"Do touch!" – 3D Scanning and Printing Technologies for the Haptic Representation of Cultural Assets: A Study with Blind Target Users

Arne Bruns*
abru857@aucklanduni.ac.nz
The University of Auckland
Auckland, New Zealand

Anika A. Spiesberger*
anika.spiesberger@uni-a.de
EIHW, University of Augsburg
Augsburg, Germany

Andreas Triantafyllopoulos
andreas.triantafyllopoulos@uni-a.de
EIHW, University of Augsburg
Augsburg, Germany

Patric Müller
patric.mueller@cbi.uni-erlangen.de
University of Erlangen-Nuremberg
Erlangen, Germany

Björn W. Schuller
schuller@tum.de
GLAM, Imperial College London
London, United Kingdom

ABSTRACT

Visiting museums can be challenging for visually impaired people, as many objects are hidden behind glass walls and information is limited to descriptions. One of the best ways to increase accessibility and inclusion in museums and other cultural heritage institutions is through the use of 3D-printed replicas. However, there are several different scanning and printing processes that not only differ in terms of effort and cost but can also produce very different results. This paper evaluates two different scanning techniques and four different printing processes in terms of these aspects and includes feedback from a group of blind and partially sighted users on the aesthetic quality and fidelity of the printed objects. We found differences between the scanning methods mainly regarding their ease of use. Of the printing methods tested, stereolithography was preferred by the majority of participants for use in the museum. Additionally, we include user comments which touch on the general aspects of presenting museum artefacts using haptic devices. Our study thus provides valuable insights into the preferences of the target users, which can be used to inform decisions about more inclusive museum experiences.

CCS CONCEPTS

• **Social and professional topics → People with disabilities**; • **Applied computing** → *Interactive learning environments*; Fine arts; • **Human-centered computing → Systems and tools for interaction design**; **Empirical studies in accessibility**.

KEYWORDS

blind and partially sighted, 3D scanning methods, 3D printing processes, cultural heritage

*Both authors contributed equally to this research.

SUMAC '23, November 2, 2023, Ottawa, ON, Canada

ACM ISBN 979-8-4007-0279-2/23/11.
https://doi.org/10.1145/3607542.3617351

ACM Reference Format:
Arne Bruns, Anika A. Spiesberger, Andreas Triantafyllopoulos, Patric Müller, and Björn W. Schuller. 2023. "Do touch!" – 3D Scanning and Printing Technologies for the Haptic Representation of Cultural Assets: A Study with Blind Target Users . In *Proceedings of the 5th Workshop on the analySis, Understanding and proMotion of heritAge Contents (SUMAC '23), November 2, 2023, Ottawa, ON, Canada.* ACM, New York, NY, USA, 8 pages. https://doi.org/10.1145/3607542.3617351

1 INTRODUCTION

"Do not touch!" is perhaps the most common sign in museums around the world. While this can be mildly annoying to the general visitor, it poses a major challenge to blind and partially sighted (BPS) people when visiting museums and other cultural heritage institutions [1, 16]. In 2020, this concerned 596 million people worldwide with distant visual impairment and a further 510 million with uncorrected near vision impairment, including 43 million who are completely blind [6]. Burton et al. [6] further predict that, due to population ageing and growth, as well as urbanisation, these figures will increase to approximately 895 million people with distant visual impairment by 2050, including 61 million blind people. Promoting accessibility to cultural heritage for BPS people is therefore becoming increasingly important.

Although most museums now provide some form of audio description for BPS people, these descriptions are usually written by a sighted person and therefore make assumptions about what BPS people want to know and what they can understand [19] or are not targeted at BPS people at all [20]. Additionally, the information required may be different for people who were born blind, those who became blind later in life, and those who are partially sighted. For this reason, and because their hands often take on the role of their eyes [16], haptic experiences can be an additional help for BPS people [1] and are among the most preferred accessibility methods [20]. They enable them to experience the object for themselves, to understand the details of an object, which facilitates a comprehensive examination of the exhibit [16], and to create an accurate mental representation which is necessary to make sense of an object [29].

There are several ways of providing tactile access to museum exhibits. The most obvious may be to offer tactile tours, as some museums do, where visitors are allowed to touch the original objects [19]. In most cases, these tours are conducted with gloves on and under professional guidance. However, many museums are reluctant to offer tactile tours, arguing that the exhibits are not suitable for touching because they are too big, too small, or too fragile [23], or not suitable for conservation reasons [12]. As a result, much effort is being put into researching ways of providing a tactile experience without touching the original object.

Manual exploration of virtual objects using a haptic interface is one method of providing tactile experiences through augmented reality. The interfaces of these systems use force feedback to provide a sense of touch [14, 28]. This allows the visitor to haptically explore something that only exists virtually and does not necessarily have to be in the same place as the original object. Various devices are being developed in this area, some of which have to be attached to the visitor and carried and others where the feedback is given by a stationary device that the visitor moves around [9, 28].

The most common method, however, is to provide replicas of the object, that can be handled by the museum visitors. Traditionally, these replicas were made using casting moulds [3], a manual process that is time-consuming and highly dependent on the original object, allowing only exact 1:1 copies [27]. Later, subtractive technologies were introduced, i. e., methods in which the replica is cut from a block of material using automated machines. However, these machines are usually limited in terms of possible geometries, are difficult to operate, and are expensive (especially for small series) [27]. The advent of additive manufacturing (commonly known as 3D printing) in the last decade has opened up many new possibilities. 3D printers work by gradually adding layers of material and are generally easier to use than subtractive methods.

With the advancement of 3D technologies, there has been much research into how 3D printing can be used for museum exhibits and the challenges posed by the different technologies [15, 22]. Moreover, there are different technologies not only for printing but also for scanning the original objects [15]. 3D scanning is a crucial first step that enables the subsequent production of objects through printing and therefore, needs to be considered. Montusiewicz et al. [22] took a closer look at the process of preparing an exhibition, pointing out that in addition to the selection of the methods and the actual scanning and printing, post-processing is required after each step, which varies in complexity and should therefore be taken into account when choosing the 3D printing technology.

However, the choice of scanning and printing methods depends on a number of factors. The most important question to ask is: What will the replica be used for? As well as being touchable and improving accessibility, 3D replicas can be used to replace originals while they are on display elsewhere or being cleaned, for conservation or planning purposes [15], to replace lost heritage after destruction, and even as museum merchandise [3]. In terms of visitor engagement, the next question is: How can replicas best be used to enhance the visit and what methods and materials do users prefer?

A number of studies have investigated how the use of 3D-printed replicas enhances the museum experience [10, 23, 30, 31]. Wilson et al. [30] found that the majority of visitors appreciate the presence of 3D-printed replicas, as they add to the enjoyment and give a better understanding of the object. Wilson et al. [31] further investigated what type of printing method and material visitors preferred. Their findings indicate that people preferred resin to sandstone, steel, and plastic when it came to reproducing the jawbone of a fossil mammal. Realism, detail and visual/tactile clarity were identified as the most important characteristics of a good representation. However, both studies used sighted visitors for their evaluation and thus, it is unclear whether BPS people would agree with their findings.

Not many studies have looked explicitly at how BPS people experience replicas, what factors are important to them, and what method or material should be used. While Reichinger et al. [25] state that users in their evaluation study liked the composite wood replica of the Egyptian Cat Sarcophagus, they do not specify what technologies they used to build it. Montusiewicz et al. [22] conducted a pilot study with one blind participant to evaluate their replicas and found that most of the details were correctly identified. Eardley et al. [10], on the other hand, found that 3D-printed architectural models were not suitable as they were too detailed and over-scaled, but that full-sized gargoyles worked well due to their size, texture, and simplicity.

This work aims to evaluate different 3D scanning and printing technologies in terms of their feasibility, especially for small exhibitions and regional museums, their costs, and the resulting fidelity of the printed objects. This fills a gap in the existing literature, as previous studies have failed to investigate the intersection of scanning and printing and, more importantly, to take into account the preferences of the target users. Explanations of the different technologies used can be found in Section 2. Section 3 gives a description of the user study with blind people. The results, including process difficulties, costs, and user evaluations of the tactile study, are presented in Section 4. The paper ends with a discussion of the findings in Section 5 and a short conclusion in Section 6.

2 3D TECHNOLOGIES

2.1 Scanning Methods

In general, tactile and non-contact methods are available for active 3D measurements of objects. For this work, a variety of scanning methods were evaluated for their feasibility. Tactile methods using a probe and strain gauges were discarded as they are only suitable for easily accessible surfaces. Two non-contact active 3D measurement methods were selected: 1. triangulation using structured light and 2. volume measurement using technical computed tomography.

2.1.1 Structured Light. Structured Light scans form a subset of light-based 3D scans. The surface is optically measured using structured light, which works by projecting a known light pattern onto the object [17] (see Fig. 1). From the deformation of this pattern, the depth of the surface can be calculated. The maximum possible size of the object to be measured is limited by the resolution of the camera and the size of the calibration plate which is required for initial calibration. The object to be measured is positioned within the structured light. The system captures both, the depth data and the colour information of the object, from this perspective [17]. After rotating the object by a specified angle, the acquisition process is restarted. Once all the intended angles have been captured, the software automatically combines the data, triangulating every pixel of the images and arranging them into a point cloud [17].

Because the system relies on detecting patterns on the object, any optical effects will cause the software to miscalculate. Shiny surfaces such as those found on metal, glass, or plastic can make it impossible to scan the object without pre-treatment [24]. Chalk spray is one way of counteracting this effect, but it is not suitable for fragile or crooked objects. Shallow curves on the object are difficult to detect because they give the software little guidance in finding points that correspond to each other and can be calculated together. Additionally, the 3D scanner can only measure surfaces, which means it cannot measure the surface the object is standing on. If the object is very irregular in shape or weight, it might tilt or wobble slightly as it is rotated. These small changes in position are enough to render an entire measurement useless, although the software can attempt to take movements into account. Reusable adhesive can help, but it has to be removed from both the real and the digital model later. Furthermore, because Structured Light scans capture the surface of an object, they do not reveal its interior.

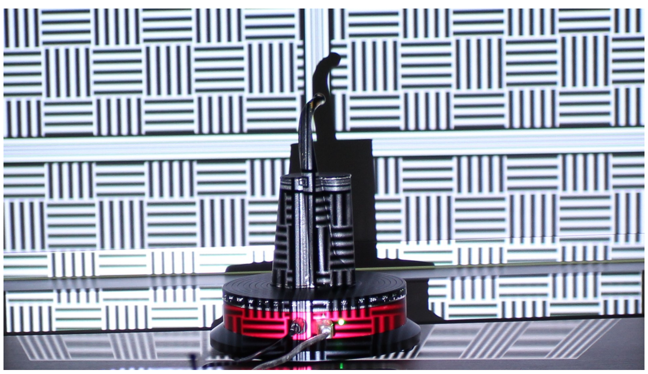

Figure 1: Structured Light scanning. The object is placed on a turntable. The deformations of the light can be seen on the scanned object.

2.1.2 Computed Tomography (CT). Most people are familiar with CT scans, which are based on the principle of image reconstruction [7], from the medical field. X-ray images are taken from multiple angles around an object, resulting in a series of 2D projections of the 3D object. Subsequently, the material density for each point in the object's volume is mathematically calculated, to create a complete three-dimensional model of the object [7].

The main problem with using CT for 3D measurement is the complexity of the operation, the long acquisition and preparation times, the cost of the equipment, and therefore the availability of such a system. The internal cost of the measurements is high, and incorrect operation can lead to unusable images, as well as damage to the system, such as destruction of the sensor. In addition, high-resolution scans generate large amounts of data that require specialised equipment to process. Also, in CT, the size of the sensor determines the size of the image that can be taken. The biggest challenges are radiation-hardening artefacts. As the X-rays pass through the model, dense materials such as metal change the spectrum of the X-rays, shadowing the in-line material and thus misrepresenting the density of the material [7]. For models made of materials with large variations in thickness, there is a trade-off between imaging accuracy and minimising artefacts. This contaminated 3D data has to be painstakingly repaired by hand and does not ensure the continuity of the fine, hollow structures. However, better segmentation algorithms can solve this problem [7].

2.2 Printing

After the scanning process, the models must be manually post-processed to make them suitable for subsequent printing by manually or automatically correcting errors such as holes, spikes, or misrepresentations. Slicer software is then used to convert the 3D model into layers of a defined production height, translated into machine-readable commands and transferred to the printer. The additive construction of the models requires additional support structures that must be removed after printing. The four manufacturing processes and machines used in this work are fused deposition modelling, stereolithography, selective laser sintering, and multi-jet printing. They are described in more detail below.

2.2.1 Fused Deposition Modeling (FDM). The process most people know as 3D printing is FDM. The printer heats a thermoplastic filament in a nozzle and extrudes it as a strand [11]. Using two axes, this nozzle is moved across a print bed to create a layer of material. The construction platform is then lowered by the defined layer height. The support material is made of the same material as the object and is printed with it. After printing, the model is immediately fully cured. The support structures can be removed manually and the model can be sanded or treated with chemicals.

2.2.2 Stereolithography (SLA). The stereolithography process is based on the controlled curing of a photopolymer using a laser or LCD screen on a build platform that is lowered into a vat of liquid [11]. After each layer is created, the platform is pulled out of the liquid photopolymer by one-layer height, resulting in a layer-by-layer build of the model. After production, the model requires post-processing. The remaining uncured photopolymer must be washed off using solvents. The support structures are removed manually and the surface and shape are reworked as desired (see Fig. 2). Depending on the material, the model must be placed in a curing oven under the influence of UV light for complete curing [11]. The printed model represents a highly accurate surface of the 3D model provided for slicing, although small imperfections from the support structure may remain. This can be converted to a smooth surface by sanding or grinding.

2.2.3 Selective Laser Sintering (SLS). As the name suggests, SLS works by selectively sintering particles. This is done in layers in a high-temperature inert gas atmosphere. New layers of powder are applied using a squeegee and a mirror-guided laser scans the layered sintering powder in the shape of one layer of the model, the building level is then lowered by one layer thickness and the process begins again [11]. The remaining material stays as a support structure, allowing cavities and complex structures to be well represented. At the end of the process, the construction space is slowly cooled in order to reduce stress in the sintered material and the model can be removed and cleaned of unused support material [11].

(a) SLA printed object still in the machine. **(b) SLA printed object after post-processing.**

Figure 2: Stereolithography (SLA) printing process. After post-processing, the object must be cured using UV light.

2.2.4 Multi-Jet Printing (MJP). MJP works on the same basic principle as an inkjet printer. It places a layer of photopolymer and photocurable support material onto a build platform, which is exposed to UV light to fuse after each layer [11]. By lowering the build platform and repeating the process, three-dimensional models can be created. Because the support material used is soluble under certain conditions, the resulting printed piece is a solid block from which the supports must be removed [11].

3 METHODOLOGY

For this work, an object from the exhibition "BarriereSprung" at the Stadtmuseum Erlangen, Germany, has been selected. The chosen object is an ear trumpet, a precursor of the modern hearing aid, from 1860, made out of painted brass sheet metal (see Fig. 3). The ear trumpet measures approximately 23 cm and was displayed in the exhibition in a glass showcase alongside a cochlear implant and a modern in-ear hearing aid to illustrate the development of assistive devices over the last two centuries.

3.1 Manufacturing of Replicas

For the Structured Light scanning we utilised the "David 2.0" system from Vision Systems GmbH (now HP 3D Structured Light Scanner). This Structured Light scanning system consists of a projector, camera, turntable, and associated software and was a spin-off from the TU Braunschweig. The size of the projected light pattern is large enough to cover the entire object, eliminating the need for manual fusing of multiple scans. The turntable, projector, and camera run automatically once the number of rotations has been set. To achieve a high level of accuracy, we used 180 scans, which took 30 minutes to complete.

The second model was built using a micro-CT scanner, a system specially manufactured by the Frauenhofer ERZT and FeinFocus GmbH to examine small technical objects and particle clusters. It consists of an X-ray tube, a sensor, and a turntable on which the object is placed. Due to the nature of our object and resolution requirements, 800 projections were taken in over 6 minutes, resulting in two models. These two models, an upper and a lower half, were manually fused using MeshMixer™, a software for working with triangle meshes.

Eight replicas were printed and post-processed; combining each of the two scanning processes with all four printing methods. We used the EOS "Formiga P 110" industrial system for SLS, the "Form 2" system from Formlab for SLA, an "Ultimaker 2+ Extended" from Ultimaker for FDM, and the "Agilista-3200W" system from Keyence Corporation for MJP. Company-provided slicers were used to prepare the models for production.

3.2 User Evaluation Study

In addition to evaluating the scanning and printing processes in terms of technical difficulty and economic viability, we carried out a tactile study. For this purpose, the "Birne 7" association contacted blind participants. The final sample consisted of six people (three male, three female) aged between 65 and 85 years (M = 73.5, SD = 8.4) attending a monthly meeting of the Bavarian Association for the Blind and Visually Impaired in Erlangen. The participants were born blind or became totally blind at different stages of their lives. All eight tactile replicas were presented. The original object was also provided as a reference.

In the first step, the participants were given the unprocessed replicas and invited to give a general opinion. Next, they were asked if they could tell a difference between the two differently scanned models. The third question was about post-processing: Participants were presented with the two models of the same material at the same time and asked to give their opinion on which of the two they would prefer. Finally, they were asked to indicate which of the eight models 1. provided the best haptic experience (ranking their first and second choices), 2. was closest to the original, and 3. would be best suited for a museum. In the end, they were given the opportunity to make further comments.

4 RESULTS

4.1 Challenges of scanning

Technical difficulties arise from the inherent principle of the two scanning methods. Both present the challenge that the measured data has to be post-processed. This can result in visible aberrations

Figure 3: Original ear trumpet used in this study.

and singularities that are hidden in the volume and cannot be processed by the printing preparation programs. Finding and repairing these defects is complex, and requires skill, expertise, and time.

4.1.1 Structured Light. Our experience shows, that Structured Light scanning can be easily used by anyone after self-guided training. The necessary tools can be purchased, built from open-source projects, or rented and set up in a museum. While open-source systems can be built for around €500, mid-range user-friendly systems cost €4,000, and large-scale hand-held systems with professional automated post-processing software are available starting at €6,500.

In our case with a mid-range system, slight variations in the object's position, caused by the vibration of the rotating table, often rendered half-hour-long scans impossible for the software to integrate into a model. The cavity and internal structure of the ear-trumpet presented an additional challenge. Since the Structured Light scanner only scans the surface of an object in one position, the internal structures were impossible to scan using this method. Instead, the internal structures had to be recreated digitally afterwards, which was time-consuming and required training in another software.

4.1.2 Computed tomography. Because CT scanners use X-rays, this approach cannot be used by "anyone", but requires specially trained personnel. Objects must therefore be transported to specialised facilities or universities. Scanning an object of our size in an industrial setting costs around €225, which usually includes the post-processing of the digital data. However, the price for this is expected to decrease as the market has a growth tendency. The main challenge in using CT to scan our museum object was beam hardening and the resulting loss of image quality. The model has sections of high but also very low material thicknesses. In the reconstruction of the volume of our ear trumpet model, a threshold in the calculated density of a specific point has to be chosen to determine whether the point is in the object material or not. Due to the artefacts a threshold problem arises. Choosing a low threshold excludes points from being allocated to the material and creates holes in the model while choosing a higher threshold causes intricate features to disappear and fringes out the edges as too many points are incorrectly associated with the material of the model. Both resulting faults can be patched manually but this is a time-consuming process.

A secondary challenge was that the object has a slanted axis leading to a slight shift in the coordinate systems of the two separately reconstructed models for the upper and the lower halves. Both models had to be manually aligned and fused. Combined with the threshold problem mentioned above, a perfect fit could not be achieved. The implementation of advanced segmentation, threshold detection, and alignment algorithms could potentially have mitigated this problem but was not realised in the scope of this project.

4.2 Challenges of Printing

As with the scanning, each of the printing processes presented different challenges and costs. In particular, the costs of the individual printing processes, not counting machine costs, are of great importance when selecting a printing process for a museum, especially a regional one. Additionally, the surface quality of all printing processes can be distinguished in the state directly after printing and after post-processing has been completed. In the following sections, we summarise our experience with the different printing processes, pointing out the costs and duration as well as the final results. An overview can also be found in Table 1.

4.2.1 Fused Deposition Modeling (FDM). The generated costs per model were €7 with a printing time of 17 hours. Some of the cheapest reliable printers are available from around €150, with well-functioning, user-friendly models starting at around €700. A range of filaments are available, covering a wide spectrum of colours, functional fillings, and thermoplastic materials, with PLA and ABS being the most common. In this study, we printed PLA models in various colours.

Without post-processing, the FDM print had a ridged, rough texture. The digital model was shown with high inaccuracy. Due to the coarse resolution of the printer, fine passages and walls cannot be reproduced well: blockages or defects occur. The individual filament layers were clearly visible and palpable in our model. The FDM model needed substantial high-density support structures that were difficult to remove. Especially with small, internal radii, the support structures were challenging to reach. Large cavities required internal supports that affected the continuity and shape of the model. Methods exist to print soluble support structures that were not available to us. Sanding the model was of limited help as the frictional heat softened the material and made it difficult to remove. However, with a lot of work, we were still able to achieve a noticeably smoother surface. Strong smoothing was achieved using the chemical tetrahydrofuran. Direct application with cotton resulted in a noticeable improvement in surface quality, but also caused the plastic to become dull. The more complex and hazardous post-processing with vaporised tetrahydrofuran was avoided in this study.

4.2.2 Stereolithography (SLA). Printing our model with SLA took about 12 hours and generated material costs of about €35 per model. Household printers are available from €250 (print volume about 12×6.8×13 cm); large printers (print volume about 33×18.5×40 cm) start at around €2,000. Liquid resins are used for printing, the most common being PLA, but Nylon and ABS are also possible. We used a general-purpose white PLA resin.

SLA needs a large network of support points (see Fig. 2a), which was easily removable by hand using a blade before hardening. Small imperfections remain at the support points after its removal. The surface had a high quality but also depicted any imperfections in the 3D dataset with great precision. Post-processing underwater with sandpaper of different grits enabled a very smooth or reflective finish, completely removing the imperfections left behind by the support structures.

4.2.3 Selective Laser Sintering (SLS). In a normal market order, high costs arise from the high machine and maintenance costs of industrial systems, while the manufacturing time is comparatively short; in our case, it took about 8 hours. Requested online services put the cost of a single model at around €100. Machines for private use are available for less than €10,000, while traditional large industrial machines cost over €200,000. For our model, we used PLA12 particles, however, many powders are possible as a substrate, including metal or ceramic.

Regarding the surface quality, SLS had the highest quality immediately after printing. The powder bed means that no support structures are required in the production process, so the model has no residual deviations from support connection points. The model had a matt, velvety surface right after printing. Grinding it with progressively finer sandpaper resulted in a smoother, yet matt, surface.

4.2.4 Multi-Jet Printing (MJP). MJP took about 9 hours and cost about €145 due to the expensive ink. The exact material is not disclosed by the manufacturers but is listed as AR-M2 and AR-S1 as photosensitive polymer inks and support structure material. The printers are expensive as this is a niche product, starting from above €10,000 with industrial systems costing over €100,000.

The MJP printed object had a high surface quality and was easily post-processed. The support structures were softened through submersion in propanol and blown out with compressed air. This process takes several days for large structures. After rinsing with propanol and water, the surfaces showed some adhesion or stickiness without further treatment. Handling and rubbing it with towels reduced but did not eliminate this stickiness. Without further treatment, an edge remained at the junction of unsupported and supported material. When sanding, care had to be used as the material of the model was of low hardness.

4.3 Results of the User Study

Regarding the two scanning processes, five out of the six participants stated that they could not tell the difference between the models. For post-processing, the results were mixed. While all six agreed that the SLS model was better when post-processed, only four felt this way about MTJ and SLA, and for FDM the split was 50:50. Their main argument was that the models felt too smooth when post-processed, which did not correspond to the original. In general, SLA was preferred to SLS by five people.

When asked to indicate which model felt best, opinions were similarly divided, but SLS and SLA were mentioned most often. When asked which model most closely resembled the original, participants mentioned SLS (post-processed), MTJ (unprocessed), and FDM (post-processed). The question of which model should be used in a museum was answered with MTJ (unprocessed), SLA (post-processed), and FDM (post-processed). All results can be found in Table 1. SLS was described as having the wrong weight to be used for the exhibition.

Additionally, one participant mentioned that the shape is more important than the surface, but that it should not be too smooth as this makes it harder to grasp and hold. In general, the ease of grasping the object was mentioned most often, indicating that this is very important for blind people. They mentioned that sharp edges should be avoided and that the weight matters, although opinions

Table 1: Results of the printing methods evaluation and user study. The table shows our assessment of the costs, ease of use, and ease of post-processing, as well as the number of times each model was mentioned by the participants in the haptic evaluation. For the first question, users were asked to indicate a first and second choice, the numbers indicate how many times the model was mentioned as a first/second choice.

	FDM		SLA		SLS		MTJ	
	unprocd.	procd.	unprocd.	procd.	unprocd.	procd.	unprocd.	procd.
Cost	very low		low		high		high	
Ease of use	easy		average		difficult		average	
Ease of Post-processing	difficult		easy		very easy		easy	
Best haptic	-/-	-/1	1/-	2/1	1/-	1/2	-/2	1/-
Most similar to the original	-	2	-	0	-	2	2	-
Best to use in a museum	-	2	-	2	-	-	2	-

differed on this, with some indicating that it should not be too lightweighted, while others mentioned that this would make it easier for older people to hold. One person also wished for the models to be labelled in Braille.

5 DISCUSSION

This work attempts to provide an overview of different 3D scanning and printing methods used for cultural heritage replicas. As well as investigating the challenges and costs associated with each method, we also conducted a user study with BPS people to assess which method they felt was most suitable for use in museum exhibits.

Our main finding relates to the importance of haptics and form. In general, shape was considered more important. While haptic similarity to the original is desirable, it is not the main criterion for choosing which replica to use in the museum. This is reflected in the results, as the processed SLA replica was rated as having the best haptic experience, and even though it was not mentioned as being similar to the original, it was still voted as the best for the museum by a third of the participants. The main requirement for the surface was that it should be easy to grasp. This finding is important because using a different material to the original is often unavoidable when objects need to be pleasant to touch, easy to clean, and robust [23]. However, the importance of the material might also depend on the specific object and may be different for art exhibitions compared to historical or science museums [13]. Future studies should therefore use more than one object to examine the relationship between material preference and object type.

In terms of the scanning methods, our users did not express a preference. In general, CT scanning produced better results,e especially for hollow objects, but as it cannot be performed by everyone, it is more expensive than Structured Light scanning. Looking more closely at the material, our user evaluation makes a clear statement difficult, as the participants were all easily satisfied. However, it can be said that they preferred the processed replicas for FDM, SLA, and SLS, and only preferred the unprocessed replica for MTJ.

As previously suggested by Bavi and Gupta [4] and Montusiewicz et al. [21], one participant wished for Braille labels on the printed replicas. While this would require some additional processing before printing, it could help to further enhance the understanding of the object. An approach similar to [25] might be plausible. They produced their Egyptian Cat Sarcophagus, half of which was a replica of the object on display and half of which was modelled as it might have been originally, with more pronounced features. In our case, it could be interesting to print two versions of the exhibit, one with more enhanced detail and Braille labelling. Another possibility is to combine 3D printing with audio information either by tracking visitors' hands [5] or by using NFC tags and sensors [8].

It should also be mentioned that our study used a small number of participants and the average age was over 70 years; it would be advisable for the future to assess whether there are differences in perception between age groups. Furthermore, although all the participants in this study were totally blind, they differed in terms of the point in their lives when they became blind. As Scianna and Di Filippo [26] suggested, this is likely to affect their perception of objects because mental concepts differ. Additionally, it might also be interesting to include a matched non-blind control group.

In terms of the costs, the FDM process was the cheapest at around €7 for the printed model, followed by the SLA model at around €35. However, it must be said that 3D technologies are still changing rapidly. This applies to both scanning and printing. With this change, technologies will become more available and cheaper. For example, photometric stereo has been shown to work for cultural heritage [18] and light-based scanning methods are already possible using high-resolution smartphone cameras.

6 CONCLUSION

According to the Universal Declaration of Human Rights, "Everyone has the right freely to participate in the cultural life of the community, to enjoy the arts and to share in scientific advancement and its benefits" [2]. However, for many BPS people, this is not the case when it comes to visiting cultural heritage institutions. For this reason, there has been increasing research in recent years into methods of improving the accessibility of cultural heritage. One method is to provide replicas of objects that can be touched.

In this study, we investigated the use of different 3D scanning and printing technologies for cultural heritage. We looked closer at their costs, feasibility, and, most importantly, their perception by the blind target users. To do so, we produced eight replicas of a museum object using two different scanning methods and four different printing methods. These replicas were then evaluated by the target users.

We used a historical artefact to conduct this study. All participants welcomed the opportunity to haptically experience museum artefacts. The results of our user study indicate that BPS people preferred replicas that provided a good haptic experience, especially those that were easy to grip. This, together with its similarity to the original in terms of shape, was considered to be the most important aspect. Further research is needed in this area regarding differences between age groups, disability backgrounds, and types of museums.

ACKNOWLEDGMENTS

Special thanks go to Maximilian Reymann of Birne7 e.V., Andre Widmann of the Stadtmuseum Erlangen, and the members of the Bavarian Association for the Blind and Visually Impaired in Erlangen, whose support made this research project possible. This work has received funding from the European Unions Horizon Europe research and innovation programme under grant agreement No. 101060660 (SHIFT).

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