Visitor Studies

Designing 3D Prints for Blind and Partially Sighted Audiences in Museums: Exploring the Needs of those Living with Sight Loss.

--Manuscript Draft--

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Article Type:	Research Article
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Keywords:	Blind and Partially Sighted; 3D Printing; Perception; Exhibition Design; Museums; Universal Design

Abstract: Modern museum practice embraces equal access for all, but access for blind and partially-sighted (BPS) audience remains problematic given the ocularcentricity of museums. Many museum professionals and BPS visitors remain frustrated by the degree of accessibility on offer. The use of 3D printed replicas as a handling surrogate represents a solution, allowing BPS visitors to engage tactually with museum content while minimising risk. However, the design of such replicas is poorly researched. This exploratory examination of the design of 3D printed replicas utilises semi-structured interviews, sensory observations and content analysis to examine BPS perceptions of museum objects in the absence of interpretational support. Interpretation was dominantly multisensory, while participants found it easier to determine material traits than object traits, with textual, geometrical and optical properties being of use. Assistive approaches rather than major alterations were favoured. Overall, museum professionals should consider how the process of 3D printing influences BPS perception.

Introduction

Blind and partially-sighted (BPS) museum visitors in the UK have historically not been a major focus in museum practice. Schools and organizations for the blind have been extant since the 18th Century and the first efforts to facilitate access to BPS individuals in public institutions date back to the 19th Century (Hayhoe, 2013). The first British museum to truly enable access for BPS individuals was Newcastle-upon-Tyne's school for the blind in 1905 (Hayhoe, 2013). This was followed by a number of other examples in the UK and across the globe, as detailed by Hayhoe (2013), but it was not until 1981, the International Year of Disabled Persons in the UK, that a co-ordinated effort was made to design museum experiences around the needs of BPS audiences (Candlin, 2010; Hayhoe, 2013). This initiative kick-started the first real efforts to design exhibitions around the needs of those living with sight loss. Progenitors such as *Sculpture for the Blind* at the Tate Gallery and *Sculpture to Touch* at the National Museum of Wales paved the way for future efforts, although these early approaches treated visual and tangible interaction similarly and the objects used were highly limited by conservational concerns (Hetherington, 2000; Candlin, 2003; Hayhoe, 2013; Chick, 2017). Despite this initial surge of interest, many authors describe a lack of uptake into standard museum practice by many British institutions at the time, a situation heavily criticised by the Attenborough Report of 1985 and its follow-up in 1988 (Hetherington, 2003; Candlin, 2003; 2010). While awareness of the issue was growing, new legislation was passed to enforce BPS inclusion in museums through the Disability Discrimination Act (1995) and the Equality Act (2010).

This legislation has led to an increase in services tailored towards BPS audiences, including specific events, handling sessions, braille guides and audio descriptions in museums across the UK (Candlin, 2008; McGee and Rosenberg, 2014). Examples such as *Raised Awareness* (Tate Modern in 2005) and *Sensing Sculpture* (Wolverhampton Art Gallery, 2003 – present) have helped to provide experiences for BPS audiences. However, providing for this audience is a difficult endeavour and many authors have highlighted the shortcomings of previous attempts and barriers to the creation of BPS content (Mesquita and Carneiro, 2016; Chick, 2017; Holloway et al., 2019). Mesquita and Carneiro (2016) carried out a survey of museums in European capitals, identifying the degree of accessibility available for BPS visitors. They found that while site accessibility and content readability was well-addressed in European museums, opportunities for multisensory engagement were far more restricted, with many limiting experiences to the audio-visual spectrum. Other authors also criticise typical BPS access approaches, highlighting their one-off nature, their limited capacity, poor advertisement and oversimplified content (Partington-Sollinger and Morgan, 2011; Eardley et al., 2016; Chick, 2017). Compounding these issues are accessibility concerns such as poor staff training, physical barriers, wayfinding issues, information accessibility and a lack of provision for guide dogs (Small et al., 2012; Mesquita and Carneiro, 2016). Many institutions also have a propensity towards the use of braille (68% in Mesquita and Carneiro, 2016), despite the low levels of

braille proficiency in the BPS community; ~5% in the UK (Phillips and Beesley, 2011; Hayhoe, 2013). Handling opportunities for BPS visitors are also typically restricted to a few select items from teaching collections and rarely offer the opportunity to interact with the main display objects (Agnanostakis et al., 2016; Mesquita and Carneiro, 2016). This policy is a product of the museum's need to protect and conserve the objects in their collections, which forms an unassailable barrier to access that remains the key issue with regards to BPS audiences (Holloway et al., 2019). Museum professionals need to overcome these barriers, especially given the forecasted increase in the BPS population in the UK towards ~4 million by 2050, compounded by an aging population (Access Economics, 2009; VisionUK, 2017; RNIB, 2018). Educational collections, a common feature of object-based museums, are often used as a solution, although these rarely house objects that inspire the same degree of awe as those on display. They are ultimately disposable.

3D printing provides a potential means to overcome this problem. This method involves the fabrication of complex objects by building up layers in a range of different materials to create a physical replica from Computer Aided Design, or CAD, data (Gibson et al., 2015; Chua and Leong, 2015). Its ability to create bespoke replicas without having to resort to expensive mass-manufacturing or risky moulding/casting makes it ideal for use by museums. The technology's potential to revolutionise the way museums present content to their audiences has been discussed by many authors (Wilson et al., 2017; 2018; Balletti and Ballarin, 2019). For BPS audiences, the creation of object replicas to act as handling surrogates has shown to be of great value. For example, the Prado Museum (Madrid) has created tangible replicas of many classic art pieces, including the Mona Lisa (Anagnostakis et al., 2016). This neatly circumvents the issue of object degradation through the medium of the disposable replica, a feature responsible for the approach's current popularity within the sphere of cultural heritage (Wilson et al., 2017; Holloway et al., 2019). Such an approach could also facilitate autonomy within the exhibition gallery, enabling BPS visitors to enjoy the museum at their own leisure, rather than be limited to specific sessions whose timing lies outside their control, a key requirement for BPS visitors (Holloway et al., 2019). As a result, museums are currently utilizing the technology to a variety of ends within BPS museum practice, including in permanent and temporary exhibitions (Chick, 2017; Stanco et al., 2017; Karnapke and Baker, 2018), in handling sessions (Koch et al., 2013; Guarini, 2015), and for assisting BPS visitors in wayfinding (Urbas et al., 2016; Rener, 2017). However, there has been little robust exploration of guiding principles for the creation tangible 3D-printed replicas, especially for BPS visitors (Wilson et al., 2017; 2018).

Sensory psychology has revealed the complex nature of haptic interaction and the multisensory nature of the human perceptual system (Lacey and Sathian, 2014; Ward, 2014; Eardley et al., 2016). The failure to recognise this has hampered some earlier attempts to provide content for BPS audiences (Candlin, 2010; Gallace and Spence, 2014; Gupta et al 2017). Haptic interaction is limited in terms of spatial resolution, with larger objects being cognitively demanding to interpret.

Haptics are unable to deal with complicated geometry, resulting in frequent simplification (Spence and Gallace, 2008; Gupta et al., 2017). Touch often contrasts with sight in our perceptual system, meaning that not every detail can be gleaned from either when in isolation. Therefore, to understand how to create useful and informative replicas for BPS audiences, we must first determine what constrains their interpretation of such objects.

This study attempted to explore the nature of BPS perception of natural history objects in order to create some initial guiding principles in the design and creation of 3D-printed replicas for BPS audiences. We explored the driving factors of BPS interpretation and how museum professionals can design around these constraints. We used interviews, observations and content analysis to explore the traits essential to BPS interpretation.

Methods and Materials

Research Questions and Design

This study's primary aim is to determine what object properties are key to BPS visitors' interpretations of museum objects, the accuracy of their judgements and how 3D printing could enhance their interpretive process. The study took place outside of an exhibition setting to explore this, seeking to understand how BPS individuals interpret objects without the guiding hand of the museum educator. The primary purpose of this was to directly extract what features and characteristics the participant could perceive within a more controlled environment. The findings in turn are intended to provide guidelines for creating tangible 3D-printed replicas for BPS audiences. The study in particular addresses the following research question:

"How do BPS individuals perceive museum objects and what guidelines do these suggest for the creation of tangible 3D-printed replicas for BPS museum applications?"

This research question can be divided into a number of distinct sub-themes that were studied in detail over the course of the project:

- How accurately can BPS individuals interpret and identify objects in the absence of assistance?
- How are sight, touch, scent and hearing utilised during object exploration?
- How are object properties related to interpretation?
- Which properties are key for object interpretation?
- What makes an object hard or easy to interpret?
- How can 3D printing assist BPS interpretation of museum objects?

In order to explore these research themes, an interview study was designed to tease apart this complex holistic issue. Each participant was asked a number of questions on their interpretations of a number

of natural history objects in an attempt to understand their interpretations and justifications. Each participant was asked four questions for each object and two further questions on all of the objects. These are: 1) Could you please describe this object while thinking aloud, focussing on its features, shape, texture and material properties?; 2) What do you think the object is made of?; 3) What do you think the object is?; 4) If you could change anything about this object to help you better understand it through 3D printing, what would you change if anything?; 5) Which object was easiest for you to perceive and understand?; 6) Which object was most difficult for you to perceive and understand?.

Participants

We contacted BPS support groups across the UK using a snowball sampling method, asking for assistance in acquiring participants for a study related to accessibility for BPS visitors in museums. These organisations recruited interested participants from within their communities. We then organized suitable sampling dates to carry out the interviews. A total of 21 participants with differing sight-loss conditions, causes and durations were sampled from several organisations: Focus Birmingham (9), BirminghamVision (4), Beacon Trust (3), BucksVision (3) and Oxford University Museum of Natural History (OUMNH) (2).

Before their interview, each participant was read the information sheet containing project information and what to expect from the interview process. The participants were given the opportunity to raise concerns, discuss outcomes and ask any questions. Consent was then acquired verbally or in writing. For verbal consent, the participant was read a confirmatory statement, which was audio-recorded along with their response. Interviews were recorded with the participant's permission. This workflow was ethically approved by both the Biomedical & Scientific Research Ethics Committee (University of Warwick) and the Medical Sciences Interdivisional Research Ethics Committee (University of Oxford) and complies with their standards of consent.

Materials

The materials used in this study were sourced from the educational collections of the OUMNH to best represent a different range of scales, features, textures, physical properties and organisms. Five objects (Fig. 1) were selected: a tortoise shell (*Manouria emrys*; OUMNH SR2203); a brain coral (*Diploporia* sp.; OUMNH SR0615); a crab shell carapace (C*ancer pagurus*) (OUMNH SR0671); a fossilised scallop shell (*Pseudopecten equivalvis*; OUMNH SR0409) and the right femur of a red fox (*Vulpes vulpes*; OUMNH SR1812). These five objects were handled by the participants over the course of the interview.

[Fig. 1 Here]

Procedure

Following the informed consent procedure, the interview began. Each participant was presented with each object in a random order and questioned. The first question (Q1) tasked participants with describing the object based on its shape, features, texture, and material properties using the think-aloud process. This process gave the participant time to properly interpret and explore the objects, while allowing them to start forming thoughts on the object as they explored it. Pre-set probing questions were used to encourage description on the subject of the shape, structure and texture of the object. This continued until the participant had responded to all the pre-made probes or had touched on all of the themes to a satisfactory degree. Whilst performing this task, the interviewer observed and documented their sensory usage during handling. Sensory usage was determined through observation, noting use or non-use of a sense during interaction with each object. Use of sight was determined when mentioning colour or other definitively optical traits, sound through tapping or knocking motions or comments on acoustic properties and scent by the action of smelling the object. Due to this 'third-person' mode of identification, it is likely that sensory usage is underestimated.

Participants were asked to identify what the object was made of and their reasoning (Q2) and identify what the object was and their reasoning (Q3). Following this, the object was described to the participant via audio description and discussed briefly to ensure full understanding. Participants were then asked what aspects of the object could be changed in order help them interpret the object through the medium of 3D printing (Q4). On completion, the next object was randomly assigned and the process repeated for the remaining objects.

After this, all of the objects were presented to the participant together, who was then asked which object was easiest (Q5) and hardest (Q6) to interpret and why they thought so. Once the participant had completed these tasks, the interview was ended. The entire interview process lasted between 25 and 50 minutes.

Analysis

The transcribed interview data was subjected to content analysis, a robust, rigorous and repeatable process that converts complex qualitative data to quantifiable, refined categories (Krippendorff, 2009; 2013; Nili et al., 2017). Content analysis was employed as a technique for a number of reasons. Questionnaires are difficult to implement with BPS audiences given the nature of sight loss. Those who can read such documents typically do so slowly, which would slow down the data collection process and result in participant fatigue. Thus, an interview protocol was employed. This followed a semi-structured approach, comprising more structured interviews with a rigid schedule of questions repeated exactly for all participants, but supported by open-ended probing questions to extract detailed responses. In order to ascertain the relative frequencies of such responses to extract the most common interpretations and justifications, content analysis was employed over thematic analysis. In

thematic analysis, quantifiability is not possible as there is no rigid definition of a unit of analysis, a consistent repeatable unit like a sentence or word, to which the codes are applied. Content analysis by comparison depends on the unit of analysis and is supported by a rigid reliability process that lends greater strength to the resulting findings (Krippendorff, 2013; Nili et al., 2017). This allows the extraction of the most common responses to each question for the objects. In this way, the procedure fulfilled the role of a verbal questionnaire, enabling open discussion, minimising the length of the procedure and allowing robust, comparable interpretations. Each of the different questions was analysed using its own content analysis scheme to quantify the range of responses given for each, with ten different coding schemes. Reponses to the first question were not analysed due to time limitations.

Each of the coding schemes was created through inductive category generation, the emergent creation of codes from data rather than deductive categorisation prior to the interview process. From this, a first-phase coding scheme (P1) was produced. The inter-rater reliability (IRR) of this coding scheme was tested by two coders working independently, agreement being tested using Krippendorff's alpha (α). This conservative estimate takes into the account the chance of random assignment of categories by either coder (Krippendorff, 2013; Nili et al., 2017). IRR was tested on a subset of four transcripts. In P1, α ranged between 0.48 and 1 depending on coding scheme, although after discussion and reconciliation of major errors and missing values, these values increased to between 0.51 - 1. The most problematic schemes were S*cheme 4: Object Changes* (α = 0.65) and *Scheme 6.2*: *Hard Reasons* (α = 0.51), which both fell outside the recommended threshold of IRR, between 0.7 and 0.8 or greater (Krippendorff, 2009; Nili et al., 2017).

This was then refined into a second-phase (P2) coding scheme. The IRR process was repeated with the same raters on four different transcripts. This resulted in higher α values in all categories, ranging between 0.62 - 1. Most schemes met the minimum criteria for a sufficiently reliable coding scheme, with the exception of *Scheme 3.2: Object Reasons* (α = 0.68) and *Scheme 6.2: Hard Reasons* (α = 0.62). Both exhibited high raw percentage agreement, 86% and 89% respectively. This depression of α is likely associated with a peculiarity in the calculation of Krippendorff's α. When a response has repetition of the same few categories, one being dominant, this results in an overestimation of errors and a deflated α value (Feng, 2015). A further stage of reconciliation of major errors resulted in improved α values in all categories, the new range being between 0.84 – 1. Thus all schemes fulfilled the minimum requirements.

Results

Sensory Usage

The participants used their senses of sight, sound, and smell to varying degrees during object interaction. All participants used touch and none used taste. Sound was used by 30-60% of all participants depending on the object (Fig. 2a). Usage of sound was highest when interacting with the

crab shell (62%) and the tortoise shell (57%), with fewer participants using sound on the remaining objects (47% fox femur; 34% scallop shell; 29% brain coral). From the raw demographic distributions, a large proportion of the participants who used sound appear to live with more severe sight loss conditions for longer durations, although this could not be statistically corroborated due to the small sample size.

Sight was used by 20-45% of all participants to understand the objects, less than that of sound (Fig. 2b). Use of sight was greatest when handling the tortoise shell (43%) and the brain coral (43%), again the remaining objects being explored with sight to a lesser degree (38% fox femur; 29% crab shell; 19% scallop shell). From the raw demographics, participants living with less severe sight-loss conditions appear to use sight more, but again this could not be statistically confirmed. This figure is likely an underestimate given the difficulties of judging when sight was used to interpret the objects.

Finally, smell was utilised the least, between 0 to 14% depending on the object (Fig. 2c). Smell was used the most for the scallop shell (14%), with similar usage for the tortoise shell and brain coral (9%) and the crab shell (5%) and none for the fox femur. Only those who had suffered from long-term sight loss used scent but again the significance was not confirmable using statistical methods.

[Fig. 2 Here]

Object and Material Identification

Material Judgements

When the participants had explored and described the objects in sufficient detail, they were asked to identify what they thought each object was made of, with accuracy ranging between ~58% in the scallop shell and 81% in the tortoise shell (Table 1).

Some objects showed a number of unpredictable interpretational trends. For example, a number of participants identified the fossilised scallop as a modern shell (29%) rather than being fossilised. This suggests that they were inferring material characters from what they thought the object was, a modern shell, rather than taking cues from its materiality. This could also be due to a lack of understanding of fossilisation. A similar trend can be observed in the brain coral, with 19% stating that the object was made of shell based on their interpretation of the object as some form of sea shell (see below).

Another notable trend was that some materials could easily be mistaken for one another. With the fox femur, many misinterpreted the material as wood (24%), plastics/resins (10%). Wood was also mentioned by a number of participants in the tortoise shell (10%), alongside other materials (19%), including clay and cement, in the scallop shell. This suggests that some materials, such as wood and bone, may be difficult for BPS persons to differentiate.

[Table 1 Here]

Participants were also asked to provide reasons why they arrived at this interpretation (Table 2). The dominant reasons included the texture (16%), consisting of its general ‘texture’ (5%), its roughness (5%), its smoothness (4%) and its graininess (2%). The shape of the object (13%) confirms the use of object interpretations in material identification while the weight (9%) was also important, a naturally informative material trait. The ‘feel’ of the object (9%), its unquantifiable textural qualities, was also commonly cited while the specific features of the object (9%) again highlight the interrelatedness of object interpretation and material qualities. The robustness of the object was also a contributor (6%), itself composed of multiple qualities such as toughness (2%), hardness (2%), fragility (1%) and rigidity (<1%). Residual sight (5%) and sound (4%) all support the use of optical and acoustic properties in minor quantities in object interpretation and the participant’s prior experience (4%) logically suggests that prior exposure to such objects can greatly assist material interpretations. Finally, the colour of the object (2%) was used, suggesting that some participants with residual colour vision found this property useful for colour identification.

[Table 2 Here]

Object Judgements

Participants were then asked to identify what the object was (Table 1), with judgement accuracy ranging between ~20 to 50%, and with object judgement lower than material judgement accuracy overall. Accuracy was highest in the crab (52%) and tortoise (58%) shells, but extremely low in all other objects. This is unusual given the simplicity of some of the objects, particularly the fox femur (24%) but may be accounted for by factoring in partially-correct responses. The majority of participants were able to get a strong idea of what the object was but their expertise or interpretation was insufficient for accurate identification. In the fox femur, for example, half of all participants were able to determine that it was an animal bone (58%), with only (24%) identifying it specifically as a leg bone, irrespective of the type of animal it was. Similar trends can be observed in the scallop shell as a mollusc or shell (62%) and the brain coral as a variety of other marine creatures (34%); a sea urchin (10%), sea anemone (5%), barnacle (5%), sea creature (10%) and a sea shell (5%). The overall ramification is that BPS individuals are able to obtain an understanding of an object without supervision but may require assistance for a more detailed identification.

As before, participants were also asked to state why they identified the object as such (Table 2). Shape was dominant (20%), which is expected given that an object’s morphology is a key property of organismal taxonomy. Its specific features (14%) and texture (11%) were again essential, these top three reasons notably being shared by those supplied for material identification. This further suggests that object and material properties are interrelated when making judgements. The prior experience of the participants (10%) was highly cited, suggesting again that previous experiences with similar objects is useful for object definition. The size of the object (8%) suggests that scale was a key

property. Optical properties, including colour (3%) and residual sight (3%) in addition to acoustic properties like sound (<1%), suggest again that multisensory properties are essential to understanding what an object is.

Enhancing Interpretability

Participants were then asked to suggest what could be changed about the object using 3D printing to help them better understand and interpret it. The majority of responses stated that no changes should be made (44%). Many of these concerns were associated with wanting to handle an accurate replica, rather than an altered copy. Also popular was audio description (16%), a well-utilised assistive solution that aids interpretation without than altering geometry. Increasing the scale of the object (11%) was also commonly cited, with the rationale that a larger scale would make some features easier to feel and interpret. Adding life context (7%), such as adding additional parts like legs and limbs, was considered potentially useful in giving more clues for participants to work with. Other alterations included internal access (4%), tangible diagrams (3%), alterations to texture (3%), change colour (3%), remove coating (2%), preserve damaged parts (2%) and enlarge specific portions (2%).

Ease of Object Interpretability

Once all objects had been interacted with, they were presented to the participant as an ensemble and each person was then asked to choose which one was easiest and which was most difficult for them to interpret over the duration of the exercise. These were computed as differential frequencies. Overall, the object with the lowest differential frequency was the brain coral, the only negatively rated object (n = -11). It was never elected as the easiest object. This was followed by the tortoise shell (n = 0), the crab shell (n = 1) and the scallop (n = 2), all three of which were roughly neutral. The fox femur on the other hand had the highest differential frequency (n = 8), indicating that this object was the easiest to interpret with no votes for the most difficult object.

Reasons for Easiest Object

Participants were also asked to provide reasons why they found their “easiest object” simple to interpret. The most common reasons for the easiest object were the object’s shape (23%), which was tied with it being distinctive (23%), suggesting that distinctive geometry of features aided object interpretation. Prior experience (19%) was also key, familiar objects being easier to interpret as discussed earlier. The specific features (9%) and the ‘feel’ of the object (9%), the holistic aspects of texture, were also important to the participant’s understanding of the objects. Other more minor reasons included the weight of the object (5%) and its texture (5%). Other responses composed less than 5%.

Reasons for Hardest Object

Participants were then asked to provide reasons for why they found their “most difficult” object challenging to interpret. Responses were dominated by lack of experience with the object (21%), marrying up with the importance of experience for making an object easy to interpret. Some simply misidentified the object (15%) and some participants found the texture difficult to interpret (12%), suggesting that some textures are confusing. Some participants also stated that the object was too complex (9%), which may explain the difficulties many had with the brain coral. The unexpected size of the object (6%) was another issue, particularly in the tortoise shell, which was deemed too small by a few participants. Some participants could not pinpoint the reason they specifically couldn’t identify the object (6%). Other responses composed less than 5%.

The majority of participants preferred object shape to not be altered through 3D printing, preferring assistive solutions such as complementary audio description. Some participants asked for a number of other provisions, including scaling up and the addition of more authentic, life-like contexts for the objects to aid interpretation. Finally, prior experience played a role in the ease of participants’ interpretations. All of these reasons can help museum professionals consider how such a 3D-printed surrogate will impact interpretation. The ways in which these findings can guide the design of tangible 3D-printed replicas for BPS audiences can now be considered.

The Nature of Tangible Interaction

Tangible interaction is not a unisensory task. A corpus of research in sensory psychology (Lederman and Klatsky, 2004; Heller and Ballesteros, 2006; Spence, 2018) and neuroscience (Sathian, 2005; Lacey and Sathian, 2014; Voss et al., 2016) shows that the senses are integrated within our perceptual systems. It is thought that this enables sensory redundancy, where multiple senses detect different overlapping characteristics of an object that triangulate to create a more robust interpretation. This means that simply creating a physical object that replicates the original geometry is insufficient for proper understanding, as discussed below. Given that BPS individuals have more limited access to the complete suite of senses, non-visual object properties become essential to BPS sensory perception, as noted by Holloway et al., (2019).

Further complications arise in relation to the ways in which the BPS community is perceived as a homogeneous group, with only extreme sight loss really being considered. Provisions in museums often focus on providing tangible interaction or audio content, with a particular bias towards providing braille, as earlier discussed (National Federation of the Blind, 2009; Phillips and Beesley, 2011; RNIB, 2018). Rarely considered is the varied nature of sight loss, from patchy vision and blurring through to light perception and lack of colour, as has been observed during this study (Bourne et al., 2013; Hayhoe, 2013; WHO, 2018). As shown here, sight and colour in particular, is still utilised in interpretation by those with residual light perception and must be taken into account

when designing tactile 3D-printed replicas. This is key, particularly in relation to their impact on previous handling experiences and tactile proficiency (Koch et al., 2013). Additionally, the European Blind Union reports that only ~9.7% of people with sight loss in Europe can be categorised as full-blind (EBU, 2020), highlighting the need to cater for the variegated nature of sight loss.

One may question whether the duration and level of experience of living with sight loss may also influence how effectively BPS individuals can interpret their surroundings. This is known as the sensory compensation hypothesis, which suggests that a lack of vision results in compensation by other senses, making touch, hearing and smell more acute (Voss, 2011; Baumgartner et al., 2015). Though a controversial topic, the general consensus is now that the amount of visual experience prior to incurring sight loss is unconnected, and congenitally and late-blind individuals show similar performance in a number of tactile tasks (Heller and Ballesteros, 2006; Baumgartner et al., 2015). Rather, the amount of experience that an individual living with sight loss has incurred appears to influence tactile proficiency and performance (Grant et al., 2000; Alary et al., 2009). This introduces more complexity to the design of 3D-printed replicas: both different sight loss conditions and also 'sensory proficiency' must be accounted for. For example, Callieri et al., (2015) demonstrated the creation of a 3D-printed replica of *Alchemy* by Jackson Pollock, a colourful composite tactile artwork. The print, however, was grayscale, eliminating potentially useful visual information for BPS individuals with residual sight.

The experience of BPS persons, both prior to sight loss and afterward, is also a key factor. A core part of constructivist ideas in informal museum learning (Falk and Dierking, 2000; Hooper-Greenhill, 2007) is that prior experience is key and here it was observed that the participants' prior experiences were linked to how easily (or not) they could identify objects. Given the limited spatial resolution of touch and the cognitive demands associated with interpreting larger objects, understanding alien objects can be a difficult task. This caused difficulty for a number of congenitally blind participants:

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

Karrey (Congenital Total Blindness)

The lack of experience in this case is tied to their total congenital blindness, which has limited their exposure to unusual objects that many would see in general media. Conversely, the same participant instantly recognised the fox femur as a bone, a far more familiar object to them. Similarly, the tortoise shell was easily recognised by many participants:

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

Iris (Congenital Minimal Visual Shape Perception)

Thus, interpreting the unfamiliar is a difficult task for anyone, potentially compounded if the onset of blindness is early. Given the propensity of museums towards the intentional use of unusual and exotic objects to inspire curiosity, presenting material to BPS individuals is a challenge that will require novel solutions. This also highlights a further issue noted in the fairly low rates of object identification, which was that a general interpretation was easily attained but anything more specific was difficult to achieve. Thus, BPS persons require further support to understand what exactly they are interacting with. This study was intentionally designed to limit assistance but in a museum setting this is easy to achieve. Standard practice includes audio guides, as demonstrated by Eardley et al. (2016) in two Portuguese museums, where audio guides provided detailed object descriptions that supported tactile handling for BPS audiences, leading to a better understanding of exhibition content. Docents and facilitators with training in assisting BPS persons are also a powerful solution. Here, many participants agreed on this well-established solution, even its potential as a priming tool:

"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... 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 Years Blindness with Light Perception)

Considerations for creating 3D-Printed Replicas

With the nature of BPS perception in mind, some key design insights can now be outlined. Given the overall multisensory nature of object interaction, the perceptual value of object traits beyond touch such as the noise a shell makes when tapped, the smell of the sea on a crab shell or the high contrast colouration on a tortoise's shell, are important for understanding. However, the capabilities of contemporary 3D printing are at this stage insufficient for replicating these authentic object traits, an issue highlighted by one of the participants:

"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)

Olfactory properties are difficult to replicate without secondary post-processing and the addition of scents. Some materials, such as ABS, also carry their own scents, which could hamper multisensory interpretation (Ngo et al., 2018). Acoustic properties will also be negatively impacted, which will rarely match perfectly with the original material in addition to the layered composition of 3D-printed objects. This will also impact tangible characteristics, such as thermal properties and texture, which could potentially deceive the handler. Colour printing for optical properties is also limited, as many modern printers only utilise a single material, particularly affordable fused filament fabrication (FFF)

solutions (Gibson et al., 2015; Chua and Leong, 2015; Chen et al., 2016). Some full-colour FFF methods are beginning to reach the market though (XYZ Printing, 2018). Full-colour printers are capable of reasonable results but the verisimilitude of colour in the final product is often limited, with lower resolution and gamut (Vanderploeg et al., 2016; Chen et al., 2016). Colour quality is also influenced by the materials used, surface properties, finishing and layer thickness. This creates a complex, multi-dimensional web of interactions where a simple material choice can have significant ramifications on object interpretation. Given the finding that material and object properties appear to be inter-related, material choice can thus interfere with interpretation.

Altering the geometry of 3D prints in order to make them more readily interpretable is also problematic. Many participants cited concerns with such approaches and instead wished to hold an unadulterated copy of the original object:

"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)

Nevertheless, while many advocated non-alteration, others noted useful interventions in which objects could be enhanced through assistive technologies and 3D printing. Audio description could assist interpretation as discussed above (Eardley et al., 2016; 2017), but increasing the size of the object was also a popular suggestion, a process that allows clearer interpretation of small structures, which would be difficult to interpret otherwise (Jafri and Ali, 2015; Hegna and Johnson, 2016):

"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 approach does incur a potential compounding problem. Some participants thought the tortoise shell was too small to represent a tortoise and the importance of size-to-object perception suggests that changing the size of an object could have a negative influence. Exaggerating features in 3D prints, a useful approach for low-relief objects, could also negatively impact perception (Ballarin et al., 2018). In relation to the fox femur, its size was important in determining the type of animal it belonged to as, in the words of one participant:

"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)

Thus, changing aspects of the geometry could prove to be counter-productive unless some context is provided for the original object or scale and such alterations are supportive. For example, an enlarged 3D-printed object could be presented alongside one at actual size.

Overall, museum practitioners should consider carefully what materials and scales are used when undertaking the creation of 3D-printed replicas for object handling by BPS audiences. They should appreciate that the choices made will inevitably have ramifications for their successful interpretation. Thus, in order to properly design such replicas, a better understanding of BPS object interpretation is required. This naturally mandates a greater research presence in the field, as discussed below, but such understanding is required before museum institutions dive headfirst into investing their already-strained capital into 3D printing technologies and replicas. For instance, are 3D-printed replicas a viable alternative to the real thing? Or do the barriers to a verisimilar replica, as discussed above, make such objects too confusing or difficult to interpret? Are 3D-printed replicas just an expensive distraction to solving the issue of accessibility? To find the answers to these questions, more research is required in order to understand the role of 3D printing for BPS content provision.

Future research opportunities

A number of emergent research strands are forthcoming. First and foremost is a further need for an empirical exploration of ways of assisting BPS visitors in their interpretation of objects, the 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.

It is also worth exploring in greater detail how the choice of material can influence perception, in order to further unpick the overlap between object and material interpretations. For example, how might choice of printing material influence the handler's interpretation of the object or how might objects can be treated so that they appeal to different senses?

Comparing how object-based museums and other more hands-on institutions, like children's museums, utilise multisensory interaction for BPS engagement may also be key. These museums have considerably more experience in creating such exhibition content and their insights may be invaluable in these first forays.

Finally, in keeping with previous studies (Wilson et al., 2017; 2018) and with principles of inclusive design, a further exploration of which features or physical properties are important to BPS audiences should be considered. In order to fully incorporate Universal Design Theory (UDT) approaches into museum practice, museum professionals must collaborate with BPS audiences in order to develop the best solutions. UDT is a design approach that attempts to make any product or environment naturalistically usable for everyone so that no one is excluded from use (Story, 1998; Null et al., 2014). The integration with UDT in the initial design of an exhibition minimises the need to make

expensive changes post-installation and grants all visitors equal access to exhibition content without needing to struggle to provide auxiliary sessions dedicated towards BPS audiences. To this end, the findings of this study must be tested within the naturalistic environment of the museum exhibition.

Conclusions

This study addressed the perception of natural history objects by BPS persons and found a complex interplay of choices that must be accounted for by museum professionals when creating 3D-printed replicas. These will prove to be challenging to overcome but their solution will help museums provide better support for BPS visitors. Firstly, BPS object interaction is multisensory. Olfactory, optical and acoustic properties are essential for perceiving and understanding objects. These must be incorporated to help facilitate clearer interpretation, no matter the difficulty.

Participants more readily identified the material of the objects over what it was and most participants were only capable of a general understanding. The reasons provided for material and object identification overlapped substantially, again suggesting that the interpretation of objects is a holistic process. Key object characteristics include texture, shape, features, weight, size, ‘feel’, relation to prior experiences and optical properties, including colour.

Participants preferred assistive solutions, such as audio descriptions and more life context, which could assist their interpretations. Altering geometry is risky and altering shape or size, two major reasons for object and material identification, could negatively influence user interpretations.

Importantly, BPS museum audiences are not homogeneous. There is a broad spectrum of different sight loss experiences and conditions, meaning that one 3D printing solution is not suitable for all. As a result, museum professionals should take into account a variety of different levels of handling experiences, prior exposure, sight-loss conditions and times of blindness onset when designing 3D-printed replicas.

3D printing technology is at this stage unable to create replicas that are truly identical to the original object and will most likely require significant post-processing to achieve such an effect. Future advances in the technology are likely to alleviate this situation.

Finally, further research avenues include investigation of how object alteration in model creation stages influence BPS interpretations of objects; how inter-dependent object and material judgements are with each other; and how BPS preferences of 3D printing in a museum context compare to those of sighted audiences. Understanding these issues is necessary to design enjoyable 3D-printed replica experiences in exhibitions under Universal Design Theory for all visitors, regardless of sight condition.

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Declaration of Interest Statement

The authors of this article have no affiliations with any organization or entity with a financial or non-financial interest in the subject matter or materials discussed in this manuscript.

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Tables

Table 1: Decisions of Material and Objects

Object	Material Correct %	Common Categories	Object Correct %	Common Categories
Scallop Shell	**58% (12)**	Stone (38%) ✓ Fossil Material (14%) ✓ Shell (29%) Other (19%)	**19% (4)**	Fossil Shell (19%) ✓ Mollusc/Shell (62%) ~ Fossil Animal (5%) ~ Other (14%)
Crab Shell	**66% (14)**	Shell (66%) ✓ Plastic/Resin (19%) Wood (5%) Other (10%)	**52% (11)**	Crab Shell (52%) ✓ Other Shell (29%) ~ Tortoise Shell (5%) Other (14%)
Tortoise Shell	**81% (17)**	Shell (75%) ✓ Bone (5%) ✓ Wood (10%) Other (10%)	**58% (12)**	Tortoise/Turtle (58%) ✓ Marine Creature (21%) ~ Animal Shell (10%) ~ Don't Know (10%)
Brain Coral	**62% (13)**	Coral (19%) ✓ Stone (42%) ✓ Shell (19%) Other (20%)	**19% (4)**	Coral (19%) ✓ Marine Creature (34%) ~ Fossil/Plant (33%) Don't Know (14%)
Fox Femur	**67% (14)**	Calcium (14%) ✓ Bone (52%) ✓ Wood (24%) Plastic/Resin (10%)	**24% (5)**	Leg Bone/Femur (24%) ✓ Limb Bone (10%) ~ Animal Bone (58%) ~ Don't Know (5%)

✓ = Answers Deemed Correct; ~ = Answers Deemed Partially-Correct

Table 2: Justifications for Choice of Material and Object

Common Material Description Categories	Freq.	Common Object Description Categories	Freq.
Texture	16% (48)	**Shape**	20% (47)
Shape	13% (39)	**Specific Feature**	14% (33)
Weight	9% (28)	**Texture**	11% (27)
Specific Feature	9% (28)	**Prior Experience**	10% (23)
'Feel'	9% (26)	**Size**	8% (19)
Robustness	6% (18)	**'Feel'**	5% (11)
Residual Sight	5% (14)	**Seems Organic**	4% (10)
Seems Organic	4% (13)	**Weight**	3% (8)
Prior Experience	4% (12)	**Mechanical Function**	3% (7)
Sound	4% (12)	**Colour**	3% (7)
Natural	4% (11)	**Structure**	3% (7)
Internal Structure	3% (10)	**Residual Sight**	3% (6)
Material-like	3% (10)	**Condition**	2% (5)
Size	2% (7)	**Material Association**	2% (4)
Colour	2% (7)	**Dead**	1% (3)
Object Association	2% (6)	**Robustness**	1% (3)
Artificially Treated	1% (3)	**Guessed**	1% (3)

Responses with Frequency < 2 are not included

Figures

Fig. 1

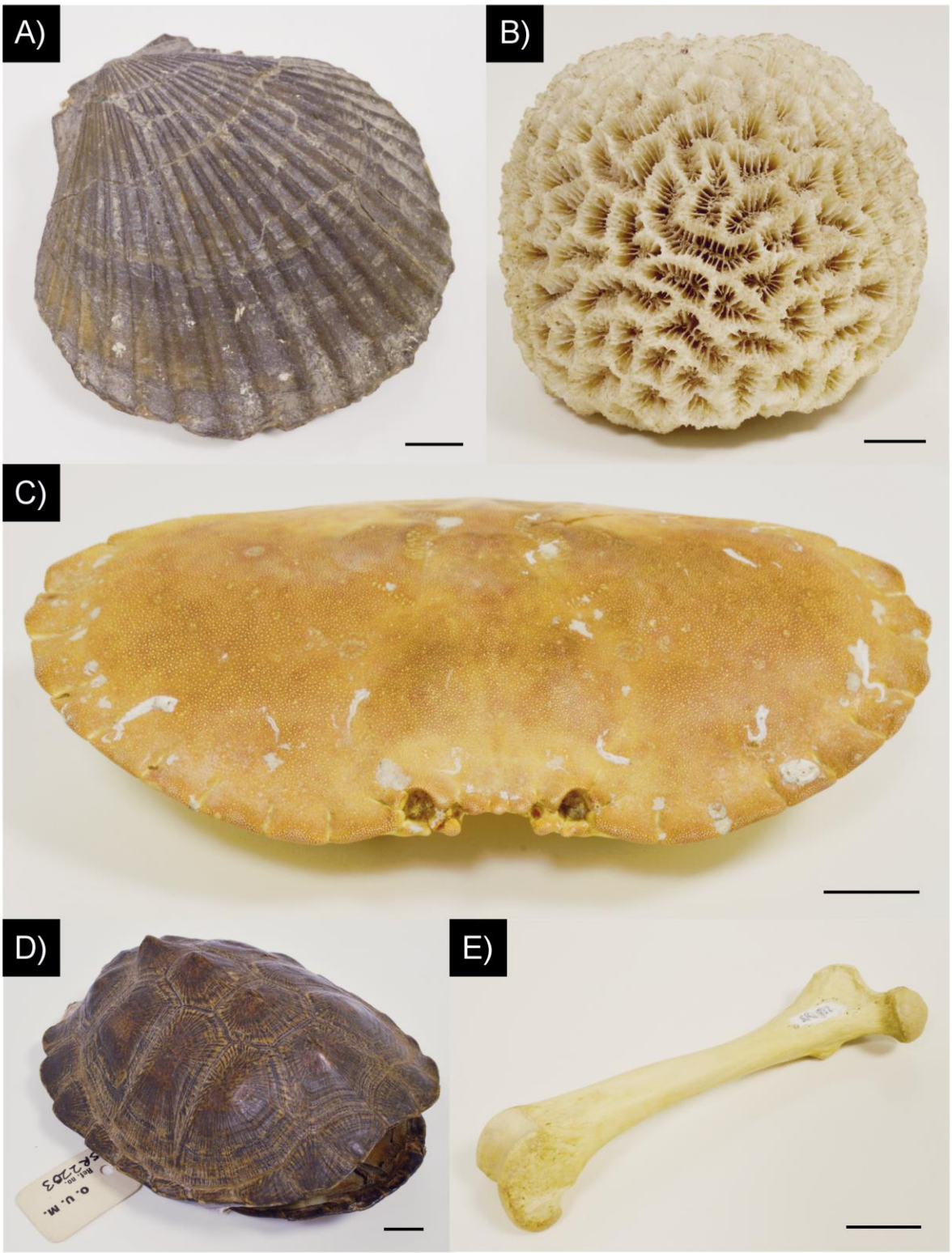

Fig. 2

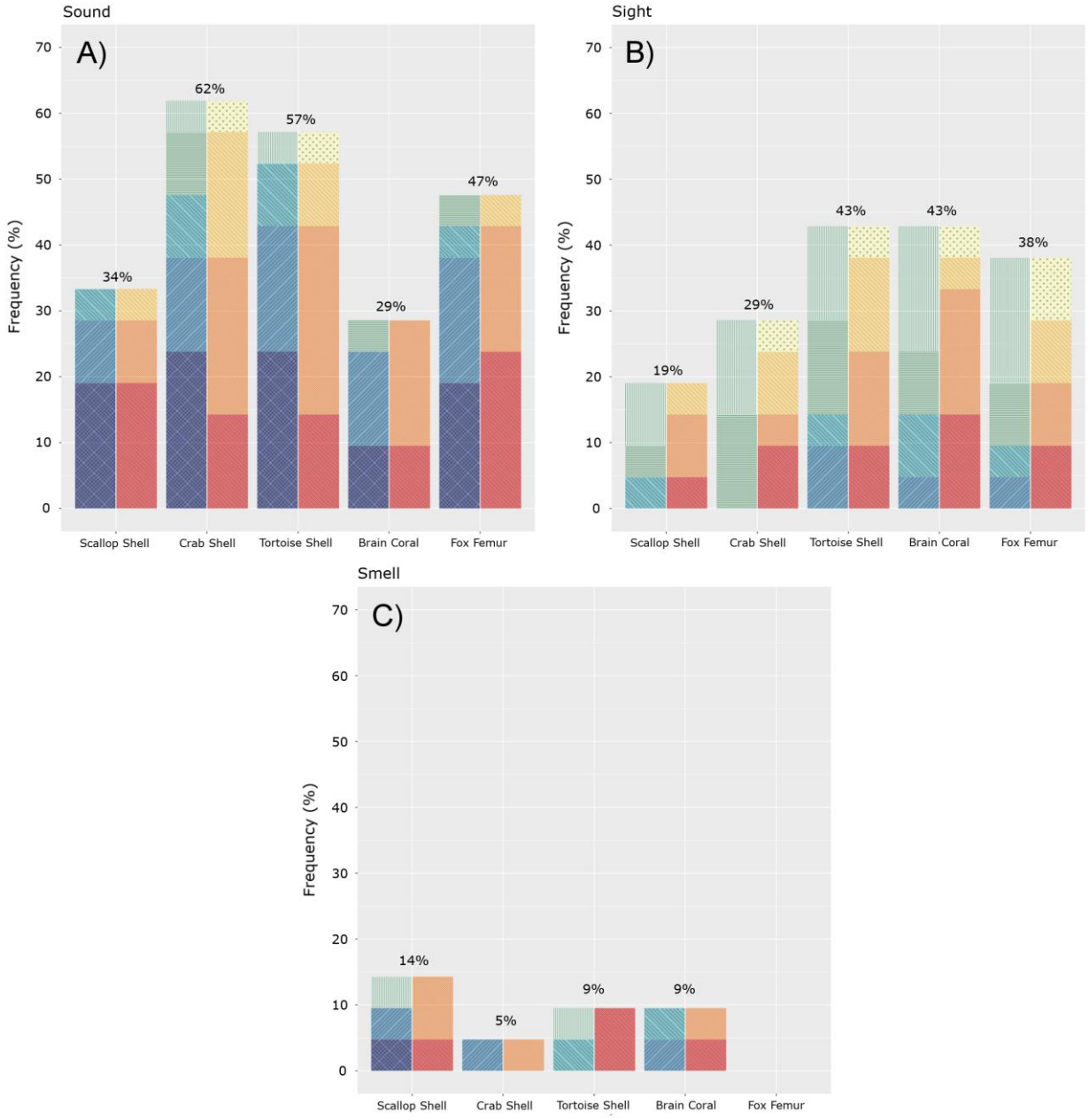
Sound
A)
Frequency (%)
34%
62%
57%
29%
47%
Scallop Shell
Crab Shell
Tortoise Shell
Brain Coral
Fox Femur
Sight
B)
19%
29%
43%
43%
38%
Smell
C)
14%
5%
9%
9%

Figure Captions

Fig. 1: Research Objects. A) *Pseudopecten equivalvis* (OUMNH SR0409) 1 cm scale; B) *Diploporia* sp. (OUMNH SR0615) 1 cm scale; C) Carapace of *Cancer pagurus* (OUMNH SR0671) 2 cm scale; D) *Manouria emrys* (OUMNH SR2203) 1 cm scale; E) *Vulpes vulpes* femur (OUMNH SR1812) 2 cm scale.

Fig. 2: Sensory usage by BPS participants during object interaction. A) Sound; B) Sight; C) Smell. 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 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.