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Low-budget 3D printed haptic navigation aids for the visually impaired

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Abstract

In a culture shaped by the visual, having a visual impairment can present many difficulties, in particular concerning orientation and spatial awareness. Tactile models that allow users to experience an environment haptically can provide the spatial, object-based and sequential information necessary to facilitate visually impaired individuals' orientation and mobility in the environment. The increasing availability of 3D printing technologies and digital model data would allow for the creation of customisable tactile models tailored to an individual's needs and without high costs for design and fabrication. In this paper we explore design and fabrication of low-budget 3D printed tactile models for testing on real users.

Categories and Subject Descriptors (according to ACM CCS): I.3.8 [Computer Graphics]: Applications—

1. Introduction

Modern developments in hardware, material science and design software allowed for the proliferation of the technology of 3D printing, also known as Additive Manufacturing, which presents a diverse array of potential applications. Traditional uses of 3D printing were focussed on rapid prototyping, allowing for the quick fabrication of prototypes of new products for form and fitting evaluation, for example an architect printing a building design to get feedback from a client. As 3D printing technology was refined and improved, its applications broadened to producing user-centred products across a vast spectrum of disciplines, from archaeology to design. Applications in social sciences can also be recently found, yet not as widely spread as technology-centred applications [MFM*16].

In this paper we discuss connections between 3D printing and applications in the area of human-computer interaction where we have very specific audience, namely visually impaired users. While there is a multitude of research into how visual impairment impacts an individual's ability to visualize their surrounding environment, and, separately, how 3D printing can be utilized for a specific target audience, including people with visual impairments, less research exists on how the former affects the latter. The challenges include designing for an audience where each individual's experience with visual impairment differs, and translating visuals into something that can be experienced haptically. Another important aspect is the economic value of the solution. Traditionally, creating customized assistive tools for the visually impaired has involved several obstacles, the first of which was the financial cost of the tools caused by limited batches of products tailored to a small user group, and the second being accessibility, meaning that manufacturing customized solutions, even if affordable, have often been difficult to access by those to whom the technology could be useful.

However, as explained in [AA15], the development of highly user-friendly interfaces now allows this technology to be accessed by non-experts, while the technology itself provides a variety of customization options in terms of textures, colours and materials. This, coupled with the technology's low cost and fast production times, opens up many possibilities for blind people, their caregivers and accessibility designers and researchers in terms of enabling them to rapidly and cost-effectively design, create and share assistive tools and components.

In this paper we are discussing the design of haptic navigation aids aimed for visually impaired people with the main focus on the simplicity of the design process and low production costs. We present the potential applications of such designs and assess these applications on potential users with a wide range of visual impairments.

2. Background and related works

Aside from the technology-related limitations, one of the challenges faced by designers of assistive tools and devices for a visually impaired user is that visual impairment itself is a broad category, influenced by a number of factors, including age and genetics, and therefore each individual's experience is different. In [CV11] a detailed study on the levels of visual impairments, causes and resulting abilities is presented. In particular, it can be seen that the main causes for visual impairment include traumas, diseases (e.g.

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glaucoma) and age-related macular degeneration. The causes of visual impairment and the resulting level of blindness affect the person's ability to perceive things and what other sensory modalities are used. As a result, in order to have any positive impact on a user's life, any tool designed for the visually impaired must either be tailored specifically towards each user's individual needs, or alternately be designed broadly enough as to be useful to those with varying levels of visual impairment.

One of the key factors for increased access to the technology in recent years was the deployment of 3D printing technologies in a wide range of applications. The main factor which facilitated that was the development of low-budget printers, increasing ease of access to digital fabrication technology and the wide range of applications that can be done by using low-budget "desktop" 3D printers. These applications include medical [Ven14] and education of people with limited abilities [MFM*16].

3D printing technology was used for a number of applications aimed at the audience of visually impaired. [AA15] provides a detailed overview of various assistive solutions, and more specifically, existing applications of 3D printing technology for the visually impaired. In particular, they show that 3D printing solution can decrease the cost of assistive solutions on the one hand and adapt to the end users' needs on the other. In general, the applications can be distinguished by the their final purposes. The work of Bajcsy et al [BLBB13] discussed the issue of improving an access to election web pages to the visually impaired by using 3D printing. The Midas Touch project at the Harvard Innovation lab aims to make paintings more accessible to the visually impaired by adding a layer of texture to 2D paintings to allow them to be haptically explored. Guide4Blind project [Kre] used 3D printing to create scale models of architectural landmarks in Soest, Germany, which were then used to produce bronze models which could be placed near the landmarks, thus allowing visually impaired users to interact with them. Also an approach to cultural heritage in application to visually impaired users was presented in [GPL11].

Additionally, 3D printing has also been used to create tactile maps for the visually impaired, an idea that existed before the advent of 3D printing but previously came at a high price with little room for customisation. However, 3d printing now offers a convenient and flexible alternative. Several studies have investigated the use of 3D printing to create tactile orientation aids for those without visual cues to guide them. The method to create tactile scale models of the environment for purposes of spatial orientation were presented in [VM06]. There the models which were presented to the users mainly include replicas of the building along with interior to allow visually impaired users to understand the environment. Gual et al [GPL14] conducted research in Barcelona with blind and visually impaired individuals to investigate the use and impact of tactile maps produced by 3D printing, also analysing how the range of tactile symbols used on such maps could be developed further.

2.1. Tactile abilities

It is estimated that the limit of tactile spatial resolution in young normally sighted individuals ranges from about 1.2 to 1.7mm in the human fingerpad, whereas the threshold for blind subjects is roughly 0.2mm lower, varying from 1.0 to 1.5mm, with research demonstrating that this enhanced tactile acuity in blind individuals is retained into old age, while declining with age in sighted populations. While it is commonly believed that when one sense is lacking, the remaining senses improve to cope with this absence, Grant, Thiagarajah and Sathian [GTS] argue that blind individuals do not have an exceptional tactile sense, instead acquiring greater proficiency with non visual modalities as the result of repeated active tactile experiences throughout their life, as they continuously have to rely on tactile shapes or texture discrimination in their everyday activities, such as choosing clothing by recognising fabric texture, recognizing coins from their shape and selecting keys.

3. Designing 3D printed objects for visually impaired people

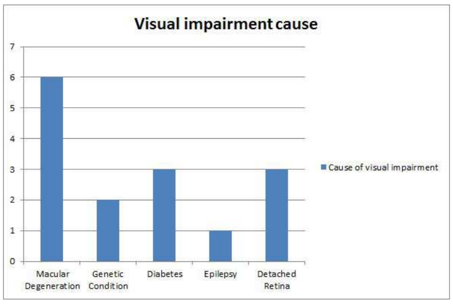
In this section we discuss the steps of our study and how we approached the challenge of designing for visually impaired users, taking into an account the simplicity of the design process and low production costs. One of the key points of this study was to take a user-centered approach, meaning that each step in the process took into consideration the potential users, their needs and how they could most benefit from the results.

In order to approach the challenge of designing for visually impaired users, it was important to first obtain feedback from the target audience in order to gain a greater understanding of their needs and requirements, and how these could be met through applications of 3D printing.

3.1. Analysis of the potential users and their needs

As part of this study, access was granted to the Bournemouth Blind Society, a local organisation that connects visually impaired people in the area, providing a space for them to socialise and take part in activities designed to accommodate their visual impairments. These members were used as an initial sample for the study, and through a series of short interviews provided a range of people of different ages, levels of visual impairment, the age at which they became visually impaired and their experience with haptic exploration. The statistical data describing the initial sample of this study can be summarised in the figure 1.

This initial discussion with the users provided insight into possible applications of 3D printing technology that could potentially be useful for the target audience. Several users pointed out the impact of their visual impairment on creative endeavours (e.g. handwriting), entertainment (television and reading) although audio solutions allowed some access. The most important issues that were raised concerned navigation and mobility, in particular with public spaces, where having a visual impairment limited their ability to move around independently; several users identified shopping centres as particularly difficult to navigate, as the layout and acoustics had a significant impact on their ability to orient themselves using sound, while the open-plan layout and wide doorways prevented them from using a cane to adequately identify the details of their surroundings. Additionally, while the level of proficiency with Braille and other forms of haptic exploration varied among the group, designing a tool that involves tactile manipulation still



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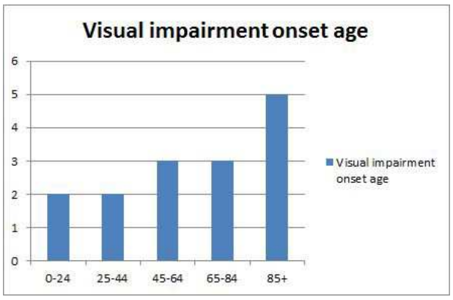

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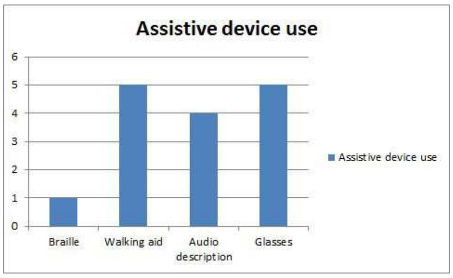


(c)

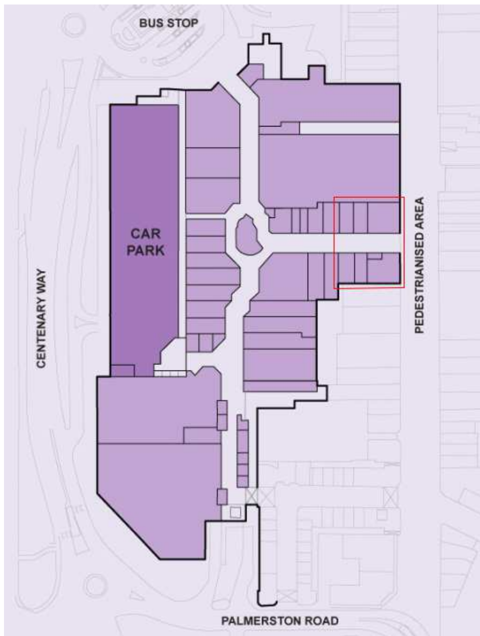
Figure 1: *Statistical information about the users participated in this research*

remains a feasible option within the scope of this project and using the tools available. As a result of this feedback, in addition to information on existing successful applications of 3D printing, the conclusion was reached that 3D printed navigational aids had the potential to be most useful for this specific target audience.

3.2. Designing 3D printable navigational aids for visually impaired

Navigation maps and Braille maps were explored separately in [VM06] and [GPL14], however in this study our goal was to create a unified approach to design 3D printed navigation aids directly influenced by the needs of the users.

First, we discuss the approach to tactile maps. For our case study we used 2D birds-eye view map of the local shopping centre, as shopping centres were identified by multiple users as being one of the public spaces most difficult for a visually impaired person to navigate.



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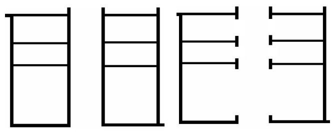

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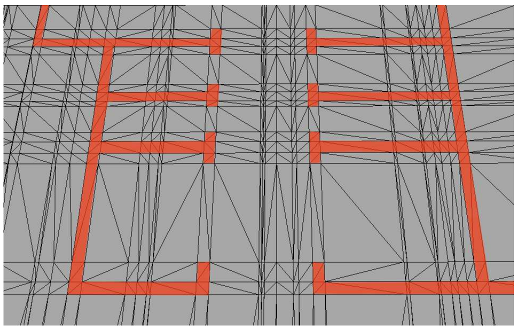

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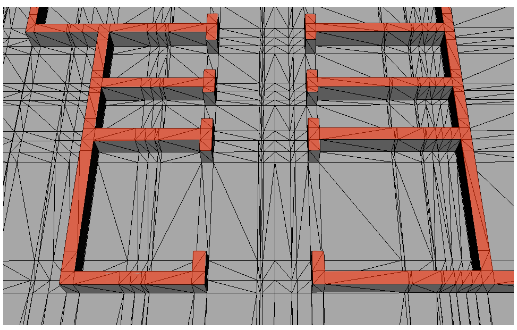

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Figure 2: *Creating the geometry for the spatial information of the environment: a) Initial map (courtesy of Sovereign Shopping Centre), b) A part of the map denoted by red in a), c) A part of the map with doors located, d) A triangulated plane of 2D profiles related to the part in c) with red colour denotes the information from the original map, e) A geometry with extruded 2D profiles.*

In our study we used three different methods to represent the spatial information of the environment in a way that could be explored haptically, all of which started from the same step: first we traced the information (the walls, the doorways, and the rooms) from a 2D map to create 2D profiles which were later used for geometry extrusion. The tracing includes the following steps. First, we isolate contours from the original map (figure 2a) by using segmentation or 2D reconstruction (figure 2b). If the original map contains additional information, such as doors, it can be also traced, or alternatively the manual input can be used (figure 2c). Finally, the resulting geometry is triangulated (figure 2d) hence resulting in 2D profiles.

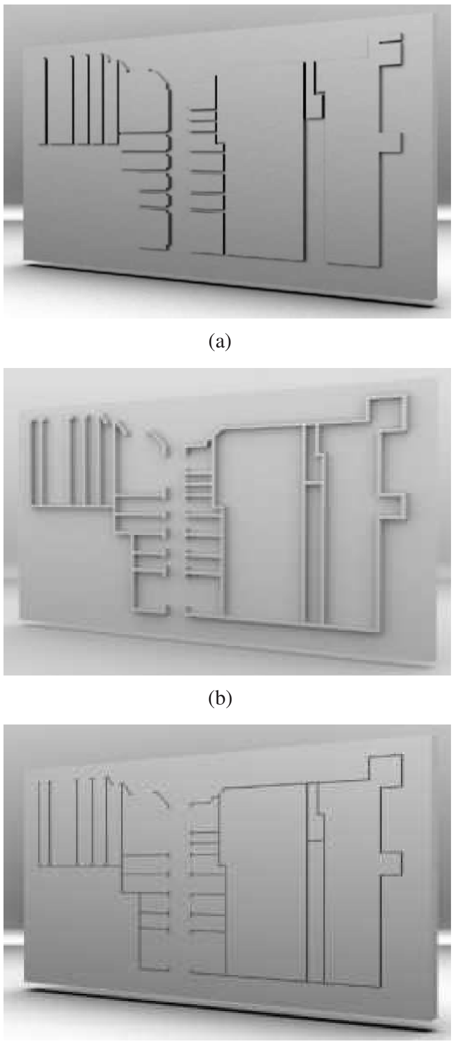
These 2D profiles were extruded in the following different ways in order to get a range of feedback from users to determine which was the most effective method:

1. The first map focused on conveying the overall shape of the building and the individual shapes of the rooms as separate blocks by extruding the "interior" shape of each room, separated by the un-extruded contour lines that formed the outline of the walls within the building as seen in figure 3a.
2. The second map (figure 3b) instead extruded from these contour lines in order to convey the dimensions of the walls, allowing for more details to be conveyed, such as the doorways of the shops.
3. The third map (figure 3c) was an inversion of the second design, whereby rather than being extruded outwards from the base mesh, the contours of the walls were instead pushed inwards, resulting in all of the base mesh being elevated except for the contour lines which were depicted as "holes" within the mesh instead.

The extruded geometry was added to the thin box by using a Boolean union operation. In general, the design for all three different methods focused on the simplicity of the design process for end users, aiming to create accessible solutions for visually impaired customers that could be easily customised. All three designs were printed on a low-end 3D printer; the results can be seen In figure 4.

The second aspect of the 3D printed navigation aids was creating printable Braille text. Braille is a system of tactile writing used by people who are blind or visually impaired, read by running a fingertip in an active scanning mode across each Braille cell, the name for the 3x2 rectangular matrix in which Braille characters are located, consisting of a combination of six dots. The standards for Braille text are that each dot has a base diameter of 1.5mm and a height of 0.43mm, with a centre-to-centre dot spacing of 2.238mm within the Braille cell [NK69], allowing each single Braille cell to be completely covered by the fingertip when reading. As mentioned previously, the estimates of spatial acuity in younger sighted and blind range from 1 to 1.7mm, thus being roughly half the centre-to-centre dot spacing in a Braille cell, suggesting that recognition of Braille characters operates closely to the tactile acuity threshold. Modelling the Braille alphabet is a straightforward process, requiring only simple geometric primitives such as cylinders or half-spheres to convey the detail required.

In order to test whether it was possible for Braille to be 3D printed, separate geometry was modelled of some Braille text, mindful of the dimensions that Braille utilises. The Braille Alphabet was used to write the words "car park" with an additional Parking symbol placed next to it, in order to also be identifiable to users with some remaining vision. As with the map design, the geometry of the Braille test and symbols were added to the thin box by using Boolean operations. The resulting model as well as the printed result can be seen in figure 5.

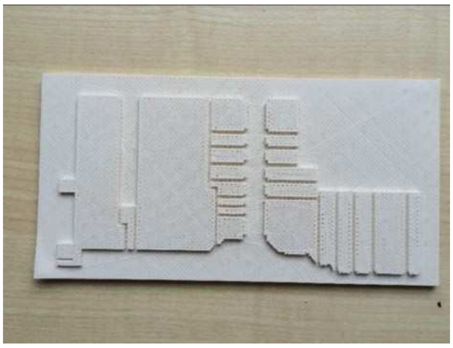


(a) (b) (c)

Figure 3: *3D renders of the map test designs for the tactile map*

4. User feedback and results

The models which were described above were printed on an Ultimaker 2 printer in order to test on the end users. The printer was deliberately chosen to be a low-end machine that could be affordable to small businesses potentially interested in working with visually impaired users. We would like to note that the prints which are presented in figure 4 and 5b are the results of several iterations, adjusting the design to the printer specifications in order to achieve the desirable quality of the results, along with the required size and short printing time.



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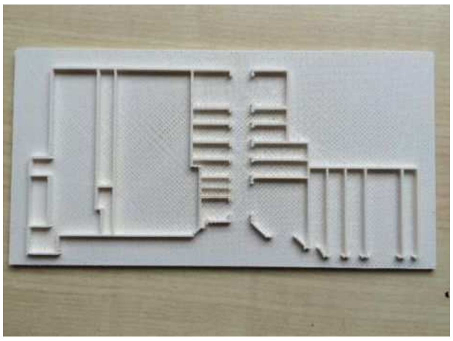

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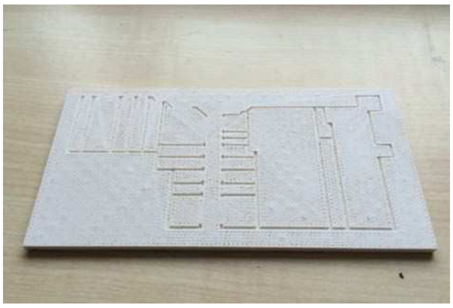

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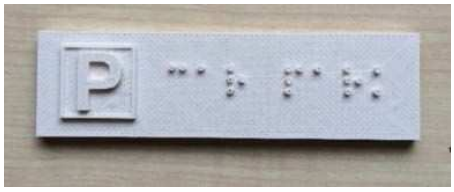
Figure 4: *A 3D printed models of the map test designs for the tactile map*

(a)



(b)

Figure 5: *The design test for 3D printed Braille and signage: a) A render, b) The 3D printed model*

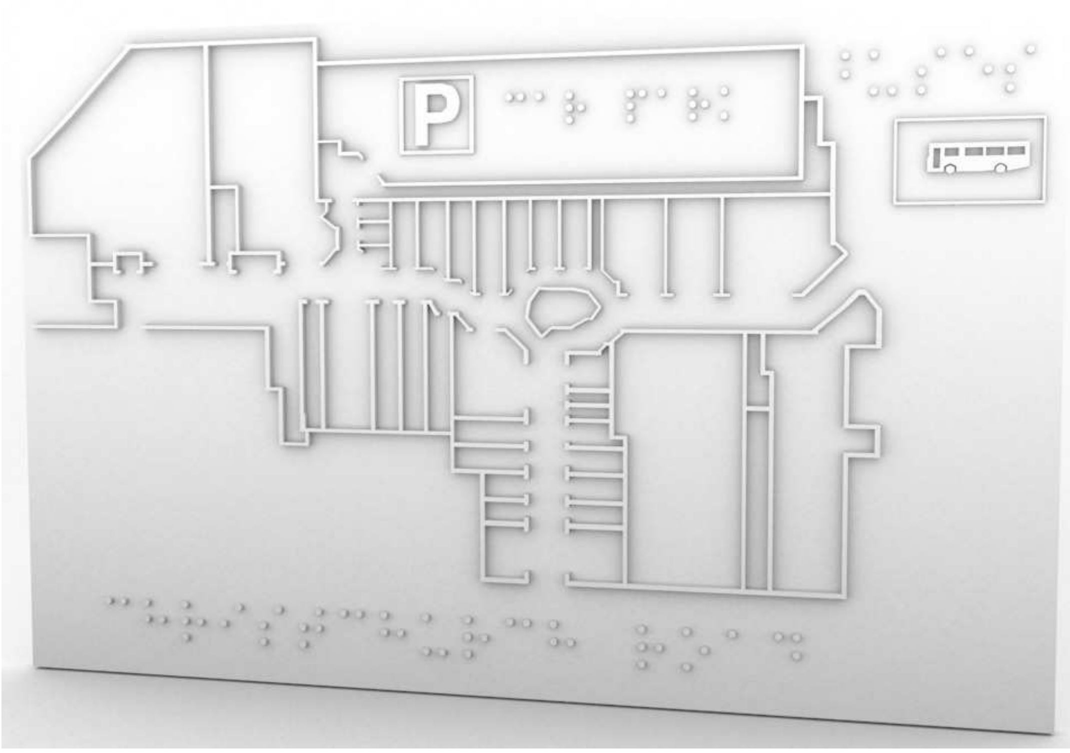
As on the design process we distinguished tactile maps and Braille prints, the feedback was collected separately. As expected, Braille printing was successful and readable by users as long as the size of Braille was within the recognisable dimensions. The car park sign with the Braille text was described by users as useful, with a good level of detail and a "nice" size, while one user noted that "once [her] fingers became familiar with the texture", reading the 3D printed Braille was an easy task to perform, while the car park symbol itself was also large enough to be viewed by users with some vision remaining.

The feedback collected regarding different design approaches can be summarised as following:

1. Design with a focus on the shapes of the rooms (map 1) received a largely positive response from the users, who noted that the map was a good size, with the width between the extrusions giving the required level of detail for them to be able to haptically explore the block extrusions and get a sense of the overall shape of the building. At the same time this kind of design requires most input from the designer as the rooms should be clearly identified, and this process can not be reliable implemented as an automatic procedure.
2. Design where the contour lines were extruded (map 2), received an overwhelming positive response, in particular from the fully blind users. Compared to the previous design, this map allowed for far greater detail to be conveyed, including the doorways of each room and the exact dimensions of the walls, with the design allowing users of varying levels of visual impairment to learn the shape of the building through both touch and sight. Out of all the designs this one was described as the most tactile by the user in our sample.
3. Contrastingly, the overall consensus for third design (map 3) was that the indentations were not wide enough for the contours to be clearly felt, and thus the design was not tactile enough to be useful in any way.

Following this feedback from the users on the range of initial designs, the second design approach was developed to incorporate this feedback. In this updated version, the entire shopping centre was modelled to the same level of detail with only the contour lines of the shopping centre walls extruded, while some Braille text was also embedded within the design to convey text descriptions of elements within the model. The resulting model is presented on the figure 6.

When this updated design was presented to the users, the feedback was once again overwhelmingly positive, with several users pleased by the fast production time and the clear evidence that their feedback had been incorporated into the design. With relation to the tactile readability of this updated design, several users noted that despite the map being scaled down in comparison to the earlier tests (in order to accommodate the printer's dimensions), the size



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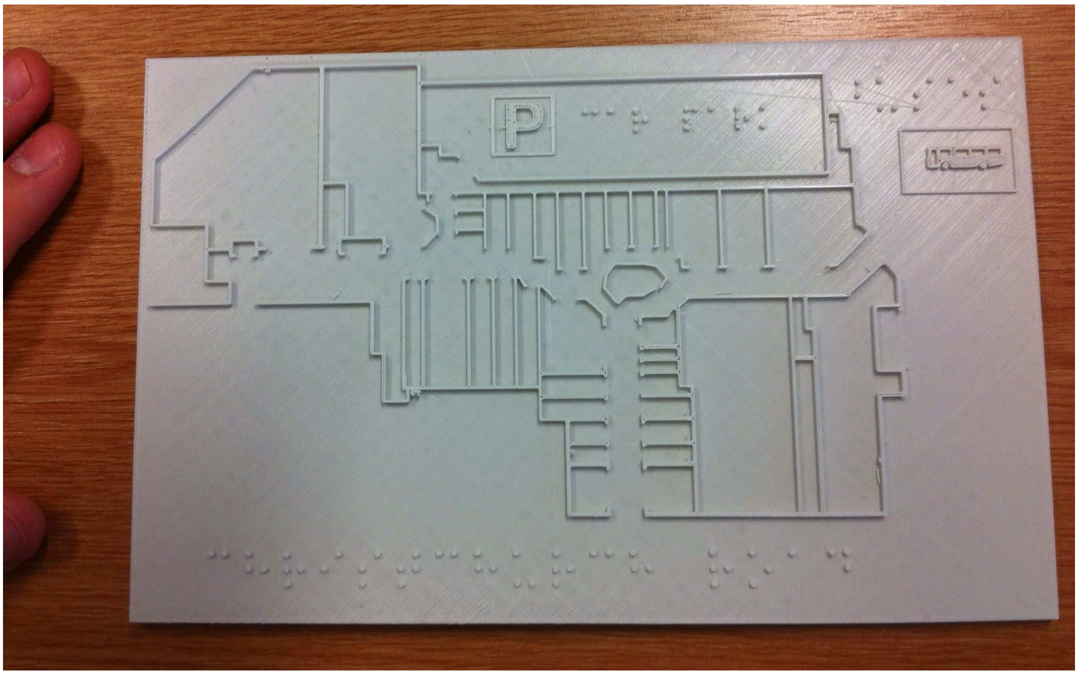

(b)

Figure 6: *The design test for 3D printed Braille and signage: a) A render, b) The 3D printed model*

of the map was suitable for their needs, allowing them to feel the details of the map, to differentiate between the various parts of the model and to easily follow the contours with their fingertips. Additionally, the Braille integrated into the map's design was described by users as "easy to read" and "helpful", with some users suggesting that, in the case of the rooms which were too small to label with Braille, a combination of a map key and a series of symbols could be used, similar to a 2D printed map, to convey this information. A further comment repeated by several users was the "nice" size of the map, able to fit easily within the user's hands, while also being lightweight and durable enough to use and carry without fear of damage.

The simplicity of the design process allowed the 3D model to be created in a very little amount of time and the physical copy to be printed in a couple of hours, hence making the whole production cycle a fast and efficient process. This case study allowed us to see the scenario of small businesses creating Braille and elevated tactile models for customers with visual impairments on-demand in a limited amount of time without significant expenses for design, fabrication and logistics.

5. Conclusions and discussion

Applications of 3D printing technology aimed towards the visually impaired is a very large research area which is due to be explored in depth. As we discussed in this paper, there is a lot of potential to be found in applications of 3D printing technology designed for the visually impaired, with a focus on the low cost of fabrication, and the ease and speed of design (compared to traditional methods and pipelines involved in assistive tool design and creation). In this paper we presented several examples of 3D printing aimed at this specific audience with the focus on the users' needs. Even though presently this technology is still not easily accessible to this audience, with advances in technology this has the potential to become more accessible over time.

Through investigations into the design of tactile navigational aids for visually impaired users and the feedback received, there is clearly potential for this project to be taken further. Thus, while existing examples of 3D printing applications are often aimed at a broad user group of visually impaired people, this project incorporates the customization potential of 3D printing by considering the specific requirements of a small set of users whose feedback directly influences the direction of the research and design. The results may include 3D printed customizable user-specific designs that produced within a short amount of time and at a low cost.

Due to the limited timeframe and resources allocated to this research, we were unable to conduct an in-depth evaluation of the impact of tactile aids on the navigation performance of users, however with a larger testing group and more resources dedicated to this area of study, analysis of the effectiveness of the proposed method may be performed in order to clearly determine the extent to which the project could have potential real-world applications. Additionally, another area with the potential for further study is the evaluation of this proposed method being utilized in different scenarios, such as comparing the effectiveness of tactile maps used by an individual versus tactile maps displayed publicly. Furthermore, in the current paper we have not discussed the aspects of how to streamline the modelling process for 3D printing in our particular case. However the issue of automatic tactile map construction given the 2D scheme along with automatic geometry generation for Braille text and other similar solutions could form the basis for further research directions.

Overall, this paper has explored the potential of how social sciences can be applied to technological advances and how 3D printing can facilitate the design of assistive tools for a specific visually impaired user-base, while also presenting this research in such a way as to be accessible to those unfamiliar with the concepts discussed. Given the growing interest for applications where social sciences meet advances in the technology, the research and advances are going to show new applications.

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