

3D Printed Street Crossings: Supporting Orientation and Mobility Training with People who are Blind or have Low Vision

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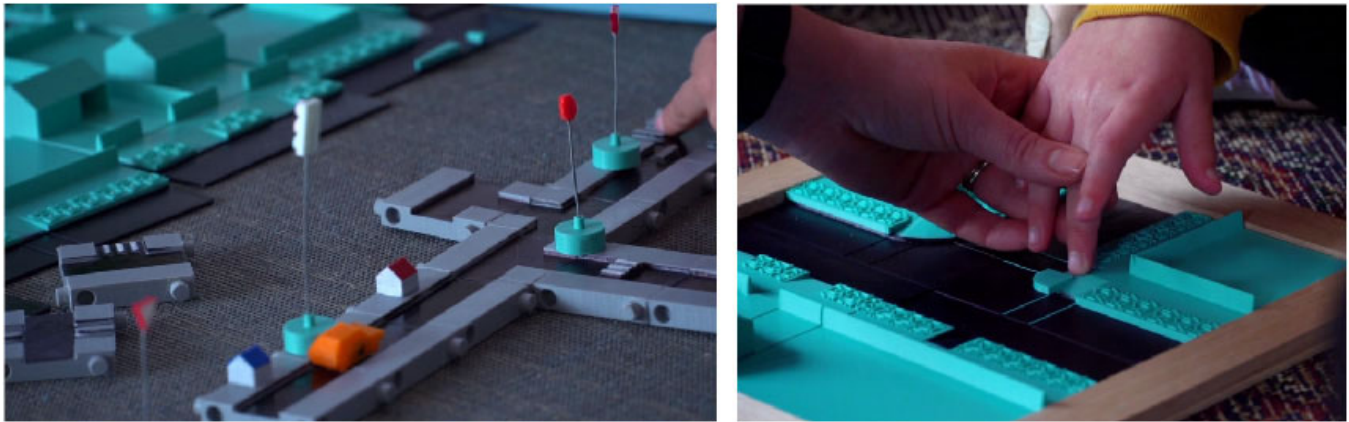


Figure 1: Co-designed 3D models being used to teach street crossing concepts at a workshop for blind and low vision children during the evaluation phase. Images courtesy of Guide Dogs Victoria.

ABSTRACT

The ability to cross the street at intersections is an essential skill, often taught to people who are blind or have low vision (BLV) with the aid of tactile maps and kits or toys. However, each of the existing mapping tools has shortcomings. We investigated whether co-designed 3D printed components can offer benefits. Guided by consultation with 11 Orientation and Mobility (O&M) professionals, we co-designed a series of 3D printed kits that they then used in their practice with BLV children who showed high levels of engagement and learning. The 3D materials were found to demonstrate the key concepts for street crossings in a portable, engaging and professional manner. They will be released for free download, enabling O&M professionals to access or modify the materials as required. We hope that use of our co-designed 3D printed tools will contribute to the safety, independence and inclusion of BLV people.

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CCS CONCEPTS

• **Human-centered computing** → **Accessibility technologies**.

KEYWORDS

Blind; Maps; Intersections; 3D Printing; Orientation & Mobility

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1 INTRODUCTION

Originally developed in the USA to support veterans injured during the second world war, **orientation and mobility (O&M)** training has become an integral part of **blind and low vision (BLV)** people's education and support [12, 56]. Specialist O&M instructors teach concepts and skills enabling BLV people to confidently travel independently, thereby gaining physical access to the world.

One of the essential skills that O&M training teaches is the ability to cross at street intersections [8]. For congenitally blind children, this begins with fundamental training about different kinds of intersections and traffic conditions. As part of this training, O&M instructors frequently make use of raised line drawings called

tactile maps and kits or toys to represent the intersections. **Here, we investigate the use of 3D printed mapping components in O&M training about street intersections.** To the best of our knowledge, we are the first to do so.

Commodity 3D printers and easy-to-use design tools like TinkerCAD are transforming the provision of accessible models and graphics to the BLV community. 3D printed models are increasingly used in schools to support BLV student access to STEM materials [35, 39, 40, 46, 57] and they are also beginning to be used for O&M training [16, 32, 51]. However their use in O&M training has been limited to printed street maps or plans of particular buildings or locations. Until now, 3D printed models have not been considered for teaching the concepts of street intersections at a more fundamental level: how the intersection is laid out; how the traffic moves; the information available to drivers; and how a BLV person can orient themselves to safely cross the road. All of this information is vital to complete a road crossing with safety and confidence.

We address three questions: (1) *What are the most important requirements for tactile materials to teach street crossing concepts for people who are blind or have low vision?* (2) *Is there a need for additional O&M tools to teach intersections that could be fulfilled using 3D printing?* (3) *If so, what are the design characteristics of such 3D models?*

To answer these questions, we employed a participatory design methodology with O&M professionals. We conducted work across three phases (Figure 2):

- In the *requirements gathering phase*, we conducted a formative study via semi-structured interviews with 11 O&M instructors to understand their current practices and to elicit how they thought 3D printed street intersection maps might be of use.
- Informed by the requirements gathering phase, we moved into the *co-design phase* to co-create three sets of 3D materials illustrating a range of intersection formations. The designs were iterative, with constant changes and additions made in response to feedback from seven O&M practitioners and two blind adults.
- In the *evaluation phase*, we gathered more formal feedback from seven O&M instructors via survey and interview. We also analysed video of sessions in which three blind children used the materials with their O&M instructors.

This work provides empirical evidence of the value of 3D printed tactile street crossing models for O&M training for people who are BLV. Our specific contributions are threefold:

- *Empirical evidence:* Evidence for the value of 3D printed models for O&M instructors when teaching BLV people about different kinds of street intersections. Blind children successfully used the materials to learn basic to advanced concepts relating to crossing streets safely. The 3D printed materials were rated as more usable than existing materials, and held advantages in terms of demonstrating key concepts, portability, engagement and being professional in appearance.
- *Design guidelines:* The first design guidelines for 3D models of street intersections and their components. For example,

3D models should be tactually distinct, with a low profile, and show only the most important features.

- *Availability:* Provision of the final 3D models on Thingiverse for O&M specialists to print or modify and use with their BLV clients.

Our studies have significant implications for O&M training, providing evidence that 3D printed models can augment or replace the current use of tactile graphics and other mapping tools. More broadly, it demonstrates the value of maker technologies like 3D printing for the development of specialised tools for the accessibility community. We hope that our freely available library of street intersection components will support O&M practices world-wide with consequent improvements in skills, safety and independence for BLV people.

2 RELATED WORK

2.1 Orientation and Mobility Training

Intersections are becoming more complex and dangerous [8], demanding focused attention and training. Even well-trained blind pedestrians crossing at a roundabout may wait up to three times longer than sighted pedestrians and make more risky decisions [1].

Because people who are congenitally blind do not receive information about the environment outside their immediate touch and hearing, concept building is always the first step towards understanding [45, 60]. In particular, understanding traffic movements and the driver's decision-making process is essential to be able to make safe decisions [6, 22]. O&M training about street crossings specifically teaches BLV pedestrians how to locate the crosswalk and crossing location, locating and using the pedestrian push button (if available), aligning to cross, and maintaining alignment while crossing [7, 8, 20]. All of these skills rely on first having an understanding of the layout of the intersection, however, it is difficult to construct a mental map with only environmental cues and verbal descriptions[52]. Tactile graphics (or 3D models) are recommended for conveying spatial relationships in general [44] and more specifically for teaching the spatial layout of intersections [22], especially when working with children [47]. In the same way, exposing congenitally blind children to maps is crucial for them to develop cognitive mapping skills [10].

2.2 Tactile Maps, 3D models and 3D Printing

Tactile mapping is a popular area of research and production. However, the main focus has been street maps for wayfinding, with maps covering a larger area and lacking the fundamental details required to understand individual street crossings. An exception is the Australian Symbols for Tactual and Low Vision Town Maps, which provide symbols for traffic lights, pedestrian lights and pedestrian crossings [3]. Much more recently, the Lighthouse for the Blind has produced a set of swell paper tactile graphics to teach the basic concepts of road crossings [23]. They include pedestrian crossings, painted line markings, lanes with direction of travel and raised medians for familiarisation. They do not include further details such as traffic lights, push buttons, Tactile Ground Surface Indicators (TGSIs) and ramps, and cannot be easily modified to teach specific crossings.

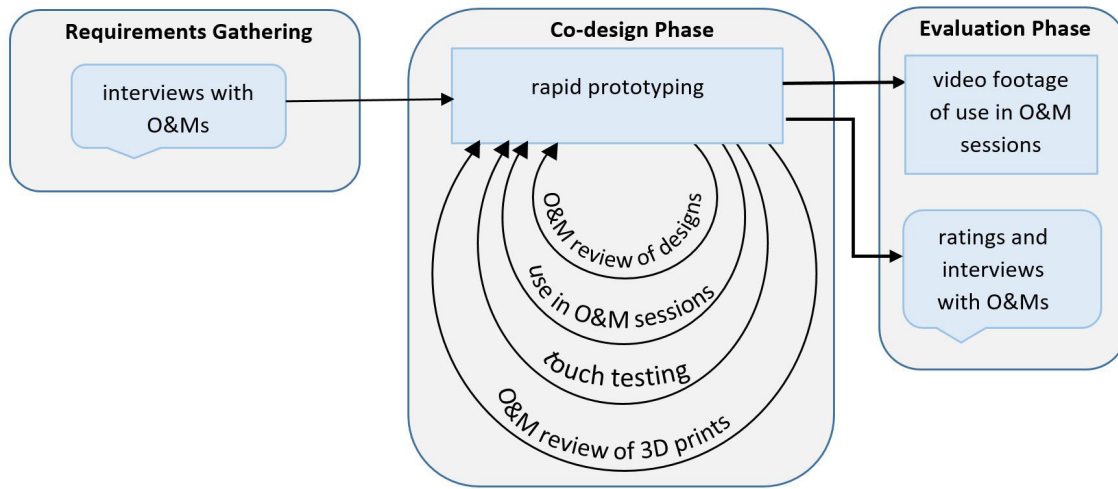


Figure 2: The participatory design process, with direction from Orientation and Mobility (O&M) instructors and touch readers at every stage.

The efficacy of using 3D printing to present tactile maps has also been explored [16, 28, 33, 53]. Evidence suggests that 3D printing can be more successful than traditional tactile graphics for conveying some types of graphical information. This of course includes graphics that are 3-dimensional in nature [19], but also iconography, as 3D printed volumetric symbols [17, 31, 42, 49] decrease reliance on more abstract symbols. Both of these benefits lend themselves to the application of 3D printing for maps and plans, as well as supporting O&M training more broadly. Work presented in [38] found that 3D printed maps were preferred and facilitated better short term recall than their tactile graphic counterparts. While 3D printing has been used to create numerous street maps and building plans for the purposes of route planning and navigation [30, 33, 55], it has not yet been considered for teaching the concepts of street crossings.

A range of kits with 3D components are already available to represent street crossings. Tactile Town [25], the Cook Kit and City-box [50] were all designed specifically for O&M purposes, although the latter two are no longer available. Alternatively, toys may be re-purposed for teaching, such as Lego or toy roads and cars.

Thus, while there has been much excitement about the advent of 3D printing for the creation of bespoke solutions for small user groups such as the blind community [11, 14, 15, 29], it is as yet unclear whether 3D printing offers advantages over existing options for O&M professionals teaching street crossings.

2.3 Participatory Design

This work primarily adopts the practice of Participatory Design [43, 48, 54]. This approach to computer system development recognises the expertise of users and therefore ensures that they play a critical role in the design process [48]. In this instance, O&M trainers are defined as the primary stakeholders because they are the people who select O&M training materials and structure their teaching in relation to the materials that they have available. As the recipients of O&M training, BLV people must of course also be included in

the design and evaluation. The active involvement of these two groups should help ensure that the work is directed to real needs, supports user values and considers the practicalities of implementation. Moreover, involvement in and ownership of the problem-solving process means that O&M professionals will be more likely to use, maintain and evolve the solutions after completion of the project [34].

3 REQUIREMENTS GATHERING

The project was initiated in response to suggestions made at a brainstorming session with O&M professionals and a blind adult. They proposed that street crossings are an important component of O&M training and that 3D printed maps might be of value.

We then confirmed interest from the broader accessibility community before proceeding with project. Two 3D printed maps depicting intersections immediately outside a conference venue were presented at a workshop attended by more than 50 accessible graphics producers, vision specialist educators, O&M professionals and touch readers. Discussions and feedback indicated that more formal investigation into 3D printed street crossings was warranted and provided suggestions for design principles.

In the first formal stage of work, detailed consultation with O&M instructors was sought to determine their requirements for maps to assist with teaching street crossings.

3.1 Method

Semi-structured interviews were conducted with 11 O&M instructors about what mapping tools they currently use to teach concepts of street crossings and/or specific street crossings, what features these maps require, and how they think that 3D printed maps might be used. Interviews were conducted individually via phone or video conference and each took 30 to 60 minutes.

3.1.1 Participants. All 11 participants were qualified and practising O&M instructors in Australia. They had a minimum of eight and

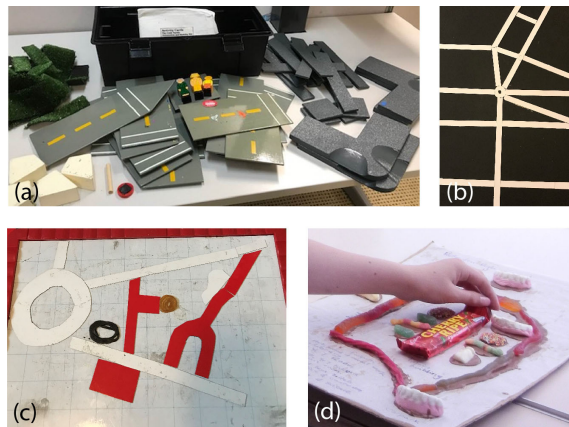


Figure 3: Some tactile mapping tools currently used to teach about intersections: (a) Cook Kit (b) handcrafting - cut strips of cardboard (c) magnets on a magnetic white board (d) handcrafting - map made with confectionery on a chocolate base. Images courtesy of Guide Dogs Victoria.

average of 17 years experience in the profession, having worked for five different organisations ($n=10$) and/or as independent providers ($n=4$). While some of the participants specialised in services for a particular age group, together they had worked with clients from babies to a 104 year old. More details regarding participants are given in Appendix D.

3.1.2 Thematic analysis. All communication was transcribed then coded using NVivo software. Three samples were coded separately by two researchers for iterative cross-checking, discussion and updating of codes. By the third sample, there was a 74% level of agreement between the two raters and no further codes were suggested. The remaining coding was performed by a single researcher for consistency.

3.2 Results

3.2.1 Current practices and tools. All of the O&M instructors interviewed actively teach street crossings. This work has two main purposes. The first, familiarisation with specific street crossings, is taught to all but the very youngest BLV clients, and is primarily done on the actual street corner. The second kind of training teaches fundamental concepts and skills, such as typical street crossing configurations. This is mainly taught to children and to new arrivals in the region:

“refugees and children, teaching them about road crossings was a bit different when you needed a tactile form to describe or get them to understand the layout of intersections.” [P5]

There was a surprising level of inconsistency in terms of the mapping tools and technologies used by various O&M instructors, some of which are illustrated in Figure 3. The most common methods, each used by seven of the 11 interviewees, were swell paper tactile diagrams, handcrafted tactile diagrams, Lego and magnetic boards. All methods were reported to have limitations, as summarised in Table 1.

Swell paper (also known as microcapsule paper) diagrams are made by drawing or printing with carbon-based inks onto specialised paper that is heated, causing the dark areas to raise to a uniform height. Only four of our 11 participants had local access to the equipment required to create their own swell paper diagrams. When available, swell paper diagrams are favoured because they are relatively quick to produce and they are portable. However, they are not durable. Concern was also expressed that, due to the high level of abstraction used in swell paper diagrams, clients require good tactile graphics reading skills to understand them, with around 15% of BLV people having poor spatial mapping skills [20].

A range of kits are available that can be used to represent road crossings, either designed for the purpose of O&M training or as toys for sighted children. These kits are used for teaching concepts, mapping specific street crossings, and asking the client to build their own map to check their understanding. Tactile Town [25] by the American Printing House for the Blind is the most well-known of these kits. Made primarily of felt, with Velcro for stability and storage, the kit is lightweight, includes a wide range of pieces for customisation of crossings, and has good visual contrast. Its main disadvantage is the prohibitively high price tag and cost for overseas shipping, meaning that the kit is only owned by one of the organisations represented by our participants. Tactile Town is not suitable for young children because it has a lot of small pieces. Nor is it used with adults because it lacks details such as ramps and Tactile Ground Surface Indicators.

“We see it more as a rainy day activity type of kit rather than teaching orientation. It’s not technical enough.” [P3]

The Cook Kit (Figure 3b) was favoured over Tactile Town for its simplicity, durability and the inclusion of ramps. However, it is no longer available and it requires some additions and modifications - fake grass was added, the standard figures are not used because they are not directional, and only two corners came with the kit. Again, it is only used with young children due to its simplicity. Citybox [50] is another kit made specifically for BLV people, however none of our participants had used it because they felt that the pieces were designed for European cities and could not be transferred to the Australian environment. It is no longer available.

Toys could also be used as kits for creating tactile street crossings in collaboration with the BLV client. Lego was the most commonly used toy, favoured because it clips together securely and components such as traffic lights and street furniture are available. The main drawback of Lego is that it does not show curves well. Furthermore, there was concern that some adults are reluctant to use children’s toys.

“I don’t think she felt comfortable using Lego in public.” [P8]

Hand crafting is the third category of methods currently used to provide tactile representations of street crossings. The most common crafting method is a magnetic white board or metal sheet with an array of magnets, usually cut from a sheet into customised shapes (Figure 3a). This method is portable and secure. This is closely followed by tactile drawing kits such as the Draftsman Tactile Drawing Board [24] or the Sensational Blackboard [18],

Method	n	Advantages	Disadvantages
Swell paper	7	Quick to produce; Portable	Requires specialist equipment; Not durable; High level of abstraction
Handcrafted tactile graphics	7	Cheap, readily available materials	Time-consuming to produce; High level of abstraction; Can look unprofessional
Lego	7	Readily available; Easy creation by BLV learners	Limited shapes; Social stigma
Magnetic board	7	Cheap; Readily available; Portable	High level of abstraction; Can look unprofessional
Tactile drawing kit	5	Portable; Quick onsite creation	Not well-known; High level of abstraction
Cook Kit	3	Durable; Tactually distinct	No longer available; Limited pieces
Tactile Town	2	Versatile with many pieces; Good visual contrast	Expensive; Missing key information
Drawing on back or hand	2	Quick; Portable	Transient; Low fidelity
Citybox	0	Good tactile & visual contrast	Specific for Europe; No longer available

Table 1: Methods used to tactually represent street crossings, the number of orientation and mobility (O&M) practitioners who had used this method from a total of 11 interviewees, and reported advantages or disadvantages

although this option was not known to all practitioners. Other handcrafting materials included fuzzy felt, foam stickers, cardboard, and even confectionery (Figure 3d). All hand crafting methods suffer from the fact that they can look quite messy and unprofessional. Unless a lot of time is spent on their production, most handcrafted solutions also employ a high degree of abstraction, requiring more cognitive effort from users. An extreme example is drawing directly on a BLV client's hand or back, which can be used anywhere and anytime but only communicates a very low level of information.

3.2.2 Required features. We also asked O&M instructors what they would like us to create with 3D printing and what features should be included. Suggestions for 'ideal' 3D printed street crossing maps could be divided into two main categories.

- (1) **Typical intersections:** O&M instructors requested durable maps illustrating typical intersections to assist with concept development. The intersections most commonly mentioned were T-intersections, 4-way intersections, roundabouts, slip lanes with traffic islands and straight roads with pedestrian refuges. Ideally, intersection maps would be A4 size. Given the typical footprint of 3D printers, 20 cm² was considered an acceptable compromise.
- (2) **Customisable intersections:** O&M instructors requested corner pieces, similar to those found in the Cook Kit, to create custom maps representing specific intersections. Ideally, a 1:64 scale would be used to align with the most common toy cars.

Participants were asked to name the features that they considered essential, nice to have, or not needed in a 3D model of street crossings. Their responses are listed in full in Appendix A. We concluded that the following features were most important: intersection type, footpath, traffic islands, zebra crossings, pram ramps, slip lanes, the kerb, pedestrian crossing lines and the gutter. It was felt that the base map should be kept simple to allow for easy comprehension. Other features could then be added to the base map if important: the grass verge, traffic lanes, Tactile Ground Surface Indicators,

traffic light poles, tram stops, tram tracks, landmarks and shore lines. Toy or model cars, buses and bicycles could be used to indicate traffic lane types, direction of travel and parking. A lot of other important information would be best discussed rather than conveyed tactually.

3.2.3 Required properties. Thematic analysis of communications during the requirements gathering phase revealed that the most common properties discussed in relation to street crossing materials were: using the materials to teach *concepts*; being able to *customise* the intersection layout using interchangeable pieces and *removable parts*; and the importance of *portability*. A full list is given in Table 2.

4 DESIGNING AND REFINING 3D PRINTED ROAD CROSSING MAPS

Using the results from the requirements gathering phase as a starting point, we conducted an iterative co-design process creating 3D printed materials to support O&M training for street crossings for BLV people.

4.1 Methodology

4.1.1 Co-design Process. 3D modelling was performed in TinkerCAD by the first author, who is an experienced accessible formats producer. 3D printing was performed throughout the design process to check that pieces were sturdy, could be printed reliably, and were tactually distinct.

4.1.2 Participants. A total of seven O&M practitioners (including five from Guide Dogs Victoria) and two blind adults provided feedback during the co-design phase, as documented in Appendix D.

4.1.3 Feedback process. As illustrated in Figure 2, the 3D designs were constantly checked by O&M professionals and touch readers, allowing for rapid prototyping with refinements made in response to their feedback.

Need	Mentions	People
teaching concepts	31	8
customisation	20	9
removable pieces	20	9
portability	16	7
client creation	15	8
standard layouts	13	7
engaging	13	6
tactually distinct	12	6
affordable	10	8
durability	10	4
high contrast	7	3
stability	2	2
professional	3	2
level of detail	–	–
playful	–	–
easy to clean	–	–

Table 2: Needs for tactile street crossing materials, as emerged from thematic analysis of communications during the requirements gathering phase, where mentions = the number of times a need was mentioned, and people = the number of people who mentioned the need. Three further needs that emerged later in the project are listed at the bottom of the table.

To begin the co-design phase, images of the designs or photographs of the first printed prototypes, along with a description of the materials and questions, were sent to Guide Dogs Victoria and all O&M professionals from the requirements gathering phase. Two people provided feedback via remote interview and another three provided written feedback. Whenever an individual made a suggestion that aligned with comments made by at least one other person, and which did not add unnecessary complexity, the design was refined and an image or tactile sample was provided to check that their idea had been interpreted correctly.

After all of the initial feedback had been incorporated and while COVID lockdown restrictions were temporarily lifted, a full set of the materials and accessories was delivered to Guide Dogs Victoria. Two O&M trainers provided their initial impressions, made suggestions for further refinements and requested more pieces. Two blind adults who read by touch also provided hands-on assessments of the materials.

4.2 Street Layout Puzzle Pieces

Addressing the first requirement for **typical intersection** layouts, collaboration through a 3D printing group for accessibility revealed that an O&M instructor at the South Australian School for Vision Impaired had already created 3D printed puzzle pieces representing the most common intersections. These are small square puzzle pieces with connectors on the edges, each demonstrating a different street layout: straight, sharp corner, T-intersection, cross intersection, cross intersection with slip lanes, and roundabout.

The puzzle pieces are intended for use by children to provide familiarity with street layouts through play. The pieces are deliberately small, printed at 5cm wide, 5cm deep and 1cm high (excluding the connectors) so that small hands can easily feel both sides of the indented road at once.

Using the same template, we added nine more street layouts mentioned by O&M instructors: a rounded corner, a cross intersection with pedestrian islands in two different arrangements, a cul-de-sac, and straight road pieces with a pedestrian refuge, chicane, wombat crossing or zebra crossing. We modified the connectors slightly for an easier fit but they still require some smoothing after printing. Black permanent ink was added on the road sections for contrast (Figure 4).

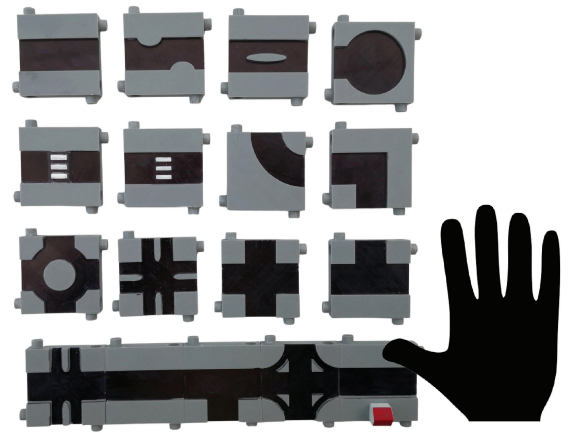


Figure 4: 3D printed puzzle pieces demonstrating standard street layouts, in relation to an 8-year-old's average hand size measuring 14.2cm long

Immediately upon receiving two sets of crossing pieces, O&M instructors requested many more straight road pieces so that learners could create a more realistic route with greater distance between the intersections. After asking a blind adult to map out a route using the puzzle pieces, we realised that a set should also include multiple T-intersection pieces to represent side streets that need to be crossed, along with two "home" pieces with a building to indicate the start and end of a route. The set continues to grow as people suggest additional intersections for inclusion.

4.3 1:64 Scale Road Edge Pieces

To address the second requirement for **customisable intersections**, a series of 3D printed street corner pieces were created at 1:64 scale (Figure 5). At this scale, the pieces would be able to work with the Cook Kit, which is no longer available, and could be used with standard toy cars and toy street furniture. In keeping with the Cook Kit, the main pieces were road edge pieces, representing public the area from the gutter to owned properties. These road edge pieces were made at the maximum size possible on an Ultimaker FDM printer, at a length of 20cm, and were 5mm tall. A variety of parts were created to allow creation of straight roads,

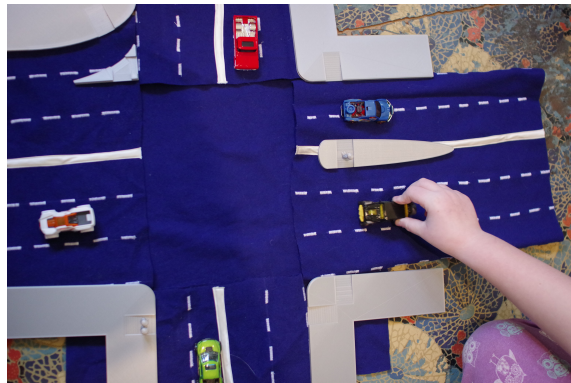


Figure 5: 1:64 road edge pieces being used with standard toys

T-intersections, cross intersections, roundabouts, slip lanes and pedestrian islands.

However, once the pieces were printed, it became obvious that a very large space was required to lay out an intersection. Also, because of its large size and use with toys, the set presented more like a play kit for children rather than a professional tool that could be used with adults. Through several conversations between the researchers and O&M professionals, the idea emerged to create smaller scale street crossings, as described in the next section.

4.4 1:128 Scale Street Corners and Components

The third set of materials were designed in response to limitations of the 1:64 road edge pieces. First, the size was halved to 1:128 scale. This reduction in scale meant that a single lane road could be added to a corner piece and it would fit on a standard FDM printer. It quickly became obvious that four of these pieces could be placed together to form an intersection inside a frame, which would prevent movement while being touched. This also meant that the new pieces could fulfil both requirements: to demonstrate **typical intersections** and be combined to create **customised intersections** to represent specific crossings. The pieces are illustrated in Figure 6 and the key design considerations are described below.

Portability and robustness is important for O&M training.

- Size was reduced to 1:128 scale for portability and compact use. Each corner measured 12.7 cm wide and 12.7cm deep.
- The base measured 1.5mm thick. This was considered the minimum thickness to provide strength while minimising plastic and printing time.

Minimal detail was included for tactual simplicity.

- In accordance with the essential features requested by O&M professionals in the requirements gathering phase (Appendix A), shorelines were added, i.e. grass on one side of the footpath and a fence/building line on the other.

A variety of parts were created to allow customisation for different intersection types and also to allow the level of detail to be built up according to the client's needs and skills.

- A variety of ramps were inserted into the street corners.
- As the scale of 1:128 is not standard, street furniture was also created: a car, bus and bicycle with a distinct front and

back, along with traffic lights, stop signs and give way (yield) signs.

Pieces were designed to be tactually distinct and recognisable.

- Gutters, footpaths and the grass verge were initially raised 5mm higher than the road to create a tactually distinct edge. However, a touch reader felt that this made the ramps too steep. The height was therefore adjusted to 3.5mm in the final model.
- Grass beside the road was represented with a low irregular 3D printed texture. The fence (or building) line on the other side of the footpath measured 8.5mm high and 4mm wide with a rounded top. Pedestrian crossing lines with rounded tops were 1mm wide and raised by 0.5mm. This was considered the minimum to be noticeable without being overly distinct, as crossing lines indicate the line of travel but are not raised in real life.
- In response to feedback from an adult touch reader, the circles on the traffic lights were raised higher and with indented centres for better tactile discriminability, in keeping with perceptual studies showing that outlined tactile symbols are more easily recognised than solid symbols [2, 41, 59].
- Braille letters were added to the signs because none of the blind touch testers were familiar with traffic sign shapes.

High contrast colours were used to assist people with low vision.

- On corner pieces, the base (road) was printed in black and the filament colour was changed to teal for the upper portions. Vehicles were printed in bright orange.

The pieces were designed to fit together with stability during tactile exploration.

- A frame was constructed to neatly fit four pieces (one intersection), preventing the pieces from moving when touched. The first frame was created using cardboard. In response to feedback from O&M instructors, a second more sturdy frame was created with magnetic backing and wooden frame.
- The street sign bases, car, bus and roundabout centre were also redesigned so that a small magnet could be inserted in the base while printing. An adhesive strip magnet was added to the base of the pedestrian islands, which were too small to contain magnets.

The designs for the 1:128 scale street corner components and accessories have been made available for free download from www.thingiverse.com/thing:5177801.

5 EVALUATION

Several sets of the 3D printed intersection pieces were produced and provided to Guide Dogs Victoria and an independent practitioner, and a set of the puzzle pieces was self-produced by South Australian School for Vision Impaired. Feedback was provided via interview and survey, and one O&M practitioner provided video recordings of some of their sessions using the materials.

5.1 Participants

As detailed in Appendix D, seven O&M practitioners completed the survey. Four actively used the materials while the other three O&M practitioners from the requirements gathering phase viewed

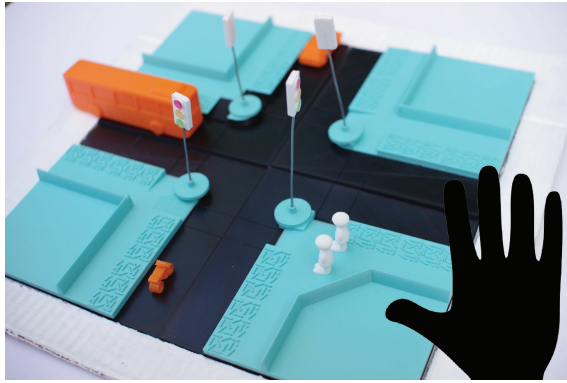


Figure 6: 1:128 street corners configured for a cross intersection with figures, traffic and signals, contained within a cardboard frame. An 8-year-old's average hand size measuring 14.2cm long is shown for reference.

the materials over Zoom. Three worked for Guide Dogs Victoria, two worked for different agencies and two were independent practitioners, all in Australia.

5.2 Survey

5.2.1 Materials. Feedback from O&M practitioners was collected through unstructured interviews and an online survey. The survey first asked for background information about the respondent, which materials they used and with whom. Respondents were then asked to rate the 3D printed materials on a 5-point Likert scale in terms of the key criteria identified as important in the requirements gathering phase (Table 2). The questions are listed in Appendix B. We did not ask about affordability because costs associated with 3D printing was largely unknown to respondents. Nor did we ask about removable parts, as that is a binary (yes/no) question.

We also asked eight questions from the System Usability Scale (SUS) [13], omitting the two questions relating to integration/consistency of IT systems because they were not relevant to the use of physical materials. The term ‘system’ was replaced with ‘materials’ as it was more appropriate and the SUS tool has been found to be robust to such wording substitutions [4]. The questions are listed in Appendix C.

Respondents were then asked to nominate what materials they would have used if the 3D printed materials were not available, and to rate this existing material using the same questions.

5.2.2 Results. Seven O&M professionals completed the survey. Of these, four had used the 3D printed materials with clients and three had not. The respondents chose a range of different existing materials to rate as their preferred tool for the same purpose if the 3D printed materials were not available: two chose the Tactile Town kit [25]; two selected hand-cut magnetic sheets on a whiteboard (Figure 3c); there was one response each for a raised line drawing kit and a track set for toy cars; and one person did not complete this section of the survey.

As shown in Figure 7, the 3D printed materials ratings were generally favourable and similar to those of existing materials in terms

of the key requirements that emerged in the requirements gathering and feedback phases. Importantly, **the 3D printed materials were rated particularly highly in terms of demonstrating the key concepts for street crossings, being portable, being engaging and being professional in appearance.**

The SUS scores were calculated and then adjusted according to the number of questions answered, as we asked eight (instead of ten) questions in total and one respondent answered only seven. The average SUS score for the 3D printed materials was 65.9 ($n=7$, $sd=17.8$), while the average SUS score for the chosen alternative was 56.25 ($n=6$, $sd=5.3$). Both these scores are below the average of 68, and can be described as ‘marginal’ [5]. As seen in Figure 8, the 3D printed materials were almost always rated more highly than the existing materials. There was an outlying low score for 3D printed materials from a respondent who did not answer questions relating to an existing material.

Both sets of materials were rated poorly in terms of assistance being needed for the client to successfully use them (questions 4 and 10). However, this may be expected.

“I think tactile materials always need some level of explanation and orientation for someone who’s blind or has low vision. Once the person is familiar with the materials I think many people would become more proficient using them.” [anonymous]

Adjusted SUS scores with questions 4 and 10 removed were 73.2 ($sd=17.2$) for the 3D printed materials and 63.9 ($sd=3.4$) for the existing materials. The 3D printed materials would therefore rate above the average SUS score of 68 and be described as ‘acceptable’ or ‘good’ [5].

Thus overall, the 3D printed materials were rated as equivalent or better than existing materials for teaching street crossings. However, these results should be interpreted with caution given the small number of participants and the high variance of responses.

5.3 Interviews and Video Evidence

Final interviews were held with four O&M professionals – one who had used the materials extensively and three who viewed the materials over Zoom. A further three O&M professionals who had used the materials provided extended comments on the survey. Further, one O&M practitioner video recorded five sessions documenting their use of the materials with three children.

The interviews, survey comments and videos were transcribed and coded in NVivo using the same themes as the requirements gathering phase. Three further requirements became evident: ‘play’, having the right ‘level of detail’ and ‘cleaning’. An additional two themes emerged as desired or achieved outcomes: ‘learning’ and ‘on-site use’.

5.3.1 New requirements. While engagement was recognised as a major theme in the first two phases of this project, the particular importance of *play* only became obvious once the materials were used with children. The O&M professional who made most use of the 3D models devised a number of learning-directed games to play with the 3D models.

“You’ve got to make it a fun game. We’re playing with people walking around on the models. Kids love it,

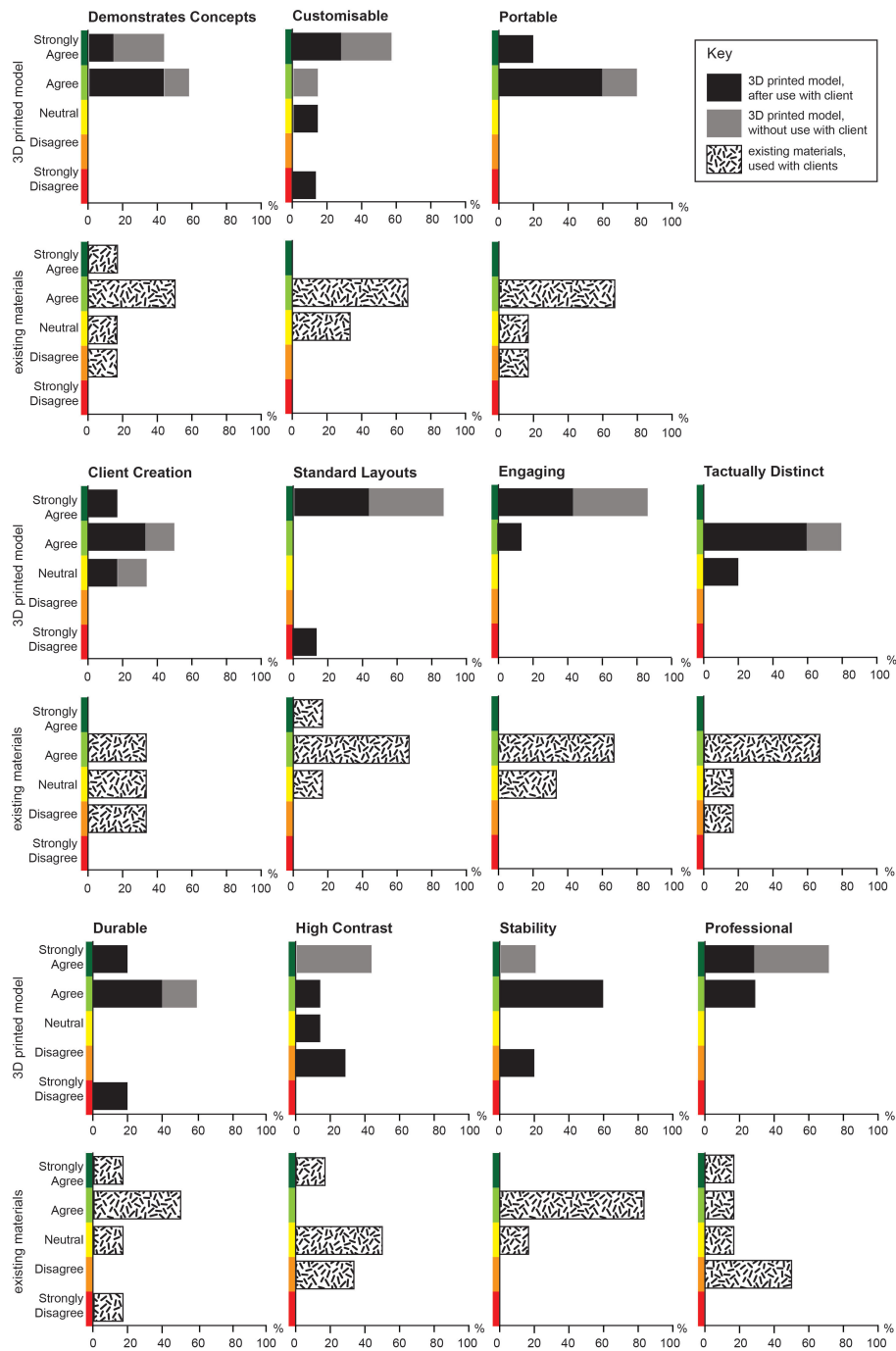


Figure 7: The 3D printed materials (top rows) compared with existing materials (lower rows) as rated by seven O&M professionals.

as long as you make it fun playing with them like a game.” [P2]

Meanwhile, the children showed their engagement with the 3D models with comments such as “Can we open the little bits?

Please can we have them?” and “I like pulling them [the corner pieces] out”. Quite often, the children would spontaneously use their fingers or the cars and figures to act out the scenarios being discussed. Fidgeting with the models and pieces actually re-directed

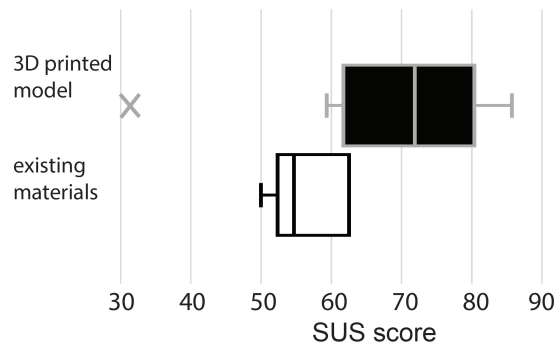


Figure 8: Adjusted scores for eight questions from the standard usability scale (SUS) for the new 3D printed materials compared with existing materials.

their attention back to the learning topics. But if they began to lose focus, the O&M instructor was easily able to re-engage the children through play-based learning such as crossing the road to buy sweets at the shop, or voicing a siren for the ‘police’ car when a road rule is broken.

The *level of detail* was an important consideration, with a balance required between keeping the maps as simple as possible for easy interpretation, whilst still including the details required to teach important concepts. Simplicity is one of the first requirements given in many guidelines on tactile graphics design, e.g. [9, 21, 44, 58]. This is perhaps where the 3D nature of the models was most advantageous, as things like ramps, gutters and fences can be shown very simply and intuitively in 3D but would require the use of more complex and arbitrary symbols on a tactile graphic [38].

Ease of cleaning has become a much more important requirement with the advent of COVID-19. The 3D printed materials were thought to be relatively easy to clean by spraying or wiping them down with an appropriate disinfectant. However, cleaning would be easier if the materials were heat resistant so that they could be placed in a dishwasher. By contrast, popular tools such as swell paper diagrams and Tactile Town (made of felt) are much more difficult to clean.

5.3.2 Outcomes. Learning and on-site use are both desired outcomes for O&M practice, which can only be achieved if the materials requirements are first met.

Learning first emerged as a theme during the co-design phase, when even the adult touch readers revealed that they had not known the shape of street signs before feeling the 3D models, and were then motivated to ask further questions about what signs drivers use. In the evaluation phase, the O&M professionals spoke about building on learning, with clients needing to learn the basic concepts first before being able to move on to more advanced concepts with the 3D printed materials. They also said that clients were able to demonstrate that they had learned new skills through their use of the materials.

“It really demonstrated to me that she’s got a really good understanding of that layout now, which I don’t

think she had as near understanding before using the model.”

Strong evidence for learning using the 3D printed materials was provided by the videos, of which three featured the same totally blind child. In the first session, the focus was on familiarisation with the pieces and the important elements of the street environment that they represent: the road, gutter, nature strip, footpath and fence. They next looked at different intersection types (T versus cross) and types of pram ramps. Once these basics were understood, they were able to move on to learning about alignment for crossing from one pram ramp to the next and expected traffic movement. The child’s first attempts to place the last two corner pieces in the frame were unsuccessful (“I have no idea. I don’t know”). This contrasted with a later session when they were able to both choose and place all four corner pieces to represent the specific intersection at their school, demonstrating that they had learned to recognise the elements on the map, understanding their relative positions and the layout of their particular intersection. Another child, who had enough vision to understand the general layout of intersections, used the 3D maps to learn about traffic movement. By the end of their session, they demonstrated a good understanding of which way to check for traffic when crossing using a pedestrian island – this was something that they had previously struggled with. Thus, the videos showed that the 3D printed materials can be used to teach a range of important O&M concepts and skills to children who are blind or have low vision.

The second desired outcome, *on-site use*, was largely dependent on portability. This aim was clearly met, with practitioners using the pieces for on-site learning.

“60% of the lesson would be actual road crossing practice, cane skills doing that, and then that would be supported by 40% of using the models to give more explanation as we were doing it. That’s what’s so great about them, they are so easy and portable ... Even the frame with the four bits in it, I just put it in the garden bed while we were crossing the road and came back to it.” [P2]

Several of the videos showed children using the maps on the path next to a street corner. Not only were the 3D printed materials small and light enough to carry, they were also secure, inexpensive and easily replaced, so that practitioners are able to use them outdoors without worrying about the possibility of losing pieces.

6 DISCUSSION

6.1 RQ1: What are the most important requirements for tactile materials to teach street crossing concepts for people who are blind or have low vision?

Thirteen key requirements for tactile street crossing materials emerged from the requirements-gathering interviews with 11 O&M professionals and an additional four were revealed in the co-design and evaluation processes. These requirements are listed in Table 2. They can be grouped into four categories: (1) support teaching the required concepts; (2) enabling preferred teaching methods; (3) accessibility; and (4) practicalities.

6.1.1 *Teaching the required concepts.* Concept development was seen as the main use for the 3D printed intersection pieces.

“[Concept development] is what I use that sort of model for. Building that understanding of what is an intersection, how does traffic flow through it, how do traffic signs work, and I suppose also the positioning – where are you in all of this?” [P2]

Customisation and *removable pieces* were the next two most important requirements so that mapping tools can be used to demonstrate both *standard layouts* and specific intersections that represent a road layout familiar to the learner, or represent the features under discussion, such as alignment at a corner with a central pram ramp. In particular, *removable pieces* would allow the *level of detail* to be increased and new concepts to be added once the basics are learnt.

6.1.2 *Teaching method.* Teaching with children is made much easier when materials are *engaging* and enable *play-based* learning. Ideally, tactile mapping tools for O&M should also allow construction by BLV people (*client-built maps*) for independence and as a means of checking their understanding.

6.1.3 *Accessibility.* Any materials for use by people who are BLV must of course be *tactually distinct* for touch readers and have *high contrast* for people with low vision. The *level of detail* is also important, as unnecessary clutter complicates the reading process [36]. *Stability* is an important issue because tactile reading relies on movement and touch [27], meaning that individual pieces can accidentally be pushed out of place or out of reach.

6.1.4 *Practicalities.* *Portability* was another high priority identified in the requirements gathering phase. This relies on size, weight, *durability* and ease of replacement (including *affordability*) if pieces become lost. Ease of *cleaning* was another practical concern that emerged later. Finally, O&M professionals want materials that are *professional in appearance* and do not look like toys so that they can be used with adults and children alike.

6.2 RQ2: Is there a need for 3D printed O&M tools to help teach intersections?

The requirements gathering phase provided clear evidence that there are gaps in the current availability of tools suitable to teach intersections for O&M, with practitioners using a wide variety of tools but finding problems with all of them (Table 1). Further, in the co-design phase we were able to produce 3D printed O&M tools that demonstrated the value of this technology for creating bespoke accessibility solutions. 3D printing was found to offer the following advantages:

- 3D models are durable and lightweight, enabling portability for use at the client’s home, workplace, or while exploring routes.
- 3D prints look professional enough to be used with adults in public places without fear of judgement or stigma.
- 3D models are engaging and can be used for play-based learning with children
- 3D prints can be designed to suit the specific context. This meant that we were able to design materials to specifically address the key concepts for street crossings. It also means

that our models can be adjusted for a variety of street layouts and traffic conditions that differ from one region to the next.

- 3D printing is affordable and can be made locally for use by a single O&M working in isolation or in poorer regions of the world.

As further evidence for the usefulness of the 3D models, six of the seven O&M practitioners who contributed to the interviews and survey comments asked about how they could access the 3D printed materials in the future.

“What happens next then? Can I get my hands on those? When can I buy some?” [P5]

And after the 3D printed street crossing materials were supplied to Guide Dogs Victoria, they began making enquiries about how to obtain further materials and have decided to apply for a grant to purchase their own 3D printer. Meanwhile, the materials are already being integrated into practice outside the scope of the research project and a second workshop using the materials with a group of children is planned through the education department. An additional set of materials was requested for use by a regional O&M practitioner who is unable to access more expensive (usually shared) resources. This clearly demonstrates the perceived value of the materials and the 3D printing technique for creation of customised tools.

While 3D printing has the potential to supplement and enhance existing resources for teaching street crossings, we do not contend that it will replace them. For example, Tactile Town is well tested and it is both generic and with enough pieces to be used across many different places and teaching goals. The main advantages of our 1:128 street corners over Tactile Town are low cost, easy cleaning, ability to print locally rather than relying on international shipping, and inclusion of more technical components such as ramps.

6.3 RQ3: What are the design characteristics of successful 3D models for supporting O&M training?

Generalising our results to allow for the creation of other materials for teaching O&M, we recommend the following design considerations:

- 3D models should be small enough for the combined pieces to easily fit on a table top (or on a car bonnet)
- Map components should fit together so that they will not be moved about when explored tactually. We used a frame with a magnetic backing for the 1:128 street corners and connectors for the puzzle pieces. Other methods could also be considered.
- The most important features to include on 3D printed maps are shorelines, e.g. showing the different sections of the streetscape most relevant to pedestrians. Further detail should be kept to a minimum or provided as add-on/removable pieces.
- Maps should be readily customised, either through the provision of multiple components or via easy 3D design.
- If roads are wider than finger width, they should be lower than surrounding features to reflect the act of stepping down from the kerb.

- 0.5mm is the minimum height for features that must be detectable but not prominent. Important features must be taller than this.
- Keep features low, both to allow easy exploration of the whole by touch [38] and so that pieces are not bulky for portability.
- All designs must be touch-tested and feedback must be incorporated.

In terms of our particular designs, the 1:128 scale street corners were most popular.

“This is my favourite.” “Mine too.” [P2 & P14]

The O&M trainer who used the 1:128 street corners with a client said that she would “definitely” continue to use these new materials as part of her practice.

The puzzle pieces were also popular, mainly because of their small size, light weight and portability. The puzzle pieces would be used for two main purposes: as a handy reference that can be used to explain the immediate environment, and as a tool for learners to create a route, reinforcing their memory of the order of steps and allowing the instructor to evaluate their understanding.

6.4 The Participatory Design Process

In accordance with the principles of value-sensitive design [26], both user groups provided different and important contributions that reflected their needs and values. Feedback from O&M instructors related mainly to functionality and teaching goals. For example, O&M instructors defined which features were important to include (or exclude) and made suggestions to improve portability and to keep pieces in place. Feedback from touch readers related mainly to recognition by touch and the related understanding of concepts. For example, they requested braille on the street signs and suggested that the ramps should be less steep. We had not considered the need to demonstrate concepts such as the shape of street signs and the fact that they are only written on one side. This (again) demonstrates the vital importance of integrating the perspectives of people with disabilities into accessibility research [37]. In accordance with the theory that participatory design contributes to a sense of co-ownership so that projects will continue beyond the immediate research scope [34], the O&M professionals we worked with have future plans to use and develop the materials.

6.5 Limitations and Future Work

Production and evaluation of materials was severely limited by lockdown conditions due to the COVID-19 pandemic. Further roll-out and evaluation will be of value. This could be done both in a controlled research setting and organically, now that the materials are available online for free download and use.

We plan to work with accessible format producers and O&M professionals to develop a guide on how to best use the 3D printed materials. This will include how to 3D print the files, how to make adjustments for regional differences, and suggested lesson plans (and games) for using the materials with children and adults who are blind or have low vision. Touch readers should also be able to use the guide to enable independent access to the learning materials.

Location-specific needs were raised by many of the O&M practitioners in the first phase of the study. While practitioners elsewhere

will be able to modify our models for their local variations, international differences in O&M needs poses an interesting research topic for future work. Ideally, resources should be able to be shared between regions, particularly for places without the ability to create their own materials.

During the requirements gathering phase, some O&M instructors requested 3D models of complex intersections that are taught frequently, such as busy intersections near public transport in the city. These were not produced as part of the current project but offer a logical next step and could be based on our current designs.

7 CONCLUSIONS

Our research investigates the use of 3D printing to provide tools for O&M training to convey spatial information about street crossings for people who are BLV. Interviews with 11 O&M professionals revealed a surprising variety in the tools they currently use to teach street crossings, which did not fulfil all of their needs. Using 3D printing for rapid prototyping, we co-designed a range of new materials with iterative feedback from O&M professionals and touch readers to ensure that their needs were met. This participatory process has also contributed to a sense of co-ownership, with plans for use and development of the materials beyond the scope of this research. The new 3D printed models can be used to achieve learning goals and hold advantages over existing materials in terms of demonstrating key concepts, portability, engagement and professional appearance. This demonstrates the value of maker technologies for the development of specialised tools for the accessibility community. We hope the freely available library 3D printable street crossing components will contribute to the safety, independence and inclusion of BLV pedestrians.

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A FEATURES WANTED ON ACCESSIBLE MAPS OF STREET CROSSINGS

Feature	E	N
Intersection type	10	0
Ramp position and type	8	3
Traffic islands	8	2
Footpath	8	2
Zebra crossing lines	7	2
Kerb	5	2
Pedestrian crossing lines	5	2
Slip lane	5	2
Tactile Ground Surface Indicators	4	4
Traffic lanes	4	4
Nature strip	4	3
Traffic lights	4	3
Corners (sharp or curved)	3	4
Tram lines	2	4
Gutter	2	1
Landmarks	1	7
Tram stops	1	4
Parking	1	3
Shoreline	1	2
Signage	1	1
Train tracks	1	0
Bike lanes	0	4
Sloped ground	0	2
Sound shadows	0	2
Traffic speed	0	0

Table 3: Selection of features as essential (E) or nice-to-have (N) for inclusion on a 3D model of street crossings by 11 orientation and mobility (O&M) practitioners in the requirements gathering phase.

B SURVEY QUESTIONS

Please rate your current preferred mapping tool in terms of the following characteristics.

Scale: Strongly disagree, disagree, neutral, agree, disagree, or strongly disagree.

1. CONCEPTS: The materials are suitable for demonstrating the most important concepts relating to intersection layouts.
2. STANDARD LAYOUTS: The materials can be used to demonstrate the standard intersection layouts.
3. CUSTOMISATION: It is possible to show a range of customised intersection layouts.
4. DURABILITY: The materials are strong, resistant to damage and can be re-used.
5. PORTABILITY: The materials are suitable for carrying and using when out and about.
6. STABILITY: The pieces stay in place when being explored by touch.
7. TACTUALLY DISTINCT: The features are easy to feel.
8. CONTRAST: The most important features are high contrast and visually distinct.
9. PRESENTABLE: The materials look like professional O&M tools.
10. ENGAGEMENT: The materials captured the client's interest.
11. CREATION: Clients are able to construct their own maps.

C MODIFIED STANDARD USABILITY SCALE (SUS) QUESTIONS

Please rate the following statements.

Scale: Strongly disagree, disagree, neutral, agree, disagree, or strongly disagree.

1. I think I would like to use the materials frequently.
2. We found the materials to be unnecessarily complex.
3. The 3D printed materials were easy to use.
4. I think that clients would need help to use the materials.
7. I imagine that most people would learn to use the materials very quickly.
8. We found the materials are very cumbersome to use.
9. We feel confident using the materials.
10. I needed to explain a lot of things before I could use the materials with the client.

D PARTICIPANT DETAILS

Participant	Location	Role	Requirements Gathering	Design	Evaluation	Kits used or viewed	Use setting
1	SA	O&M	Yes	Yes	Yes	Puzzle pieces	Group
2	Vic	O&M	Yes	Yes	Yes	Both	Individual + Group
3	Vic	O&M	Yes	Yes	Yes	Corners	Group
4	Vic	O&M	No	No	Yes	Corners	Group
5	Vic	O&M	Yes	Yes	Yes	Both	None
6	Vic	O&M	Yes	No	Yes	Both	None
7	NSW	O&M	Yes	Yes	Yes	Both	None
8	Qld	O&M	Yes	No	No	Puzzle pieces	None
9	Vic	O&M	Yes	Yes	No	Both	None
10	SA	O&M	Yes	No	No	None	None
11	Vic	O&M	Yes	No	No	None	None
12	Vic	O&M	Yes	No	No	None	None
13	Vic	O&M	No	Yes	No	Both	None
14	Vic	O&M	No	Yes	No	Both	None
15	Vic	Touch reader	No	Yes	No	Both	None
16	Vic	Touch reader	No	Yes	No	Both	None

Table 4: Participant details across the requirements gathering, design and evaluation phases. All were located in Australia in the states of Victoria (Vic), South Australia (SA), New South Wales (NSW) and Queensland (Qld).