo, TD, Kashani, A, Imbalzano, G, Nguyen, KTQ, Hui, D. 2018. Additive manufacturing (3D printing): A review of materials, methods, applications and challenges. *Composites Part B*, 143: 172-196. https://doi.org/10.1016/j.compositesb.2018.02.012

Nili, A, Tate, M and Barros, A. 2017. A Critical Analysis of Inter-Coder Reliability Methods in Information Systems Research. ACIS2017: Australasian Conference on Information Systems. Hobart, Australia, 3rd-6th December, 2017.

Noble, G and Chatterjee, HJ. 2008. Enrichment Programmes in Hospitals: Using Museum Loan Boxes in University College London Hospital. In: E Pye (ed.). The Power of Touch: Handling Objects in Museum and Heritage Contexts. Left Coast Press: Walnut Creek. 215-223.

Nofal, E, Reffat, RM, Boschloos, V, Hameeuw, H and Moere, AV. 2018. The Role of Tangible Interaction to Communicate Tacit Knowledge of Built Heritage. *Heritage*, 1: 414-436. https://doi.org/10.3390/heritage1020028

Norman, D. 2013. The Design of Everyday Things. Basic Books: New York.

Norman, DA and Draper, SW. 1986. User Centred System Design: New Perspectives on Human-Computer Interaction. Lawrence-Erlbaum Associates: Hillsdale. https://doi.org/10.1201/b15703

Norman, D, Miller, J and Henderson, A. 1995. What you see, Some of What's in the Future, And How we Go About Doing it: HI at Apple Computer. CHI'95: Mosaic of Creativity. Denver, Colorado, 7-11 May, 1995. https://doi.org/10.1145/223355.223477

Null, R. 2014. Universal Design: Principles and Models. CRC Press: Boca Raton. https://doi.org/10.1201/b15580

O'Reilly, MK, Reese, S, Herlihy, T, Geoghegan, T, Cantwell, CP, Feeney, RNM and Jones, JFX. 2016. Fabrication and Assessment of 3D Printed Anatomical Models of the Lower Limb for Anatomical Teaching and Femoral Vessel Access Training in Medicine. *Anatomical Science Education*, 9: 71-79. https://doi.org/10.1002/ase.1538

Office for National Statistics. 2017. Overview of the UK population: July 2017. Available at: https://www.ons.gov.uk/peoplepopulationandcommunity/populationandmigration/populationestimates/articles/overviewoftheukpopulation/july2017 [Last Accessed: 19/10/2017].

Olson, BR, Gordon, JM, Runnels, C and Chomyszak, S. 2014. Experimental Three-Dimensional printing of a Lower Palaeolithic Handaxe: An assessment of the technology and analytical value. *Lithic Technology,* 39: 172-172. https://doi.org/10.1179/2051618514Y.0000000004

Onol, I. 2008. Tactual Explorations: A Tactile Interpretation of a Museum Exhibit through Tactile Art Works and Augmented Reality. In: E Pye (ed.). The Power of Touch: Handling Objects in Museum and Heritage Contexts. Left Coast Press: Walnut Creek. 91-106.

Owen, R. 1842. Report on British Fossil Reptiles. Part II. Report of the Eleventh Meeting of the British Association for the Advancement of Science; Held at Plymouth in July 1841. John Murray: London.

Owen, R. 1845. Odontography or A treatise on the comparative anatomy of the teeth, their physiological relations, mode of development, and microscopic structure in the vertebrate animals. Volume 1. Hippolyte Bailliere: London.

Owen R. 1849. A history of British Reptiles. Volume 1. Cassell & Company Limited: London.

Pallud, J and Monod, E. 2010. User experience of museum technologies: the phenomenological scales. *European Journal of Information Systems*, 19: 562-580. https://doi.org/10.1057/ejis.2010.37

Palmer, JW. 2002. Web Site Usability, Design, and Performance Metrics. *Information Systems Research*, 13: 151-167. https://doi.org/10.1287/isre.13.2.151.88

Paris, SG. 2002. Perspectives on Object-Centered Learning in Museums. Lawrence Erlbaum Associates: London. https://doi.org/10.4324/9781410604132

Paris, SG and Hapgood, SE. 2002. Children Learning with Objects in Informal Learning Environments. In: SG Paris (ed.). Perspectives on Object-Centered Learning in Museums. Lawrence Erlbaum Associates: London. 37-54. https://doi.org/10.4324/9781410604132

Partington-Sollinger, Z and Morgan, A. 2011. Shifting Perspectives: Opening up museums and galleries to blind and partially sighted people. RNIB: London.

Petrelli, D, Ciolfi, L van Dijk, D, Hornecker, E, Not, E and Schmidt, A. 2013. Integrating Material and Digital: A New Way for Cultural Heritage. *Interactions*, 20: 58-63. https://doi.org/10.1145/2486227.2486239

Payne, EM. 2013. Imaging Techniques in Conservation. *Journal of Conservation and Museum Studies,* 10: 17-29. https://doi.org/10.5334/jcms.1021201

Phillips, J. 1871. Geology of Oxford and the Valley of the Thames. Clarendon Press: Oxford. https://doi.org/10.5962/bhl.title.32635

Phillips, L. 2008. Reminiscence: Recent Work at the British Museum. In: HJ Chatterjee (ed.) Touch in Museums: Policy and Practice in Object Handling. Berg: Oxford. 199-204.

Phillips, A and Beesley, L. 2011. Braille Profiling Project. RNIB: London.

Pitts, MJ, Williams, MA, Wellings, T and Attridge, A. 2009. Assessing Subjective Response to haptic feedback in Automotive Touchscreens. In: A Schmidt, A, Dey, T Selder, O Juhlin (eds.). Proceedings of the 1st Internation Conference on Automotive User Interfaces and Interactive Vehicular Applications. ACM: New York. 11-18. https://doi.org/10.1145/1620509.1620512

Pletincx, D. 2007. Virtex: a multisensory approach for exhibiting valuable objects. In: H Gottlieb. (ed.). Know How Books: Museums. Epoch, The Interactive Institute. 3-31.

Politis, I, Langdon, P, Adebayo, D, Bradley, M, Clarkson, PJ, Skrypchuk, L, Mouzakitis, A, Eriksson, A, Brown, JWH, Revell, K and Stanton, N. 2018. An Evaluation of Inclusive Dialogue-Based Interfaces for the Takeover of Control in Autonomous Cars. In: IUI '18 23rd International Conference on Intelligent User Interfaces. ACM: New York. 601-606. https://doi.org/10.1145/3172944.3172990

Polizzi, KG. 2003. Assessing Attitudes toward the Elderly: Polizzi's Refined version of the Aging Semantic Differential. *Educational Gerontology*, 29: 197-216. https://doi.org/10.1080/713844306

Pollalis, C, Minor, EJ, Westendorf, L, Fahnbulleh, W, Virgilio, I, Kun, AL and Shaer, O. 2018. Evaluating Learning with Tangible and Virtual Representations of Archaeological Artifacts. In: Y Fernaeus, D McMillan, M Jonsson, A Girouard, J Tholander (eds.). TEI'18 Proceedings of the Twelfth International Conference on Tangible, Embedded, and Embodied Interaction. ACM: New York. 626-637. https://doi.org/10.1145/3173225.3173260

Pop, IL and Borza, A. 2016. Technological innovations in museums as a source of competitive advantage. In: A Abraham, S Kovalev, V Tarassov, V Snasel, M Vasileva, A Sukhanov (eds.). Proceeding of the 2nd International Scientific Conference SAMRO 2016, Vol. 1. Springer: Switzerland. 398-405.

Porter, M. 1938. Behaviour of the Average Visitor in the Peabody Museum of Natural History, Yale University. Publications of the American Association of Museums 16: Washington DC.

Pursey, T and Lomas, D. 2018. Tate Sensorium: an experiment in multisensory immersive design. *The Senses and Society*, 13: 354-366. https://doi.org/10.1080/17458927.2018.1516026

Pye E. 2001. Caring for the Past: Issues in Conservation for Archaeology and Museums. James and James ltd.: London.

Pye, E. 2008a. The Power of Touch: Handling Objects in Museum and Heritage Contexts. Left Coast Press: Walnut Creek.

Pye, E. 2008b. Understanding Objects: The Role of Touch in Conservation. In: E Pye (ed.). The Power of Touch: Handling Objects in Museum and Heritage Contexts. Left Coast Press: Walnut Creek. 121-138.

Quagliarini, E, Clini, P and Ripanti, M. 2017. Fast, low cost and safe metholodogy for the assessment of the state of conservation of historical buildings from 3D laser scanning: The case study of Santa Maria in Portonovo (Italy). *Journal of Cultural Heritage*, 24: 175-183. https://doi.org/10.1016/j.culher.2016.10.006

Racicot, R. 2017. Fossil Secrets Revealed: X-Ray CT Scanning and Application in Paleontology. *the Paleontological Society Papers*, 22: 21-38. https://doi.org/10.1017/scs.2017.6

Radywyl, N, Barikin, A, Papastergiadis, N. and McQuire, S. 2015. Ambient Aesthetics: Altered Subjectivities in the New Museum. In: A Witcomb, K Message (eds.). The International Handbook of Museum Studies: Museum Theory. John Wiley & Sons: Chichester. 417-436. https://doi.org/10.1002/9781118829059.wbihms120

Rahman, IA, Adcock, K and Garwood, RJ. 2012. Virtual Fossils: a New Resource for Science Communication in Paleontology. *Evolution: Education and Outreach*, 5: 635-641. https://doi.org/10.1007/s12052-012-0458-2

Re, A, Albertin, F, Avataneo, C, Brancaccio, R, Corsi, J, Cotto, G, de Blasi, S, Dughera, G, Durisi, E, Ferrarese, W, Giovagnoli, A, Grassi, N, Lo Giudice, A, Mereu, P, Mila, G, Nervo, M, Pstrone, N, Prino, F, Ramello, L, Ravera, M, Ricci, C, Romero, A, Sacchi, R, Staiano, A, Visca, L and Zamprotta, L. 2014. X-ray tomography of large wooden artworks: the case study of "Doppio corpo" by Pietro Piffetti. *Heritage Science*, 2: 19. https://doi.org/10.1186/s40494-014-0019-9

Reeve, J and Woolard, V. 2015. Learning, Education, and Public Programs in Museums and Galleries. In: C McCarthy (ed.). The International Handbooks of Museum Studies: Museum Practice. John Wiley & Sons: Chichester. 551-575. https://doi.org/10.1002/9781118829059.wbihms989

Reichinger, A, Neumüller, M, Rist, F, Maierhofer, S and Purgathofer, W. 2012. Computer-Aided Design of Tactile Models: Taxonomy and Case Studies. In: K Miesenberger, A Karshmer, P Penaz, W Zagler (eds.). Computers Helping People with Special Needs. 13th International Conference, ICCHP 2012. Springer-Verlag: Berlin-Heidelberg. 497-504. https://doi.org/10.1007/978-3-642-31534-3_73

Remondino, F, Menna, F, Koutsoudis, A, Chamzas, C and El-Hakim, S. 2013. Design and implement a reality-based 3D digitization and modelling project. Available at: https://www.researchgate.net/publication/265590698_Design_and_implement_a_realitybased_3D_digitisation_and_modelling_project_International_Congress_on_Digital_Heritage_28_Oct_-_01_Nov_Marseille_France_2013 [Last Accessed: 24/07/2018].

Rener, R. 2017. The 3D Printing of Tactile Maps for Persons with Visual Impairment. In: M Antona, C Stephanidis (eds.). Universal Access in Human-Computer Interaction. Designing Novel Interactions. 11th International Conference UAHCI 2017. Vancouver, Canada, July 9-14 2017. Proceedings Part II. Springer: Switzerland. 335-350. https://doi.org/10.1007/978-3-319-58703-5_25

Rennie, LJ and Johnston, DJ. 2004. The Nature of Learning and its Implication for Research on Learning from Museums. *Science Education*, 88: S4-S16. https://doi.org/10.1002/sce.20017

Rieppel, O. 2001. Tooth implantation and replacement in Sauropterygia. *Paläontologische Zeitschrift*, 75: 207-217. https://doi.org/10.1007/BF02988014

RNIB. 2018. Eye Health and Sight Loss Stats and Facts. RNIB: London.

Robinson, ES. 1928. The Behaviour of the Museum Visitor. American Association of Museums: Washington DC.

Roschelle, J. 1995. Learning in Interactive Environments: Prior Knowledge and New Experience. In: JH Falk, LD Dierking (eds.). Public Institutions for personal learning: Establishing a research agenda. American Association of Museums: Washington DC. 37-51.

Rosenzweig, E. 2015. Successful User Experience: Strategies and Roadmaps. Elsevier: Waltham. https://doi.org/10.1016/B978-0-12-800985-7.00001-6

Roto, V, Law, E, Vermeeren, A and Hoonhout, J. 2011. User Experience White Paper: Bringing clarity to the concept of user experience. Dagstuhl Seminar on User Experience 2010. Wadern, Germany, 15-18 September, 2011.

Roussou, M and Katifori, A. 2018. Flow, Staging, Wayfinding, Personalization: Evaluating User Experience with Mobile Museum Narratives. *Multimodal Technologies and Interact*, 2: 32. https://doi.org/10.3390/mti2020032

Rowe, T, Ketcham, RA, Denison, C, Colbert, M, Xu, X and Currie, PJ. 2001. The *Archaeoraptor* forgery. *Nature*: 410: 539-40. https://doi.org/10.1038/35069145

Ruffell, A, Majury, N and Brooks, WE. 2012. Geological fakes and frauds. *Earth-Science Reviews*, 111:224-31. https://doi.org/10.1016/j.earscirev.2011.12.001

Sá, AM, Echavarria, KR, Griffin, M, Covill, D, Kaminski, J and Arnold, D. 2012. Parametric 3D-fitted frames for packaging heritage artefacts. In: D Arnold, J Kaminski, F Niccolucci and A Stork (eds.). VAST12: International Symposium on Virtual Reality, Archaeology and Intelligent Cultural Heritage. Eurographics Association: Switzerland.

Saldaña, J. 2016. The Coding Manual for Qualitative Researchers. Sage: California. 3rd Edition.

Salgado, M and Kellokoski, A. 2005. ÄÄNIJÄLKI: Opening Dialogues for Visually Impaired Inclusion in Museums. Available at: http://www.cultureforall.info/doc/experiences_and_examples/opening_dialogues_for_visually_impaired_inclusion_in_museums.pdf [Last Accessed: 19/10/2018].

Samuels, J. 2008. The British Museum in Pentonville Prison: Dismantling barriers through Touch and Handling. In: HJ Chatterjee (ed.). Touch in Museums: Policy and Practice in Object Handling. Berg: Oxford. 253-260.

Santagati, C, Galizia, M and D'Agostino, G. 2013a. Digital reconstruction of Archaeological Sites and Monuments: Some Experiences in South-Eastern Sicily. In: E Ch'ng, V Gaffney, Chapman (eds.). Visual Heritage in the Digital Age. Visual Heritage in the Digital Age. Springer: London. 205-232. https://doi.org/10.1007/978-1-4471-5535-5_11

Santagati, C, Inzerillo, L and Di Paola F. 2013b. Image-based modelling techniques for architectural heritage 3D digitalization: Limits and Potentialities. In: P Grussenmeyer (ed.). XXIV International CIPA Symposium 2013. XL-5/W2. International Society of Photogrammetry, Remote Sensing and Spatial Information Sciences: Germany. 555-560. https://doi.org/10.5194/isprsarchives-XL-5-W2-555-2013

Sathian, K. 2005. Visual Cortical Activity during Tactile Perception in the Sighted and the Visually Deprived. *Developmental Psychobiology*, 46: 279-286.

Sathian, K and Stilla, R. 2010. Cross-modal plasticity of tactile perception in blindness. *Restorative Neurology and Neuroscience.* 28: 271-281.

Sauerwein, E, Bailom, F, Matzler, K and Hinterhuber, HH. 1996. The Kano Model: How to delight your Customers. Available at: https://www.researchgate.net/publication/240462191_The_Kano_Model_How_to_Delight_Your_Customers. [Last Accessed: 04/03/2019].

Saunders, M, Lewis, P and Thornhill, A. 2012. Research Methods for Business Students. Pearson Education ltd: England. 6th Edition.

Sauro, J and Lewis, JR. 2012. Quantifying the User Experience: Practical Statistics for User Research. Elsevier: Amsterdam. https://doi.org/10.1016/B978-0-12-384968-7.00002-3

Schifferstein, HNJ. 2010. From salad to bowl: The role of sensory analysis in product experience research. *Food Quality and Preference*, 21: 1059-1067. https://doi.org/10.1016/j.foodqual.2010.07.007

Schorch, P. 2014. Cultural feelings and the making of meaning. *International Journal of Heritage Studies*, 20: 22-35. https://doi.org/10.1080/13527258.2012.709194

Schorch, P. 2015. Museum Encounters and Narrative Engagements. In: A Witcomb, K Message. (eds.). The International Handbook of Museum Studies: Museum Theory. John Wiley & Sons: Chichester. 437-457. https://doi.org/10.1002/9781118829059.wbihms121

Schilling, R, Jastram, B, Wings, O, Schwarz-Wings, D and Issever, AS. 2013. Reviving the Dinosaur: Virtual Reconstruction and Three-dimensional Printing of a Dinosaur. *Radiology*, 270: 864-871. https://doi.org/10.1148/radiol.13130666

Schwandt, H and Weinhold, J. 2014. 3D Technologies for Museums in Berlin. In: G Diprose, JP Bowen, N Lambert (eds.). Electronic Visualization and the Arts. EVA London 2014. BCS: London. 255- 261. https://doi.org/10.14236/ewic/eva2014.30

Scopigno, R, Cignoni, P, Pietroni, N, Callieri, M and Dellepiane, M. 2014. Digital Fabrication Technologies for Cultural Heritage (STAR). In: R Klein, P Santos (eds.). Proceedings of the Eurographics Workshop on Graphics and Cultural Heritage. Eurographics Association: Switzerland. 75-85.

Scopigno, R, Cignoni, P, Pietroni, N, Callieri, M and Dellepiane, M. 2017. Digital Fabrication Techniques for Cultural Heritage: A Survey. *Computer Graphics Forum*, 36: 6-21. https://doi.org/10.1111/cgf.12781

Seales, WB, Griffioen, J, Baumann, R and Field, M. 2010. Analysis of Herculaneum Papyri with X-Ray Computed tomography. 10th International Conference on Non-destructive Investigations and microanalysis for the Diagnostic and Conservation of Cultural and Environmental Heritage. Florence, Italy, 13th-15th Apr, 2010.

Senesi, GS, Allegretta, I, Porfido, C, De Pascale, O and Terzano, R. 2017. Application of micro X-ray fluorescence and micro computed tomography to the study of laser cleaning efficiency on limestone monuments covered by black crusts. *Talanta*, 178: 419-425. https://doi.org/10.1016/j.talanta.2017.09.048

Seppälä, K, Heimo, O, Korkalainen, T, Pääkylä, J, Latvala, J, Helle, S, Härkänen, L, Jokela, S, Järvenpää, L and Saukko, F. 2017. Examining User Experience in an Augmented Reality Adventure Game: Case Luostarinmäki Handicrafts Museum. In: D Kreps, G Fletcher, M Griffiths (eds.). Technology and Intimacy: Choice or Coercion. 12th IFIP TC 9 International

Conference on Human Choice and Computers, HCC12 2016. Springer: Switzerland. 257-276. https://doi.org/10.1007/978-3-319-44805-3_21

Shah, NFMN and Ghazali, M. 2018. A Systematic Review on Digital Technology for Enhancing User Experience in Museums. In: N Abdullah, WAW Adnan, M Foth (eds.). i-USEr 2018: User Science and Engineering. Springer: Switzerland. 35-46. https://doi.org/10.1007/978-981-13-1628-9_4

Sharp, A, Thomson, L, Chatterjee, HJ and Hannan, L. 2015. The Value of Object-Based Learning within and between Higher Education Disciplines. In: HJ Chatterjee, L Hannan (eds.). Engaging the Senses: Object-Based Learning in Higher Education. Ashgate Publishing ltd.: Surrey. 97-116.

Short, DB. 2015. Use of 3D Printing by Museums: Educational Exhibits, Artifact Education and Artifact Restoration. *3D printing and Additive Manufacturing*, 2: https://doi.org/10.1089/3dp.2015.0030

Sirr, SA and Waddle, JR. 1999. Use of CT in Detection of Internal Damage and Repair and Determination of Authenticity in High-Quality Bowed Stringed Instruments. *RadioGraphics*, 19: 639-646. https://doi.org/10.1148/radiographics.19.3.g99ma09639

Sketchfab. 2018. The British Museum: A museum of the world, for the world. Available Online: https://sketchfab.com/britishmuseum. [Last Accessed: 20/06/2018].

Slater, SF and Narver, JC. 2000. The Positive effect of a Market Orientation on Business Profitability: A Balanced Replication. *Journal of Business Research*, 48: 69-73. https://doi.org/10.1016/S0148-2963(98)00077-0

Small, J, Darcy, S and Packer, T. 2012. The embodied tourist experiences of people with vision impairment: Management implications beyond the visual gaze. *Tourism Management*, 33: 941-950. https://doi.org/10.1016/j.tourman.2011.09.015

Smith, CS. 1989. Museum, Artefacts, and Meanings. In: P Vergo (ed.). The New Museology. Reaktion Books ltd: London. 6-40.

Smith, L. 2015. Theorizing Museum and Heritage Visiting. In: A Witcomb, K Message (eds.). The International Handbooks of Museum Studies: Museum Theory. John Wiley & Sons: Chichester. 459-484. https://doi.org/10.1002/9781118829059.wbihms122

Smithsonian. 2018a. Smithsonian X 3D Database. Available Online: https://3d.si.edu/. [Last Accessed: 20/06/2018].

Smithsonian. 2018b. Smithsonian Guidelines for Accessible Exhibition Design: Smithsonian Accessibility Program. Smithsonian Institution: Washington DC.

SMMT. 2018. SMMT Motor Industry Facts 2018. Available at: https://www.smmt.co.uk/wp-content/uploads/sites/2/SMMT-Motor-Industry-Facts-June-2018.pdf. [Last Accessed: 04/03/2019].

Sodini, N, Dreossi, D, Chen, R, Fioravanti, M, Giordano, A, Herrestal, P, Rigon, L and Zanini F. 2012. Non-invasive microstructural analysis of bowed stringed instruments with synchrotron radiation X-ray microtomography. *Journal of Cultural Heritage*, 135: 544-549. https://doi.org/10.1016/j.culher.2012.04.008

Soile, S, Adam, K, Ioannidis, C and Georgopoulos, A. 2013. Accurate 3D textured models of vessels for the improvement of the educational tools of a museum. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, XL-5/W1: 221-217. https://doi.org/10.5194/isprsarchives-XL-5-W1-211-2013

Solima, L and Tani, M. 2016. Do Not Touch! How 3D Printing can open the way to an accessible museum. XXVIII Convegno Annuale di Sinergie: Management in a Digital World: Decisions, Production, Communication. Udine, Italy, 9 – 10 June, 2016.

Solway, R, Thompson, L, Camic, PM and Chatterjee, HJ. 2018. Museum object handling groups in older adult mental health inpatient care. *International Journal of Mental Health Protection*, 17: 201-214. https://doi.org/10.1080/14623730.2015.1035520

Spence, C and Gallace, A. 2008. Making Sense of Touch. In: HJ Chatterjee (ed.). Touch in Museums: Policy and Practice in Object Handling. Berg: Oxford. 21-40.

Sportun, S. 2014. The Future Landscape of 3D in Museums. In: N Levent, A Pascual-Leone (eds.). The Multisensory Museum: Cross-disciplinary Perspectives on Touch, Sound, Smell, Memory and Space. Rowman and Littlefield: Plymouth. 331-340.

Staatliche Museen zu Berlin. 2018. Gipsformerei. Available at: https://www.smb.museum/en/museums-institutions/gipsformerei/craft/moulding-techniques.html. [Last Accessed: 07/01/2019].

Stanco, F, Tanasi, D, Allegra, D, Milotta, FLM and Lamagna, G. 2017. Virtual Anastylosis of Greek Sculpture as Museum Policy for Public Outreach and Cognitive Accessibility. *Journal of Electronic Imaging*, 26: 011025. https://doi.org/10.1117/1.JEI.26.1.011025

Statista. 2019. Number of cars sold worldwide from 1990 to 2019 (in million units). Available at: https://www.statista.com/statistics/200002/international-car-sales-since-1990/. [Last Accessed: 04/03/2019].

Stelzner, J, Ebinger-Rist, N, Peek, C and Schillinger, B. 2010. The application of 3D computed tomography with X-rays and neutrons to visualize archaeological objects in blocks of soil. *Studies in Conservation*, 55: 95-106. https://doi.org/10.1179/sic.2010.55.2.95

Stevenson, RJ. 2014. The Forgotten Sense: Using Olfaction in a Museum Context: A Neuroscience Perspective. In: N Levent, A Pascual-Leone (eds.). The Multisensory Museum: Cross-disciplinary Perspectives on Touch, Sound, Smell, Memory and Space. Rowman and Littlefield: Plymouth. 151-166.

Stone, R. 2000. Altering the Past: China's Faked Fossils Problem. *Science*, 330: 1740-1741. https://doi.org/10.1126/science.330.6012.1740

Story, MF. 1998. Maximizing Usability: The Principles of Universal Design. *Assistive Technology*, 10: 4-12. https://doi.org/10.1080/10400435.1998.10131955

Sully, D. 2015. Conservation theory and practice: materials, values and people in heritage conservation. In: C McCarthy (ed.). The International Handbook of Museum Studies: Museum Practice. John Wiley & Sons: Chichester. 293-314. https://doi.org/10.1002/9781118829059.wbihms988

Talboys, GK. 2011. Museum Educator's Handbook. Ashgate: Farnham. 3rd Edition.

Tam, CO. 2015. Three Cases of using Object-Based Learning with University Students: A Comparison of their Rationales, Impact and Effectiveness. In: HJ Chatterjee, L Hannan (eds.). Engaging the Senses: Object-Based Learning in Higher Education. Ashgate Publishing ltd.: Surrey. 117-132.

Tanja, K, Ozretic-Dosen, D and Skare, V. 2017. Understanding competition and service offer in museum marketing. *Academia Revista Latinoamericana de Administración*, 30: 215-230. https://doi.org/10.1108/ARLA-07-2015-0159

Tashakkori, A and Creswell, JW. 2007. Exploring the Nature of Research Questions in Mixed-methods Research. *Journal of Mixed-Methods Research*, 1: 207-211. https://doi.org/10.1177/1558689807302814

Tavakol, M and Dennick, R. 2011. Making sense of Cronbach's alpha. *International Journal of Medical Education*, 2: 53-55. https://doi.org/10.5116/ijme.4dfb.8dfd

Taylor, J and Watkinson, D. 2007. Indexing Reliability for Condition Survey Data. *The Conservator*, 30: 49-62. https://doi.org/10.1080/01410096.2007.9995223

Tembe, G and Siddiqui, S. 2014. Applications of Computed Tomography to Fossil Conservation and Education. *Collection Forum*, 28: 47-62. https://doi.org/10.14351/0831-4985-28.1.47

Teshima, Y, Matsuoka, A, Fujiyoshi, M, Ikegami, Y, Kaneko, T, Oouchi, S, Watanabe, Y and Yamazawa, K. 2010. Enlarged Skeletong Models of Plankton for Tactile Teaching. In: K Miesenberger, J Klaus, W Zagler, A Karshmer (eds.). Computers Helping People with Special

Needs. 12th International Conference, ICCHP 2010, Vienna, Austria, July 14-16, 2010, Proceedings, Part II. Springer: Berlin-Heidelberg. 523-526.

Themistocleus, K, Agapiou, A and Hadjimitsis, DG. 2016. Experiencing Cultural Heritage Sites using 3D Modeling for the Visually Impaired. In: M Ioannides, E Fink, A Moropoulou, M Hagedorn-Saupe, A Fresa, G Liestøl, V Rajcic and P Grussenmeyer (eds.). Digital Heritage. Progress in Cultural Heritage: Documentation, Preservation and Protection. Springer: Switzerland. 171-177.

Thomas, DR. 2006. A General Inductive Approach for Analysing Qualitative Evaluation Data. *American Journal of Evaluation*, 27: 237-246. https://doi.org/10.1177/1098214005283748

Tiballi, A. 2015. Engaging the Past: Haptics and Object-Based Learning in Multiple Dimensions. In: HJ Chatterjee, L Hannan (eds.). Engaging the Senses: Object-Based Learning in Higher Education. Ashgate Publishing ltd.: Surrey. 57-75.

Teddlie, C. and Tashakkori A. 2009. Foundations of Mixed-methods Research: Integrating Quantitative and Qualitative Approaches in the Social and Behavioral Sciences. Sage: California.

Torabi, K, Farjood, E and Hamedani, S. 2015. Rapid Prototyping Technologies and their Application in Prosthodontics, a Review of Literature. *Journal of Dentistry, Shiraz University of Medical Sciences*, 16: 1-9.

Tucci, G, Bonora, V, Conti, A and Fiorini, F. 2017. High-Quality 3D Models and their use in a Cultural Heritage Conservation Project. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, XLII: W5. https://doi.org/10.5194/isprs-archives-XLII-2-W5-687-2017

Turner, H, Resch, G, Soutwick, D, McEven, R, Dube, AK, Record, I. 2017. Using 3D Printing to Enhance Understanding and Engagement with Young Audiences: Lessons from Workshops in a Museum. *Curator: the Museum Journal*, 60: 311-333. https://doi.org/10.1111/cura.12224

Udo, JP and Fels, DI. 2010. Enhancing the entertainment experience of blind and low-vision theatregoers through touch tours. *Disability & Society*, 25: 231-240. https://doi.org/10.1080/09687590903537497

United Nations. 2008. Convention of the Rights of Persons with Disabilities (CRPD). Available at: https://www.un.org/development/desa/disabilities/convention-on-the-rights-of-persons-with-disabilities.html [Last Accessed: 19/10/2018].

Urbas, R, Pivar, M and Elesini US. 2016. Development of tactile floor plan for the blind and the visually impaired by 3D printing technique. *Journal of Graphic Engineering and Design*, 7: 19-26. https://doi.org/10.24867/JGED-2016-1-019

Vaismoradi, M, Turunen, H and Bondas, T. 2013. Content analysis and thematic analysis: Implications for conducting a qualitative descriptive study. *Nursing and Health Sciences*, 15: 398-405. https://doi.org/10.1111/nhs.12048

Vanderploeg, A, Lee, SE and Mamp, M. 2016. The application of 3D printing technology in the fashion industry. *International Journal of Fashion Design, Technology and Education*, 10: 170-179. https://doi.org/10.1080/17543266.2016.1223355

Van der Snickt, G, Martins, A, Delaney, J, Janssens, K, Zeibel, J, Duffy, M, McGlinchey, C, Van Driel, B and Dik, J. 2016. Exploring a Hidden painting Below the Surface of René Magritte's *Le Portrait*. *Applied Spectroscopy*, 70: 57-67. https://doi.org/10.1177/0003702815617123

Vavřik, D, Kumpová, I, Vopálensky, M and Lautenkranc, J. 2017Analysis of Baroque Sculpture Based on X-Ray Fluorescence Imaging and X-ray Computed Tomography Data Fusion. 7th Conference on Industrial Computed Tomography, Leuven: Belgium, 7-9 Feb 2017.

Vi, CT, Ablart, D, Gatti E, Velasco, C and Obrist, M. 2017. Not just seeing, but also feeling art: Mid-air haptic experiences integrated in a multisensory art exhibition. *International Journal of Human-Computer Studies*, 108: 1-14. https://doi.org/10.1016/j.ijhcs.2017.06.004

VisitBritain. 2018. Annual Survey of Visits to Visitor Attractions: Latest results. Available at: https://www.visitbritain.org/annual-survey-visits-visitor-attractions-latest-results. [Last Accessed: 23/03/2019].

VisitBritain. 2019. 2019 Inbound Tourism Forecast. Available at: https://www.visitbritain.org/2019-inbound-tourism-forecast. [Last Accessed: 23/3/2019].

vom Lehn, D and Heath, C. 2016. Action at the exhibit face: video and the analysis of social interaction in museums and galleries. *Journal of Marketing Management*, 32: 1441-1457. https://doi.org/10.1080/0267257X.2016.1188846

Voss, P. 2011. Superior Tactile Abilities in the Blind: Is Blindness Required? *The Journal of Neuroscience*, 31: 11745-11747. https://doi.org/10.1523/JNEUROSCI.2624-11.2011

Voss, P, Alary, F, Lazzouni, L, Chapman, CE, Goldstein, R, Bourgoin, P and Lepore, F. 2016. Crossmodal Processing of Haptic Inputs in Sighted and Blind Individuals. *Frontiers in Systems Neuroscience*, 10: doi: 10.3389/fnsys.2016.00062. https://doi.org/10.3389/fnsys.2016.00062

Vredenberg, K, Isensee, S and Righi, C. 2002. User-Centred Design: An Integrated Approach. Prentice Hall PTC: New Jersey.

Walter, P, Sarrazin, P, Gailhanou, M, Hérouard, D, Verney, A and Blake, D. 2018. Full-field XRF instrument for cultural heritage: Application to the study of a Caillebotte painting. *X-Ray Spectrometry*, https://doi.org/10.1002/xrs.2841

Wang, X. 2013. Mortgaging the future of Chinese paleontology. *Proceedings of the National Academy of Sciences*, 110: 3201. https://doi.org/10.1073/pnas.1301429110

Ward, J. 2014. Multisensory Memories: How Richer Experiences Facilitate Remembering. In: N Levent, A Pascual-Leone (eds.). The Multisensory Museum: Cross-disciplinary Perspectives on Touch, Sound, Smell, Memory and Space. Rowman and Littlefield: Plymouth. 273-284.

Warnett, JM, Titarenko, V, Kiraci, E, Attridge, A, Lionheart, WRB, Withers, PJ and Williams, MA. 2015. Towards in-process x-ray CT for dimensional metrology. *Measurement Science and Technology*, 27: 1-14. https://doi.org/10.1088/0957-0233/27/3/035401

Wehner, K. and Sear, M. 2010. Engaging the Material World: Object knowledge and *Australian Journeys*. In: SH Dudley (ed.). Museum Materialities: Objects, Engagements, Interpretations. Routledge, Oxon. 143-161.

Weisen, M. 2008. How accessible are museums today? In: HJ Chatterjee (ed.) Touch in museums: Policy and Practice in Object Handling. Berg: Oxford. 243-252.

Wellings, T, Williams, MA and Pitts, M. 2008. Customer perception of switch-feel in luxury sports utility vehicles. *Food Quality and Preference*, 19: 737-746. https://doi.org/10.1016/j.foodqual.2008.03.004

Wellings, T, Williams, MA and Tennant, C. 2010. Understanding customer's holistic perception of switches in automotive human-machine interfaces. *Applied Ergonomics*, 41: 8-17. https://doi.org/10.1016/j.apergo.2009.03.004

Wellings, T, Pitts, MJ and Williams, MA. 2012. Characterizing the experience of interaction: an evaluation of automotive rotary dials. *Ergonomics*, 55: 1298-1315. https://doi.org/10.1080/00140139.2012.708057

White, RH. 2013. Resolving the Carving: The Application of Laser Scanning in Reconstructing a Viking Cross from Neston, Cheshire. In: E Ch'ng, V Gaffney, Chapman (eds.). Visual Heritage in the Digital Age. Visual Heritage in the Digital Age. Springer: London. 33-42. https://doi.org/10.1007/978-1-4471-5535-5_3

Whitehead, D and Schneider, Z. 2012. Mixed-methods research. In: Z Schneider, D Whitehead, G LoBiondo-Wood, J Haber (eds.). Nursing and Midwifery Research: Methods and Appraisal for Evidence Based Practice. Elsevier: Australia. 4th Edition.

WHO. 2018. ICD-11 for Mortality and Morbidity Statistics. Available at: https://icd.who.int/browse11/l-m/en [Last Accessed: 19/10/2018].

Willcocks, J. 2015. The Power of Concrete Experience: Museum Collections, Touch and Meaning Making in Art and Design Pedagogy. In: HJ Chatterjee, L Hannan (eds.). Engaging the Senses: Object-Based Learning in Higher Education. Ashgate Publishing: Surrey. 42-56.

Wilson, P, Williams, MA, Warnett, JM, Attridge, A, Ketchum, H, Hay, J, Smith, MP. 2017a. Utilizing X-Ray Computed Tomography for heritage conservation: the case of *Megalosaurus bucklandii*. I2MTC 2017 IEEE International Instrumentation and Measurement Technology Conference, Torino, Italy, 22-25 May, 2017. https://doi.org/10.1109/I2MTC.2017.7969983

Wilson, P, Stott, J, Warnett, JM, Attridge, Smith, MP and Williams, MA. 2017b. Evaluation of Tangible 3D-Printed Replicas in Museums. *Curator: the Museum Journal*, 60: 445-465. https://doi.org/10.1111/cura.12244

Wilson, PF, Stott, J, Warnett, JM, Attridge, A, Smith, MP and Williams MA. 2018a. Museum Visitor Preference for the Physical Properties of 3D Printed Replicas. *Journal of Cultural Heritage*, 32: 176-185. https://doi.org/10.1016/j.culher.2018.02.002

Wilson, PF, Smith, MP, Hay, J, Warnett, JM, Attridge, A and Williams, MA. 2018b. X-ray computed tomography (XCT) and chemical analysis (EDX and XRF) used in conjunction for cultural heritage conservation: the case of the earliest scientifically described dinosaur *Megalosaurus bucklandii*. *Heritage Science*, 6: 58. https://doi.org/10.1186/s40494-018-0223-0

Witcomb, A. 2006. Interactivity: Thinking Beyond. In: S MacDonald (ed.) A Companion to Museum Studies. Blackwell Publishing ltd: Oxford. 353-361. https://doi.org/10.1111/b.9781405108393.2006.00027.x

Witcomb, A. 2015. Toward a pedagogy of feeling: Understanding How Museums Create a Space for Cross-Cultural Encounters. In: A Witcomb, K Message (eds.). The International Handbooks of Museum Studies: Museum Theory. John Wiley & Sons: Chichester. 321-324. https://doi.org/10.1002/9781118829059.wbihms116

Wu, P, Wu, X, Jiang, TX, Elsey, RM, Temple, BL, Divers, SJ, Glenn, TC, Yuan, K, Chen, MH, Widelitz, RB and Chuong, CM. 2013. Specialised stem cell niche enables repetitive renewal of alligator teeth. *Proceedings of the National Academy of Sciences*, 110: E2009-E2018. https://doi.org/10.1073/pnas.1213202110

XYZPrinting. 2018. Da Vinci Color. Available at: https://www.xyzprinting.com/en-GB/product/da-vinci-color. [Last Accessed: 19/10/2018].

Yin, RY. 2018. Case Study Research Design and Methods. Sage: California. 6th Edition.

Yong, AG and Pearce, S. 2013. A Beginner's Guide to Factor Analysis: Focusing on Exploratory Factor Analysis. *Tutorials in Quantitative Methods for Psychology*, 9: 79-94. https://doi.org/10.20982/tqmp.09.2.p079

Yoon, SA, Wang, J and Elinich, K. 2014. Augmented Reality and Learning in Science Museum. In: DG Sampson, D Ifenhaler, JM Spector, P Isaias (eds.). Digital Systems for Open Access to Formal and Informal Learning. Springer International Publishing: Switzerland. 293-305. https://doi.org/10.1007/978-3-319-02264-2_18

Younan, S. 2015. Poaching Museum Collections Using Digital 3D technologies. *CITAR Journal*, 7: 25-32. https://doi.org/10.7559/citarj.v7i2.152

Yu, N and Kong, J. User experience with web browsing on small screens: Experimental investigations of mobile-page interface design and homepage design for news websites. *Information Sciences*, 330: 427-443. https://doi.org/10.1016/j.ins.2015.06.004

Zheng, P, Yu, S, Wang, Y, Zhong, RY and Xu, X. 2017. User-experience based product development for mass personalization: a case study. *Procedia CIRP*, 63: 2-7. https://doi.org/10.1016/j.procir.2017.03.122

Zhou, K, Liao, J and Zhou, X. 2018. Counterfeiting ancient Chinese Armour using 3D-printing technology. *Multimedia Tools and Applications*, https://doi.org/10.1007/s11042-018-6462-y.

11.A APPENDIX A: INTERVIEW SCHEDULE USED IN CHAPTER 4 INTERVIEWS

Version 1.4.2 07/02/2017

Interview Schedule for Chapter 4 Interviews

This document provides a schedule to be adhered to during the process of carrying out an interview with a participant in order to ensure that the process between participants is coherent and reliable. Major questions will be repeated verbatim. Some deviation may be expected based upon the needs or direction of the participant, but the overall structure should remain consistent.

I. **Opening Statements**

A. (*Greetings and Introduction*) [Shake Hands] Hello there. My name is Paul Wilson and I am a PhD student from the University of Warwick carrying out research trying to find out what members of the public think about the introduction of touchable 3D printed replicas in the Museum.

B. (*Stating the Purpose*) If you have some spare time, I would like to ask you some questions about what you know about 3D printing and gather some of your opinions about whether 3D printed objects can be a part of the museum experience.

C. (*Motivation*) The primary motivation of this is to help inform us how museums exploiting the power of 3D printing can best make use of them.

D. (*Asking and Time Constraints*) Would you like to take part? The process shouldn't take too long and should take between 10-15 minutes.

[On Acceptance, the interview process proceeds as follows]

II. **Pre-Interview**

A. (*Thanks and Outline*) Thank you for participating. I have here an information sheet for you to take with you that will provide a bit more information [Pass over Numbered Information Sheet]. As I said earlier, I am working with the University of Warwick and the Oxford Natural History Museum to look at the potential of introducing touchable 3D prints into the museum and whether or not our visitors think they can benefit their experience.

B. (*Interview Process*) I'll run through the interview structure now. First of all, I will ask you some questions on what you know about 3D printing. Then I'll let you have a go at handling them and let you ask any questions. After that, there will be a few more closing questions on what you think about 3D printing and the museum, after which we will be done. Do you have any questions about the overall interview process?

C. (*Consent and Ethical Requirements*) Excellent. Before we begin there are a few things to care of. First of all, I'll need you to sign these two consent forms, one of which will be retained by me and the other by you. Please fill in this consent form [Hand over consent form] and sign and date them down the bottom if you would. Would you like me to read through the statements with you?

The interview will be recorded using this device [Gesture to Device], provided you have checked the option for doing so. Any audio recordings we make will be transcripted onto paper. Do you have any further questions?

D. (*Wrap-up*) Good stuff. Now let's move on to the interview.

[Setup and Ensure Audio-Equipment is working if used.]

III. Interview Pt. 1

A. **Question 1:** What do you know about 3D printing? [Optional Probe: Do you know anything about how it works?/So you would say that you are an expert?/Have you ever heard of it?]

So, 3D printing is the process by which we can turn a digital file into a 3D physical objects. The process is quite simple, and involves dividing an object up into layers, like so [using prop], and then laying down each layer on top of the other additively until the entire shape is made. It's as simple as that.

B. **Question 2:** Have you ever encountered touchable 3D printed replicas within a museum exhibition before? [Probe: Tell me more about it/Where did you see it?].

C. (*Introduction of Specimen*) So, here we have a 3D print of a very special fossil called *Phascolotherium bucklandii*. This is one of the oldest and most precious fossils here in this Museum and, as you can see from this image, represents the lower jawbone of one of the very first ancient mammals ever found in the fossil record. It is also one of the oldest, which makes it an important specimen for studying the history of mammals. Because the specimen is so important however, it is kept in conditioned cupboards away in the back of the museum where it is safe, which makes it difficult to show to our visitors. Fortunately, 3D printing can come to the rescue! Here we have a 3D print of the jaw, scaled up so that you can see all of the detail and a cast of the original specimen treated to look exactly like the original.

[Give Print to Participant to interact with halfway and through rest of dialog].

D. Now, I have several other prints for you to have a look at [Bring out the remaining 3D prints], all of the same *Phascolotherium* specimen.

[Discussion with Participants]

IV. Interview Pt. 2

A. Thank you for that, now we'll move onto the final stage of the interview. I'm going to ask you some questions with regard to 3D printing and your personal opinions on the subject.

B. **Question 3:** Do you think handling 3D prints like these could enhance your museum experience? [Probe: What in particular do you think they would add?]

D. **Question 4:** Do you think that touchable 3D printed replicas like these should be present in more museums? [Probe: Why do you think that?]

E. **Question 5:** Would the opportunity to handle such 3D printed replicas encourage you to visit museums more or less often? [Probe: Why would it?]

F. **Question 6:** Earlier I asked you about why you came to the museum today. Do you feel that interacting with 3D prints like these could help you to achieve you set out to do? [Probe: Would they make your visit worth it?]

V. Closing Statements

A. (*Closing Statements*) Excellent, thank you very much for your time and effort. Your insights will be extremely valuable to the museum and my research. Before we close, do you have any additional comments for any of the print that you would like to add? [Get record of comments made by participant and answer any questions].

B. Excellent. Thank you very much once again, it's been a pleasure. [Shake hands once more]. Remember to take your information sheet and consent form with you. If you have any more questions or queries, feel free to contact me using the details on the information sheet. Enjoy your time at the museum.

[End of Interview Procedure]

11.B APPENDIX B: GUIDED QUESTIONNAIRES USED IN CHAPTER 5

First page

No.

11.B Appendix B: Semantic Differential Questionnaire for Phase 2

Version 1.1.0
Version Date: 14/06/17

HOW TO USE: Please place an X mark along each bar for each 3D print presented to you, matching how you personally think that the object looks or feels between those two words.

Each end point represents the extreme of the word associated with it, with the mid-point being the neutral point in between the words.

EXAMPLE: Barry is asked to rate a block of ice, finding it very cold. On the Cool - Warm scale, he decides to mark the scale very near the Cool end to reflect this.

Cool |X———|———| Warm

Repeat this for each scale for each print on both sides of the Worksheet.

Q1: Please Rate Each of the Six Prints Presented to you in its respective Box:

Print 1: Clear Resin

Good Quality	|———|———|	Bad Quality	Durable	|———|———|	Brittle
Clear	|———|———|	Unclear	Smooth	|———|———|	Rough
Expensive	|———|———|	Cheap	Glossy	|———|———|	Matte
Soft	|———|———|	Hard	Realistic	|———|———|	Unrealistic
Heavy	|———|———|	Light	Detailed	|———|———|	Undetailed
Weak	|———|———|	Strong	Boring	|———|———|	Interesting

Print 2: Colour Sandstone

Good Quality	|———|———|	Bad Quality	Durable	|———|———|	Brittle
Clear	|———|———|	Unclear	Smooth	|———|———|	Rough
Expensive	|———|———|	Cheap	Glossy	|———|———|	Matte
Soft	|———|———|	Hard	Realistic	|———|———|	Unrealistic
Heavy	|———|———|	Light	Detailed	|———|———|	Undetailed
Weak	|———|———|	Strong	Boring	|———|———|	Interesting

Print 3: Painted Resin

Good Quality	|———|———|	Bad Quality	Durable	|———|———|	Brittle
Clear	|———|———|	Unclear	Smooth	|———|———|	Rough
Expensive	|———|———|	Cheap	Glossy	|———|———|	Matte
Soft	|———|———|	Hard	Realistic	|———|———|	Unrealistic
Heavy	|———|———|	Light	Detailed	|———|———|	Undetailed
Weak	|———|———|	Strong	Boring	|———|———|	Interesting

Second page

Print 4: White Resin

Good Quality		Bad Quality	Durable		Brittle
Clear		Unclear	Smooth		Rough
Expensive		Cheap	Glossy		Matte
Soft		Hard	Realistic		Unrealistic
Heavy		Light	Detailed		Undetailed
Weak		Strong	Boring		Interesting

Print 5: Blue Plastic

Good Quality		Bad Quality	Durable		Brittle
Clear		Unclear	Smooth		Rough
Expensive		Cheap	Glossy		Matte
Soft		Hard	Realistic		Unrealistic
Heavy		Light	Detailed		Undetailed
Weak		Strong	Boring		Interesting

Print 6: Stainless Steel

Good Quality		Bad Quality	Durable		Brittle
Clear		Unclear	Smooth		Rough
Expensive		Cheap	Glossy		Matte
Soft		Hard	Realistic		Unrealistic
Heavy		Light	Detailed		Undetailed
Weak		Strong	Boring		Interesting

Q2: Please Rank each Print in the Order that you would prefer to see them in a Museum Exhibition as a touchable component:

Please Tick One Box per Print

	Not Preferred — Preferred
Clear Resin	
Colour Sandstone	
Painted Resin	
White Resin	
Blue Plastic	
Stainless Steel	

Q2a: Why would you prefer to see the print you most preferred?: ____________________

Q2b: Why would you not prefer to see the print you least preferred ?: ____________________

11.C APPENDIX C: INTERVIEW SCHEDULE USED IN CHAPTER 6 INTERVIEWS

Version 1.0.2 09/04/2018

Interview Schedule for Chapter 6 Interviews

This document provides a schedule to be adhered to during the process of carrying out an interview with a participant in order to ensure that the process between participants is coherent and reliable. Some deviation may be expected based upon the needs or direction of the participant, but the overall structure should remain consistent.

I. **Opening Statements**

A. (*Greetings and Introduction*) [Shake Hands] Hello there. My name is Paul Wilson and I am a PhD student from the University of Warwick carrying out research into how the museum can best provide for blind and partially sighted people.

B. (*Stating the Purpose*) What we would like to know is what blind and partially sighted people can perceive with touch when it comes to museums objects, so that we can both choose objects that are more easily interpretable and help to inform exhibition designers about the best ways to incorporate content for visitors who are blind and partially-sighted within the museum.

C. (*Motivation*) We intend to use the information you give us to help make museums more accessible for the blind and partially sighted and also improve the design of our installations here at the museum.

D. (*Asking and Time Constraints*) Would you like to take part? The process should take up to 30 minutes total.

[On Acceptance, the interview process proceeds as follows]

II. **Pre-Interview**

A. (*Thanks and Outline*) Thank you for participating. I have here an information sheet for you to take with you that will provide a bit more information [gesture to Numbered Information Sheet]. As I said earlier, I am working with the University of Warwick and the Oxford Natural History Museum to look at what our visitors who are blind or partially sighted can perceive. As we're working with Natural History here, I have several different natural objects that I am going to ask you to handle.

B. (*Interview Process*) Excellent. So, the plan is that I am going to give you each of the five objects I mentioned earlier in a specific order. I will present them to your hands directly, so don't worry about having to find anything.

For each of these I will ask you to describe the object, followed by a few questions about the object itself and what you think about it. We'll then repeat that for each of the five objects in turn. Once we've done that, we'll finish up with two questions about all of the objects, after which we'll be done. Does this sound satisfactory?

C. (*Consent and Ethical Requirements*) Excellent. Before we begin there are a few things to care of. First of all, are you able to provide written consent?:

- If YES, please have a read through the information sheet and ask questions as required. Once you are happy, please sign the consent form and provide demographics if you like. Once you are done, we'll get underway.

- If NO, we'll need to do things differently. We'll need to get verbal consent from you. Simply put, I'll read you the Information Sheet and you will have the opportunity to ask questions as you like, feel free to interrupt as needed. After that, I'll read you through each point of consent and I'd like to say Yes if you Agree, and No if you don't.

Additionally, we would like to record the interview via audio. You are well within your rights to object to this however, though we'll need to take notes. This will make the whole process longer. Any audio recordings we make will be transcripted onto paper and you may request to review a copy of these documents to ensure that you have not been misrepresented.

D. (*Wrap-up*) Good stuff. Now let's move on to the interview.

[Setup and Ensure Audio-Equipment is working if used and any other necessary peripherals]

III. **Object Description**

A. (Procedure) So, as I said earlier I'm going to present you with an object, and I am going to think aloud about it. Do you know what think aloud is? It's fairly simple. As you feel and explore the object, just say whatever comes to mind. I'd like you to describe the in terms of its features, shape, texture and material qualities in this manner. Do not attempt to name the object or what you think it is made of at this point. Then I will ask you a few other questions about the object and we'll repeat with the next one for five total objects. Does this make sense to you?

B. (First Object) [First object in a random list is presented]

Question 1: (Think Aloud) Could you please describe this object while thinking aloud, focusing on how it's features, shape, texture and material properties? **Do not attempt to name it yet, there will be time for that later**. [Probes:

- Describe the texture of the object? Does it feel soft of rough?
- Is that texture uniform?
- Are there any prominent features on the top or bottom?
- Can you feel any smaller structures?
- Can you feel any ridges or bumps?
- Describe the outline of the shape.
- Can you feel anything inside the object?
- What about the weight of it? Does the weight fit its size and shape?
- How hard is the object? Give it a press/squeeze]

Question 2: What do you think the object is made of? What is leading you to that conclusion?

Question 3: What do you think the object is? What is leading you to that conclusion?

[Interviewer describes the object to the participant what the object is and features that they may have missed.]

Question 4: If you could change anything about this object to help you better understand and perceive it, what would you change?

C. (Repeat with Next Randomised Object) Repeat until all five objects have been described and evaluated).

IV. **Finishing Questions**

A. (Overview) Before we finish, I would like to ask you a few questions about all of the objects in general.

B. (Questions)

Question 5: (Question) Which object was easiest for you to perceive and understand? Why?

Question 6: (Question) Which object was most difficult for you to perceive and understand? Why?

D. (*Closing Statements*) Excellent, thank you very much for your time and effort. Your insights will be extremely valuable to the museum and my research and hopefully will allow us to make museums a better place for visitors who are blind or partially sighted. Before we close, do you have any additional comments that you would like to make? [Get record of comments made by participant and answer any questions].

E. Excellent. Thank you very much once again, it's been a pleasure. [Shake hands once more]. Remember to take your information with you and I'll send you a copy of verbal consent if needed. If you have any more questions or queries, feel free to contact me using the details on the information sheet. You may also request a copy of the final report when it is published, which I will forward on to you at no cost.

[End of Interview Procedure]