Accessible Maps for the Blind: Comparing 3D Printed Models with Tactile Graphics

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ABSTRACT
Tactile maps are widely used in Orientation and Mobility (O&M) training for people with blindness and severe vision impairment. Commodity 3D printers now offer an alternative way to present accessible graphics, however it is unclear if 3D models offer advantages over tactile equivalents for 2D graphics such as maps. In a controlled study with 16 touch readers, we found that 3D models were preferred, enabled the use of more easily understood icons, facilitated better short term recall and allowed relative height of map elements to be more easily understood. Analysis of hand movements revealed the use of novel strategies for systematic scanning of the 3D model and gaining an overview of the map. Finally, we explored how 3D printed maps can be augmented with interactive audio labels, replacing less practical braille labels. Our findings suggest that 3D printed maps do indeed offer advantages for O&M training.

ACM Classification Keywords
H.5.2. Information Interfaces and Presentation: User Interfaces - Input Devices and Strategies Human Factors, Experimentation

Author Keywords
Accessibility, Blindness, Mapping, Orientation and mobility training, 3D Printing, Vision impairment

INTRODUCTION
The difficulty and consequent fear of travel is one of the most disabling consequences of blindness and severe vision impairment [44] affecting confidence and quality of life [27]. Orientation and Mobility (O&M) training is widely used to address this barrier to independent living by familiarising vision impaired people with their local environment or with new locations and routes before travel. Raised line drawings, called *tactile graphics*, are commonly used as part of this process, with tactile maps helping the viewer to build up a mental model of the geography while still safe indoors [43, 49].

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Current sector guidelines recommend the use of tactile graphics to convey graphical content such as maps and graphs to people with a severe vision impairment [16, 7]. In addition handmade or commercially available 3D models are occasionally used to show inherently three-dimensional information such as human anatomy to vision impaired students. At present their use is rare because of the difficulty and cost of procurement or production. Commodity 3D printers are set to change this, allowing 3D models to be produced at comparable effort and price to tactile graphics.

The obvious advantage of 3D models over tactile graphics is that they allow the direct representation of three-dimensional objects and so have applications when teaching biology, chemistry and other STEM subjects [30, 1, 53]. It is less clear whether 3D models offer benefits over tactile graphics for other kinds of graphics that are more easily represented in two dimensions, such as the maps and plans used in O&M training. Opinion is divided. On one hand we have "Some concepts can be more precisely and easily portrayed using tactile graphics, such as maps [than with 3D printing]" [1] and a survey of 30 people with severe vision impairment showed a preference for tactile maps over (handmade) models [43]. Others advocate the use of 3D prints for floor plans and maps [50, 20, 23].

The primary contribution of this paper is to answer this important question. Participant comments in two exploratory pilot studies (§Pilot Studies) suggested that 3D printed maps may be more easily understood and more memorable than tactile maps. To test this we conducted a controlled user study with 16 severely vision impaired adults, comparing task performance, recall and user preference on tactile maps and 3D models of a park and train station. This is one of the first studies directly comparing 3D prints with their tactile equivalent (§Background & Related Work). The main study (§Main Study) confirmed a strong user preference for 3D plans, which were easier to understand due to the use of 3D iconic symbols and allowed relative height of the pedestrian bridge to be more easily understood. There was also some advantage in short term recall but not for longer term recall.

Our second contribution is an analysis of the touch reading strategies used to explore the tactile graphics and 3D models in the study (§Touch Reading Strategies). Vision impaired students must be explicitly taught how to touch and scan tactile graphics to first gain an overview before systematically exploring the components [3, 40]. As 3D models differ in form from tactile graphics, it was unclear whether the same exploration techniques are applicable and how touch readers should be taught to read 3D maps and plans. We found that the strategies for exploring the 3D models differed from those used for tactile graphics, with more frequent use of flat hands over the top of the graphic to gain an overview. This is the first such analysis we know of and provides important information for educators and O&M trainers.

Our third contribution is a case study exploring the design of interactive audio labels for 3D printed maps. Interactive audio labels provide a clearer tactile experience and enable people who cannot read braille, including young children or adults with age-related eye conditions, to understand the graphic. They also allow information to be provided at different levels of detail and for labels to be updated without the need for reprinting. We describe a participative design process in which low-cost "maker community" electronics were used to provide robust interactive audio labels on a 3D printed campus map. The findings inform the design of larger interactive 3D printed floor plans aiding navigation of both sighted and vision impaired visitors in public spaces such as train stations, shopping centres, museums or offices.

Our studies have significant implications for O&M training, suggesting that 3D prints augment or replace the current use of tactile maps. They also inform the design of professional guidelines for the use and design of accessible 3D prints and of teaching strategies for reading them (§Guidelines).

BACKGROUND & RELATED WORK

Tactile Graphics

Graphics are most commonly presented to people with severe vision impairment using written or verbal descriptions or tactile graphics [13]. Accessibility guidelines recommend the use of tactile graphics for graphics in which spatial relationships are important, such as maps, plans and technical drawings [37, 7]. The most common production methods are embossing with raised dots using a braille embosser, printing onto swell paper and thermoforming [42]. Swell paper contains microcapsules of alcohol. When the paper is heated, dark printed areas swell to an elevation of around 0.5mm. Thermoforming uses vacuum and heat to press a plastic copy from a handmade mould. Thermoforming supports more varied textures and, depending upon the precise material and production technique, allows more three-dimensional images with height differences of up to 2-3cm. It is not possible, however, to create raised elements with tall sharp vertical sides. While both embossing and swell paper allow a tactile graphic to be printed from a digital image, thermoforming requires a physical mould. It is therefore more expensive and requires storage space for the moulds if they are to be kept for reuse. Preferences vary but a survey of 30 adults with severe vision impairment showed a preference for maps printed on swell paper over thermoform or (handmade) models [43].

Tactile graphics are primarily used for education, particularly for STEM, and for O&M training [49, 43]. Studies show that both children and adults benefit from tactile maps and that they facilitate building survey like exocentric representations of geographic space [49, 5].

3D Models

A number of computer-mediated technologies for presenting accessible graphics have been developed in the last decade. These include: sonification, e.g. [10, 51]; haptic feedback, e.g. [39, 15] and combined audio and haptic feedback, e.g. [18, 41]. Zeng and Weber [55] review the use of these for accessible maps. While these technologies offer some advantages over tactile graphics, in general they are too expensive and/or more difficult than tactile graphics to understand and so tactile graphics remain the presentation medium of choice.

Handmade or pre-existing models are sometimes used to show inherently three-dimensional information such as human anatomy or molecular structures. They are much less common because of the difficulty and cost of production and distribution. However, 3D printing now brings the cost of 3D models in line with that of tactile graphics. In the near future, 3D printing will allow quick and affordable creation of accessible 3D models in the school, workplace or home. Furthermore, models are specified digitally and so can be distributed and stored electronically, although production time, physical storage and integration with text may be more problematic.

As a consequence, accessibility researchers and the vision impaired community are excited by the potential of 3D printed models. Most research has focussed on educational uses, especially in STEM. Buehler et al. [12] evaluated the use of 3D printing for students with special needs including visual impairment. Case studies include: Kolinsky [30] (accessible biological and astronomical images); Grice et al. [19] (accessible images from the Hubble telescope); Agarwal et al. [1] (3D printed molecules to explain DNA transcription and translation); Wedler et al. [53] (3D printed molecules for applied computational chemistry); and McDonald et al. [35] (3D printed graphics to teach graphic design theory). Brown and Hurst [9] describe a tool for automatically generating 3D printed line graphs from equations or tabular data sets, while Hu [25] investigated 3D printed bar charts. Kane and Bigham [26] incorporated generation of 3D prints into a programming course for vision impaired students. Kim and Yeh [28] and Stangl et al. [47, 46] investigated the use of 3D printed movable tactile pictures for inclusion into books for young children with vision impairment.

Other research has explored the usability of 3D printed maps and plans for O&M training. Voigt and Martens [50] suggested the use of 3D printed models of buildings for O&M training while Celani and Milan [14] reported that six vision impaired volunteers were positive about 3D printed floor plans. Gaul et al. [20, 23] tested the use of 3D printed maps for O&M training with four vision impaired participants, demonstrating that the maps could be understood and used to follow a route. Taylor et al. [48] describe a web-based tool for generating 3D printable maps from OpenStreetMap data.

None of the aforementioned studies compare 3D printed models with tactile graphics. Such studies are considerably rarer. Braier et al. [6] compared flat tactile graphics showing various sorts of charts such as scatter plots and bar charts with tactile graphics in which the height of an element reflected the element's value. They found that for most charts this improved task performance. Gual et al. [21] found that it was easier to recall the position of eight abstract symbols in a key if a mixture of 2D and 3D volumetric symbols were used rather than 2D symbols. In a subsequent study Gual et al. [22] compared speed and accuracy for finding and identifying symbols on a tactile floor plan with 2D symbols and on a 3D printed floor plan that used a mixture of 2D and 3D volumetric symbols. This found the use of 3D volumetric symbols significantly reduced location time and reduced discrimination errors. However, other aspects of map use were not evaluated. Our study extends this earlier research by investigating whether 3D models offer benefits over the kind of tactile maps and plans that are currently used in O&M training.

Haptic Exploration

Haptic perception has been extensively studied. Exploring an object by touch is a sequential process requiring significant cognitive effort [24]. Different movements are required for perceiving different aspects of an object by touch, such as lateral movement for texture, enclosure for global shape and contour following for exact shape [32].

It is much easier to acquire a general overview of a graphic using visual perception than it is using haptic perception [52]. For this reason vision impaired students are explicitly taught to first touch and scan a tactile graphic to obtain an overview before systematically exploring the components [3, 40]. Training has also been shown to enhance symbolic understanding and further knowledge of O&M concepts [54]. While strategies used by touch readers when reading braille have been studied, e.g. [36], to the best of our knowledge strategies used for reading tactile graphics or 3D models have not. Our study provides the first analysis that we know of.

Interactive Audio Labels

Braille text occupies considerable more space than standard text. For this reason it is common for tactile graphics, including maps and plans, to be labelled with short braille keys whose meaning is explained in a separate braille legend. Legends add cognitive load because of the need to shift attention between the graphic and legend or to memorise the legend. Furthermore, many vision impaired people cannot read braille. Consequently, a number of technologies have been suggested for augmenting tactile graphics with interactive audio labels.

A number of commercial products provide audio feedback by overlaying the tactile graphic on a touchscreen, e.g. [31] while the Talking Tactile Pen from Touch Graphics provides audio feedback when the pen touches elements on the graphic. Other approaches include hand tracking [38], placing QR codes on the tactile graphic that trigger audio feedback through a smartphone [2], or augmenting the tactile graphic with 3D printed conductive tactile lines that trigger audio feedback when touched [8].

Interactive audio labels are perhaps even more useful with 3D printed models because of the low fidelity of 3D printed braille. Shi et al. [45] explored the use of 3D strummers printed as part of the model and paired with a smartphone, however empirical testing revealed problems with reliability and that the strummers interfered with exploration. In Mapsense, Brule et al. [11] placed 3D printed and other items on a touchscreen with tactile overlay to provide interactive audio feedback for vision impaired children. Giraud et al. [17] used low cost electronics embedded in a laser cut map with 3D printed pieces to provide interactive audio labels. They found improved short term memorisation of space and text compared with tactile graphics with a braille legend. Our case study into the design of a campus map further explores the design space for low-cost interactive labels on 3D printed maps.

PILOT STUDIES

The initial motivation for this research came from a pilot study we ran to gather feedback from vision impaired adults on possible applications of 3D printing for accessibility. Twenty-one severely vision impaired adults were shown a wide variety of 3D models–buildings, cityscapes, floor plans, street maps, 3D graphs, anatomical models, topographic and prism maps. A subset of the 3D models were also created as tactile diagrams on swell paper by a researcher with extensive experience in tactile graphic production and standards. The tactile graphics were restricted to maps, floor plans and building elevations, as most other objects were considered inherently three-dimensional.

Participants were extremely enthusiastic about 3D prints and overwhelmingly preferred them to the equivalent tactile graphic. The clear preference for 3D models of street maps and floor plans over tactile maps and plans was unexpected, as we had not believed that 3D models offered advantages. In fact, maps for O&M training were by far the most common type of 3D model desired by the blind participants. Participants commented that 3D models more closely correlate with a blind person's experience of the world:

"It certainly helped me ... because as a totally blind person, life is 3D." (Q1)

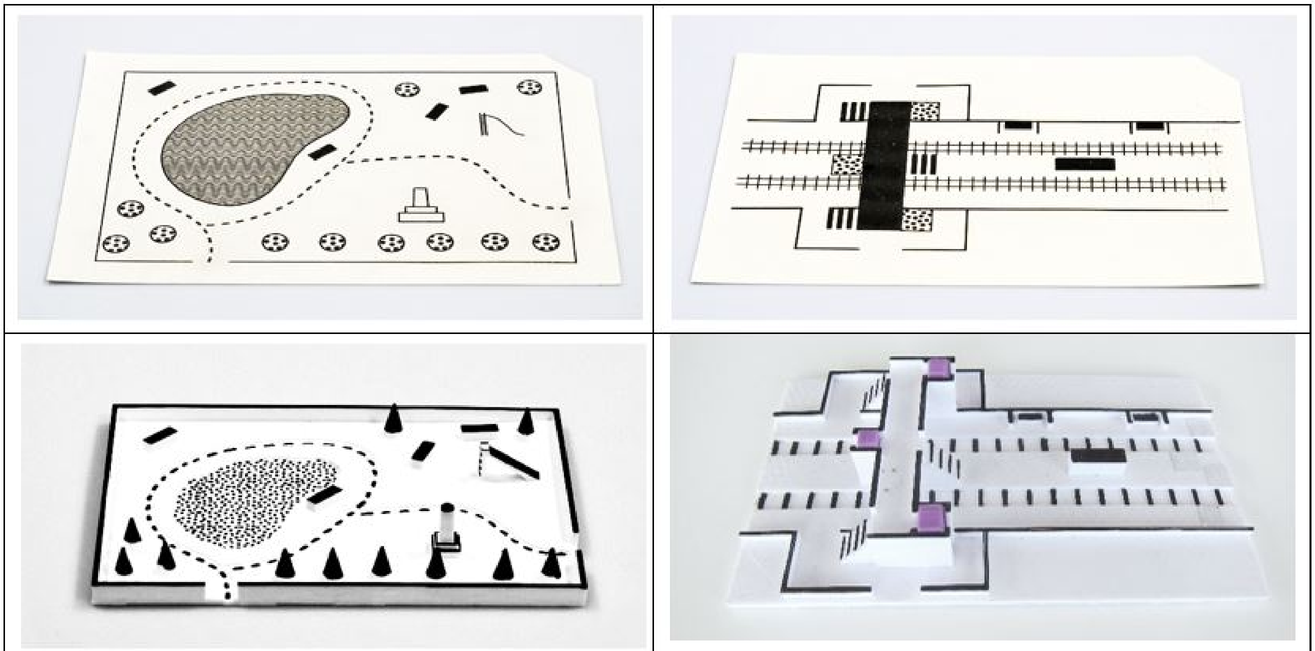
"It is more like a sighted person looks at things. You get it all at once." (Q2)

They also commented that the addition of height gave them more information, was easier to interpret and more memorable.

"The buildings raised up helps. Because I'm not used to reading maps." (Q3)

"I think I'd remember more from having the ... height dimension." (Q4)

In a second pilot study, we ran a hands-on workshop at the Round Table Conference on print disability. Some 25 accessible format producers, teachers and vision impaired users were presented with tactile graphics and 3D printed models showing floor plans and street maps of the conference venue. The positive response to the 3D prints reinforced the findings from the first pilot study that 3D printing could have significant benefits for O&M training. Comments suggested that the 3D maps were more engaging and several participants commented that 3D modelling allowed more intuitive representations of stairs, walls and doorways.



Recall: 1. How many entrances are there? 2. In which quadrant is the monument? 3. Where is the line of trees? 4. When you go in the south entrance, in which direction is the lake? 5. When you go in the east entrance, in which direction is the playground? Route-finding: 1. If you are on the seat at the north west corner, which is your nearest exit? 2. What is the shortest pathway between the two entrances? Please show us and explain in words.	Recall: 1. How many entrances are there? 2. Which side is the pedestrian bridge on? 3. How many lifts are there? 4. When you go in the south entrance, what is in front of you? 5. When you come down the middle set of stairs, what is in front of you? Route-finding: 1. If you are on platform 1, where is the nearest exit? 2. How would you get from platform 1 to platform 4? Please show us and explain in words.

Figure 1. One of the park maps and train station plans as tactile graphics and 3D models with associated questions used in the main study. Note the use of iconic 3D symbols representing the slide and stairs in the park map and the raised pedestrian bridge in the train station plan.

MAIN STUDY: COMPARING TACTILE MAPS & 3D PRINTS

Our pilot studies revealed a clear preference for 3D printed maps and floor plans over their tactile equivalent. We conducted a controlled study to investigate possible reasons for this so as to better understand the trade-offs between these two different media.

The comments of participants in the pilot studies, e.g. Q1, Q2, Q3 suggested that 3D models may be more understandable. We hypothesized two possible reasons for this. Previously Gaul et al. [22] identified that 3D volumetric symbols allowed more memorable abstract symbols than 2D but did not identify or study the benefits of iconicity. Visual maps make heavy use of iconic symbols such as using a stylised drawing of a bike to label a bike path or a stylised pick and shovel to label a mine [34]. Symbols in tactile graphics are less iconic and generally use more abstract shapes and textures so that they can be readily discriminated by touch. 3D printing allows symbols that are more iconic reducing the need for the reader to consult a legend. Furthermore, previous research suggests that both sighted and vision impaired people find it considerably more difficult to recognise an object by touch from a tactile drawing than from a model of the object [29, 33]:

Hypothesis 1: 3D maps will be easier to understand than tactile maps because 3D iconic symbols and features can be recognised more easily than their 2D equivalent.

The other reason that we thought 3D models may be more understandable is a perceptual mismatch between touch and the vision-based conventions used in tactile graphics such as perspective and depth cues like occlusion. From numerous comments by participants in our studies, it is clear that touch readers must consciously interpret these conventions when reading a tactile graphic, This mismatch is also supported by analysis of drawings of congenitally blind people [4].

Hypothesis 2: Relative height of objects in a 3D model will be more easily understood and offer performance advantage for tasks in which understanding this is necessary.

The comments of participants in the pilot studies, e.g. Q4 suggested that 3D models may lead to more vivid mental image and be more memorable:

Hypothesis 3: Touch readers will find it easier to construct a detailed mental model using a 3D map, as reflected in better recall of features and layout.

We also wished to explore whether different hand movements are used to read 3D models and tactile graphics and to identify more effective strategies for reading 3D models.

Participants

Sixteen adult touch readers participated in the study. Two had a low level of vision, four were blind but had some visual memory and the remainder were congenitally blind. Participants were aged from 23 to 71, with an average age of 47 years. Eleven of the participants had experience with 3D printed models prior to the session. To mitigate against a recruitment bias toward those excited by the prospect of 3D printing, we attempted to recruit participants representing a broad spectrum of technology adopters and incorporated objective performance measures into the experimental design.

Materials

The test materials consisted of tactile graphics produced on swell paper and 3D printed models. The 3D models were designed using Tinkercad and Sketchup and printed on an Ultimaker 2 Extended 3D printer using white PLA plastic. Features on the 3D model were highlighted with a black permanent marker to mirror the visual information provided in the tactile graphics. The only labels were braille numbers for the train station platforms. The size of the maps corresponded with common production methods, with A4 tactile size graphics (25-26cm wide) and slightly smaller 3D models (17-20cm wide).

The tactile graphics were created by a researcher with extensive experience in tactile graphic production, following industry standards [37, 7]. Design of the 3D maps was based on the same principles as tactile graphics, with simplification and reduction of information (e.g. using a slide to represent a whole playground) and distances distorted to create distinct gaps between items and space for fingers to follow pathways. Both the tactile and 3D models were refined through several iterations based on user feedback to ensure they were optimal representations within the limitations of the media.

Three types of map were produced: A simple neighbourhood map with streets and buildings with doors; two parks with paths, a lake, trees, seats, a playground and other features; and two train stations with train lines, platforms, a pedestrian bridge connecting the platforms, stairs and lifts. Each map was produced as both a tactile graphic and equivalent 3D printed model. The maps were based on amalgamations of several real life maps to ensure that the features and layout were realistic but that participants could not rely on prior knowledge to answer the test questions. Figure 1 shows two of the maps used in the study.

As the neighbourhood map was designed for training purposes, it was simple but included buildings of differing heights and important features on the sides and base to encourage full exploration of the 3D model. Parks were chosen because they allowed the use of iconic symbols and train stations were chosen because they were the type of model most commonly requested in the first study and because the height of the pedestrian bridge was important in understanding its function.

Methodology

The study began with a training phase to familiarise participants with tactual exploration of a 3D model and provide forewarning about the type of questions they would be asked in the test phase. Participants were shown the neighbourhood map, with both formats provided simultaneously. Explicit instructions were given to "feel the sides of the buildings all the way to the base to find the doors". Participants were free to explore the graphics for as long as they wanted.

During the test phase, each participant was shown one of the park maps as a tactile graphic and the other as a 3D model, and then the same for the train station plans. A 2×2 Latin square design was used to counterbalance format and order of presentation across four participant groups with similar distribution of age, gender, vision level and prior exposure to 3D models.

For each graphic, the participant was provided with a short verbal description stating the type of map and its features, e.g. "This is a map of a neighbourhood. It shows streets, blocks, and buildings with doors." In order to test Hypothesis 1, participants were not provided with a key to the symbols. Instead, they were instructed to verbally request the meaning of any item they could not guess, e.g. "What is this?" (*definition*), and to confirm the meaning of items for which they needed to guess, e.g. "Is this a seat?" (*confirmation*). The participant indicated when they were ready for the graphic(s) to be removed. They were then asked a series of questions to test their *recall* before the graphic was returned and the participant was asked two *route-finding* questions. Example questions are illustrated in Figure 1. A further four questions were asked for each of the test graphics:

- I enjoyed exploring the map.
- I was able to build a detailed mental model of the map.
- I had to put a lot of effort in to understanding and reading the map.
- The map held my attention.

Ratings were given on a five-point Likert scale from strongly disagree to strongly agree.

After exposure to the graphics depicting the two parks, and again after exposure to the graphics depicting the two train stations, participants were asked which format they preferred and why.

At the end of the study, participants were asked three final questions:

- Did you use different techniques to explore the tactile graphics and the 3D models?

- Which format gave you the most detailed picture in your mind's eye?
- Please describe the two parks you saw at the start of the study.

This final question (added after the first four participants) was posed without warning and was designed to test longer term recall.

Sessions took approximately 1 hour. Two investigators were present and video footage was taken to record tactile exploration of the graphics and verbal responses. Classification of tactile strategies, timing and rating of answers were recorded independently by two researchers and then verified.

Results

User preference

The 3D models were generally preferred over their tactile equivalents. When answering route-finding questions in the training phase, the majority of participants chose to use the 3D model, as shown in Table 1. Participants also showed a strong preference for 3D models when asked directly after exposure to the two park maps and the two station plans. This preference is statistically significant according to one-sample Wilcoxon signed ranks test on the aggregated data ($z(47)=3.13$, $p<.01$ (one-tailed)). This accords with the results from the pilot studies.

map	tactile graphic	both	3D model
neighbourhood	5	2	9
park	3	0	13
station	4	1	11

Table 1. Preferred format by map type, as revealed through use (neighbourhood map) or self-reporting (park maps and station plans).

Agreement to the statements "I enjoyed exploring the map" and "The map held my attention" did not differ greatly between the two formats.

The 3D models for the train station maps were modified slightly after being shown to the first four participants on the basis of their feedback as this reflected a flaw in our design:

> *"I preferred the tactile.*
> *Because you've got more room, more space".*

No such comments were received after the models were modified to provide more space for participant fingers to fit under the pedestrian bridge and the height of the walls was reduced from 1cm to 0.5cm. Preferences of the first four participants are included in Table 1, potentially reducing favorability of the 3D model of the station.

Understandability

Ease of understanding was measured with ratings of the statement, "I had to put a lot of effort into understanding and reading the map" (Figure 2). Participant were more likely to agree or strongly agree that effort was required when given the tactile graphic (21 times across the park and station) compared with the 3D model (15 times). A Wilcoxon signed rank test revealed this difference to be statistically significant ($z=2.34$, $p<0.01$ (one-tailed)).

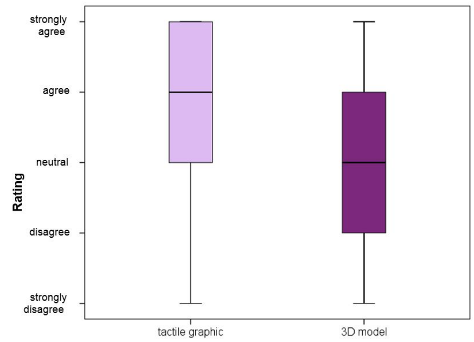


Figure 2. Responses to "I had to put a lot of effort into understanding and reading the map".

Hypothesis 1 was supported, with 3D models showing a clear advantage over tactile graphics through greater clarity of symbols (Figure 3). Participants asked for confirmation of an item's meaning twice as often for tactile graphics (median=6 items over the two map types) compared with 3D models (median=3). This difference was statistically significant according to a Wilcoxon signed rank test ($z=2.08$, $p<.05$). A difference was likewise revealed in the number of times participants requested the definition of items for tactile graphics (median=2.5) compared with 3D models (median=0; $z=2.47$, $p<.05$).

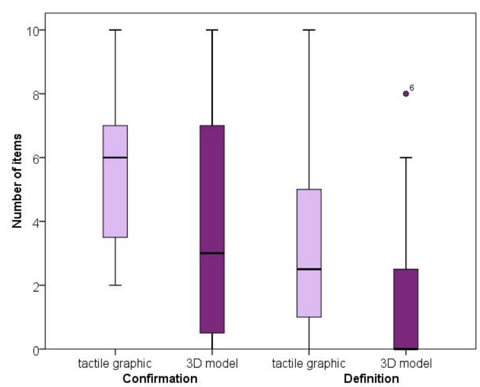


Figure 3. Number of items for which confirmation or identification was requested.

Comments by the participants supported this finding:

> *"The 3D model is much more realistic. The symbolic stuff made sense."*

> *"I had to ask what trees were on the flat graphic. I had to ask what the steps were. The things aren't so obvious as when you're looking at a 3D."*

It was also clear that the participants liked the use of 3D iconic symbols, many smiling or expressing pleasure when they recognised an object.

There was some limited support for Hypothesis 2 that 3D models will aid understanding of relative height and offer performance advantage for tasks in which understanding this is necessary. Participants reported that the 3D pedestrian bridge and stairs on the station plan assisted in interpreting the graphic.

> *"In relation to each other, you can tell this is a railway line and it goes under the bridge. Whereas on the flat model, you have to really put it into perspective in your mind and remember to understand that it is a bridge, it is not flat."*

> *"That makes more sense seeing the bridge go up, whereas the 2D was confusing."*

Use of a 3D model appeared to result in a modest improvement in accuracy for route-finding questions relating to the multi-level train stations with platforms and a pedestrian bridge: Participants answered correctly a total of 21 times using the 3D models, compared with 17 times using the tactile graphics (Figure 4). However, this difference was not statistically significant (z=1.10, p=.24 (one-tailed)).

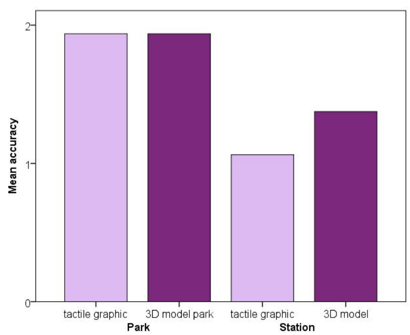


Figure 4. Bar graph showing average number of correct responses to route-finding questions (max=2).

We also measured the total time taken by participants to explore the maps as a measure of ease in understanding (Figure 5). However, this was highly variable, ranging from 62 seconds to more than 10 minutes (max=656 sec). In addition to ease of understanding, the total time spent is likely to also reflect other factors such as use of the think-aloud protocol and fatigue, with station maps always presented after the park maps. Some participants also reported being aware of spending extra time exploring height on the 3D models.

> *"With the 3D, I was conscious of adding research of the vertical. There is more information there. It adds to the task."*

According to a Wilcoxon signed ranks test, participants spent significantly less time exploring the 3D model of the park compared with the tactile graphic (z(15)=2.48, p<.05 (two-tailed)), whereas there was no significant difference in the time spent exploring the station maps across presentation mode (z(15)=1.03, p=.30 (two-tailed)).

Mental models and memorability

Hypothesis 3 that use of 3D models would assist in creation of clearer mental models and result in improved memory performance was supported for short term recall (Figure 6) but not for longer term recall.

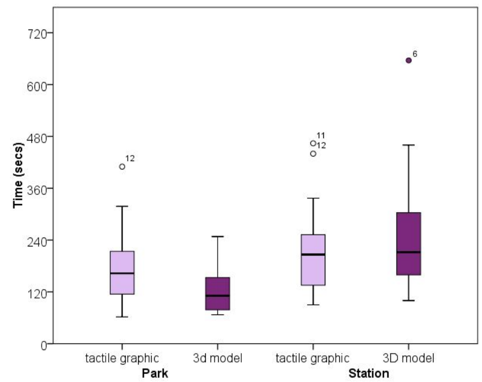


Figure 5. Total time spent exploring the maps.

Immediately after exposure, the majority of participants reported that the 3D models gave a more detailed picture in their mind's eye, with 14 favouring the 3D models compared with only one who preferred the tactile graphic. This marked difference was statistically significant (z=3.56, p<.01 (one-tailed). They made statements such as as

> *"I felt like I was walking through it [using the 3D model]".*

and spoke about the 3D model being more realistic:

> *"[The tactile graphic is] flat. It's not realistic. What you're seeing is not how things actually are. If you are using 3D, you can place yourself in the environment more easily."*

> *"[The tactile graphic train station] is quite hard for me to visualise. With the 3D, I could straight away picture exactly what was there."*

There was no trend in ratings of the statement "I was able to build a detailed mental model of the map" due to a ceiling effect, with most respondents in agreement for both formats (Figure 5).

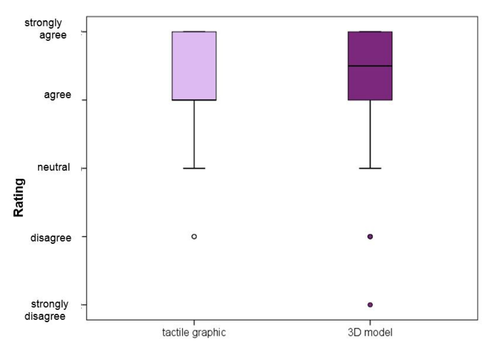


Figure 6. Responses to "I was able to build a detailed mental model of the map" .

As shown in Figure 7, use of the 3D model resulted in a modest but statistically significant gain in accuracy on questions testing memory of the map layout (t(15)=2.11, p<.05 (one-tailed)). Participants were able to answer an average of 7.31 memory questions correctly using the 3D models (sd=1.92) compared with only 6.63 questions using the tactile graphics (sd=1.67).

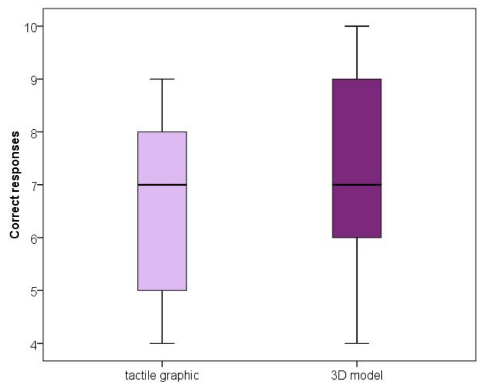


Figure 7. Accuracy for recall questions (max score=10).

However, there was no evidence to support longer term memorability as recall of the two park maps at the end of the session was similar regardless of format. Of the twelve participants asked this question, seven remembered both parks equally well, three had a better recall of the tactile graphic and two had better recall of the 3D model. Interestingly, some participants found it difficult to remember the presentation medium, suggesting that the maps were internally encoded in the same way regardless of the original presentation media.

TOUCH READING STRATEGIES

Techniques for exploring tactile graphics are taught explicitly. We were interested to know whether the strategies used for tactile graphics could be transferred for use with 3D models without modification. All participants used two hands with multiple fingers and followed features such as walls and pathways on both tactile graphics and 3D models. After encouragement in the training phase to "feel the sides of the buildings all the way to the base to find the doors", all participants explored the tops, sides and base of tall elements on the test 3D models. Although restrictions were not imposed, participants used all maps flat on the table without picking them up. This contrasts to other 3D models which are typically picked up.

Six of the sixteen participants were aware of using different techniques to tactually explore the 3D models compared with their usual technique for touching tactile graphics. Three of these participants explained that they were able to gain a better overview of the 3D printed maps by placing their hands over the top.

> *"I put my hands down from the top to explore the 3D with both hands."*

Independent observation of hand movements revealed that participants placed their hands over both type of graphic to gain an overview, but more frequently for the 3D models (13 participants) than tactile graphics (7 participants). This difference was statistically significant ($\chi^2(1)$=3.24, p<.05 (one-tailed).

Touch readers are taught to first systematically scan a tactile graphics so as to obtain an overview, usually in a circular pattern starting at the edges of the graphic. There was concern that 3-dimensionality could potentially obstruct the scanning process during this exploratory phase.

> *"It is easier to trace paths on the tactile because it is smoother. On the 3D there are more obstacles."*

We identified a number of distinct hand movements used to explore the graphics in this first exploratory phase (Figure 8). A circular pattern was used to explore more of the tactile graphics (53%) than 3D models (41%) in the exploratory phase, however the difference was not statistically significant (χ^2=1.00, p= .16 (one-tailed)).

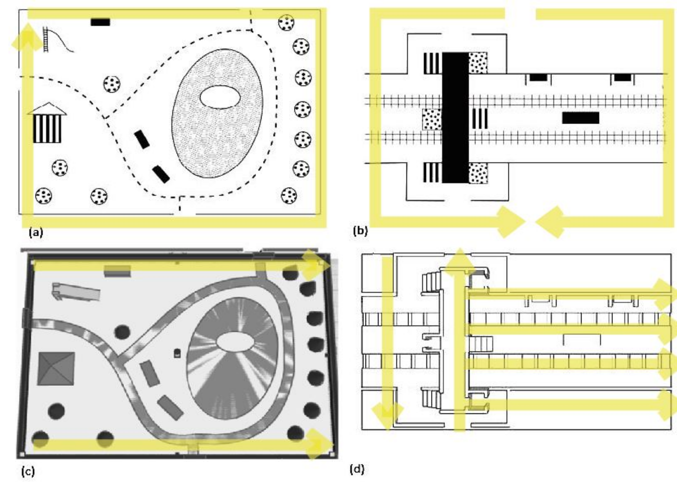


Figure 8. Example hand movements during the exploratory phase: (a) circular and complete (b) circular and complete, using two hands simultaneously (c) non-circular and incomplete (d) non-circular and complete.

Furthermore, the mode of presentation did not affect whether the initial exploration covered all areas of the graphic (7 out of 32 incomplete explorations regardless of format), nor the time required to complete the initial exploration (median=21 seconds for tactile graphics; median=24 seconds for 3D models; z=.14, p=.89). This provides encouraging evidence that scanning during the exploratory phase is not inhibited by the introduction of 3-dimensional elements on tactile maps.

The investigators noticed that hands were held more vertically to read the 3D models due to the need to reach over tall elements. This could force use of the finger tips rather than the more sensitive pads of the fingers.

AUGMENTING 3D MAPS WITH AUDIO LABELS

Our controlled main study did not consider provision of labels (apart from platform numbers) since part of the experimental design required participants to query the meaning of unknown symbols. One difficulty when designing 3D printed models or tactile graphics is finding sufficient space for braille labels. This is a particular problem for street maps or plans of building complexes with many labels, for which it is common to use symbols with an associated braille legend. A potentially better approach is to provide interactive audio labels on the 3D map. This also allows access by non-braille readers and dynamic updating of labels. While interactive labels are not suited to all maps used in O&M training they are well-suited to maps of public spaces, such as train stations, which will be used by many people.

In this section we describe a case study exploring the use of commonly available electronic components to augment 3D printed maps with interactive audio labels. We built a map of the Monash University Caulfield Campus, which has 12 buildings of varying heights (up to ten floors). A campus map was chosen as it is typical of the sort of building or public space for which O&M training is requested. The accessible map was intended to convey the campus geography, building names and key information about what is within each building.

Four principles were used to guide the development. These were based on lessons learned from prior research, particularly [45] and experience with 3D maps in our other studies:

- The audio trigger points should not significantly alter the surface of the 3D print;
- The user should not require specialist technology to interact with the map;
- The interface for the audio label trigger points should be intuitive and easy to use;
- The technology should be robust and relatively inexpensive.

Key design considerations were scale and the design of the interactive audio labels. We employed a user-driven design methodology, developing three models with iterative refinements based on feedback from vision impaired students.

Model I

The campus map was modeled using Sketchup and scaled to be printed in one job on an Ultimaker 2+ (approximately 20cm x 20cm). Outlines were simplified and building height was approximately to scale. Audio feedback was provided using a Bare Conductive Touch Board: an Arduino based board with 12 capacitive touch points and pre-loaded with a script that can play mp3 files from a microSD when a touch point is activated. The top of each building was painted with capacitive paint and connected to the board by conductive thread.

Testing by vision impaired users revealed that although audio feedback was welcomed, the prototype was unusable because the audio labels were constantly being triggered while the touch reader explored the model with their hands. Instead, users wanted to be able to trigger the audio labels with a deliberate user action. Furthermore, the model was too small: It was difficult for participants to access and understand the bridges and paths in tight spaces between buildings.

Model II

The second model addressed these two issues. The model was printed at double size (in all axes) and a small fingertip-sized indented circle on the top of each building was used to house the audio trigger point. A conductive disc placed in each circle was connected back to a Bare Conductive Touch Board.

When tested with vision impaired participants, the second model proved much more effective in conveying both spatial and pathfinding information, as well as providing usable audio labels. However, there were still three usability issues. The first was that the increased height of the buildings made it difficult for hands to reach into all parts of the campus map. Some pathways between buildings, while wide enough for fingers to access, were obscured or difficult to reach due to the height of the adjacent buildings. When asked if the differing heights of the buildings was important, participants agreed that they should be representative of their actual heights, and that this was useful information (giving some indication of the number of floors). However, relative heights could convey the same meaning.

The second issue is that touch readers could not distinguish between different kinds of ground features such as lawn, streets and pathways.

The third issue was that, while the fingertip sized indentations were better, touch readers were still accidentally triggering audio labels as they explored the map.

Model III

The final model addressed these three issues and was a more polished prototype. In this iteration the buildings were printed at half height (10 storeys being 50mm high), which allowed easier exploration but still provided relative information about building heights. To help with identification of pathways and streets, the model was placed on a 500mm x 350mm acrylic sheet, with main pathways and streets laser etched with textures. The capacitive touch points were again recessed circles, however sensitivity was adjusted. The touch board was also programmed so that audio could be triggered by a single touch, double touch or long touch to enable multiple levels of information. One participant was particularly excited by this prospect:

> *"To have audio feedback is excellent... And I suppose you could have levels of information ... Are there toilets in that block? Is there a cafeteria? I know what subjects and what faculty that is but even a sub-menu of things that I keep tapping and get more and more and more information out of it."*

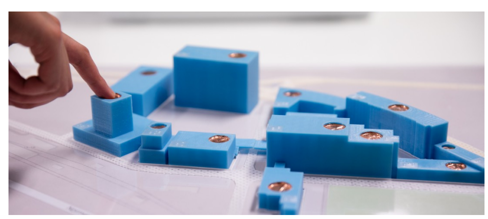


Figure 9. Interactive Campus Map: Model III

Feedback on Model III was very positive. The change in height proved to be crucial in allowing users to explore the map effectively and to use it for route-finding. One participant said:

> *"I like it! As part of orientation to going to this campus, to be able to present something like that before you get there, or in conjunction with having your O&M to find out what's actually there, it would be really good."*

Touch readers found the trigger-points to be robust, readily understood and used. Evaluation of the model reinforced the usefulness of such models in O&M training as blind students were able to independently discover new buildings and routes. The audio labels were also relatively cheap: The total cost for the prototype was approximately US$75.

We are continuing to refine the design and are now exploring the use of low profile button-like trigger points that can provide greater tactile feedback when triggering audio, along with the use of smartphones connected by bluetooth to the model to deliver audio, rather than requiring a dedicated speaker.

One disadvantage of the current models are that assembly requires a knowledge of basic electronics and several hours of work. In the future, we intend to modify the design so that the map can be produced and assembled by those unfamiliar with electronics. Current consumer 3D printers such as the Ultimaker 3 allow printing with two materials. Given conductive printing filament is available, conductive buttons and cores could be printed throughout a model meaning only simple connection from model to touch board would be required.

GUIDELINES

An important practical outcome of our work is a number of guiding principles for the design of 3D printed maps and plans based on user feedback and performance across all studies:

1. As with tactile graphics, additional explanations should accompany 3D models to provide a context in which to understand the model;
2. The 3D model must physically allow the reader's fingers sufficient space to easily explore the salient features. Adequate space must be allowed for fingers to explore all pathways including access under overhanging objects. This may require widening of streets and laneways;
3. The height of buildings and walls should represent their relative height but the vertical scale can differ from the horizontal scale. Heights should be low enough for the fingers to easily reach the base;
4. Features like streets or paths that are intended to be traced by finger can be easily understood and followed if an indented path wide enough to contain the finger tip is used rather than the raised lines commonly used in tactile graphics;
5. Where possible, use iconic 3D symbols to represent stairways, buildings and other 3-dimensional landmarks;
6. Be careful to ensure that there are no sharp points on map elements that could cause discomfort if the touch reader moves their fingers over it quickly or places their hands on top of the map.

When providing interactive audio-labels:

7. Audio trigger points should not be intrusive or distort the appearance of the 3D map;
8. Triggering of auditory information should be the result of a definite action;
9. The use of different interaction gestures to convey levels of information allows users to build their understanding to the depth they wish.

Our studies have also led to insights into training touch readers to read 3D maps:

1. Instruction in techniques for reading 3D models is required, in the same manner that training is now given for reading tactile graphics.
2. Encouragement is needed to feel the sides and base of objects. There is a tendency to touch only the tops of map elements, causing lower features to be missed.
3. A quick overview of 3D maps can be gained by placing both hands on top of the map.

CONCLUSIONS & FUTURE WORK

We investigated whether 3D printed maps offer benefits over the current use of tactile maps in O&M training. While it is clear that 3D models offer benefits when representing inherently three-dimensional objects, it was not clear whether they also offered benefits for maps.

In a controlled user-study with 16 severely vision impaired adults we found a strong user preference for 3D plans. While it is possible that that selection and response bias influenced this preference for the new technology, a mitigating bias towards the more familiar tactile representation was also expected. Performance measures revealed that the 3D maps were easier to understand than tactile equivalents due to the use of 3D iconic symbols and allowed relative height of map elements to be more easily understood. There was also some advantage in short term recall but not for longer term recall.

We conjecture that the fundamental reason why 3D prints were generally preferred to tactile graphics is a perceptual mismatch between touch and the vision-based conventions used in tactile graphics such as aerial or side views and depth cues like occlusion to show relative height. The use of 3D prints reduces the need for these conventions and so we infer reduces the cognitive load required to understand the graphic. While our studies provide partial support for this we plan to explore this interesting question further.

We have also investigated techniques for augmenting 3D printed maps with interactive audio-labels. Interactive audio-labels provide several benefits over braille labels, including a clearer tactile experience and enabling people who cannot read braille to understand the graphic. They also allow information to be provided at different levels of detail and for labels to be updated without the need for reprinting. We explored how low-cost "maker community" electronics can be used to provide robust interactive audio labels on 3D printed maps. Such maps could be provided in public spaces such as train stations or shopping centres to improve accessibility.

Our studies have significant implications for O&M training, suggesting that 3D prints augment or replace the current use of tactile maps. Based on our studies we have developed some initial guidelines for the design of accessible 3D prints and for teaching touch readers to read them. One limitation of our main study was that participants were touch readers with experience reading tactile graphics. A replication of the study with participants with recent vision loss is needed to determine whether similar benefits are found.

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