TITLE: Evaluation of touchable 3D-printed replicas in museums

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ABSTRACT

The multisensory aspect of the museum, while neglected for many years, is undergoing a resurgence as museum workers have begun to push towards re-establishing the senses as a major component of museum pedagogy. However, for many museums a major roadblock lies in the need to conserve rare objects, a need that prevents visitors from being able to interact with many objects in a meaningful way. This issue can be potentially overcome by the rapidly evolving field of 3D printing, which allows museum visitors to handle authentic replicas without damaging the originals. However, little is known about how museum visitors consider this approach, how they understand it and whether these surrogates are welcome within museums. A front-end evaluation of this approach is presented, finding that visitors were enthusiastic about interacting with touchable 3D printed replicas, highlighting potential educational benefits among other considerations. Suggestions about the presentation of touchable 3D printed replicas are also discussed.

KEYWORDS

3D Printing, Heritage, Natural History, Exhibition Design, Multisensory, User Experience

INTRODUCTION

The idea of touch as a medium for display in the museum is typically associated with the forbidding signage found in nearly every museum around the world; ‘DO NOT TOUCH’ or ‘FRAGILE’, products of the ‘Glass-Case’ paradigm that dominates museum practice today (Dudley 2012). The reasons for this are understandable and well meaning; the preservation of cultural and natural heritage

for future generations to come, but it was not always this way. Archival records from the inception of the public museum over 300 years ago show that rich nobles were allowed to handle artefacts, a practice that faded into obscurity once public museums became accessible to citizens of all classes (Classen and Howes 2006; Candlin 2008; 2010). Combined with a hypothesized shift towards ocularcentrism associated with the rise of modernist scientific principles (Neumüller et al. 2014; Witcomb 2015), touch has become confined to the expert curator while the visitor is left to appreciate these objects of antiquity as best they can from afar. The situation has remained this way for some time, although the past two decades have seen a resurgence in effort to change the paradigm. Driven by a shift towards constructivist learning ideologies (Hooper-Greenhill 2007), many calls have been made to bring back the senses, particularly touch, into the exhibition space (Paris 2002; Pye 2008a; Chatterjee 2008; Levent and Pascual-Leone 2014). The reasons for this are readily apparent; many authors have noted that direct interaction with museum objects appears to encourage enjoyable and, most importantly, memorable lifelong experiences which mesh very well with the dominantly constructivist educational paradigm in the postmodern museum (Schorch 2014; Baker 2015; Dudley 2015; Bell 2016). As a result, multisensory experiences are becoming increasingly common in museums in the form of touch tours, exhibitions and handling sessions (Candlin 2010). Though scarce, published evaluations have showed these interventions to be extremely successful (Davidson et al. 1999; Kuo et al. 2016).

While this approach has been thoroughly embraced by science centres and children's museums, the fact remains for more traditional museums that multisensory interaction risks the precious objects that museums are charged with protecting and provides a barrier to this approach. Even where multisensory experiences have been exploited by these kind of museums they generally include objects or replicas made specifically for that exhibition or objects derived from teaching collections. While interesting in their own right, these objects lack the sense of awe that manifests itself in authentic objects of true antiquity (Spence and Gallace 2008; Hampp and Schwan 2015). Understandably this is to preserve these key objects from degradation for without the expert hand of the curator to supervise, the risk of damage is significant (Spence and Gallace 2008; Candlin 2010; Pilegaard 2015). Where objects are fragile the issue is even more prevalent as any handling or un-conditioned exposure could result in significant lasting damage. This produces something of a conundrum: how can we encourage multisensory experiences with significant historical objects when that risks their destruction?

One way of dealing with this issue through much of the history of museums has been the creation of authentic replicas, typically casts of original objects among other objects, used as a surrogate for handling, preserving the original object and for exhibitionary purposes (Hartfield 1994; Bohn 1999; Malenka, 2000; Bearman 2011; Eardley et al. 2016). This process, while producing accurate replicas are often difficult to distinguish from the originals, is also a labour-intensive approach that can be time-consuming and potentially costly (Lindsay et al. 1996; J. Hay, pers.

comm.). Moulding procedures are also risky, fragile items being likely to break during the moulding process if due care is not properly exercised. There is also a risk of silicones leaching into the specimen if it is not properly protected with in addition to the need for experienced workers familiar with the materials and processes (Goodwin and Chaney 1995; Monge and Mann 2004; Le Cabec and Toussaint 2017; J. Hay, pers. comm.). A more modern counterpart to this approach is that of 3D printing, where there has been an increase in build quality and falling costs over the past few decades. 3D printing is a term that describes a range of methods for producing a physical replica of a digital object in a wide array of materials via additively stacking layers of material on top of each other to create a three-dimensional object. Over the past few years it has risen to mainstream recognition and popularity through the media and is being exploited in a variety of business sectors, especially heritage (Metallo and Rossi 2011; Scopigno et al. 2014; 2017; D'Agnano et al. 2015). The major advantage of this approach is the ability to non-destructively sample objects; (using scanning methods such as x-ray computed tomography (Abel et al. 2011) and laser-scanning (Fantini 2008)) in order to create spatially and geometrically accurate replicas that are disposable and scalable in addition to their relative inexpense (Scopigno et al. 2014; D'Agnano et al. 2015). These touchable 3D printed replicas are already being used by museums for research (McKnight et al. 2015), repatriation (Cronin 2015), restoration (Laycock et al. 2015) and in exhibitions (Olson et al. 2014). They have also been used with increasing frequency for multisensory experiences with 3D printed replicas of historical objects for museum visitors (Capurro et al. 2014; Dima et al. 2014; D'Agnano et al. 2015; Marshall et al. 2016) although the number of studies that evaluate this latter approach is limited (Neumüller et al. 2014; Di Franco et al. 2015). To the authors' knowledge, research investigating how museum visitors interact and perceive such 3D printed replicas is thus limited and little is known about how museum visitors regard the idea of touchable 3D printed replicas.

In this paper, we present a front-end evaluation of touchable 3D printed replicas as a permanent fixture within the exhibition space. The study was carried out at Oxford University Museum of Natural History (OUMNH), a museum that already features permanent multisensory experiences that encourage museum visitors to interact directly with museum specimens. We evaluate this idea using short, semi-structured interviews paired with content analysis, communicating directly with museum visitors within the exhibition space in order to assess their opinions on the introduction of touchable 3D printed replicas into the museum.

METHODS AND MATERIALS

Materials

All of the materials used in this project are derived from the OUMNH specimen of the fossil mammal *Phascolotherium bucklandii* (OUMNH J.20077), which is a lower jawbone (Fig. 1). This specimen was transported to the X-Ray Computed Tomography (XCT) facilities at WMG - University of Warwick where it was scanned using a Zeiss XRadia 520 Versa CT scanner. XCT is a technique in

which an object is scanned in three-dimensions by firing X-rays from a source through the target object that are either attenuated or pass through and are received by a detector. This creates an X-ray intensity image or radiograph based upon the density of the object and its internal features. Radiographs of the object are taken at regular angular increments through 360º and reconstructed to create a three-dimensional volume. From this internal information can be extracted, making XCT an excellent methodology for inspecting specimens or objects buried within a matrix which are fragile and/or have a complex internal structure (Kumar et al. 2011; Wilson et al. 2017).

[Figure 1]

From the scan data, the *Phascolotherium* jaw was separated from the surrounding matrix via segmentation and a number of surface files were exported for 3D printing in a variety of materials (Mahindru and Mahendru 2013). 3D printing is the process by which a digital file is computationally divided into a series of layers that are additively stacked on top of each other to create an accurate physical model (Mahindru and Mahendru 2013; Torabi et al. 2015). Five 3D prints were created using different printing methods: Fusion Deposition Modelling (FDM), Powder-Based 3D Printing (3DP), Laser Sintering (LS) and Stereolithography (SL) (Torabi et al. 2015; Scopigno et al. 2017). These prints were used in the interview process and handled by participants before, during and after the interviews (Fig. 2).

[Figure 2]

Demographics

The demographics of the sampled participants can be found in Fig. 3. Of the 76 participants, the gender split is 58% Male (n = 44) to 42% Female (n = 32) (Fig. 3a). This may be indicative of males having a greater interest in the subject of touchable 3D prints and/or in the technology, but this aspect was out of the scope of the interview process.

Age ranges (Fig. 3b) show representation in all age categories, dominantly in the 08-17, 35-44 and 45-54 categories with 24% (n = 18), 30% (n = 23) and 20% (n = 15) respectively. Other age categories show smaller representation compared to these; 18-24 at 5% (n = 4), 25-34 at 8% (n = 6), 55-64 at 7% (n = 5) and 65+ at 7% (n = 5). As a result, the sample appears to lack thorough representation from young and older adults although this is likely in part due to the attraction of families towards the workshop format, while perhaps of less interest to other age categories.

[Figure 3]

Sampling and Data Collection

Sampling was undertaken using a convenience sampling approach, the interview process taking place within the main exhibition hall of the OUMNH in the form of a workshop-style set-up.

The principal researcher sat at this workshop and visitors who approached were told about the fossil specimen, *Phascolotherium bucklandii*, and were encouraged to handle the 3D prints in addition to a plaster cast of the original. Visitors who showed a sufficient level of engagement beyond temporary, cursory interest were then asked whether or not they would like to take part in an interview as part of a research project. A minimum age of 8+ was placed upon participants in order to ensure that all participants were able to communicate clearly and concisely.

These semi-structured interviews were first pilot-tested on a number of museum visitors and non-museum visitors (n = 18) and were refined before being implemented properly within the museum environment. These interviews asked visitors questions on the topic of 3D printing, what they knew about it; whether or not they would enhance their museum experience, would they like to see them in more museums and would they visit more if they were present. Each interview was subsequently recorded and later transcribed.

Content Analysis

The interview transcripts were then subjected to content analysis, a technique commonly used to investigate complex qualitative phenomena in an objective manner within the field of user experience, among other disciplines (Wellings et al. 2008; Karapanos et al. 2009; Krippendorff 2013). It provides the advantage of being able to detect common themes across texts, images and audio files that would be impossible to detect via other methodologies and converts a dense mass of qualitative data into a more manageable form (Krippendorff 2013).

First, the principal investigator read through the transcriptions to identify common themes among the responses to the questions and then inductively created a set of categories for each question and its responses in order to classify the answers. Following initial category creation, these categories were refined by preliminary coding to create a coding scheme.

This was then subjected to inter-rater reliability assessment using Krippendorff's Alpha (α) (Krippendorff 2013). This was carried out on 10% of the total sample (n = 8 or 32 units of analysis), with both the principal investigator and the inter-rater coder independently coding these same transcripts. The first iteration failed to meet the generally accepted minimum agreement rating of 0.8 (Krippendorff 2009; 2013) and was further revised, computing a final α of *0.899*, indicative of a reliable coding scheme.

RESULTS

In this section, the results from the content analysis of museum visitor responses will be described for each of the four questions asked.

Theme 1: What do you know about 3D Printing?

In total, the vast majority of participants (n = 74) had heard of 3D printing, with only 3% of the total sample having not heard of it (Fig. 4). In both cases these visitors belonged in the 08-17 age category. However, nearly half of the surveyed visitors, although having heard of the technology, had no understanding of how 3D printing worked (47%). 21% could provide relatively simple or incorrect assumptions about how they believed 3D printing functions while a further 16% of interviewees understood at least the basics of how 3D printing operated. A further 3% of visitors owned or had operated a 3D printer before and were familiar with the technique while 9% of visitors had some familiarity with 3D printing via their profession or job and demonstrated clear understanding of the details of how 3D printing methods operated. As a result, a total of 71% of participants did not express proper understanding of 3D printing while 29% expressed a degree of understanding of 3D printing technologies.

When divided by age groups, each level of knowledge shows a roughly even distribution of ages, with one notable exception. Participants in the 08-17 category show the lowest levels of knowledge, and as well as being the only representatives not to have heard of this technology (11%), 55% of participants in this age group knowing nothing about its operation, 28% having only simple conceptions and only 5% knowing how it operates, with no representation at higher levels of knowledge. No other age categories show trends of note.

[Figure 4]

Theme 2: Do you think that handling 3D touchable printed replicas like these could enhance your museum experience?

When asked if they thought that handling touchable 3D printed replicas could enhance their museum experience, the overwhelming majority (93%) of sampled visitors stated that it would (Fig. 5), compared to only 3% who were neutral on the subject, a further 1% who stated that it would not.

Of those who responded positively, 36% stated that it would enhance their understanding and enjoyment of museum exhibits. Within this category were four discrete subcategories: 12% who stated enhancement of enjoyment and understanding for all age groups, 3% for all age groups while also allowing greater appreciation of the specimen, a further 18% for children specifically and 3% for children specifically while also allowing greater appreciation of the specimen. The next most common reason was that of allowing multisensory interaction with the objects (18%) while others suggested that handling such replicas would help to preserve the original specimen (15%). For this latter category, 8% suggested just that it would preserve the original object while 4% suggested it would also aid understanding and enjoyment for all age groups, and a further 3% suggested that it would do the same, but for children specifically. The next most common reason was that it would allow visitors to better appreciate the object or specimen than they normally would if it was behind a glass case

(13%). The remaining proportion of positive responses suggested other benefits including assistance for visually-impaired visitors (4%), allowing visitors to touch and feel things they never normally would and, as a result, feel 'behind the scenes' (1%) and permitting geographical access to specimens in more museums (1%). 5% of visitors responded positively, but did not provide a valid reason for believing so.

Of the two interviewees who responded neutrally, one stated that they found the touchable 3D prints to be adequate but would have preferred to touch the original thing (1%) while the other cited fears of dropping and damaging the 3D prints if they were too heavy (1%).

In stark contrast, only one participant responded negatively. This participant expressed concern by stating that they would have much preferred to have touched the real thing and found the 3D prints boring by comparison (1%). The participant belonged to the 08-17 age category, suggesting that some younger participants may share similar concerns. This was the only negative response to this question. No notable trends are apparent among age groups.

[Figure 5]

Theme 3: Do you think that touchable 3D printed replicas like these should be present in more museums?

When asked if touchable 3D printed replicas should be present in more museums, again the overwhelming majority of interviewees responded positively (Fig. 6). 80% responded that they would like to see touchable 3D printed replicas in more museums while another 4% also responded that they would, but only if certain requirements were met. 14% of interviewees responded neutrally, stating that while it could be positive, a number of considerations would need to be taken into account first. Again, only a single participant responded negatively (1%).

Of those who responded positively, the most commonly cited reason as before was the enhancement of understanding and enjoyment for museum visitors (32%), 18% stating for all age groups while the other 14% stated for children specifically. As before, the next most popular reason was that this approach allowed multisensory engagement with replicas of objects (11%) while allowing greater appreciation of the objects (8%), and the preservation of the original object from potentially damaging handling (6%) were again cited as reasons for seeing touchable 3D prints in more museums. Other reasons stated were the ability to share specimens between museums (geographical access) (5%), allowing visitors to feel 'behind the scenes' (4%), potential commercial benefits to the museum (1%) and wanting to see this approach around the world (1%). 12% of participants responded positively, but were unable to supply a valid reason.

Some visitors responded positively (4%), but only if certain conditions were met. 3% stated that they would only wish them to be in more museums provided that they looked as realistic as

possible while another 1% wished to see them, provided that they did not detract from the existing exhibits.

A number of interviewees responded neutrally to this question (14%), citing some concerns that need to be taken into account before implementing touchable 3D printed replicas in more museums. 5% expressed concerns about the cost of 3D printing and whether or not museum institutions could afford them while 4% stated that perhaps these 3D prints did not belong in all types of museums, typically in those with more abstract content. A further 2% cited both cost and the type of museum as being a concern. 1% stated that they should complement but never replace the original specimens, citing fears of removal of the genuine specimens for safekeeping and using these 3D printed replicas as surrogates. Finally, 1% stated that they liked the idea but that it would make the museum using the technology less special.

Again, only a single respondent responded negatively (1%), citing concern that the touchable 3D printed replicas were not the real object and were thus uninteresting, a similar response to that noted above. Again, this participant belonged in the 08-17 group. No notable trends are apparent among age groups.

[Figure 6]

Theme 4: Would the opportunity to handle such 3D printed replicas encourage you to visit museums more or less often?

When asked if the opportunity to handle 3D printed replicas would alter their visiting habits, the majority of responses were again positive although not to such a great extent as seen in Themes 2 and 3 (Fig. 7). Again, the large majority (62%) responded that they would visit more but 30% responded that this would not change their visiting habits, while again only 1% responded negatively, saying that it would make them visit less.

Of those who responded positively, again the most commonly cited reason was the enhancement of education and enjoyment (25%), 8% stating that it would be beneficial for all age groups while 17% stated that it would beneficial for children specifically. The next most common reason was again the allowing of multisensory engagement with the replicas of the objects (15%) while others again suggested that greater appreciation of the objects than just behind a glass case (8%) would encourage them to visit more. The remaining responses make up a relatively small proportion, with some visitors stating that they would visit more because it would help to preserve the original object (3%); if it were advertised (1%); that they would make visits longer and more worthwhile (1%); and the sparking of interest in 3D printing technology (1%).

Of those who responded that they would not change their visiting habits, the majority (18%) cited two major reasons. The first was that such touchable 3D prints would certainly enhance their visit but not encourage them to visit more (9%) and the second being that the subject matter of the

museum or a specific exhibit would be of far more interest over just having the ability to touch objects. A further 5% suggested that touchable 3D printed replicas might influence their choice of museum when choosing between one that had such replicas and one that did not while 3% stated that they visit museums a lot already so it would be unlikely to change that habit. Other reasons included the limitations on time of daily life that are far more significant (1%) and that museums would need to create specific exhibits or events using these 3D printed replicas (1%).

Only a single respondent responded negatively (1%) and again cited concerns that because the prints are not the real object, they are not interesting. Again this participant belonged to the 08-17 age group.

Notable among the age groups was the enthusiasm by participants in the 08-17 category. The vast majority in this age category (72%) responded that the introduction of these touchable 3D printed replicas would encourage them to visit museums more, compared to 1% who stated that they would not change their visiting habits and a further 1% who would visit less. This shows that the introduction of touchable 3D printed replicas would be a major draw for the younger visitors. No other age groups show any significant trends.

[Figure 7]

Summary

To summarise the results of the content analysis of interviewee responses:

- While the vast majority of the sampled visitors had heard about 3D printing, most do not understand the manner in which it operates or are only able to offer simple conceptions and ideas about it, particularly noticeable in those in the 08-17 category. This certainly does not apply to all visitors however and nearly a third (29%) understand at a minimum the basics of its operation, ranging all the way up to a professional understanding.

- Responses to the introduction of touchable 3D printed replicas is overwhelmingly positive, with the majority of visitors responding very positively to the idea of these 3D prints enhancing their museum experience and that they should be present in more museums. The dominant reasons for this positivity are tied to potential increases to understanding and enjoyment while visiting museums, the simple ability to touch and interact with accurate replicas and the ability to better appreciate specimens on display than in traditional display media.

- However, while the majority of visitors stated that these replicas would encourage them to visit museums more, a significant proportion stated that these would not influence their visiting patterns,

suggesting that touchable 3D prints would not be a guaranteed way of attracting museum visitors and represent only part of the overall experience.

DISCUSSION

A Different Approach

In all, the general response to the idea of touchable 3D printed replicas in museums as part of this study appear to be extremely positive, with the vast majority of interviewed visitors agreeing that the introduction of these could enhance their museum experience and would be something that they would like to see in more museums. Many others were particularly vocal when it came to being able to touch the mammal jaw replicas, with similar themes of increased enjoyment and learning emerging from the responses of many of the research participants:

"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 (08-17)

This comment highlights the earlier mentioned glass-case paradigm that remains dominant in museum displays to date. The majority of modern and historical museum displays involve some variant of the theme of placing a barrier between visitor and object, naturally designed to protect the object from harm, be it a glass box or a physical barrier that prevents prying hands from getting too close to objects of significance and/or antiquity (Dudley 2012; Kreps 2015). This glass-case paradigm represents a major roadblock to the idea of multisensory experiences in museums and unless the problem can be overcome, prevents the shift towards a multisensory paradigm that is called for by many authors (Dudley 2010; 2015; Levent and McRainey 2014; Kreps 2015). Many visitors also expressed frustration at these physical barriers during the interviews, as is expressed in the words of Rosetta:

"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)

Similar empathy was raised particularly by younger visitors and their parents, who expressed some negativity about older, glass-case approaches:

"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)

These sentiments were echoed by other participants, namely that handling the objects was more engaging and interesting than merely looking at them behind glass cabinets. Across all responses, a majority of interview participants cited a potential increase in learning and enjoyment as the dominant reason that this approach would enhance their experiences in a museum. Other advantages such as preserving the original object while also enjoying multisensory engagement with it, allowing them to appreciate the specimens in much more detail than they would normally and creating a sense of being 'behind the scenes' and experiencing the object as a curator would. The ramification of this commonality suggests that touchable 3D printed replicas could help museum visitors to engage, enjoy and learn from exhibition content to a greater degree than via traditional display media. The ability to better appreciate the detail of the specimen is also significant as it allows visitors to closely investigate objects of interest and in doing so, may in turn enhance the learning and experience derived from exhibition content, making them feel closer to the object and more in tune with exhibition.

Despite this positivity, it is also worth considering the negative. One participant responded negatively across questions and stated that because the prints were not the real thing, they were boring and of little interest. The fact that this participant was a younger visitor may be indicative that younger visitors may regard 3D printed replicas poorly when compared to the real thing. The lack of sampling at ages lower than 8 in this study means that this topic is not explored in this study, but identifying the perceptions of the museum's youngest visitors could be instrumental in understanding a potential wider issue.

Also notable is that this approach may not be as likely to change the visiting habits of museum goers. Nearly a third of respondents stated that they would not alter their visiting habits, citing a multitude of reasons, particularly that printed replicas would indeed enhance their visit but would not be enough to encourage them to come back any more frequently. Another major reason highlighted was that the subject matter would be a more significant draw to a museum compared to the presence of 3D prints. Both of these points suggest that merely adding touchable 3D printed replicas to an existing exhibit may be unlikely to trigger an increase in visitor appreciation, indicating that providing interesting, complementary content through 3D printed replicas is key in this approach.

Previous research into multisensory experiences has also shown that visitors enjoy the ability to interact with museum objects. Davidson et al. (1999) provide one of the earliest evaluations of an exhibition designed from the ground up to be completely multisensory at the Boston Museum of

Science, showing evidence of increased learning impact from visitors in addition to the increased visitor attraction to the exhibits compared to its unaltered state. Kuo et al. (2016) also reported on another multisensory exhibition known as 'Rebuilding the Tong'an Ships', reporting >90% satisfaction ratings in addition to an increase in interest in the topic after visits compared to before. A large amount of anecdotal evidence of visitors enjoying such multisensory experiences also exists (Dudley 2010; Wehner and Sear 2010; Levent and McRainey 2014; Shorch 2014; 2015). Previous studies using 3D printing in multisensory exhibits also provide similarly positive results. Dima et al. (2014) carried out an evaluation on a small 3D printed replica of a chess piece using the theatrical projection technique known as 'Pepper's Ghost', reporting positive results from visitors who handled the print. Marshall et al. (2016) reported findings of significant interaction from museum visitors with an application of the digital, 3D printed interaction system VIRTEX at the Museon The Hague, although no satisfaction data were collected. Other authors highlight the potential educational advantage of 3D printed physical models, although in the majority of cases, this is only as a footnote to other research aims within heritage (Rahman et al. 2012; Leakey and Dazamabova 2013; Laycock et al. 2015; Du Plessis et al. 2015). However, as noted previously, there are a limited amount of studies that have carried out rigorous visitor evaluations into multisensory experiences and their 3D printed counterparts, a trend noted by Neumüller et al. (2014). Indeed, the lack of research that investigates the detail, workflows and methodologies of creating such replicas is lacking on the whole with a lot of questions worth considering, such as the issue of scale, materials and even ways to present them to audiences; this is discussed further below.

A key point is that these 3D printed replicas could be an aid to understanding and enjoyment for museum visitors, thus enhancing the visitor's museum experience. This, realistically, is only natural given the well-known relationship between multisensory experiences and enhanced memory retention (Stevenson 2014; Ward 2014; Tiballi 2015) and has been well-documented with non-3D printed object replicas as well (Taylor 1973; Davidson et al. 1999; Kuo et al. 2016). Several authors report the connection between physical interaction and learning and research into neuroscience and educational psychology shows that there is a strong connection between multisensory interaction and the encoding of memory (Pye 2008b; Lacey and Sathian 2014; Ward 2014; Reeve and Woollard 2015). Thus, as a result, the introduction of touchable 3D printed replicas of museum objects is an approach that already meshes well with modern concepts of museum learning and could provide a new way to facilitate multisensory learning on the exhibition floor.

Presenting Touchable 3D Printed Replicas

Throughout the interview process, other concerns were raised by visitors on the subject of how these touchable 3D prints should be presented. These concerns are key to creating the best multisensory

experiences for visitors using replicas and should be taken into account by those looking to implement this form of exhibit.

First and foremost, the level of understanding of the subject of 3D printing needs to be addressed. Results from this analysis show that while a majority of visitors have heard of 3D printing, nearly half of these had little understanding of how it worked while another fifth had only a rudimentary understanding. This shows that many visitors are unlikely to have had contact with any form of 3D printing, let alone 3D printed replicas. As a consequence, it may be necessary to take this lack of understanding into account when designing exhibits that incorporate touchable 3D printed replicas. Visitors should be made aware that the touchable items are indeed 3D prints and should include a simple explanation of how 3D printing works, in addition to plain, easy to understand information on the original size of the specimen and the materials used, as in the words of 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)

This should help mitigate potential misinterpretation of the material on display and providing this basic information should ensure that visitors come away with accurate conceptions.

Another theme articulated by many visitors was that of the physical properties of the 3D prints. Many interviewees expressed some preferences towards one of the 3D prints, mostly focussing on their realism. Many stated that the more authentic and realistic looking that the 3D prints were, the better:

"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 noted that both the weight and the thermal properties are also important when handling these objects, encouraging them to be as close to the real objects as physically possible:

"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)

These points are interesting and represent a topic in relation to verisimilitude, one that is readily apparent in the creation by hand of replicas of original objects. The question of the 'accurate replica' is of pertinent interest when creating copies of original artefacts and typically museum professionals have long favoured the creation of 'accurate replicas', those that best capture the essential aesthetic and physical characters of an object, in addition to the weight, feel and materiality of the original (Bohn 1999; Müller 2002). This process can often be time consuming and expensive, requiring many work hours and their associated costs in labour to create a worthy replica (J. Hay, pers. comm.). In comparison, 3D printing is much simpler and more parsimonious, requiring much less time (although costs may vary, see Scopigno et al. 2014; 2017) to create, although arguably at the expense of realism that one gets from a replica painstakingly recreated from the original. 3D prints, unless printed with the highest resolution resins, generally suffer from visual artefacts and layer structures that are hallmarks of the technique (Olson et al. 2014; Scopigno et al. 2014). The replication of photorealistic colour is also limited at this stage, but further developments within the 3D printing sector are likely to improve the visual fidelity of 3D models over time (Scopigno et al. 2014; 2017; Gibson et al. 2015). Thus the choice of method is a trade-off between the time and costs of creating the replica and the overall fidelity of the final product relative to the original.

It is thus important to provide the most appropriate material that best complements the type of object, considering how our interpretation of what something should feel like based on sight often differs compared to how it actually feels in the hand (Spence and Gallace 2008) and 3D printed replicas it seems should be created to replicate the original as closely as possible. However, as highlighted by Neumüller et al. (2014) and Spence and Gallace (2008), little is known about how people regard these properties in physical models, particularly when it comes to 3D printing. Some authors have highlighted the issues of past approaches in this vein, such as Candlin (2003) who carried out an interview study with blind and partially sighted (BPS) visitors and reported their dissatisfaction with regard to how they are provided for in the museum environment. These visually-impaired interviewees expressed the importance of the physical properties of touchable objects, as in the words of one interviewee:

"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…"

Contrarily, other research has shown that authenticity perhaps is not as important to visitors as it would seem. Di Franco et al. (2015) presented a study on how museum visitors regard authenticity of objects, finding that it does not play a particularly prominent role for some visitors, but was not completely unimportant. They found that authenticity takes a backseat to the opportunity to gain knowledge, constituting a contrast to the feedback of visitors from this study. Given this contrast combined with large void on the topic of the physical properties of tactile replicas and potential touchable 3D prints, this appears to be a research area which could provide key insights into the creation of tactile replicas and could help to inform exhibition designers about the best ways in which to exploit these new cutting-edge display techniques, especially when considering the huge array of printing techniques on the market and the qualitative differences between them.

Another key consideration is the potential for touchable 3D printed replicas to provide access to accurate specimens for BPS visitors (Candlin 2003; Spence and Gallace 2008). Museums in the UK are attempting to provide better facilities for BPS visitors, especially under pressure from the Disability Discrimination Act (1995) and the more recent Equality Act (2010) (Weisen 2008; Candlin 2008; 2010; Mesquita and Carneiro 2016; Chick 2017). Temporary exhibits, touch tours and drop-in sessions have been provided in response (Candlin 2003; 2006; Bieber and Rae 2013; McGee and Rosenberg 2014; Eardley et al. 2016), in addition to three-dimensional tactile images designed for BPS visitors to better envisage larger structures (Neumüller and Reichinger 2013; Neumüller et al. 2014). However, as highlighted above, the problem of allowing visitors to handle objects is to risk damage, a fact that prevents the wide scale adoption of the provision of permanent facilities for BPS visitors (Hetherington 2000; 2003; Spence and Gallace 2008). The creation of completely disposable, risk-free touchable 3D printed replicas thus provides a way to circumvent these problems and start providing enhanced, hands-on experiences for BPS visitors (Solima and Tani 2016).

Overall our understanding of presenting 3D prints to museum audiences remains in its early stages, but a skeleton of an approach has been highlighted here of the early stage considerations worth exploring by museum professionals. In time, once greater understanding of visitor preference is acquired, touchable 3D printed replicas may become an invaluable resource for museum exhibition and display.

CONCLUSIONS

The data show that the majority of museum visitors interviewed during this study responded positively to the idea of introducing touchable 3D printed replicas to the museum. From this study, the following key points can be drawn:

- Museum visitors thought that touchable 3D printed replicas could enhance their museum experience and agreed strongly that they should be present in more museums. While the majority of interviewees also agreed that this approach would encourage them to visit more museums, nearly a third stated that it would not cause them to change their visiting habits.

- While mostly positive, the minor amount of negative feedback indicates that the fact these specimens are not real may be an issue for younger visitors and needs to be explored further. Learning and enjoyment, better appreciation of artefacts, preservation of the original and being given the ability to interact with museum items were the most popular reasons for visitors wishing to see more of these touchable 3D printed replicas.

- While the majority of sampled visitors had heard of 3D printing (98%), understanding of visitors of process of 3D printing is lacking, with ~70% not understanding the basic principles. This should be addressed by complementary information on how it operates if using 3D printing as part of any exhibit to prevent confusion.

- The use of 3D prints as a tool for presenting objects in exhibitions is under-utilised and under-researched, highlighting a gulf of knowledge with regards to physical properties, authenticity and other modes of presentation that need to be properly addressed before the wide-scale implementation of this approach. The trade-off between realism and manufacturing time of 3D printing when compared to more traditional museum replication methods is a subject that also needs to be considered.

- Touchable 3D printed replicas could be of value as a tool for more inclusive exhibition design, helping to provide access to exhibitions for blind and partially-sighted visitors alongside other marginalized groups within the museum environment.

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Figures

Figure 1: The original *Phascolotherium bucklandii* specimen. Scale bar is 5mm.

Figure 2: The 3D prints used in the investigation. From left to right, these are; Blue Thermoplastic (ABS), Stainless Steel, Multi-Material Resin (VeroClear and VeroWhite), Colour Sandstone and White Resin (VeroWhite). The 3D prints are scaled up from the original specimen by a factor of approximately six.

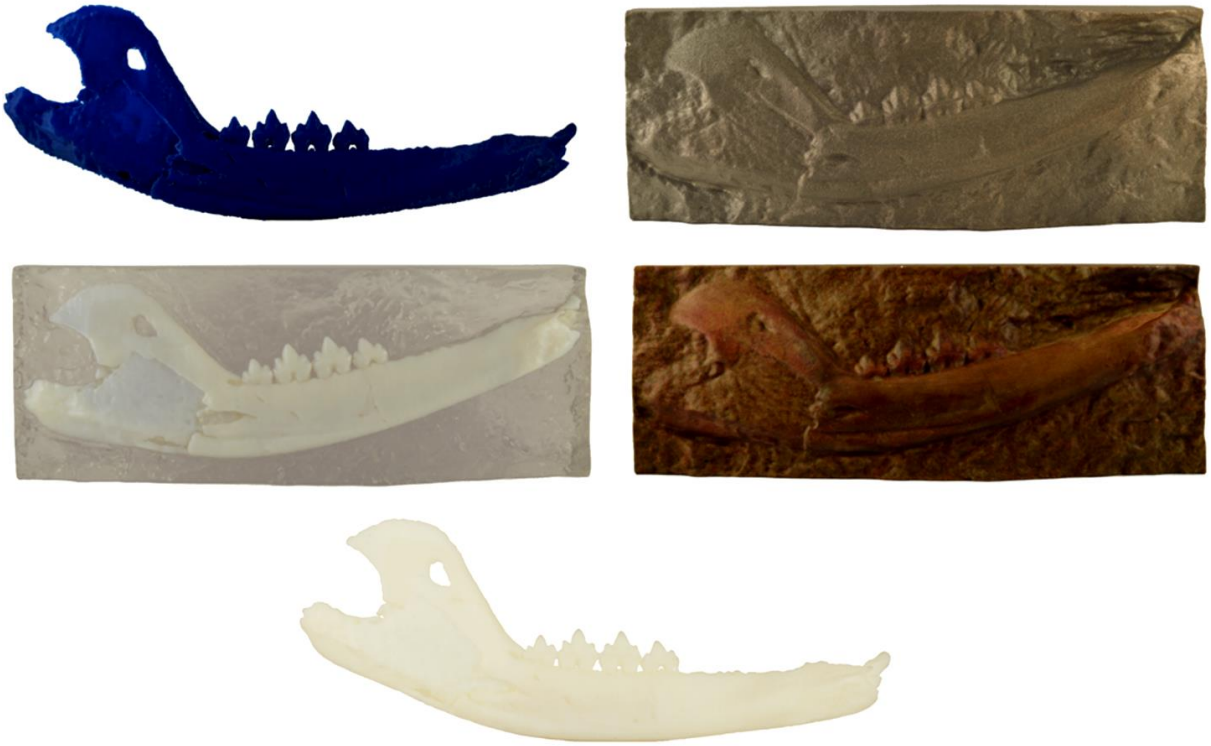

Figure 3: Demographics of sampled population. a) Gender distribution. b) Age Distribution. Yellow (Dots) = 08-17, Green (Horizontal) = 18-24, Light Blue (Diagonal Left) = 25-34, Dark Blue (Diagonal Right) = 35-44, Purple (Vertical) = 45-54, Red (Cross-hatched) = 55-64 and Orange (Hexagonal) = 65+. Created using ggplot2 in R.

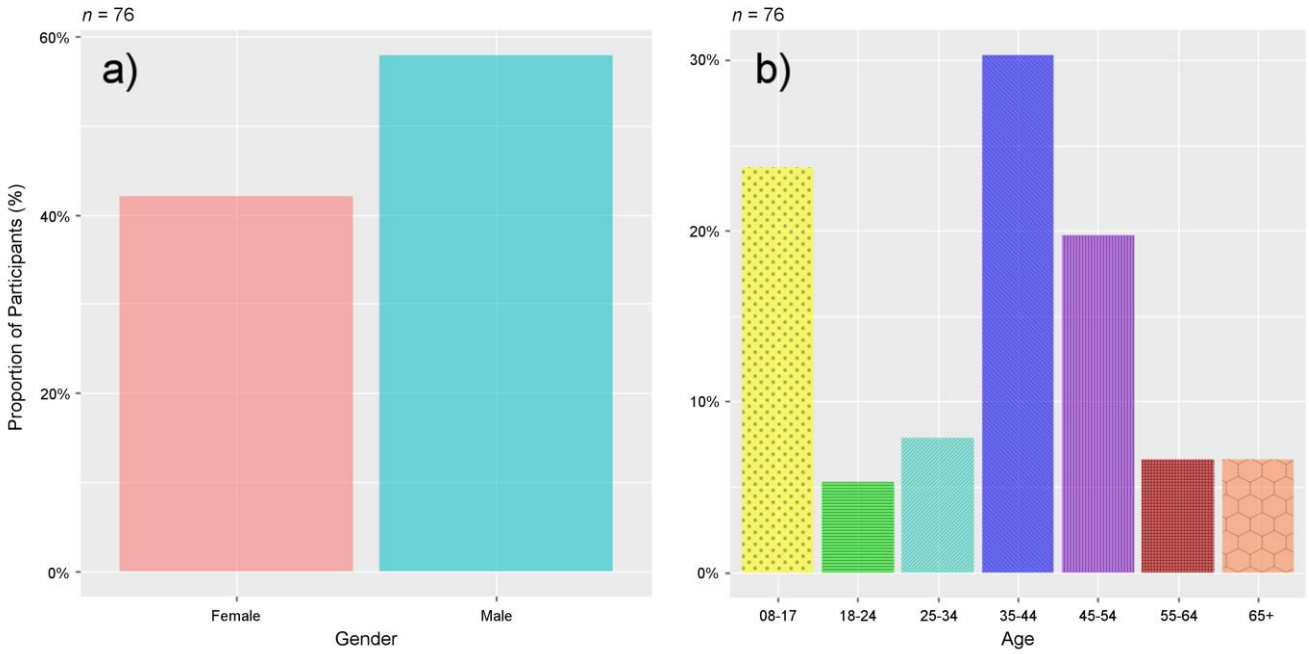

Figure 4: Theme 1: What do you know about 3D Printing? Results of Content Analysis. Colours and patterns represent age groups. Yellow (Dots) = 08-17, Green (Horizontal) = 18-24, Light Blue (Diagonal Left) = 25-34, Dark Blue (Diagonal Right) = 35-44, Purple (Vertical) = 45-54, Red (Cross-hatched) = 55-64 and Orange (Hexagonal) = 65+. Created using ggplot2 in R.

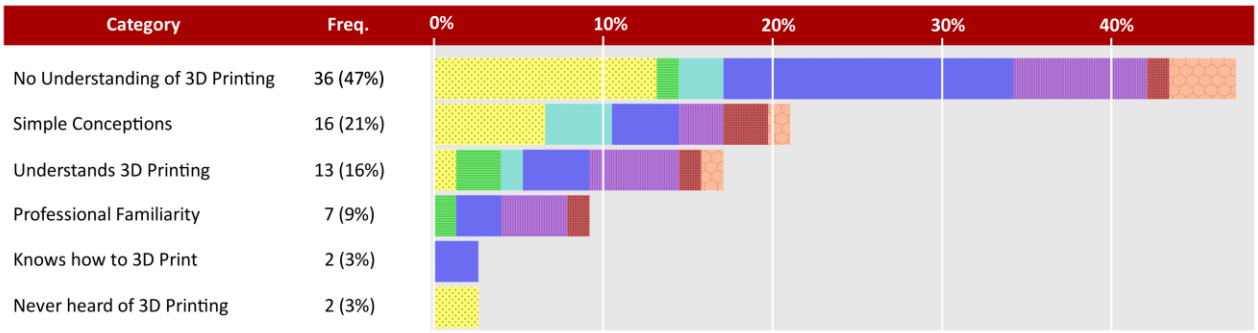

Figure 5: Theme 2: Do you think that handling 3D touchable printed replicas like these could enhance your museum experience? Results of Content Analysis. Colours and patterns represent age groups. Yellow (Dots) = 08-17, Green (Horizontal) = 18-24, Light Blue (Diagonal Left) = 25-34, Dark Blue (Diagonal Right) = 35-44, Purple (Vertical) = 45-54, Red (Cross-hatched) = 55-64 and Orange (Hexagonal) = 65+. Created using ggplot2 in R.

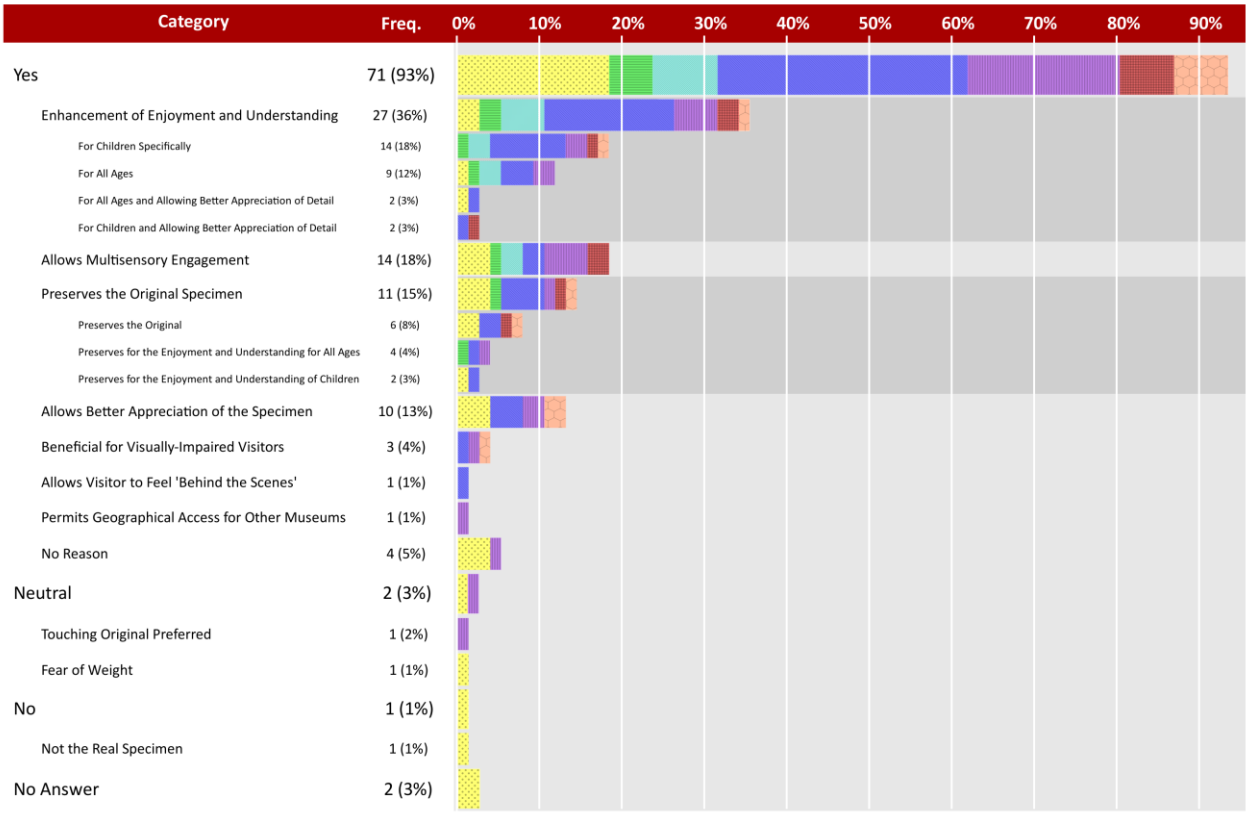

Figure 6: Theme 3: Do you think that touchable 3D printed replicas like these should be present in more museums? Results of Content Analysis. Colours and patterns represent age groups. Yellow (Dots) = 08-17, Green (Horizontal) = 18-24, Light Blue (Diagonal Left) = 25-34, Dark Blue (Diagonal Right) = 35-44, Purple (Vertical) = 45-54, Red (Cross-hatched) = 55-64 and Orange (Hexagonal) = 65+. Created using ggplot2 in R.

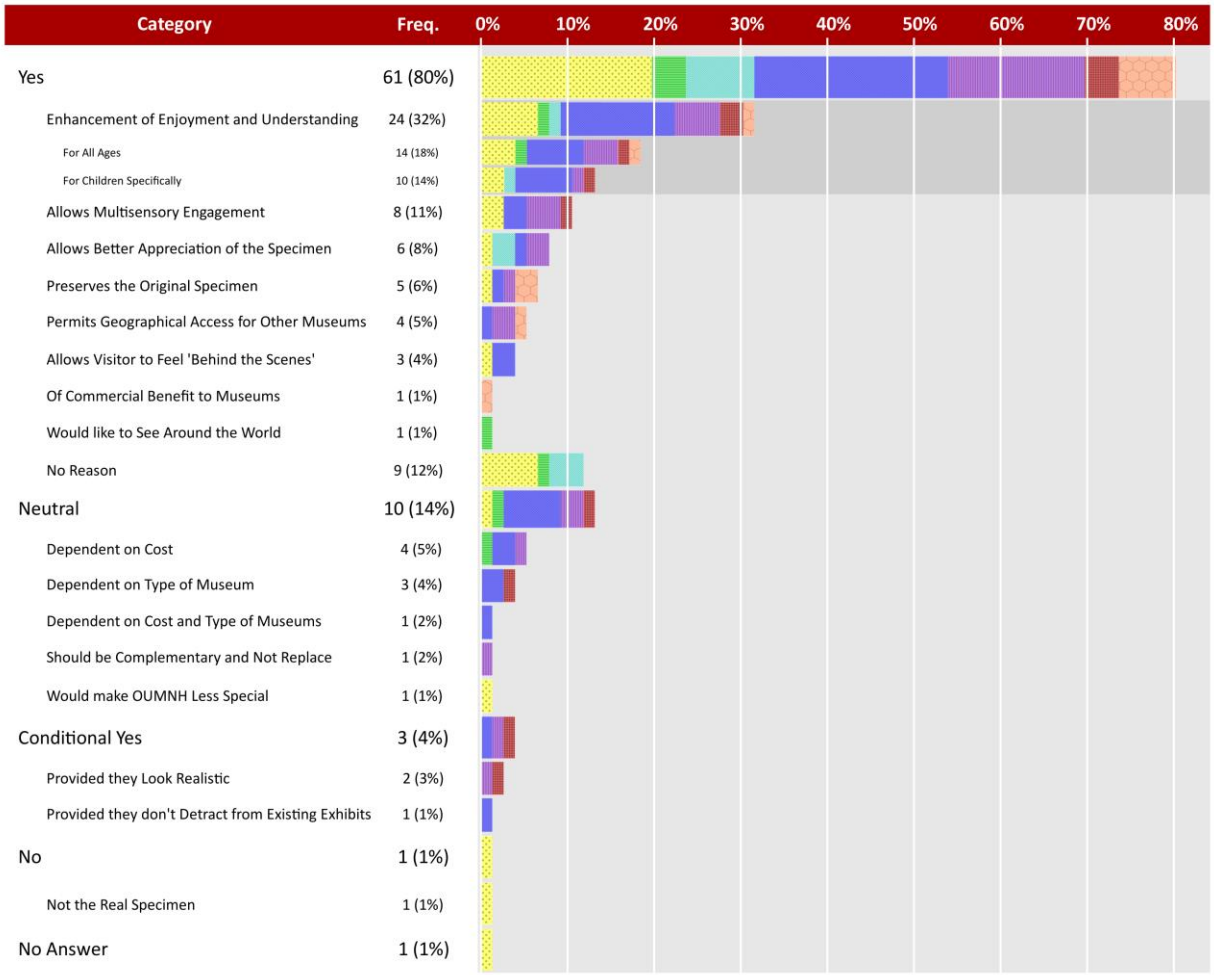

Figure 7: Theme 4: Would the opportunity to handle such 3D printed replicas encourage you to visit museums more or less often? Results of Content Analysis. Colours and patterns represent age groups. Yellow (Dots) = 08-17, Green (Horizontal) = 18-24, Light Blue (Diagonal Left) = 25-34, Dark Blue (Diagonal Right) = 35-44, Purple (Vertical) = 45-54, Red (Cross-hatched) = 55-64 and Orange (Hexagonal) = 65+. Created using ggplot2 in R.