# THE CROSS-SENSORY GLOBE

Co-Designing a 3D Audio-Tactile Globe Prototype for Blind and Low-Vision Users to Learn Geography

UTTARA GHODKE | INCLUSIVE DESIGN | 2019

# THE CROSS-SENSORY GLOBE:

## Co-Designing a 3D Audio-Tactile Globe Prototype for Blind and Low-Vision Users to Learn Geography

Submitted to OCAD University in partial fulfillment of the requirements for the degree of Master of Design in Inclusive Design
Toronto, Ontario, Canada, April 2019

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Uttara Ghodke

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# ABSTRACT

This MRP presents a co-operatively and iteratively designed 3D audio-tactile globe that enables blind and low-vision users to perceive geo-spatial information. Blind and low-vision users rely on learning aids such as 2D-tactile graphics, braille maps and 3D models to learn about geography. I employed co-design as an approach to prototype and evaluate four different iterations of a cross-sensory globe that uses 3D detachable continents to provide geo-spatial haptic information in combination with audio labels. Informed by my co-design and evaluation, I discuss cross-sensory educational aids as an alternative to visually-oriented globes. My findings reveal affordances of 3D-tactile models for conveying concrete features of the Earth (such as varying elevations of landforms) and audio labels for conveying abstract categories about the Earth (such as continent names). I highlight the advantages of longitudinal participatory design that includes the lived experiences and DIY innovations of blind and low-vision users and makers.

# PUBLICATIONS

Some of the materials, ideas and figures in this thesis has previously appeared in the following:

**Ghodke, U., Yusim, L., Somanath, S., Coppin, P. (2019). The Cross-Sensory Globe: Participatory Design of a 3D Audio-Tactile Globe Prototype for Blind and Low-Vision Users to Learn Geography. Proceedings of the 2018 Designing Interactive Systems Conference-DIS 19. doi.org:10.1145/3322276.332368**

# CONTENTS

# LIST OF FIGURES

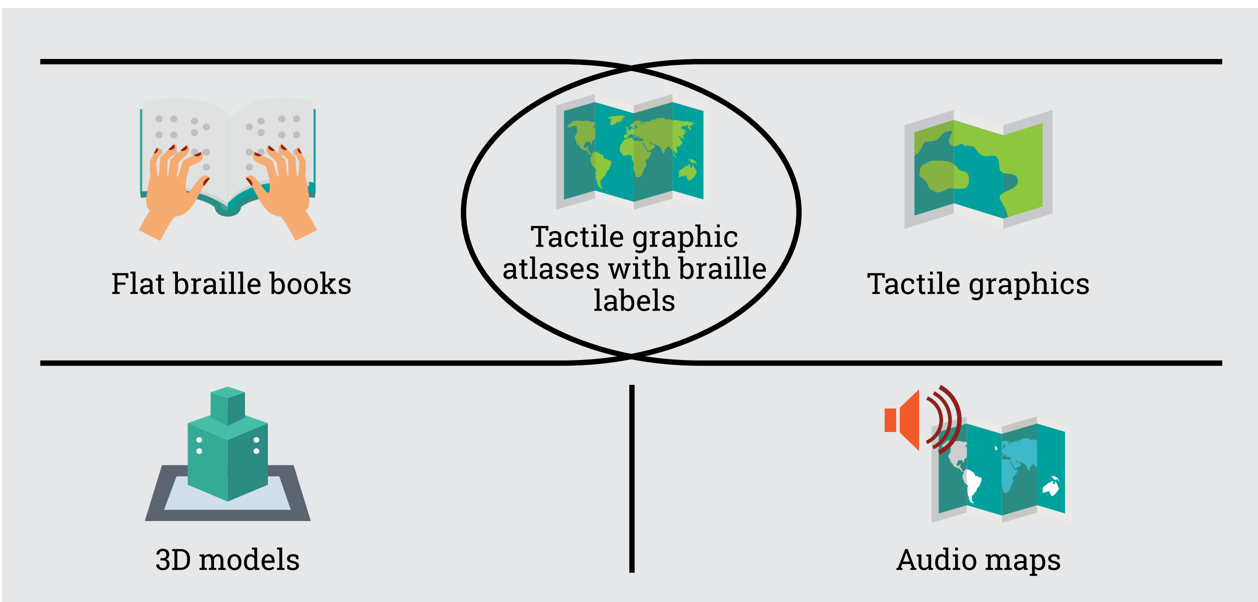
# 1. PREFACE



## SITUATION

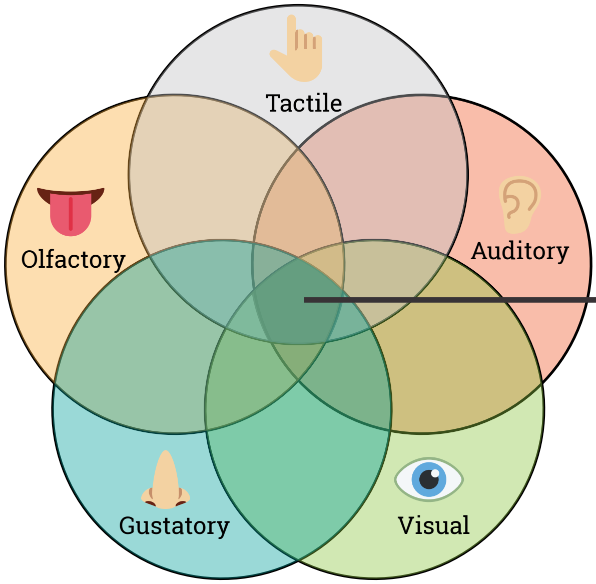
How do blind and low-vision learners perceive

**geo-spatial information?**

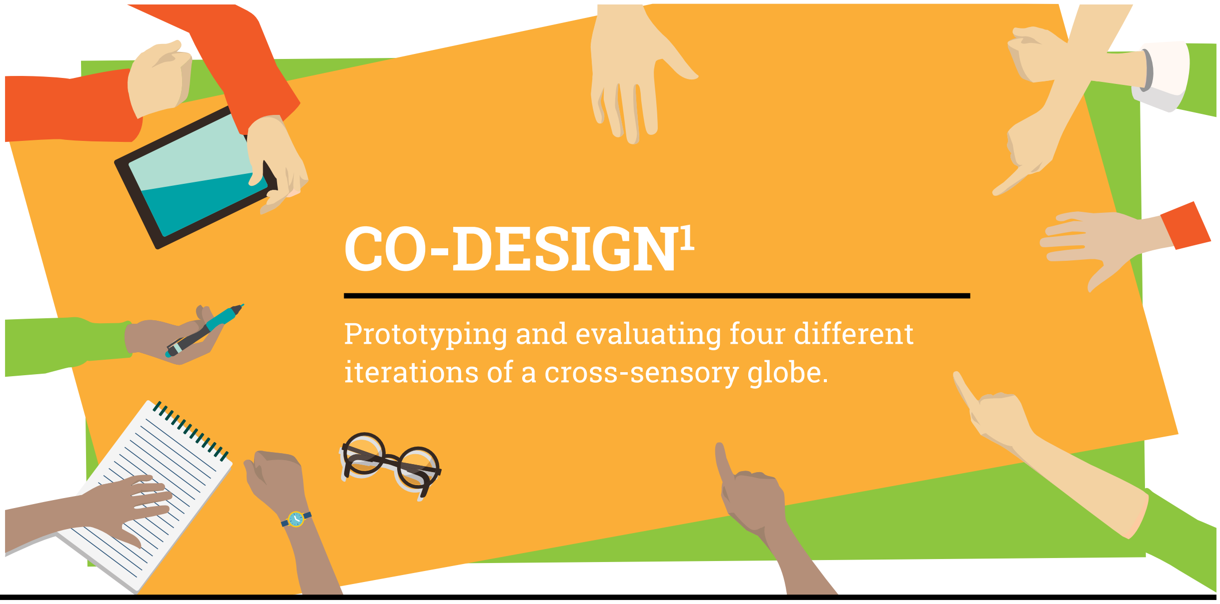


## OVERARCHING GOAL

### BUILD CROSS-SENSORY LEARNING AIDS




## METHODOLOGY




**Keywords:** cross-sensory; non-visual; visual impairment; co-design; 3D tactile; participatory design; blind; inclusive design; globe; 3D globe

1.Co-design (in its origins also called co-operative or participatory design) is an approach to designing products by successfully involving the stakeholders, designers, researchers and end-users in the design process in order to help ensure that the end product meets the needs of its intended user base [59,67].

**A** Lessons learned by a research team which included a learner facing complete blindness.

**B** Four iterations of cross-sensory audio-tactile globe.

1. **Iteration 1:** 3D tangible topography.
2. **Iteration 2:** Removable tangible 3D continent pieces.
3. **Iteration 3:** Magnets and reels to retract back to the globe.
4. **Iteration 4:** PenFriend audio to label continent, countries and cities.

**C** Long-term prototyping efforts showed that using a cross-sensory globe model can help convey Earth's geo-spatial information to blind and low-vision learners.

## 3D TACTILE MODEL

- Varying elevations
- Shape of continents
- Distances between continents
- Size of landmasses


## AUDIO LABELS

- Country names
- Continent names
- Water bodies

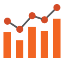
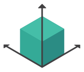
**D** The study also highlights the advantages of using a longitudinal (long-term) co-design and prototyping process that includes the lived experiences and DIY innovations of blind and low-vision learners.

# 2. INTRODUCTION



## PROBLEM SPACE

### CONVENTIONAL LEARNING AND TEACHING TOOLS

-  Textbooks
-  Diagrams
-  Graphs
-  Maps
-  Models

Many blind and low-vision learners do not have access to all of these conventional learning aids. Specifically, when the learner faces a visual impairment but the subject is inherently spatial and tangible (such as geography), traditional aids provide limited information [56].

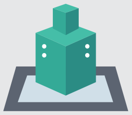
### ALTERNATIVE LEARNING AIDS

[12, 31, 48]

Tactile graphics

Tactile graphic atlas with braille labels

Flat braille maps



3D models

Audio maps

However, these alternative learning aids are expensive, less readily available, and pose several challenges for the learner, making them less useful [58, 93].

## MOST COMMON ALTERNATIVE LEARNING AIDS

### BRAILLE MAPS COMBINED WITH RAISED-LINE GRAPHICS (TACTILE GRAPHICS)

These are used by blind and low-vision learners to build a mental model of geography [70, 86].

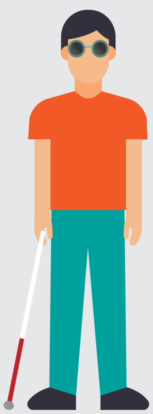
## BUT BRAILLE MAPS PRESENT A NUMBER OF PROBLEMS

### 1. LOW BRAILLE LITERACY

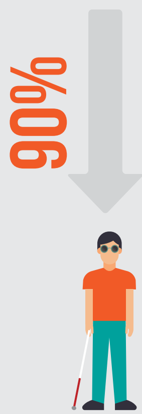
According to the National Federation for the Blind, in 2010 fewer than 10% of the 1.3 million people who are legally blind in America are braille readers [13, 59]. Following this, the American Printing House of the Blind issued a report stating that, in 2016 only 8.2% out of 62,528 blind students in the US used braille as their primary communication form [4, 13].

According to the World Health Organization (WHO) there are 45 million people who are blind or low-vision worldwide, and only 10% of them can read braille [13, 84, 91].

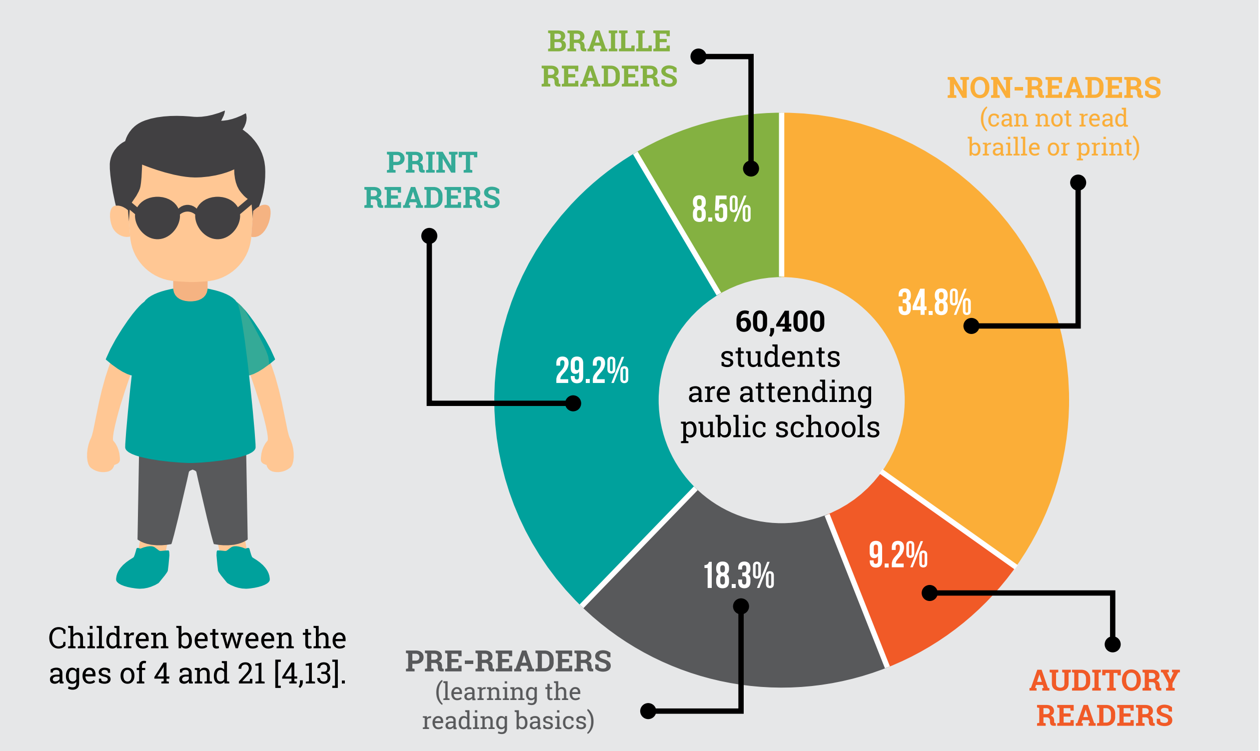
World Health Organization



**45 MILLION**
blind and low-vision people worldwide.

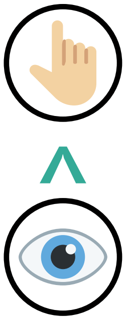



**10%**
of blind and low-vision population is braille literate.




## 2. LESS DETAILED PERCEPTION

Tactile perception provided by 2D graphics and braille maps is much less detailed than visual perception because of the lower capacity of tactile memory [49, 92]. Yoshida. and her research team found smaller memory during tactile exploration compared with visual exploration. Their experiment shows that, when humans are touching with the fingertips, that is all that is held in memory. Unlike visual perception, haptic system is almost amnesic when operating outside of the fingertips [92].



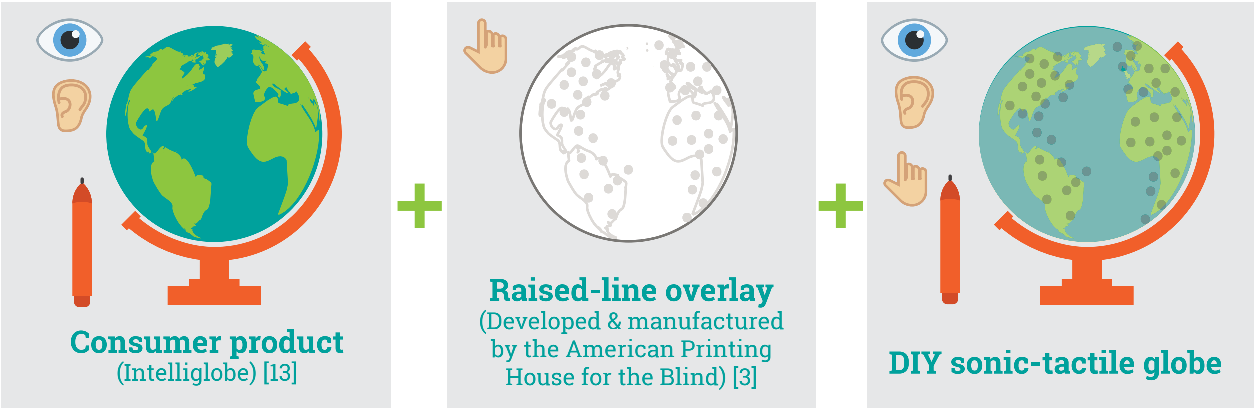
## 3. TACTILE MAPS ARE BIG

Braille cells are standardized and cannot be changed, unlike letter forms, which can easily be adjusted [23, 30, 34, 46].


All of these limitations prevent blind and low-vision learners from experiencing the full potential of maps and models.

# RESEARCH MOTIVATION

The research is primarily motivated by gaining direct insights about previous challenges and strengths through our exposure to a homemade DIY sonic-tactile globe built by one of our participants, P1. In response to several limitations of braille-based and 2D raised-line maps, P1 developed a globe combining a consumer product (Intelliglobe) and a raised-line overlay (developed and manufactured by the American Printing House for the Blind).



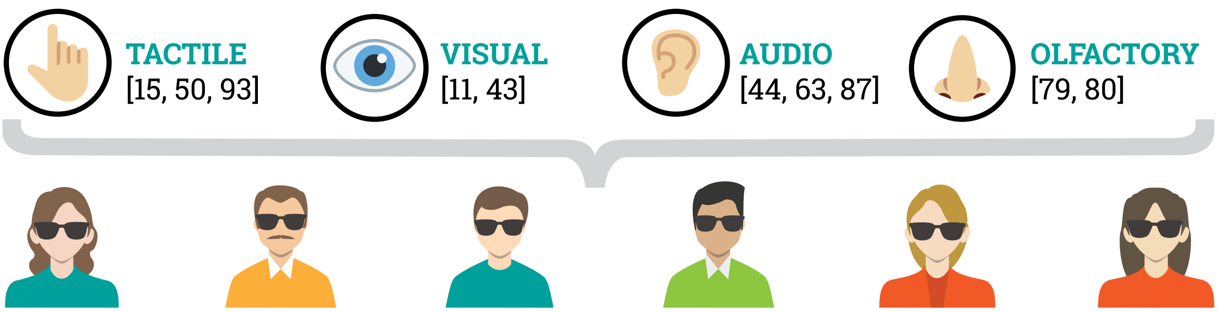

While more useful than traditional globes, the above globe still presents certain challenges. Such as:

- Difficult to distinguish the shapes and sizes of landmasses because of its very subtle and low relief.
- Time-consuming to perform tasks such as locating specific countries.

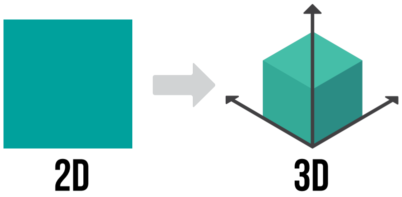
One of the key strengths of P1's globe was the use of interactive audio labels and wireless audio pen. The research team also simultaneously focused on retaining this existing strength of P1's audio-tactile globe.

# INSPIRATION FROM LITERATURE

To address some of these challenges, researchers have explored using a combination of modalities including tactile, audio, olfactory and cross-modality to build accessible maps and models for blind and low-vision learners.

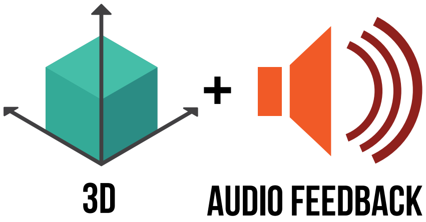


Research shows that converting 2D tactile graphics to 3D models is beneficial in tactile visualization, especially for blind and low-vision individuals [16, 83]. Converting 2D to 3D allows for the following advantages:




- Direct representation of three-dimensional object.
- Comparison of different objects in relation to each other.
- Easy and accurate representation of shapes and sizes.

When augmented with audio feedback, 3D maps and models have a wider effect on the accurate display of geographical information [14, 54, 60, 88, 89]. Some of such advantages are as follows:




- Braille labels occupy space on maps and models.
- In order to fit braille in limited space, braille legends are used. But legends add cognitive load and shift of attention.
- Once braille is printed, it can only be reprinted in order to be updates. Unlike braille, audio labels can be updated and stored electronically.
- Many blind and low-vision learners are not braille literate.

## RESEARCH QUESTIONS

1. How might we prototype a 3D audio-tactile globe which can aid blind and low-vision learners to explore the relative distances between landmasses, understand Earth's relief and physical features, and conceptualize abstract shapes of the landmasses?

2. What benefits and limitations do 3D audio-tactile globes have compared to 2D raised-line audio-tactile globes?

## ADVANTAGES OF LONGITUDINAL CO-DESIGN METHODOLOGY

**1.** Longitudinally co-designing[2] 3D audio-tactile globe that will help blind and low-vision users learn about topics related to geography.

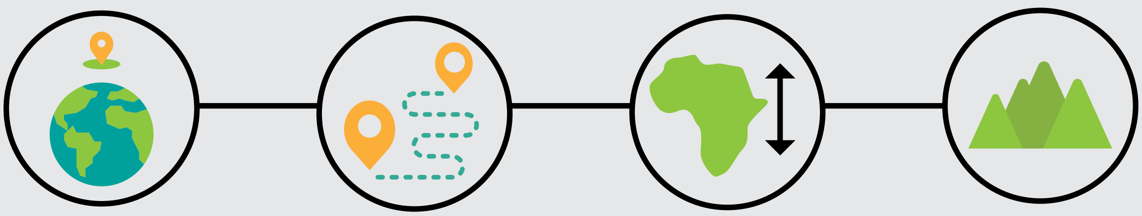
## CASE STUDY OF TWO DIFFERENT ASSISTIVE CROSS-SENSORY GLOBES

**2.** Case study of two different assistive cross-sensory globes
Reviewing the creation of two assistive cross-sensory globes using a longitudinal design approach:

- 2D raised-line combined with audio labels.
- 3D tactile combined with audio labels.

## CROSS-SENSORY AUDIO-TACTILE GLOBE PROTOTYPE

**3.** Cross-sensory globe prototype that can help P1 and other blind and low-vision students learn about the Earth's geo-spatial information including:



**Locations and shapes of continents**

**Distances between continents**

**Sizes of landmasses**

**Relief features**

**2**.Long-term co-design or longitudinal co-design: Interacting with the same participant repeatedly but observing the use of different prototypes each time base.

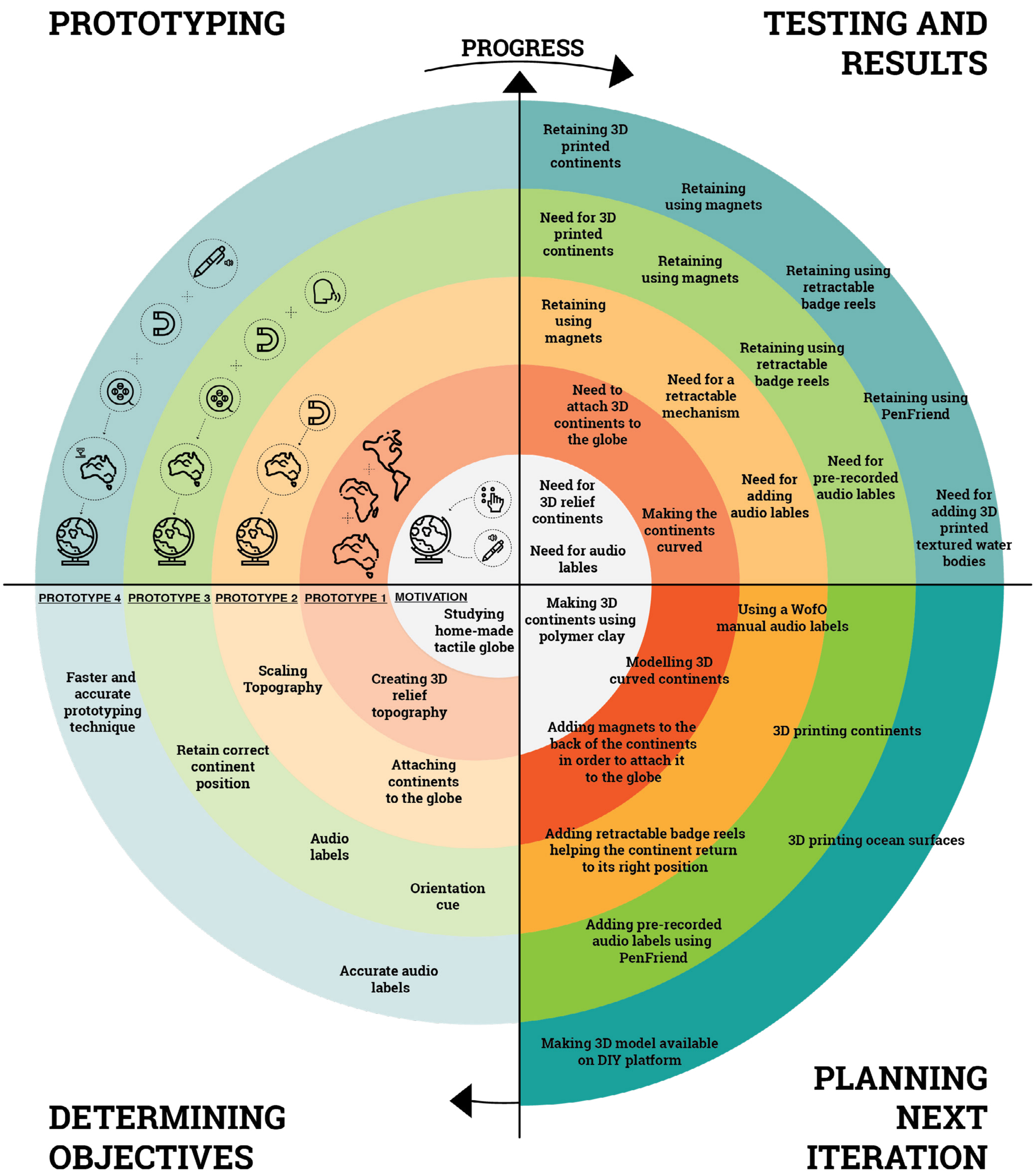
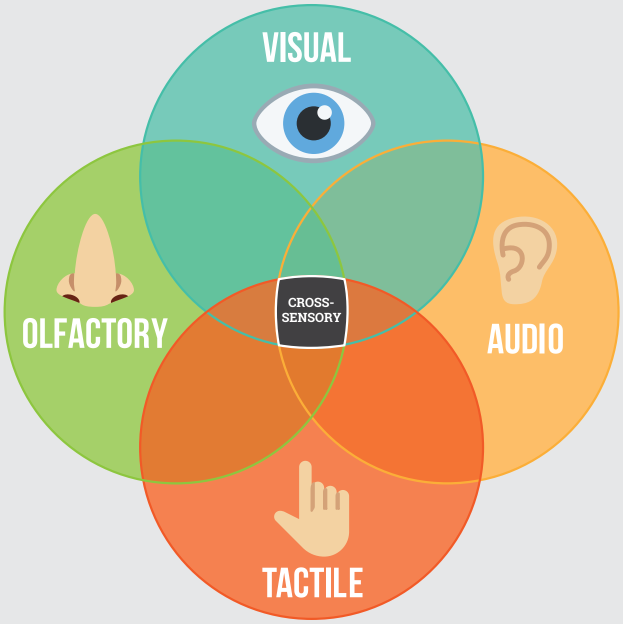



**Figure 1:** Design spiral visualizing the entire design process. The investigation began with building on the insights gathered from P1's homemade audio-tactile globe. Using co-design we built and evaluated multiple prototypes alongside P1 over a span of 10 months. Following a longitudinal (long-term) approach helped improve P1's user experience by addressing the challenges and retaining the strengths of his globe in our iterations.

# 3. LITERATURE REVIEW

| Tactile Graphics | 3D Tactile Maps & Models | Tangible user interfaces | Interactive Audio Labels | Olfactory Maps & Models | Cross-Sensory Maps & Models |

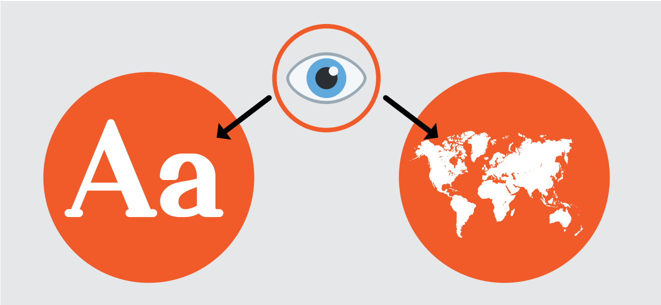
Various literature that focuses on the use of tactile [3, 9, 22, 39, 83], audio [14, 27, 86], olfactory [79, 80] and cross-sensory (multiple-modality) cues for geographical learning aids.



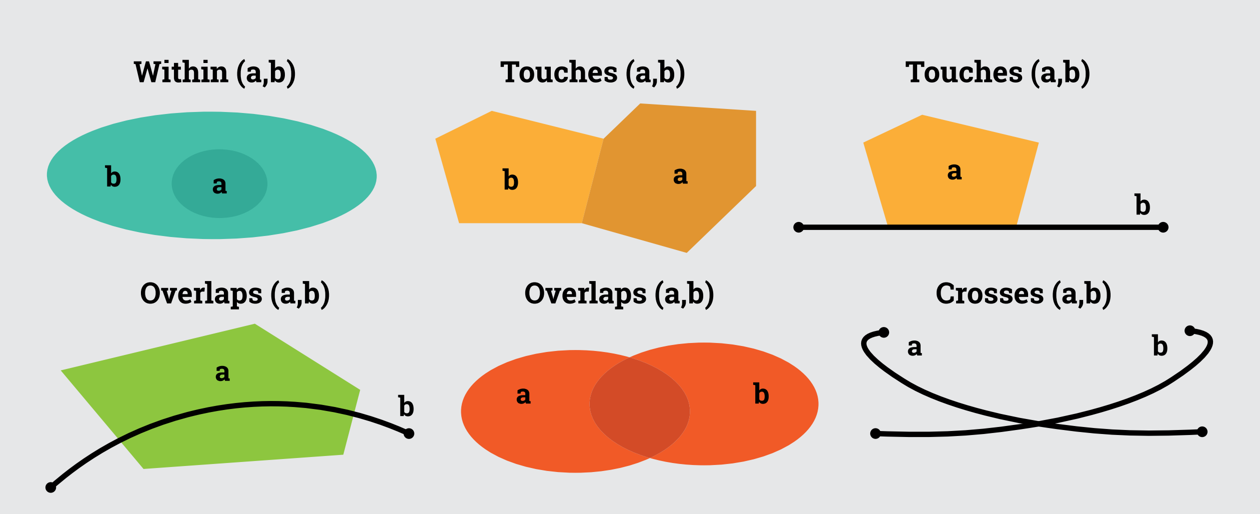

## TACTILE GRAPHICS

### WHERE ARE TACTILE GRAPHICS USED?

Tactile graphics, also known as 2D raised-line graphics are used to replace written text and visual diagrams [18].



## TACTILE GRAPHICS ARE USED TO COMMUNICATE SPATIAL RELATIONSHIPS [24]

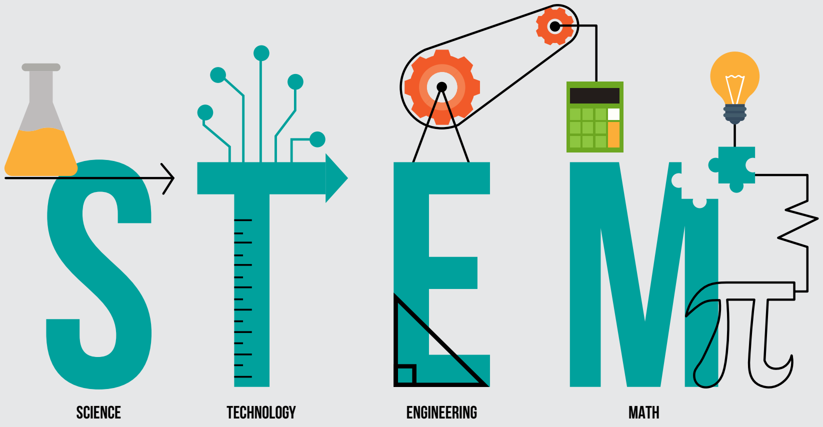



## PRODUCTION METHODS OF TACTILE GRAPHICS

| Swell Touch Paper | Metal Embossing | Thermoforming |
|---|---|---|
| (Special paper onto which images can be printed to create tactile diagrams [70, 81, 82]) | (Stamping/embossing process for producing raised or sunken designs or relief in sheet metal [26]) | (Moulding process of plastic sheets by heating it to a pliable forming temperature, forming to a specific shape in a mold, and trimming to create a usable product [3, 81]) |

## WHERE ARE TACTILE GRAPHICS USED?

Tactile graphics are mainly used in STEM education for blind and low-vision users. Raised-line graphics are typically used in STEM education for blind learners [4, 66, 70, 74, 75].

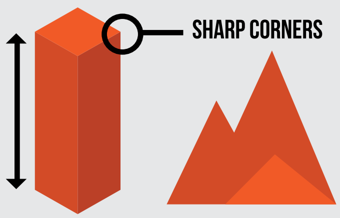


## WHERE ARE TACTILE GRAPHIC MAPS USED?

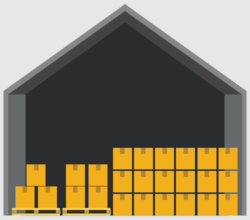
Orientation and Mobility (O&M) focuses on instructing individuals who are blind or visually impaired with safe and effective travel through their environment. A tactile graphic map can assist blind and low-vision learners with the layout of a built environment, e.g. a museum, or a natural environment, e.g. a public garden. The use of such maps in O&M training allows the users to build a mental model of the environment while still safe indoors [4, 64, 71].

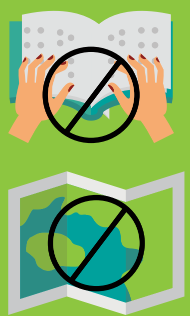
## LIMITATIONS OF TACTILE GRAPHICS

Cannot create tall and sharp corners.




Requires large storage space for manufacturing moulds used to make the tactile graphics .



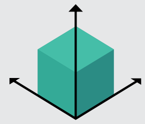


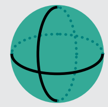
### WHY DOES THIS WORK NOT INCLUDE TACTILE GRAPHIC AND BRAILLE?

+ Previous limitations observed with braille-based labels and legends.
+ Production and storage limitations of tactile graphics.
+ Supporting this, Zeng and Weber also studied these advantages and challenges faced with tactile graphics and reported that low-cost paper-based tactile maps do not meet the increased need of blind and low-vision individuals [93].

## WHERE ARE 3D MAPS AND MODELS USED?

Several researchers have explored adding sonification to two-dimensional tactile graphics and surfaces such as screens and tactile drawing pads [88]. But these devices fail to accurately represent spatial data (height, elevation, depth and shapes) [31, 65]. Here, 3D maps and models offer easy and accurate representation of shapes, sizes and comparison of different objects in relation to each other [17, 35, 45, 47].

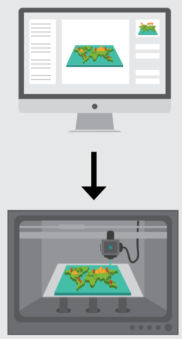




## PRODUCTION METHODS OF 3D MAPS AND MODELS.

Pre-existing and handmade 3D models are sometimes used to show inherent three-dimensionality. These methods are much less common because they are time-consuming and have a high cost of production [93].

With the invention of 3D printers, the cost of 3D models is in line with tactile graphics [10, 67]. 3D printing, also known as additive manufacturing used 3D digital files to creative three-dimensional objects using additive processes. In 3D printing, an object is created by laying down successive layers of material. 3D printing enables the production of custom and complex functional shapes using less material than traditional manufacturing methods [10, 90].



## ADVANTAGES OF 3D PRINTED MAPS AND MODELS

| | | |
|---|---|---|
| Less Expensive. | Easily available. | Can depict relative heights and depths. |
| Design file can be distributed and stored electronically. | Quick and less time-consuming in production. | Scaled and accurate representation of 3D objects. |

[10]

## LITERATURE SUPPORTING STEM EDUCATION USING 3D MODELS

Kim and Yeh used 3D-printed and laser-cut tactile pictures as an inclusive tool for blind and low-vision children. These movable pictures allow visually impaired students to understand spatial concepts such as in/out, up/down and high/low [45].

Michele Hu found that 3D-printed graphs and bar charts are more effective in conveying statistical data than 2D tactile graphs. She used a co-design methodology which included one blind participant and two teachers [39].

Agarwal used 3D-printed mapping to create DNA molecules structures for better tactile exploration for blind and low-vision students [1].

Samantha McDonald and Alejo Navarrete explored the use of laser cutting and 3D printing to make graphic design accessible for visually impaired learners [9, 55].

## USING 3D MODELS FOR GEOGRAPHY RELATED TOPICS

Brandon Taylor and his research team developed a web tool to allow  visually impaired users to specify locations and customize 3D map models for production with 3D printers [83].

Horowitz and Schultz used 3D-printed digital terrain models in geoscience data visualization. Although this research was not focused on blind users, the inclusive 3D designs can also be used by marginalized learners [38].

For more than a century, the Perkins Institution for the Blind are using three-dimensional maps and models for conveying geo-spatial information to blind and low-vision individuals [62]

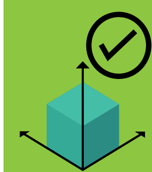
## LITERATURE ALSO STRONGLY SUPPORTS THE USE OF 3D RELIEF GLOBES

Steven Perston Ruggles, a man who was blind, built a 13-foot large tactile relief globe for the Perkins School of the Blind. Prior to the 1830s, tactile maps were usually custom-made for a few individuals who were blind. This globe is made from over 600 pieces of wood, is painted in bright colors and supported by a wooden frame that includes longitude and latitude markers in braille. The globe was built to allow Perkins students to tactilely learn about the Earth's geography. Country borders and natural landmarks like mountains and rivers are raised so they can be identified by touch [62]. Today, this globe is on display in the Perkins Museum. It is considered probably the first of its kind in America. It has twice been restored, once in 1940 and again in 2004 and is considered a major milestone in map-making [62]. Made by George Philip & Son Ltd the Philips World relief globe is 440 mm tall including  the base. This is a ceramic globe made in 1952 and also currently places at the Perkins School for the Blind [62].

Designed in 1786, the terrestrial & celestial globe was commissioned from Edme Mentelle by King Louis XVI for the Dauphin's education. The first globe, moving & in relief, is inserted inside 2 hemispheric segments: the upper section shows the Old World & the lower one the New World. Mentelle's globe demonstrates how advanced these teaching tools were for their time [85].

Other researchers and institutes have developed various versions of 3D relif globes for blind and low-vision education [35, 57, 78].

**Figure 1:** Tunley Braille globe made using metal embossing [36].



## WHY DOES THIS WORK INCLUDE THREE-DIMENSIONAL REPRESENTATION?

+ Literature strongly supports the use of 3D for better representation of spatial information.
+ This project also includes 3D printing because of the several advantages observed with this production method.

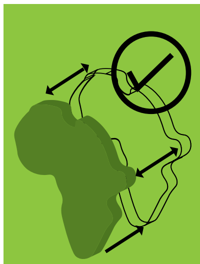
This MRP also studies the broad literature available in the tangible interfaces (graspable interfaces) domain. In a tangible user interface, the user interacts with digital information through the physical environment. Unlike graphical interfaces, a tangible interface represents the input in the physical world and makes the digital or graphical information directly graspable. One direct application of tangible interface in perceiving geo-spatial information is facilitating better user experience by directly picking up the continents or countries from a map or model so that physical interaction occurs between the user and the interface itself.

Numerous researchers have investigated the benefits of using tangible objects and interfaces for facilitating better learning among blind and low vision individuals. The Perkins School for the Blind proposed the use of tangible 3D removable pieces specifically for teaching geography to blind and low-vision learners. They have created various different versions of puzzle maps with pieces representing shapes of political boundaries of countries and continents [62].

Systems such as the 'Bricks' by Fitzmaurice, Ishii and Buxton introduce the concept of graspable user interfaces that allow direct control of electronic or virtual objects through physical handles. Their study sheds light on the many benefits of graspable user interfaces compared to Graphical User interfaces. Some of these include: encouraging two handed interactions, facilitating interactions by making interface elements more "direct" and more "manipulable" by using physical artifacts, richer understanding of spatial relationships, and allowing multi-person collaboration [29].

To study the benefits of using 3D models integrated with audio, Shi and Lawson conducted two studies with Teachers of the Visually Impaired. Their apparatus included 3D printed open source models and other prototyping materials like play-dough, stickers and markers. Participants were asked to use the prototyping tools to modify the 3D models based on how the user would interact with them. Their findings show that blind and low-vision students became familiar with tangible 3D models and audio instructions quickly and used them independently. Their studies reveal that cross-sensory tangible aids like these provide a much more interactive and customizable learning experience. This is because, they allow students to gain more knowledge from auditory and visual information which is not available through traditional teaching aids [75].

Lastly, researchers like Marshell and Schneider also study how tangible interface learning also facilitates various kinds of collaborative activities, physical interactions, and external representations. Studies reveal that the main impact of tangible interfaces is to promote constructive behavior (exploration, collaboration, and playfulness of the task) [51, 72].



## WHY DOES THIS WORK INCLUDE TANGIBLE CONTINENT PIECES?

+ Inspired from various advantages of tangible interfaces (graspable interfaces) compared to graphical interfaces.
+ To facilitate direct physical interactions and exploration of geo-spatial information and spatial relationships.
+ To provide much more interactive and customizable user experience.

# INTERACTIVE AUDIO LABELS

Literature shows that building on the strengths of audio labels, many researchers have investigated the addition of audio labels to tactile maps and models to replace braille and other visual labeling systems [27].

Landau and Gourgey have developed a "Talking Tactile Tablet" to provide feedback from interactive graphics [47].

Baker and others have explored placing QR codes to trigger audio feedback using smartphones [7].

With the use of a laser-cut tactile apparatus, Giraud found improved short term recall of space with the use of audio labels as compared to a braille legend [33].

APH has also developed country maps with interactive labels for the blind. The pen serves as a personal "tour guide" that gives the reader information about each location visited on the map via multiple layers of audio recordings [42].

Following this, the MIGS (Minimal Geographic Information System) created by Brittell, Young and Lobben uses auditory display to covey spatial data to blind and low-vision users [14].

### WHY DOES THIS WORK INCLUDE INTERACTIVE AUDIO LABELS?

+ Interactive audio labels are used because of the several advantages observed over braille labels.
+ The use of audio labels allowed the globe to easily include country and continent labels without occupying any space.

# OLFACTORY MAPS AND MODELS

Sorokowska and Karwowski conducted an experiment to test if blind people can use olfactory abilities to replace vision. They found no difference in scent recognition by blind in several olfactory-related memory tasks [80].

Kate McLean has been doing significant work in developing Smell Maps of various cities: Amsterdam, New York, Paris and many more. Her work primarily focuses on olfactory map experiences and is not specially targeted towards the blind and low-vision population [79].

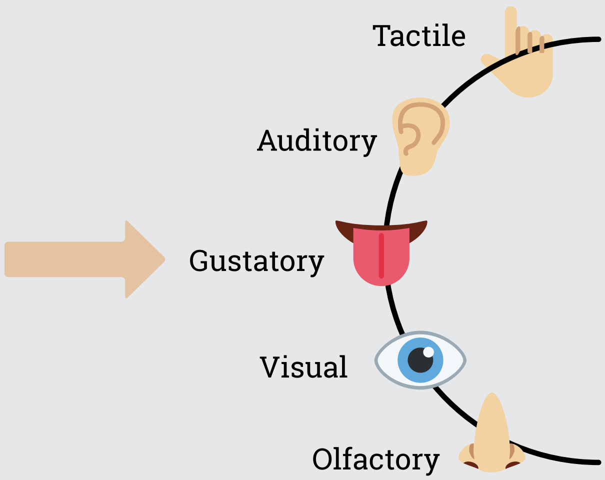
### WHY DOES THIS WORK NOT INCLUDE SMELL?

+ No need was observed for olfactory modality with our participants.
+ Users may have allergies or sensitivities to strong scents.

## WHAT ARE CROSS-SENSORY LEARNING AIDS?

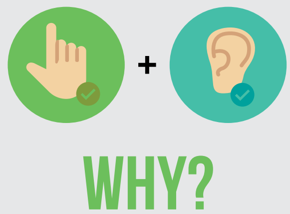
Cross-sensory design involves two or more different sensory modalities for information representation.

**INFORMATION**




## WHY CROSS-SENSORY?

Many researchers have developed cross-sensory learning aids which use audio-tactile to replace the visual modality for blind and low-vision users. According to Manduchi and Kurniawan, an audio-tactile sensory substitution allows one or more of the remaining spatial senses to replace or complement vision [51]. Our work primarily falls into the audio-tactile domain of cross-sensory learning tools. For geographic information, the most common combination of perceptual modes literature supports is cross-sensory audio-tactile representation [2, 4, 24, 25, 58, 68].




Holloway, Marriott and Butler propose using 3D audio-tactile maps in the place of 2D tactile graphics based on a detailed study they conducted with 16 blind participants. Augmenting 3D-printed models with interactive audio labels, they propose a set of guidelines for effective 3D audio-tactile map making for blind and low-vision individuals [37].

Brule and Perrios researched the advantages of using co-design with blind and low-vision users to develop multi-sensory interactive maps. Their findings outline the need for audio-tactile tools and methods to help children to acquire spatial skills [17].

Tac-tiles: Multi-modal Pie Charts for Visually Impaired Users was developed by Wall and Brewster. It represents geographic information with the use of a graphics tablet augmented with a tangible overlay tile with dynamic pin-array speech/audio feedback [88].

The Perkins School for the Blind is also currently investigating into the advantages of 3D audio-tactile maps by developing a 3D touch-responsive map. When pressure from the user's fingers is sensed through the conductive paint on the miniature buildings, audio feedback is produced [62].

# 4. STUDYING THE P1'S AUDIO-TACTILE GLOBE

Motivation of the research | The interview with P1 | P1's motivation to build the Globe | Building the globe | Insights gathered from P1's globe

## MOTIVATION OF THE RESEARCH

PARTICIPANT 1

Developing cross-sensory learning aids for blind and low-vision individuals has been primary the goal of our research team. While conducting a co-design session for one such research topic, we met our primary research participant, who we refer to here as P1. P1 is an adult male from Toronto, Canada, who faces complete blindness. P1's experience using maps and models has been entirely non-visual. During our first interaction with P1, he revealed that he owns a variety of braille books and tactile graphic worlds maps. He mentioned  the difficulties he encounters due to limitations of standard audio maps and tactile raised-line maps.

## THE INTERVIEW WITH P1

Over a three-hour session, we conducted a semi-structured interview with P1 while he demonstrated his globe.

### INTERVIEW QUESTIONS

+ How was the globe built?
+ What was P1's motivation to build the globe?
+ Navigating spatial relationships?
+ Identifying countries and continents?
+ Importance of 3D representation?
+ Why is there a need for separate continent pieces?

## P1'S MOTIVATION TO BUILD THE GLOBE

> I wanted to be able to do things like figure out where did Columbus come from [P1].

> I basically wanted to have a picture of the world we live in [P1].

In response to several limitations of braille-based 2D world maps, P1 developed his own custom globe. P1 was motivated to learn more about the location of various countries, oceans and their shapes. P1 also mentioned the desire to know more about the places his friends reside in.

## BUILDING THE GLOBE

### STEP 1

#### INTELLIGLOBE + INTELLIPEN

- Consumer product (not intended for blind users)
- 12" Diameter
- Reads out audio information about geography and relevant facts through the touch of a wireless Intellipen

### STEP 2

#### APH TACTILE OVERLAY

- Customized product for blind and low-vision users
- Provides tactile representations of latitude, longitude and land elevations
- Countries labeled in Braille using abbreviations (e.g. ITALY=ITA)

### STEP 3

#### INTELLIGLOBE + APH OVERLAY

- Intelliglobe provides audio feedback
- APH overlay provides tactile feedback

**Figure 2:** A customized interactive audio-tactile earth globe made by P1, (a) Intelliglobe with APH tactile overlay, (b) Using the wireless touch Intellipen to identify countries.

**Figure 3:** Close-up view of APH overlay with Intellipen.

**Figure 4:** P1 using self-made interactive audio-tactile globe.

# INSIGHTS GATHERED FROM P1'S GLOBE

## A. MOTIVATION TO COMBINE SOUND AND TACTILE

Having no tactile labels on the Intelliglobe was a leading motivation for P1's DIY combination of a tactile and sonic globe. The Intelliglobe includes one key problem: Unlike the tactile overlay, it conveyed abstract categories in the form of audio labels. However, it was completely smooth. There was no sonic or tactile information to convey the types of concrete structures represented by outlines and shading on a visually-oriented globe.

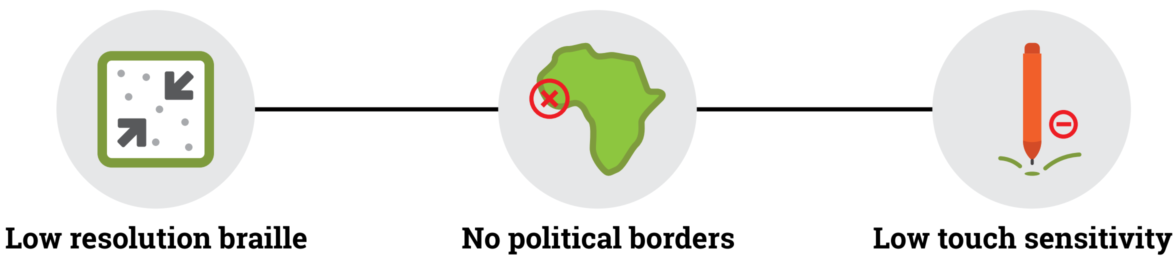
> "There are no labels on this overlay so I don't know what anything actually is [P1]."

Attaching the tactile overlay to the Intelliglobe was a big improvement because it enabled P1 to access highly symbolic information (the categories assigned to concrete structures of the Earth) such as country names via audio labels. This counteracted the shortcoming of the tactile overlay, that it included only iconic representation but no symbolic representations. At the same time, this also counteracted the major weakness of the Intelliglobe, by adding highly iconic representations (information about concrete structures of the Earth such as landforms) to the Intelliglobe.

---

## B. NAVIGATION AND SPATIAL RELATIONSHIPS

Navigating various land masses was time-consuming due to the low spatial resolution of the braille overlay and a lack of political borders. In conversations with P1 we learned that since the Intelliglobe and Intellipen were not designed to be used with the tactile overlay, the pen can have some issues with registering the locational information through the overlay. This caused P1 to have to press down multiple times at the same location to get the sonic label, causing confusion about where the pen is on the globe.




> "(Takes 43 seconds to find Canada) It takes me a long time, but it's really the information I never had before [P1]."

## C. IDENTIFYING INFORMATION ABOUT COUNTRIES AND CONTINENTS

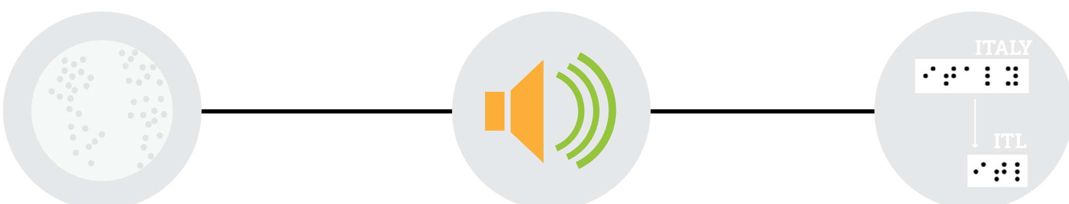
While the APH tactile overlay provides relevant shape and size using textures, this was not prominent enough to identify countries and continents. P1 also mentioned that it was almost impossible to recognize the countries without audio labels.

> I play around with it now and then, when I am talking to a person on the Internet from a certain country and I want to find it. I find it, and I now have the sense that [points to Central America] this is Central America, so I am getting an idea of how our continents look [P1].

> If you tap on an ocean it will tell you which ocean it is. What it doesn't give is the shape. Just knowing something is an ocean isn't enough information for me. I need the shape and the size relative to other things [P1].

Braille abbreviations are used as country labels which makes it more tasking to find countries (eg. ITALY=ITA)

> You can see on these maps they made an attempt to label it but braille is so big that this says PAK. If you are kind of familiar you can tell this is Pakistan. But if its a map you are not that familiar with then braille means you have to have a legend somewhere and you have to look things up and it becomes tedious, and you have to keep one hand on one spot and find the thing on the legend with the other hand [P1].



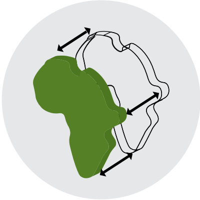

**Subtle tactile overlay** | **Absolute need for audio labels** | **Braille abbreviations are not useful**

# D. IDENTIFYING INFORMATION ABOUT COUNTRIES AND CONTINENTS

Over a century ago, the Perkins School for the Blind also supported the need to have tangible 3D removable pieces to teach blind students shapes of continents and countries [P1].

> I think if the continents could come out that would be pretty cool, because it's not always easy to decide where one continent finishes and one starts. I did once have a puzzle, designed for kids that was the US, and all the states could be pulled out. I had some trouble labeling them but the idea is nice because when you hold it in your hand you get the shape [P1].

Having removable continent pieces would make it much easier to understand the boundaries of the continents since haptic and tangible exploration affords a quicker and more complete perception of continent shapes.



# E. IDENTIFYING INFORMATION ABOUT COUNTRIES AND CONTINENTS

P1 also spoke about some of the shortcomings of raised-line graphics in terms of how much detail can be communicated with changes in texture.

> What I have seen sometimes texture is not as easy to distinguish with touch as it is visually. Also, braille maps definitely lose a lot of information. The only advantage is they can be so much bigger. I think if the continents could come out that would be pretty cool, because it's not always easy to decide where one continent finishes and one starts. I did once have a puzzle, designed for kids that was the US, and all the states could be pulled out. I had some trouble labeling them but the idea is nice because when you hold it in your hand you get the shape [P1].

The subtle textures of the overlay used to represent the change in topography lacked detail. Similar to what we found in the literature, one observation the research team made during this session was that raised-lines surface maps may not be as effective as a full 3D model. This was because it was essential to use genuine GIS scaled topography to depict land elevations.

# 5. PROTOTYPING

Prototype 1 | Prototype 2 | Prototype 3 | Prototype 4

Inspired from literature and insights gathered from studying P1's globe, the research team (4 researchers + 1 participant) used a series of co-design sessions to begin developing a 3D prototype for a tactile globe. Our goal was to address the challenges that P1 identified in their globe while also retaining the strengths (audio labels) of their prototype globe. The procedure for this study consisted of semi-structured interviews and weekly co-design sessions to iterate on our prototypes with P1. We recorded all the sessions for posterior qualitative data analysis.

## PROTOTYPE 1

### AIM OF PROTOTYPE 1

- Showing much more realistic change in topography using 3D modeling techniques.

### MATERIALS USED FOR PROTOTYPE 1

#### 2D PRINTED COUNTRY MAPS

- Flat printed continent maps were used as a base for prototyping.
- The maps were printed to the scale of a 12" globe.

#### 12" EARTH GLOBE

- Consumer product.
- Hollow interior
- Average size available for desk globes.

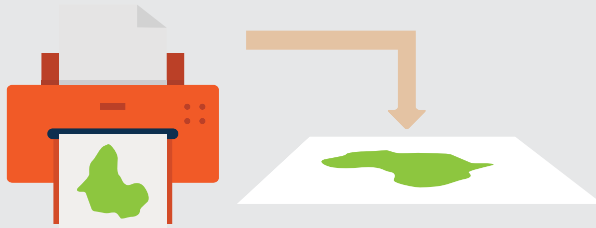
#### EASY BAKE POLYMER CLAY

- Easy bake polymer clay was used for hand modeling.
- Inexpensive and easily available.
- Flexible and easy-molding properties for making reliefs.

## PROTOTYPING PROCESS

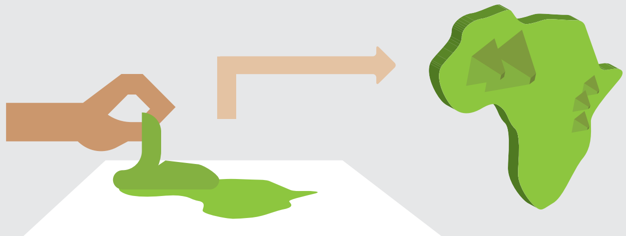
**STEP 1**

**Printing 2D maps.**



**STEP 2**

**Hand clay modeling.**



**STEP 3**

**Baking at 350°F for 20 minutes.**

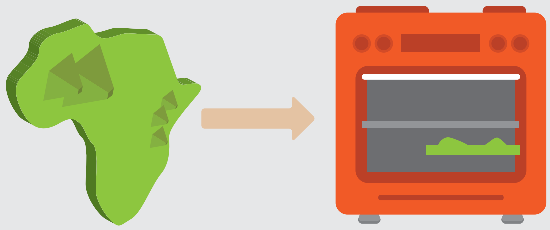


**Figure 5:** 3D tactile country shapes of USA, Africa, and Australia made using polymer baking clay.

## TOTAL COST OF PROTOTYPE 1

$20 CAD - $30 CAD

# TESTING AND RESULTS


**Figure 6:** P1 identifying the 3D tactile pieces.

> Is this how Africa looks like? Oh my god! I would have never imagined that. Oh wow, I have no idea Australia is so small compared to Africa [P1].

> The USA has some mountainous features again, but it’s not very distinctive [P1].

## INSIGHTS GATHERED FROM USER TESTING PROTOTYPE 1

**A.**

### SEPARATE CONTINENT PIECES

P1 thought that having separate continent pieces allow him to learn about their unique shapes and also relative sizes.

**B.**

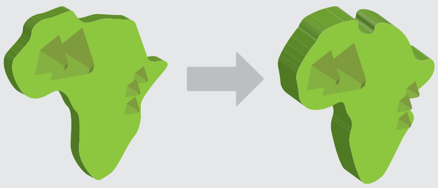
### CHOICE OF MATERIAL

P1 liked the used of easy bake polymer clay since it was good to the touch and does on feel harsh or rough on the fingers.

**C.**

### SCALING RELIEF FEATURES

P1 also mentioned that the differences in the ratios of the lower and higher elevations was too subtle to be noticeable. P1 recommended providing scale information and more prominent relief features to exaggerate the areas with the highest elevations in the next prototype.



# PROTOTYPE 2

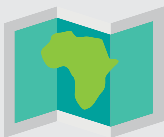
## AIM OF PROTOTYPE 2

- Molding polymer clay to represent the Earth's topography, with higher elevation features exaggerated (based on feedback c from Prototype 1).
- P1 also expressed the need to have the tangible continent pieces which can be attached back to the globe.

## MATERIALS USED FOR PROTOTYPE 2

*Retained from prototype 1

**12" EARTH GLOBE**

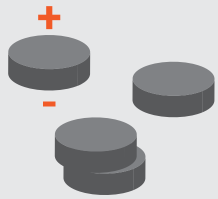


*Retained from prototype 1

**2D PRINTED COUNTRY MAPS**

*Retained from prototype 1

**EASY BAKE POLYMER CLAY**




**RARE-EARTH MAGNETS**

- 10 mm × 2 mm
- Easily available
- Inexpensive
- Lightweight
- Much stronger magnetic fields compared to ferrite or alnico magnets

**Figure 7:** Curved continent pieces of North America, Europe and Africa made using polymer baking clay.

**Figure 8:** Attaching the rare-earth magnets to the curved continent pieces representing North America and Africa.

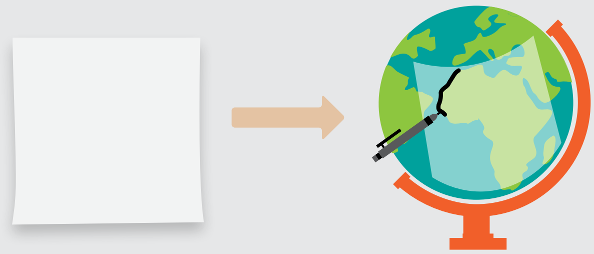
## TOTAL COST OF PROTOTYPE 2

$60 CAD

## PROTOTYPING PROCESS

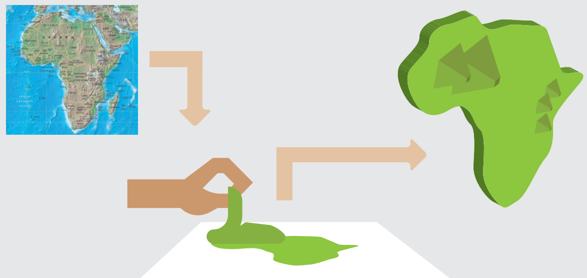
**STEP 1**

**Tracing the continents.**



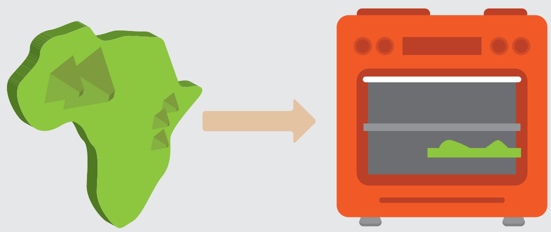
**STEP 2**

**Hand clay modeling with reference to a physical map.**



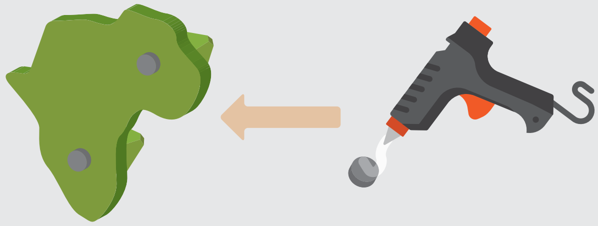
**STEP 3**

**Baking at 350°F for 20 minutes.**



**STEP 4**

**Attaching magnets using a glue gun.**



**STEP 5**

**Attaching the continents to the globe.**

## TESTING AND RESULTS


**Figure 9:** Curved continent pieces made using polymer baking clay and rare-earth magnets.

> These magnets are great. That is genius! I like it. It snaps back on in the right place. But what if all the pieces are off the globe? How do you put them back in the right spot? Maybe there could be something to guide the user for the right direction. The configuration of the globe wouldn't necessarily keep their shape if you took out two adjacent countries [P1].

> Yeah, like if we had Europe on there, with Germany and France it would be easier unless the magnets can actually select the spot they can snap back on. It needs something to put back exactly on the same spot. You know what I mean [P1]?

## INSIGHTS GATHERED FROM USER TESTING PROTOTYPE 2

**A.**

### SCALED RELIEF FEATURES

P1 indicated that the exaggerated relief for the higher elevations made it easier for him to distinguish between mountains, plateaus and plains.

**B.**

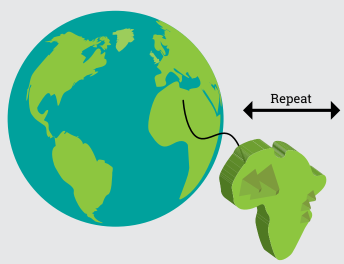
### USING RARE-EARTH MAGNETS

P1's feedback indicated that the rare-earth magnets were effective in reattaching the tangible pieces back to the globe and should be retained in the next iteration.

**C.**

### RETURNING CONTINENTS TO THEIR ORIGINAL POSITION

P1 described a need for a mechanism or convention to enable a blind or low-vision user to register the continent pieces back to their appropriate locations after removal. Some type of continuous physical connection (rather than being completely detached) could enable the user to explore a continent shape while still allowing them to trace the continent back to its appropriate location on the globe's surface.



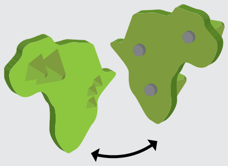
## AIM OF PROTOTYPE 3

- Having a mechanism to register the continent pieces to the globe without detaching them (based on feedback c from Prototype 2).
- Having audio feedback to convey abstract features (continent names).

## MATERIALS USED FOR PROTOTYPE 3

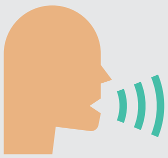
*Retained from prototype 1 & 2

**12" EARTH GLOBE**



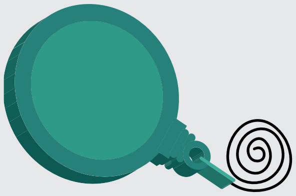
*Retained from prototype 1 & 2

**TANGIBLE CONTINENT PIECES + MAGNETS**



*Manually speaking out the continent/country names

**WIZARD OF OZ AUDIO (WoZ)**



**RETRACTABLE BADGE REELS [5,6]**

- Small compact cord that is wound onto a spring coil mechanism. The coiled spring allows the cord to retract back after it is extended
- Lightweight
- Inexpensive

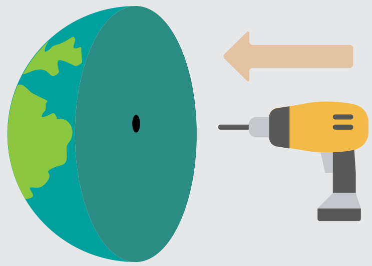
## TOTAL COST OF PROTOTYPE 3

$50 CAD - $60 CAD

## PROTOTYPING PROCESS

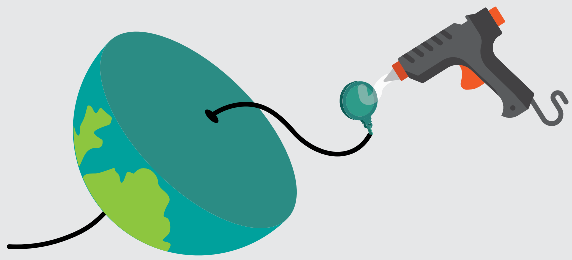
**STEP 1**

Drilling holes for the retractable reel's cord.



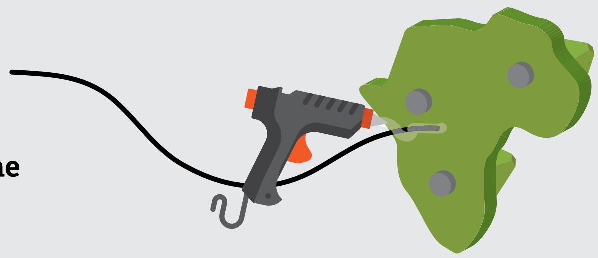
**STEP 2**

Gluing the reel inside the globe.



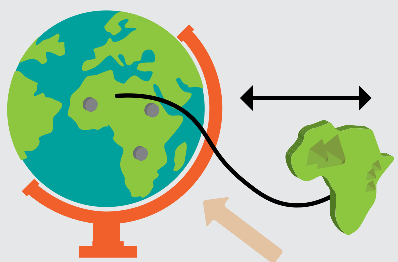
**STEP 3**

Gluing the end of the cord to the tangible continent piece.



**STEP 4**

Attaching the continent piece back onto the globe.



**STEP 5**

Using WOZ technique to speak out the continent and country names when touched.


**Figure 10:** Attaching the continents to the globe for testing the use  of retractable badge reels and rare-earth magnets.

**Figure 11:** Curved continent pieces made using polymer baking clay, rare-earth magnets and retractable badge reels.

## PRELIMINARY EVALUATION OF PROTOTYPE 3

Our third prototype increased our confidence about the potential effectiveness of the features added thus far. To gain broader feedback about the strengths and benefits of our globe, we recruited four participants along with P1 to test our prototype globe.

### THE PARTICIPANTS

All facing varying levels of vision loss, ranging from low-vision to complete blindness.

### TASK 1

Timed task

- Locate North America
- Locate South America
- Locate Central America
- Locate Europe
- Locate Spain
- Trace Columbus's journey from Spain to Central America

### TASK 2

User experience questions about:

- Mental Demand
- Physical Demand
- Temporal Demand
- Performance
- Effort
- Frustration

(Experienced when completing 'Task 1' with Prototype 3)

### TASK 3 - SEMI STRUCTURED INTERVIEW

1. Do you like the reel mechanism or the magnet mechanism better?
2. Do you like the size of the globe, or could it have been bigger for a better experience?
3. Do you have any complaints about the current state of the prototype?
4. What would be your intended use for this kind of globe?

**Figure 12:** P2 using Prototype 3 to trace Columbus's journey from Spain to Central America.

**Figure 13:** P1 trying to locate Europe on Prototype 3.

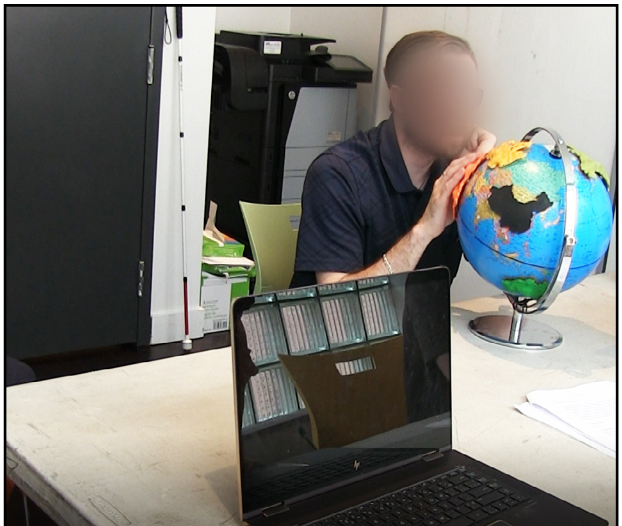


**Figure 14:** P3 trying to locate Africa on Prototype 3.

> It definitely needs per-recorded audio with it [P2].

> Pulley, with the magnet helps to put it back in the right position. With the pulley it automatically puts it in the right spot, as a blind person I am always trying to keep orientation [P1].

> I feel like it gets really confusing to locate the north and south pole because of the tilt. If the axis was just straight vertically, it would have been much easier [P4].

## INSIGHTS GATHERED FROM USER TESTING AND PRELIMINARY EVALUATION OF PROTOTYPE 3

**A.**

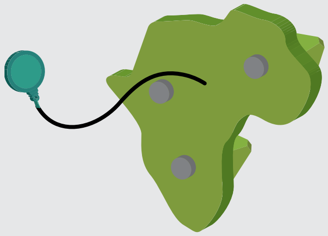
### REMOVING AXIAL TILT

Participants also mentioned the desire to not have the natural tilt on Earth's axis. They expressed the need to have a straight vertical axis instead.

**B.**

### USING REELS + MAGNETS

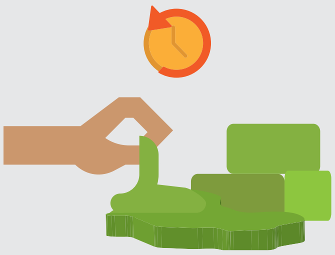
4 of 5 participants preferred the use of reels combined with magnets. We decided to retain both of these for our next prototype iteration.



**C.**

### USING 3D PRINTED PARTS

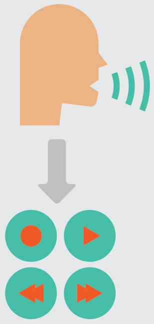
Hand clay modeling was very time consuming and did not result in very precise representations of the elevations. In order to address this, participants suggested using 3D-printed continents which would result in accurate representations of GIS data.



**D.**

### USING AUTOMATED LABELS

Some participants suggested combining our prototype with an automated voice labeler called PenFriend [51] to provide pre-recorded and clearer audio labels. Using pre-recorded labels would allow blind and low-vision users to use the globe without assistance from visual users unlike the WOZ technique.



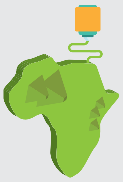
## AIM OF PROTOTYPE 4

- Using 3D CAD modeling and 3D printing to make the tangible continent pieces (based on feedback c from Prototype 3).
- Removing the axial tilt from the globe.
- Adding pre-recorded PenFriend labels.

## MATERIALS USED FOR PROTOTYPE 4

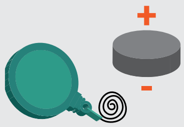
*Retained from prototype 1 & 2 &3

**12" EARTH GLOBE**



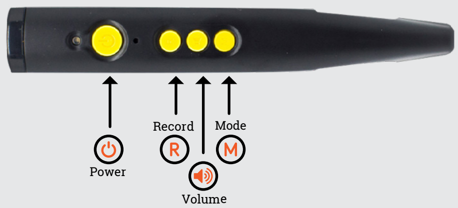
*Based of Prototype 3 Insight C

**3D PRINTED TANGIBLE CONTINENT PIECES**



*Retained from prototype 3

**MAGNETS+ REELS**




**PENFRIEND-VOICE LABELING SYSTEM [15]**

- Product for blind and low-vision users.
- Digital pen which reads barcodes from adhesive stickers.
- Built-in audio storage and microphone.
- Allows to save custom recording, re-record and playback information.

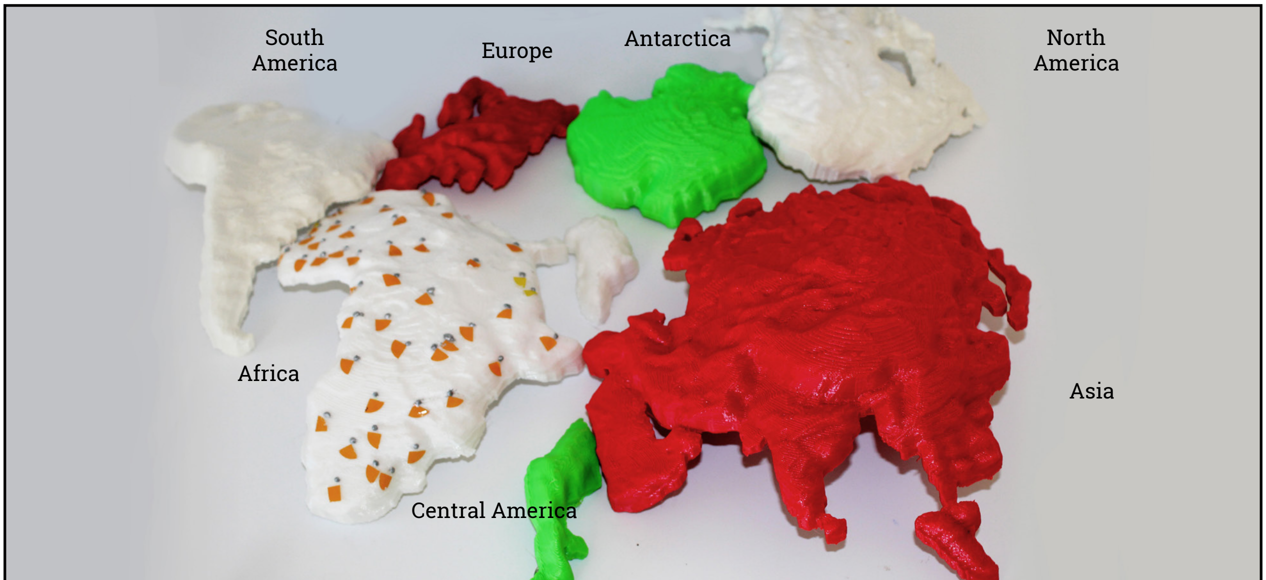
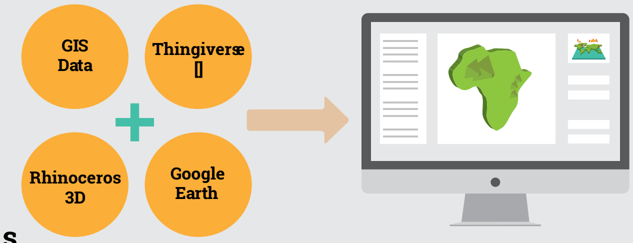



**Figure 15:** 3D printed continents.

## PROTOTYPING PROCESS

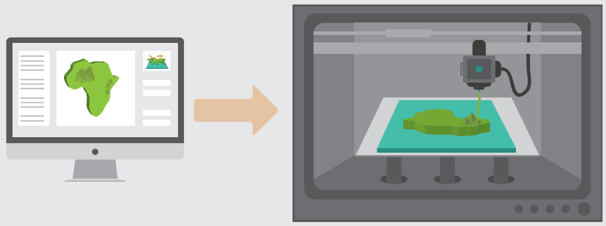
STEP 1

Making 3D continent models.



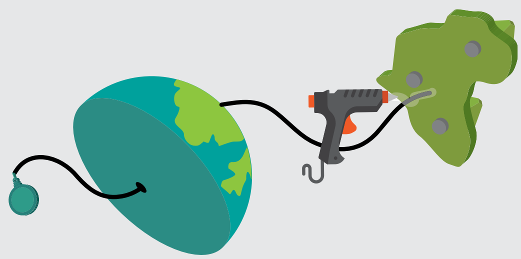

STEP 2

3D printing using PLA (Polylactide).



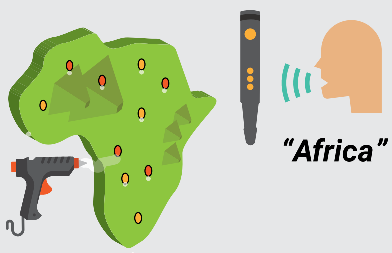
STEP 3

Adding magnets and reels.



STEP 4

Adding PenFriend stickers and 3D raised line dots using 3D glass liner to convey specific locations of the stickers to blind and low-vision users.




STEP 5

Removing the axial tilt from the globe.

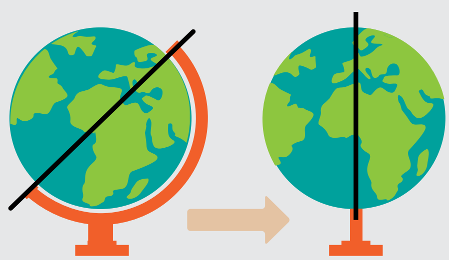



**Figure 16:** Cross-sensory globe (prototype 4), 3D printed removable continent pieces with PenFriend audio labels.


**Figure 17:** Testing 3D-printed continent shapes with PenFriend.

**Figure 18:** 3D-printed Africa with PenFriend audio labeling stickers and pen.

## TOTAL COST OF PROTOTYPE 4

$240 CAD - $260 CAD

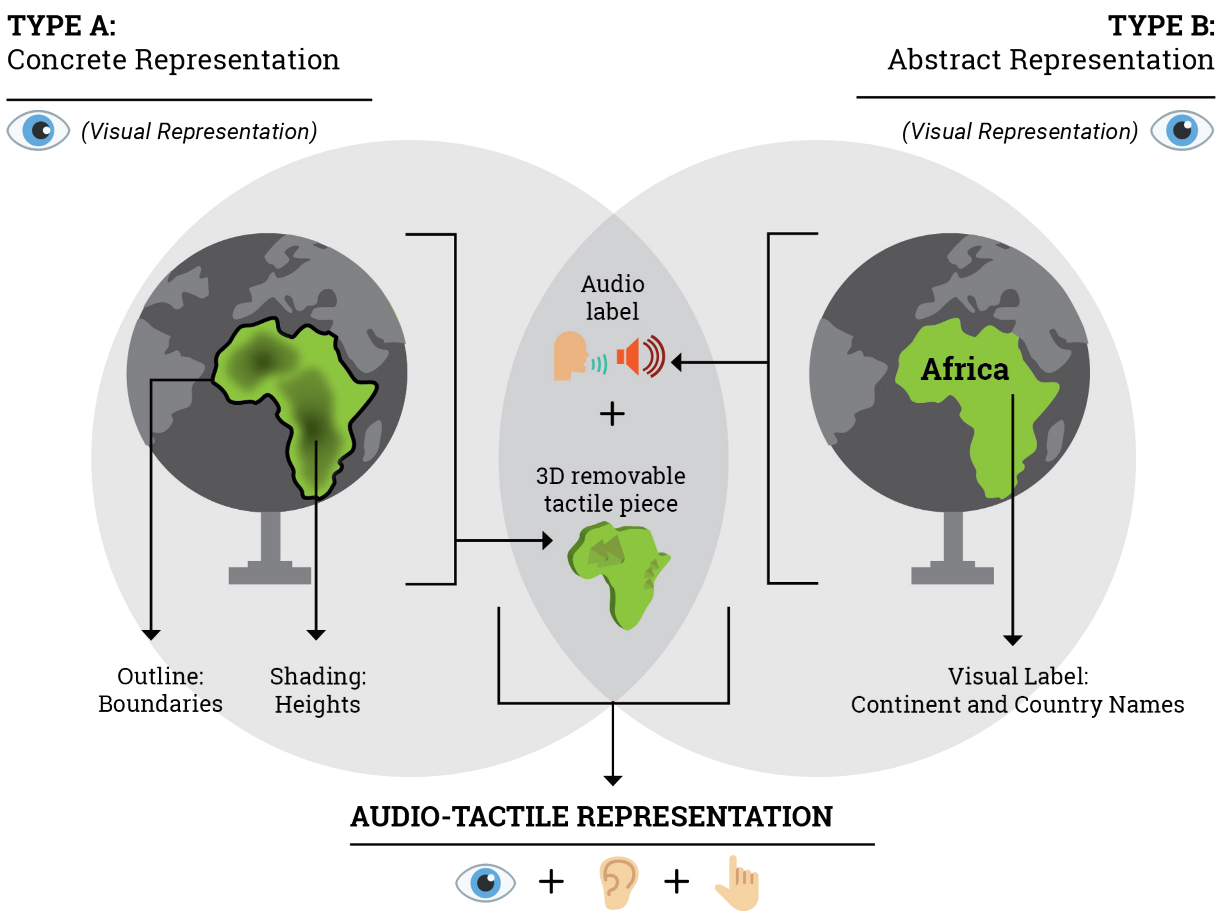
# 6. DISCUSSION AND LESSONS LEARNED

Cross-Sensory correlations of Pictorial and Symbolic Properties of Visual Globes

Advantages of participatory design coupled with a longitudinal design process

From our multiple prototype iterations, discussing and testing with participants, and multiple co-design sessions, we learned two main lessons which aid in building cross-sensory geography learning aids like globes and maps for blind and low-vision users. We also report on the lessons learned from employing a long-term co-design methodology.

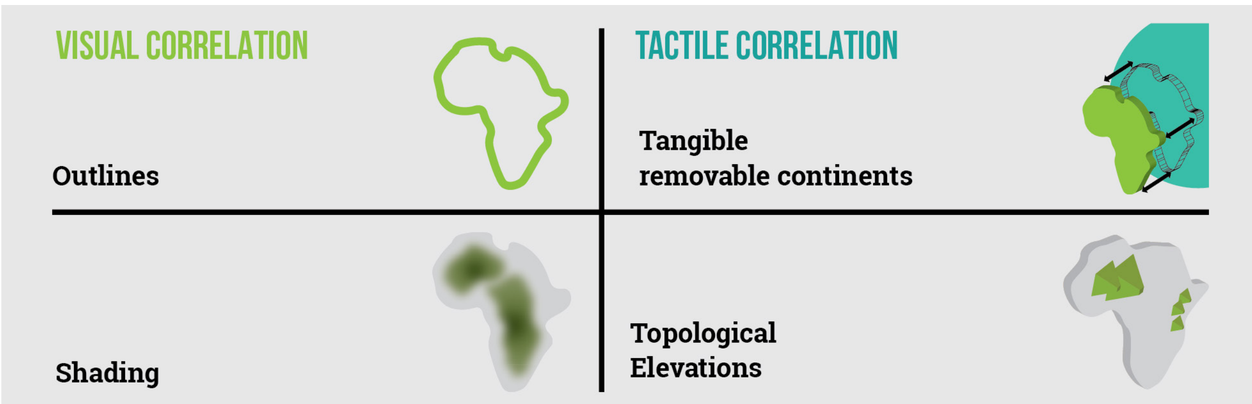
## CROSS-SENSORY CORRELATIONS OF PICTORIAL AND SYMBOLIC PROPERTIES OF VISUAL GLOBES



## TYPE A:

In visually-oriented maps and globes, shaded outlines, for example, convey spatial and topological features of the Earth's concrete structures. Outlines, for example, are routinely employed to convey edges of continents or countries. Through shading, variations of value (how light or dark an area of the map appears) can convey, for example, a feeling of higher or lower elevation, with lighter values conveying higher elevations and darker values conveying lower elevations.

We found that an effective tactile correlate of a pictorially represented concrete feature of the Earth was a tangible 3D model that could be removed from the globe to afford tactile exploration of the shape. The physical shape of the removable piece conveys information about the edges of continents. The model should be configured so that it bears a spatial and topological resemblance to the spatial and topological features of the part of the Earth that it is representing, with lower Earth elevations corresponding to the areas of the removable piece that are more proximal to the globe surface and higher elevations corresponding to the areas that are more distal from the globe surface [20,21].




## TYPE B:

In visually-oriented maps and globes, more symbolic graphics, such as written labels, should effectively convey more abstract categories that have been assigned to those concrete structures of the Earth, such as country and continent names.

An auditory correlate of a more symbolically represented abstract category, such as the written name or description of a country of continent, would be a spoken description. A tactile correlate would be braille [20,21].

A discussion during a co-design session between two blind participants reveals the type of misunderstanding that is likely when someone only has access to Type B spoken or written descriptions of the spatial and topological features of the Earth. The task was to identify Italy by manipulating a number of 3D models of countries that we had developed for the session. The participants knew that Italy is frequently described as having a boot-like shape. As one of the participants struggled with the task, we clarified that the shape resembles a boot with a high heel, akin to what would have been worn by one of the Three Musketeers. The participants were so amused that they laughed out loud. Each had imagined and described a completely different style of boot so the revelation that Italy was shaped like a musketeer boot was amusing to them. This example demonstrates how a spoken or written description ambiguously conveys spatial and topological aspects of the Earth's concrete structures (such as the shape of Australia). In other words, an audience could imagine many possible shapes under the category Australia [20,21].

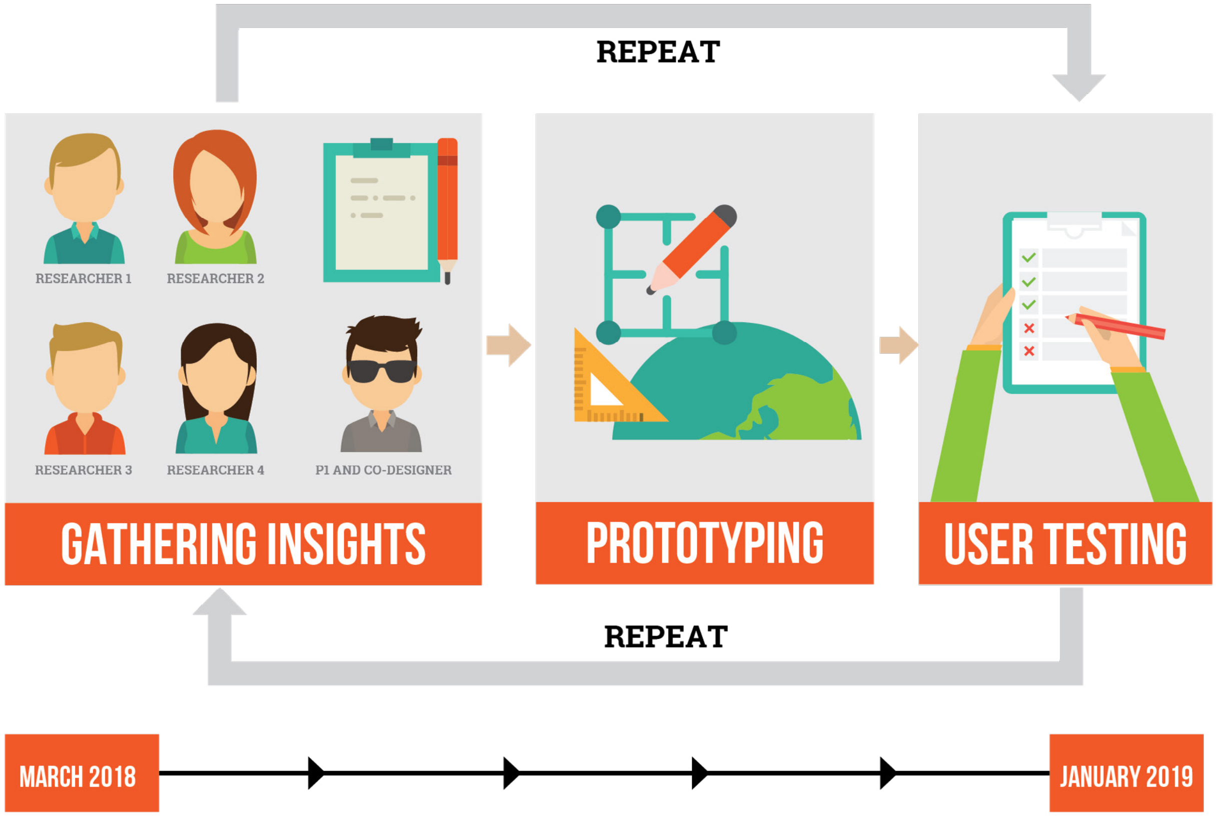
**RESEMBLANCE OF ITALY WITH MUSKETEERS BOOT**

> **P2:** I have been told that ITALY looks like a 'boot' shape.

> **Researcher:** Yes it does. Like a Musketeer's boot.

> **P2:** Haha, well, I would never know that, since I have never seen a Musketeers's boot!

From our study, we learned that a globe composed of tangible removable 3D models (to convey Type A spatial and topological features of the Earth's concrete structure) with audio labels indexed to those 3D models (to convey Type B abstract categories that those structures are deemed to fall under) overcame some of the previously described challenges. During user testing, we observed that our participants learned to recognize and understand spatial and topological features of the Earth's concrete structures, along with the corresponding audio labels [20,21].




The four low-fidelity globe prototypes further revealed the many benefits of using the co-design approach to problem solving, especially when working with specific end-user groups such as blind and low-vision users [8, 70]. P1's personal experience with building a globe positively impacted the co-design sessions because he could contribute his firsthand knowledge, both informed by his lived experience and what he had learned from building his DIY prototype.

Firstly, we believe that working with P1 through all four co-design phases helped us discover and refine essential user requirements over time. It was the inclusion of diverse perspectives during the co-design process that consistently drove the evolution of our prototypes to be more inclusive of the participants' unanticipated but specifically identified needs. For instance, we continued using a globe with a tilted axis until one of the users mentioned the need for a vertically oriented globe. Only after we implemented this orientation change in Prototype 4 did we discover how it resolved problems by distributing the physical weights of the continents equally, easing navigation when using the audio pen, and by enabling faster location of the north and south poles.

Secondly, the longitudinal design methodology engendered a clearer focus and increased our confidence in our findings through sustained interactions with the same user. Videotaping the  co-design sessions helped us observe specific and nuanced user interactions and formulate a more robust resource to draw upon during our qualitative analysis.

Lastly, a long-term, iterative investigation allowed for a more agile and flexible environment that allowed us to experiment with a diversity of ideas in a low-risk atmosphere. A longitudinal study of prototypes based on the insights from a single co-design session (or usability test) would not have presented the same level of flexibility in the research design. The collected data from co-design sessions and prototype testing revealed unanticipated patterns which helped inform the subsequent iterations of prototypes in a meaningful manner.

We maintain that designing longitudinally provided us with unique insights that might not be possible with a single co-design session. Supporting this, we suggest that designers and researchers would benefit from using a longitudinal research design and long-term investigations primarily focusing on user experience, as opposed to usability alone [8, 19, 29, 76].

**Figure 19:** P1's globe (left), prototype 3 (middle), prototype 4 (right).

# 7. CONCLUSION AND FUTURE WORK

This MRP has contributed to an understanding of how cross-sensory learning aids such as globes can be developed for blind and low-vision learners. Our findings from the initial interviews and from the co-design sessions resulted in the development of a low-fidelity tactile-sonic globe that provides information about the concrete structure of the Earth (spatial features such as landforms, elevations, topography, shapes, relative sizes and so on ) as well as the abstract properties of such structures (such as the names of countries and continents). Preliminary evaluations of our prototype indicate that our simple prototype can be helpful for people to gain general information about the Earth.

As a first step towards building cross-sensory learning aids, there are several opportunities for improving our work. In future iterations, it would be helpful to have a larger group of people involved in the co-design sessions to determine other possible uses cases of a globe. In addition, our current prototype (prototype 4) is a simple low-fidelity system that uses PenFriend to create audio labels. To fully understand the benefits and limitations of our system, it will be important to build and deploy higher-fidelity systems in usability testing sessions. Some options for building high-fidelity systems include building a touch-enabled globe combined with audio to provide a full exploration experience. We would also like to investigate the potential benefits of our simple prototyping techniques for a wider audience by making downloadable 3D files available for 3D printing in combination with audio labels through public DIY platforms such as Instructables [40].

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