NON-VISUAL DRAWING TOOL

Co-Designing a Cross-Sensory 3D Drawing Interface for and with Blind and Partially Sighted Drawers during Covid-19

by
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ABSTRACT

Drawing as an activity aids problem solving, collaboration, and presentation in design, science, and engineering in addition to artistic creativity and expression in the arts. Although drawings are some of the most ancient and cross-cultural examples of human creativity, blind and low vision learners still lack an inclusive and effective drawing tool, even in the digital age. Raised-line drawing kits aim to provide this, but blind participants found these to be barely comprehensible, most likely attributed to the fact that a line representing a surface edge reflects a visual bias that violates haptic principles of perception. In contrast, participants found 3D models to be more effective. For this reason, a drawing tool for the blind should afford 3D perceptual cues.

Furthermore, my investigation of blind and sighted drawers reveals how they continuously react to their prior marks while developing their drawings. How could this be afforded by a 3D drawing tool non-visually? Through, co-design sessions (conducted during the Covid-19 pandemic) with blind and partially sighted drawers (BPSD), I prototyped a 3D construction kit with a digital interface to translate 3D-haptic drawings of a custom-designed kit into an online virtual environment, suitable for 3D printing and collaboration.

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We would like to acknowledge that this project was conducted on the land of the Massachussett tribe. We wish to be thankful to be welcomed and acknowledge the lands on which we are privileged to reside

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TERMINOLOGIES

1. Haptic: relating to the sense of touch, in particular relating to the perception and manipulation of objects using the senses of touch and proprioception.

2. Analog: Relating to information represented by physical objects.

3. Bi-manual: Use of both hands

4. Tactile: designed to be perceived by touch

5. Kinesthetic: relating to a person's awareness of the position and movement of the parts of the body by means of sensory organs (proprioceptors) in the muscles and joints.

6. Proprioceptive: relating to stimuli that are produced and perceived within an organism, especially those connected with the position and movement of the body.

7. Multi-sensory: Engaging more than one sense at a time.

8. Prototype: A prototype is an early sample, model, or release of a product built to test a concept or process.

9. Storyboarding: Storyboarding is an iterative, interaction design methodology that uses a series of sketches or pictures to demonstrate an end to end solution for a user scenario. This type of low fidelity prototype is used to illustrate design concepts and obtain feedback early in the design process.

10. Wizard of Oz Method: The Wizard of Oz method is a process that allows a user to interact with an interface without knowing that the responses are being generated by a human rather than a computer by having someone behind-the-scenes who is pulling the levers and flipping the switches.

11. Think Aloud Method: A think-aloud (or thinking aloud) protocol is a method used to gather data in usability testing in product design and development

12. P1: Participant 1; P2: Participant 2

13: BPSI: Blind and Partially Sighted Individuals; BPSD: Blind and Partially Sighted Drawers

COLLABORATORS

Design for me is multidisciplinary and I would like to acknowledge the efforts, insights and time of the following individuals without whom this project would not be possible.

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Chapter 1

INTRODUCTION

Drawings are made by individuals from a range of disciplines, including the visual arts, design, engineering, architecture, science and beyond. Though often associated with artistic creativity, drawing is an important instrument for problem solving in design, science, and engineering (Cicalò, 2017). Despite advancements in technologies that can provide perceptual cues across a variety of sensory modalities, blind and partially sighted learners still lack an effective drawing tool that could foster their inclusion in the many disciplines and activities where drawing is required.

1.1 Perceiving Drawings Non-Visually

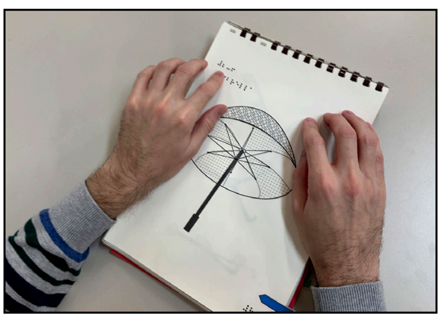


Figure 1a: BPSI participant exploring a tactile perspective view representation of an umbrella

Figure 1b: Saturn wooden relief being explored by BPSI participant

Raised line graphics are a common technique used to make graphics or drawings accessible for blind and partially sighted learners. Han et al. 2020 found that most raised-line graphics in STEM (Science, Technology, Engineering, Math) textbooks follow visual cues of their source images, such as perspective foreshortening, to convey depth, or textures to convey shadows, even though those lines are presented haptically. Although some studies claim that raised line perspective views are useful with training (Heller et.al, 2005), Han (2020) reported how blind and partially sighted participants found these raised line graphic representations of objects difficult or impossible to comprehend, engendering recognition errors, more so when they lacked visual experience (even with training). In contrast, it was found that 3D models are much easier to comprehend.

1.2 Context for Project

Research and development focused on digital multi-sensory feedback tools for blind and partially sighted drawers (BPSD) is an active area of research (a comprehensive review on drawings tools can be found in section 3.2). However, much of this research is not commercially available. I sought to fill a gap in knowledge on an effective digital drawing tool for blind users that would increase collaboration between BPSI and sighted users and offer a means for BPSD to convey their perspectives, thus informing the design of educational materials for blind and partially sighted learners. Despite research and development efforts focused on drawing tools for BPSI, access and representation in education and industry is still limited. In 2015, The National Federation of the Blind estimated that 42 percent of blind and partially sighted Individuals are in the workforce, however **less than 15 percent** have earned a bachelor's degree and **more than a quarter** did not finish high school (National Federation of the Blind, 2019). Although multi-sensory feedback components such as audio and haptic elements have been explored to a certain extent, research conducted in this area is still limited. This project advances knowledge of non-visual drawing and identifies an innovative solution, through a 3D drawing kit for BPSI. It proposes a cost-effective and accessible solution to a previously visually biased skill.

1.2.1 Research Objectives

The aim of this project is to better understand the challenges faced by BPSD when using current tools to inform the co-design of a multi-sensory tool that supports BPSD. To achieve this, the following objectives were outlined.

1. Better understand current challenges experienced by blind and partially sighted individuals in art and design.
2. Review literature on current analog and digital drawing tools to better understand challenges and opportunities for new types of drawing tools as well as innovative ideas about drawing that are less influenced by assumptions of sighted drawers which in turn could more inclusively serve the needs of BPSD.
3. Conduct iterative co-design sessions with BPSI participants to inform prototyping.
4. Synthesize findings and recruit these to inform a path forward in non-visual drawing.

1.2.2 Research Question

How can limiting sighted bias aid in developing an intuitive drawing tool for blind and partially sighted individuals?

Chapter 2

METHODOLOGY

2.1 Study Design

The study design was longitudinal in nature which involved iteratively working with the same blind and partially sighted drawers over an extended period of time through participatory design. Participatory Design (PD) is an iterative approach to research that involves exploration, discovery, prototyping and assessment. It aims for "[participants] and researchers to critically examine the impacts of... incremental redesigns in progress" (Spinuzzi, 2005, p 167). In this project the term participatory design is used interchangeably with the term co-design. This project used qualitative methods to ensure sighted bias was acknowledged and the lived experience of blind and partially sighted participants with an art and design background was amplified. This multi-phase research plan involved: Induction, Iterative Co-Design and Evaluation. These phases are outlined below:

2.1.1 Induction

I began this phase with observing publicly available videos via YouTube of blind individuals drawing, while awaiting REB(Research Ethics Board) approval. In addition, a literature review on the current state of drawing tools was conducted. Following REB approval, I conducted semi-structured interviews with 2 blind and partially sighted participants from art and design backgrounds. The gaps identified by these interviews informed the next phase of iterative co-design and prototyping.

2.1.2 Iterative Co-Design and Prototyping

Equipped with an understanding of challenges with drawing from the induction phase of this project, I explored components of a drawing toolkit for BPSI through iterative co-design sessions with the participants of the study. Initially I conducted a blind folded exploration of materials and identified strengths and challenges. My initial co-design sessions informed the development of a **Storyboard (Prototype 1)** that offered opportunities for spatial design through geometric construction tiles and consisted of a digital component to share creations. The next step involved the development of a **Wiz-**

ard of Oz Method (Prototype 2) to prototype a design for scanning geometric tiles to create digital models. This method enabled me to get user feedback regarding how to structure the experience for informing the design of a fully digital prototype (Prototype 4 below). I further developed the analog components of the drawing toolkit **(Prototype 3)** from our findings by 3D printing shapes and creating wax sticks (strings of yarn dipped in melted wax). Additional off the shelf components such as Play-Doh and loop scissors were added based on findings. **Prototype 4** was created to test the feasibility of scanning a 3D geometric shape and creating a virtual 3D model

2.1.3 Evaluation

The analog components (3D geometric shapes, wax sticks, Play-Doh, Velcro and scissors) of the prototype were tested through an evaluation phase where participants used and assessed the components of the toolkit by creating a range of representations.

2.2 Design Process Spiral

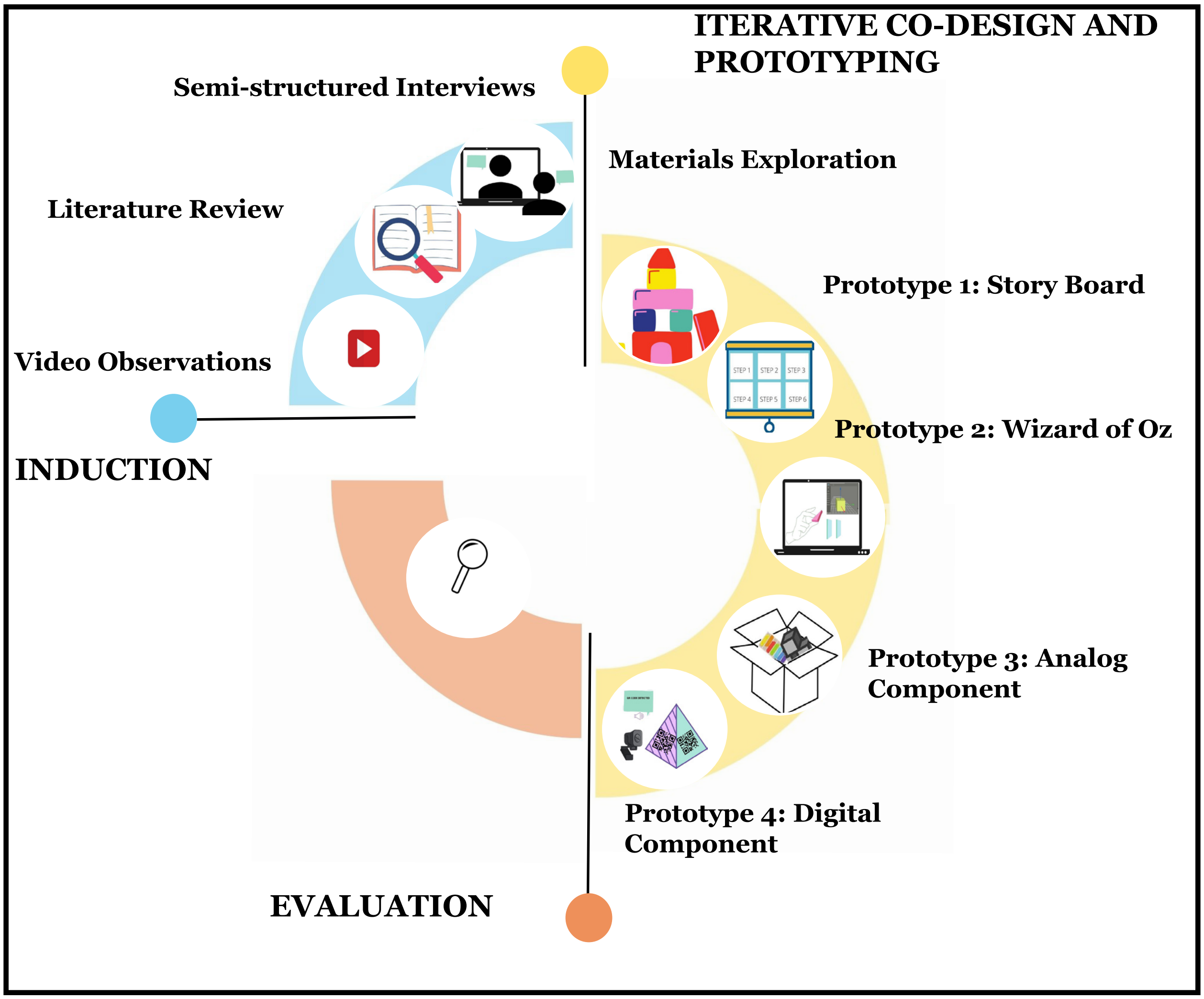


Figure 2: Design process used in the project including induction, co-design and evaluation phases.

Chapter 3

INDUCTION

While awaiting approval from the university Research Ethics Board (REB), I conducted observations via publicly available videos of both sighted and BPSD. Concurrently, I produced a literature review of published studies as well as an environmental scan of practices available online that were not yet published in the literature. Following REB approval, I conducted semi-structured interviews with two blind and partially sighted participants from art and design backgrounds (P1 and P2). Both shared their experiences with a variety of tools and described how an “ideal” drawing tool could help them create spatial structures more effectively. Highly preferred features included tactile feedback and digital representation for ease of sharing. The gaps I found informed the next phase of iterative co-design and prototyping.

3.1 Video Observations and Inferences

Observations and inferences from my observations of publicly available videos of blind drawers are summarized below.

Video 1 consisted of a blind painter. The painter used their fingers and paint to draw a circle with their non-dominant hand as a reference point to position the shape. The painter appeared to feel the texture of the paint with their hands.

Video 2 consisted of students using a 3Doodler(3Doodler, 2021) product, which is a type of 3D drawing pen. Students are shown to draw raised line shapes. Students use their non-dominant hand as a reference point. Video also shows a student using what seems like a grid. Video shows an adult (teacher/classroom aid) assisting students with drawing.

Video 3 consisted of a blindfolded individual trying to draw a figure. It appears to show the paper placed on a tactile grid. After using both hands to position herself on the paper by feeling the edges the user starts drawing parts of the face, similar navigational methods are used to add colors.

In video 4 the user mentions everything in his world is 3D and it is difficult for him to put a 3D thing onto a flat piece of paper. He uses a regular sharpie and paper to draw and draws as much as possible without lifting the pen. User shares placement and navigational challenges while drawing, uses his non-dominant hand for the second drawing to establish a reference point and stabilizes it there to know where he drew the first shape.

Video 5 shows a teacher trying to teach blind students orthographic and isometric perspectives for engineering drawing using tactile and modified drawing tools. The teacher used a tactile drawing board, a 30-60-90 triangle with indents or notches made along the sides and a regular compass. The student uses tape to stabilize the paper. She uses a 3D cube which is explored through touch as a reference for her drawing and the 30-60-90 stencil to complete her drawing.

3.1.1 Video Inferences

Video observations informed my inferences about blind drawers, indicating the need for use of **continuous feedback** to build mental models as well as the importance of **bimanual(use of both hands)** components and **3D structures**. Specifically:

• Drawers rely on continuous perceptual feedback to place newer marks in relation to previously placed marks throughout the drawing process. For BPSD, perceptual feedback was largely tactile.

• BPSD utilize both hands during drawing.

• Tools employed by BPSD include raised line and traditional paper with pencil and stencils as an aid.

• 3D models, though not traditionally considered drawing, afforded continuous tactile feedback to produce models.

3.2 Literature Review and Environmental Scan

My preliminary study with online video documentation of drawers provided insights into strategies employed in everyday life, outside of the world of academic research and development. I conducted a literature review and environmental scan to understand the current status of drawing tools available for blind and partially sighted individuals.

Bornschein and Weber (2017) reviewed drawing tools for blind and partially sighted individuals, finding that many have been experimented with in the past, but only a few are being used for practical purposes in everyday life by BPSI drawers. The authors suggest that the most common analog (non-digital) drawing methods available are raised line kits. These kits provide tactile feedback through the use of special paper to draw on or add tangible structures to a standard sheet of paper, for example, a special foil (called a drawing film) that is raised when pressure is applied with an ordinary pen. Other techniques include drawing on swell paper or other heat-sensitive materials with a heated tip pen to produce perceptible structures.

Currently researchers have broadened their media use to share findings. Thus, I found a blog on the Perkins School of Learning website titled, Art in Science: Tools for drawing for students with visual impairment (L. Hospital, December 2016). It provides an overview of analog drawing tools currently available, such as the Draftsman from APH (American Printing House), the InTACT SketchPad from E.A.S.Y. LLC, Sensational Blackboard, Sewell EZ Write N Draw Raise Line Drawing Kit, TactiPad, Swail Dot Inverter, Quick Draw Paper from APH, Raised-Line Drawing Board, & APH Tactile Graphics Kit. These tools essentially use raised lines to provide tactile feedback and are currently used for demonstrating simple math and science concepts and for creating raised line drawings for students.

Kamel and Landay, 2002 explored the importance of digital drawing for collaboration. According to the authors, digital drawing tools provide a distinct advantage to sighted users because they enable online collaboration and sharing. There has been ongoing research to develop digital drawing tools with audio and haptic feedback systems to provide blind and partially sighted individuals with the ability to create graphical information and share it digitally. The Tangram Workstation, for example, is a drawing workstation for blind users which consists of a two dimensional tactile pin matrix display for input and output (Bornschien et al. 2018). Different input modalities such as palettes of standard shapes accessible by menu or gesture interaction as well as freehand drawing by a digitizer stylus enable a blind user to create a drawing. Another example is the IC2D grid based drawing system which is a computer aided drawing system that has a user interface enabling navigation & drawing on the screen using audio feedback (Kamal and Landay, 2000). Some studies have tried exploring a combination of audio and haptic systems for guided drawing or handwriting in blind and partially sighted students e.g the AHEAD system or HIPP system. These studies use a haptic device such as the Phantom Omni which was a device developed to touch and manipulate virtual objects (Rassmus-Gröhn et al., 2013). With more research being focused on multi sensory feedback systems, recent drawing tools for blind have become more sophisticated, one such example is the Feelif Pro. Feelif Pro is an adapted tablet with special accessible apps that combine haptics (in this case: vibrations), sounds, an embossed grid and text-to-speech using Voice Assistant. The tactile grid is a transparent embossed grid of dots laid over the smart devices screen (D.O.O., 2021). More recently 2.5 D tactile shape display techniques are being explored which indicate opportunities for 3D design creations for blind and partially sighted individuals (Siu, 2019). Despite multi-sensory drawings tools being currently available very few are being widely used.

3.2.1 Literature Review and Environmental Scan Inferences

My inferences of the gaps found in current published literature as well as the environmental scan are listed below

- The literature review revealed a need for affordable and intuitive drawing tools for non-visual drawers, despite advances in 2D and 2.5D technologies
- Most drawing tools developed for blind and partially sighted individuals focus on raised line drawing technologies which limit opportunities for spatial representation.
- Tactile feedback components were commonly used across all drawing tools, some explored auditory feedback components as well indicating preference for multi-sensory feedback in development.
- Navigational methods that appeared to be intuitive for non visual drawers such as a 3x3 grid (similar to a phone grid) were used to develop a tactile drawing grid component.
- Tools offering intuitive bimanual continuous feedback while providing opportunities for spatial representation with digital components were not found.

3.3 Semi-Structured Interviews with Blind and Partially Sighted Drawers

Insights from the video observation study as well and the review of literature and environmental scan formed the basis of my semi-structured interviews with participants.

3.3.1 Participant recruitment

Following REB approval, participants were recruited for the study via email. Two participants demonstrated interest in the study. Detailed consent forms were signed before proceeding to interview and co-design sessions. Both participants came from an art and design background, indicating their motivation to participate in the study as a means to find better tools for drawing and to assist in creating them.

3.3.2 About the participants

P1 is an artist who has a degenerative condition impacting their vision since a young age and is interested in pursuing industrial design. P1 is completely blind in the right eye and low-vision in the left eye.

P2 is an architect who is completely blind in both eyes and lost their vision 12 years ago. P1 engages in free form painting and creating artwork while P2's work relies on creating and editing architectural drawings in relation to existing designs.

3.3.3 Tactile facility and the creative process

Participants indicated a strong inclination to continue creating and are actively participating in drawing with strategies and tools that work for them. Both participants indicated a preference for tactile feedback materials in their current work.

P1 suggested *" I enjoyed painting with my fingers 'cause I can actually feel the texture".* They also indicated using high contrast colors and guidelines to create their artwork. P2 lost their sight 12 years ago and have since been working on developing tactile facilities since sight loss is not something they grew up with. P2 went through a training process to be able to understand drawings through touch. It took months of practice to develop what they referred to as a **"tactile facility"**. Before developing tactile facility P2 used word description for their work which wasn't adequate. P2 indicated that the creative process of their design work was intact, what was missing was finding tools that aquately helped communicate their ideas.

P2: *" I'll often say that without sight the creative process is intact, the creative process is intellectual, it's how you think about things it's how you solve problems, it's how you define problems how you sort of research , do everything and then the drawing or the act of drawing that's just the tool set, that's like the tools that are typically used; so to* *me the creative process is intact I just need more and better tools to work with to more efficiently develop those ideas articulated and share them"*

3.3.4. Tools and Strategies Used: Challenges and Useful features

P1: *"I prefer to draw something I thought was either abstract or fantasy because sometimes I find it hard to mimic what was in front of me…if I was to paint an apple, well I know what an apple looks like it's red however certain kind of apples have different tonality to it, some has a little more greenish and has a little more yellowish so it was hard for me to distinguish in that way so I would draw like probably an abstract apple what I would think the apple should look like or in an abstract way something like that"*

Both participants indicated challenges and strengths with tools and materials previously used and features that they would prefer in a drawing tool. Challenges with tools mentioned were difficulties with mixing colors, using traditional tools such as a paintbrush, and creating detailed visual patterns for designs. P2 had previously explored the Sewell Line Drawing Kit and The InTact Sketch Pad, P1 had no experience using drawing tools traditionally developed for the blind however had previous experience using materials such as the T ruler, curve ruler, exacto knife and rubber cement to score and cut up designs. Current tools and strategies used included: Origami, plasticine, embossed printers, wiki sticks(wax sticks), high contrast paint, stencils/rulers/duct tapes as guidelines.

P2 stated *"once coming across the wax sticks to work with, that changed what I could do and how I could share it and really became a quick way of sketching and sharing so that was liberating and got me back to the more active creative side of things graphically, of working with it and being able to reconnect the creative process to the ways of really developing the concepts other than describing them in words which is never so good when you're dealing with something physical like architectural space."* Both participants shared their experiences with using a variety of tools and described how an "ideal" drawing tool will help them create. Highly preferred components listed included tactile feedback and digital representation for ease of sharing.

P2 suggested *" having a digital graphic interface both a simultaneous input and out-*

put device that would be fantastic, but that to me so far that lives out there as a Unicorn- maybe one of these days."

3.3.5 Inferences from Semi-Structured Interviews

Semi-structured interviews with both participants helped build my initial understanding of the current challenges participants experience with drawings tools and preferred methods and materials used. My inferences from semi-structured interviews are listed below

- Both participants were not satisfied with the current available drawing tools.
- Both participants preferred using analog methods to draw with commonly available materials such as wax sticks, plasticine, cardboard, origami etc
- Both participants shared a preference for tactile feedback and the ability to share drawings digitally as highly preferred requirements in a drawing tool.

Chapter 4

ITERATIVE CO-DESIGN AND PROTOTYPING

Based on my growing understanding of challenges and opportunities for non-visual drawing from the induction phase of the project (video observations, literature review, and semi-structured interviews), I hypothesized that a 3D construction kit might provide the type of continuous perceptual feedback sought by participants through opportunities to create spatial representations instead of raised line drawings. In what follows, I describe how I explored potential components of a drawing toolkit for BPSI through an iterative process including co-design sessions with the participants of the study.

4.1 Materials Exploration

I conducted a series of blindfolded explorations of materials to understand haptic and kinesthetic feedback afforded by off-the-shelf construction kits of various types. Materials explored included a 3D Pen, Pictionary Air (Pictionary Air : Mattel Games, 2021), Tinker Toys, Wax Sticks, Theraputty, customized origami blocks, and 3D construction tiles (Figure 3). Drawing involved creating simple shapes and objects through haptic and sometimes kinesthetic feedback. Simple shapes were selected as a starting point to understand what is afforded by each material. I video recorded each of the explorations and noted my observations for the same. I analyzed details of the strengths and challenges of each material for use in drawing. Details are listed in a table format in Figure 3.

4.1.1 Summary of Findings from materials explorations:

- **3D Polygon Representations**: Tools such as Theraputty, origami construction blocks and geometric tiles provided opportunities for easy bimanual construction of 3D objects while experiencing continuous haptic feedback.
- **3D Wire frame Representations**: Tools such as Tinker Toys, wax sticks and a 3D drawing pen provided bimanual feedback and flexible construction of simple shapes.

Tinker Toys were limited in flexibility due to the use of junctions at angles that did not meet every need. The 3D drawing pen was used with a heated 1.75mm PLA (poly-lactic acid) filament and was limited in its ability to afford continuous feedback due to the time required for it to cool.

- **2D Representations**: Pictionary Air (an augmented reality gaming application), along with a 3×3 tactile plexiglass grid, was used to create simple shapes. The tool was limited in providing continuous haptic feedback to accurately represent shapes with and without a grid.

4.1.2 Materials Exploration Table

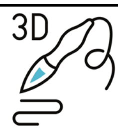
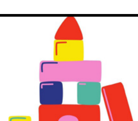
 **3Doodler**	• **Activity**: Drawing Simple shapes (circle, square) • **Strengths**: Flexible material, easy to maneuver. • **Challenges**: Difficult for active haptic feedback(filament has to cool down before it can be touched), might require some training to understand speed and control of tool.
 **Pictionary Air**	• **Activity**: Drawing Simple shapes (circle, square) • **Strengths**: Kinesthetic input allows easy creation of shapes in air with digital interface. • **Challenges**: Minimal tactile feedback to control size and accuracy of shape.
 **Tinker Toy**	• **Activity**: Drawing Simple shapes (circle, square) • **Strengths**: Bi-manual, allows for continuous tactile feedback. • **Challenges**: Restrictive because of junctions.
 **Wax Sticks**	• **Activity**: Drawing Simple shapes (circle, square) • **Strengths**: Bi-manual, allows for continuous tactile feedback, flexible. • **Challenges**: Stickiness may wear off with repeated use.
 **Theraputty**	• **Activity**: Create objects in combination with origami blocks. • **Strengths**: Bi-manual, flexible , continuous tactile feedback. • **Challenges**: Shape does not hold in place to nature of material.
 **Origami Blocks**	• **Activity**: Create objects in combination with theraputty and curved design ruler. • **Strengths**: Bi-manual, continuous tactile feedback, easier to manipulate than wire frame tools. • **Challenges**: Unstable construction
 **Geometiles**	• **Activity**: Create simple objects • **Strengths**: Easy to manipulate, sturdy, combinations of simple shapes can be used to form 3D objects, can be used to construct along both horizontal and vertical surfaces. • **Challenges:** Not flexible material

Figure 3: Materials exploration table

4.2 Co-Design and Prototyping

Following Materials Exploration, I moved on to conduct co-design sessions with both participants. Initial co-design sessions with P1 consisted of analyzing their current artwork and supporting their efforts to create a drawing of their own design based on the materials available at home. Due to the Covid-19 pandemic, all sessions were conducted virtually via Zoom.

4.2.1 Co-Design with P1: Origami Art Analysis and Creating a Turtle Shell

Figure 4a: 3D origami artwork created by participant P1 named "Lilies beyond the naked eye"

Co-design sessions with P1 involved analysis of artwork previously created and making new 3D artwork. P1's inspiration for their artwork came from trying to create art that can be easily perceived by blind individuals

P1: *"I couldn't add in that attention to details to make my flowers look anymore 3D than it already is, so then I thought to myself you know this is not working 'cause to me this still looks pretty much like a 2D image of a blobs of colors, so I thought why don't I try making origami lilies."*

Analysis of artwork revealed the use of tactile 3D tools, including origami flowers, pipe cleaners and spirograph for background details. High contrast colors were used to suggest colors that might glow in the dark. Challenges encountered by P1 included a lack of tactile tools to create details in drawings and limited origami patterns for 3D constructions.

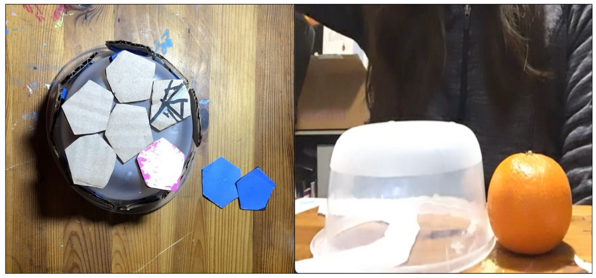


Figure 4b: Cardboard tiles used to create 3D shell of turtle by P1 (Left). P1's framework for creating a 3D turtle using everyday objects (Right)

The next co-design sessions involved creating a turtle using day-to-day items. P1 created their own cardboard hexagon and polygon tiles to form the turtle shell. P1 indicated that it would be useful to have preset tiles that can be put together to form 3D structures. Shapes that could be beneficial for construction as indicated by P1 included: triangles, squares, circles, hexagons, pentagons and stars.

4.2.2 Findings:

1. In order to add more detail to their creations P1 found 3D designs more accessible. Having prior knowledge and a memory pattern for how to create lilies out of Origami helped P1 develop their 3D artwork. Other tools and strategies used included spirograph patterns, which were created out of stencils and tactile pipe cleaners to add details to the stems.
2. P1's next creation involved creating a 3D turtle shell. In order to create a visual model of the turtle shell, P1, along with insights from the researcher, built a skeleton of the creation using a bowl, an orange and fins using paper.
3. Further development of the shell involved cutting out cardboard pentagons. P1 tried to cover her bowl using multiple pentagons. However, she was not able to complete the shell due to limitations in shapes. I observed that creating individual shapes to form the shell was an arduous process for P1 and they noted that it would be beneficial to include a variety of geometric shapes in that kit which could help drawers create 3D structures /models for blind.

4.2.3 Inferences:

1. Tactile feedback and 3D elements were preferred methods to create structures for P1.
2. P1's indicated that creating individual shape tiles was challenging, hence the drawing tool concept needs to incorporate an easy method to create 3D structures.

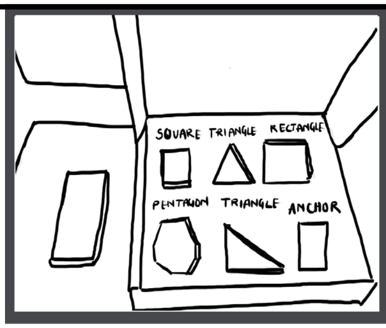
4.3 Prototype 1

My initial co-design sessions with P1 informed the development of a Storyboard (Prototype 1) that offered opportunities for spatial design through geometric construction tiles and consisted of a digital component to share creations. The concept design provides opportunities for individuals who are blind to be able to create 3D drawings from a set of geometric tiles with QR-codes (machine-readable code consisting of an array of black and white squares, typically used for storing URLs or other information for reading by the camera on a smartphone). Each tile could then be scanned into the digital environment to simultaneously create a 3D digital file that can be saved or shared with others. This prototype provides bimanual continuous haptic feedback to create models for individuals who are blind while providing a digital representation of the same model in order to collaborate with sighted individuals.

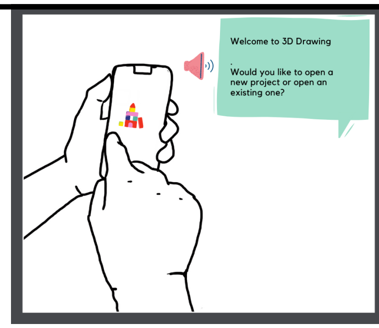
4.3.1 Findings:

The 3D Drawing Toolkit Prototype was presented to the Perceptual Artifacts Lab group where the participants provided feedback. Applications and limitations were noted as follows:

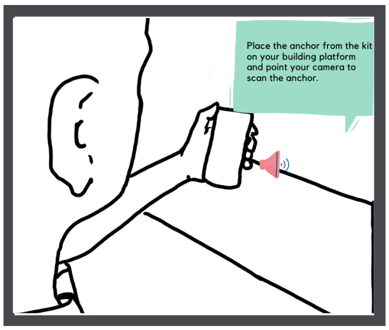
1. DESIGN: May be beneficial for prototyping 3D models in design contexts such as in industrial design or architecture.
2. STEM : May be beneficial to create basic diagrams and to convey geometric concepts required to understand surface areas and volume for Science, Technology, Engineering and Math (STEM) curricula.
3. The design is limited in it's freestyle "drawing" component due to difficulty creating more complex structures with basic shapes. More flexible components may need to be added to the toolkit, such as Play-Doh or plasticine.
4. The design may be limited in its ability to scan "whole" structures due to restricted camera views and AR technology i.e. ability of the camera to scan QR codes only at certain angles



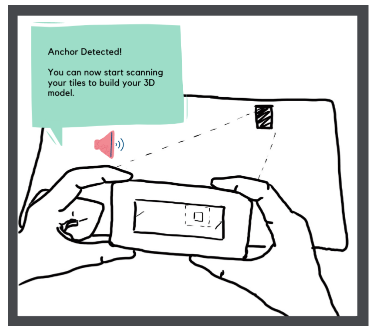
The 3D Drawing Toolkit consists of simple geometric shapes labeled with QR codes



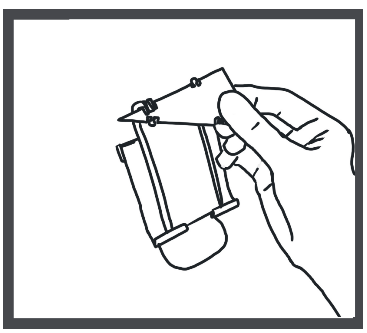
Download & Open App: The participant downloads the 3D drawing app and clicks on it to activate it.

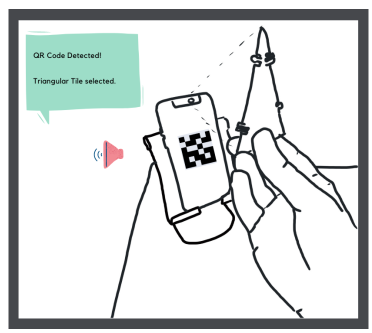


Audio Instruction: The app provides audio instructions to set up the building platform

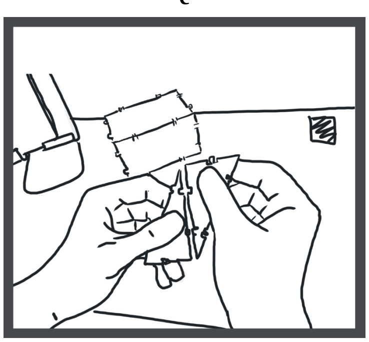


Scanning Anchor: The participant scans anchor to set up building platform.

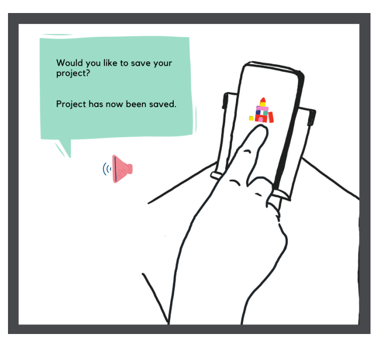




Scanning Tiles: Participant scans individual tiles that they want to build with, each tile is marked with a QR code to create virtual models when the code is detected.



Join Tiles to Build: Participant snaps 3D tiles to build a larger 3D model



Save Project: Participant saves project as a file that can be exported and mailed to a collaborator

Figure 5: Prototype 1: Story board of 3D drawing toolkit

4.4 Co-Design with P2: Analyzing architectural drawings

The co-design sessions with P2 involved analyzing methods currently used by P2 to access building design represented in architectural drawings.

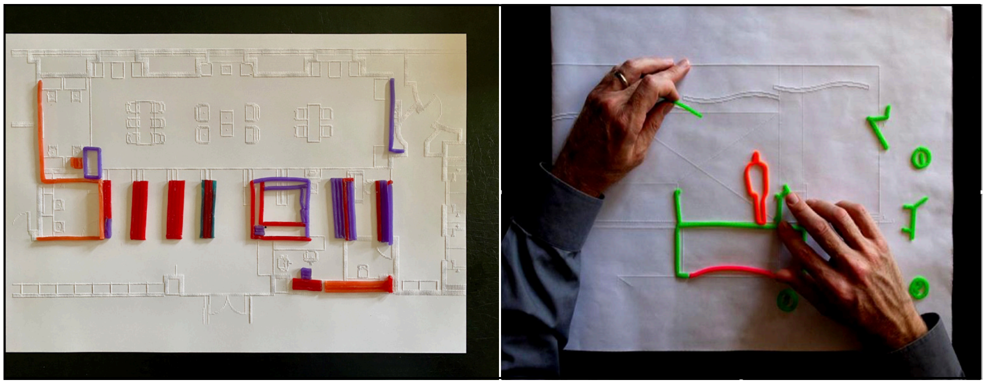


Figure 6a: Image of a plan view drawing created by P2 using wax sticks (Left). Image of an P2 using wax sticks to edit plan view drawings (Right)

P2 printed enlarged drawings from an embossed printer and used wax sticks of two levels of thickness to make changes to the drawing. The thickness of two types of wax sticks was used as "line weights" to indicate walls (for thicker lines) and doors or glass (for thinner lines). Other components included arrows made out of wax to indicate movement or circulation through space. P2 measured lines in relation to embossed drawings through touch. P2 described their difficulties with cutting the wax sticks by manipulating scissors and inconsistencies in the colors of the sticks leading to confusion when information is perceived by sighted individuals. Although most of P2's work does not involve 3D representation, P2 indicated that it would be useful for a drawing toolkit to contain options to represent 3D structures in the drawings such as for landscape design and handrail design.

In a handrail design process, P2 tried using wax sticks to create the concept for the design. This was unsuccessful as wax sticks only provided opportunities to create 2D drawings, but the process was successful after switching to a 3D-printed prototype.

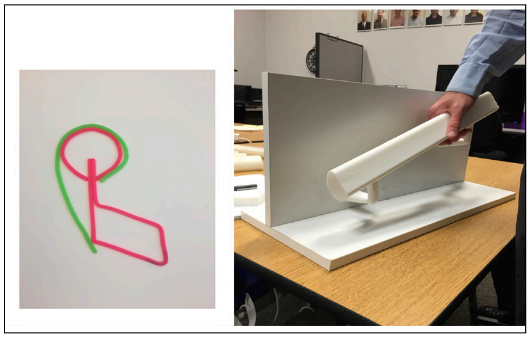


Figure 6b: Image of handrail design process used by P2.

4.4.1 Findings:

1. Wax Sticks may provide an option for creating line based drawings and adding additional details to a figure. Due to the nature of wax sticks being flexible and providing tactile feedback, they might be a beneficial component of the drawing toolkit.
2. P2 described some difficulties with using scissors, although difficulty with scissor use may not be a common challenge. An easy opening loop scissor adaptation could be considered as an additional component of the drawing toolkit.
3. P2 indicated confusion among sighted users regarding the color of the wax sticks, it can be considered to make single color wax sticks to avoid such confusion.
4. P2 indicated challenges with using wax sticks during some components such as landscape design and handrail design process and suggested that 3D geometric shapes might be beneficial for creating these components.

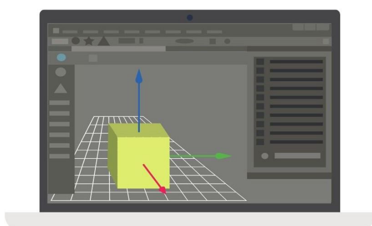
4.4.2 Inferences:

1. The toolkit needs to incorporate components that provide opportunities for 2D raised lines as well as 3D components.
2. Wax sticks can be added to the toolkit, however custom wax sticks may be required to avoid confusion with colors.

4.5 Prototype 2

Next steps involved the development of a Wizard of Oz (Prototype 2) to test the experience of scanning geometric tiles for creating digital models.

Method : The Wizard of Oz method provides an efficient technique to test user interaction with computers and facilitate rapid iterative prototyping.
Aim : To test the experience of scanning tiles while simulating creating digital files that can then be saved and shared as well as exported to a 3D printer or CAD software.

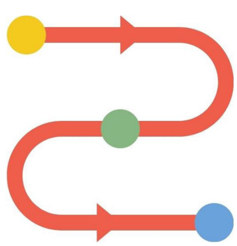


STEP 1: CREATING EASY CAD MODELS USING TINKERCAD

CAD Models of geometric tiles were created based off an off the shelf magnetic tile set and imported into the Tinker CAD program

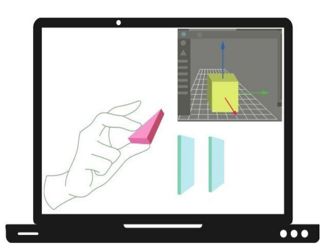
STEP 2: PROVIDING P1 WITH OFF THE SHELF GEOMETRIC TILES

P1 was provided with an off the shelf set of magnetic geometric tiles, P1 identified the shapes present in the set as square, triangle,
right triangle and rectangle.



STEP 3: WALKING P1 THROUGH THE WOZ PROCESS

P1 was walked through the process of the Wizard of Oz Prototype in which they would hold individual tiles up to the computer. Once they received auditory feedback saying “tile detected”, they could then go on to place the tile in order to create a structure.



STEP 4: CREATING A HOUSE

P1 followed the process of holding each tile up to the computer while the researcher provided auditory feedback such as “square tile detected”, “triangle tile detected” and so on. P1 then went on to connect the pieces together to form a simple structure of the house. The researcher at the same time manually placed the CAD models of the individual pieces to create a virtual model of the house using the same shapes.

Figure 7a: Steps of Wizard of Oz Prototyping Process (Prototype 2)

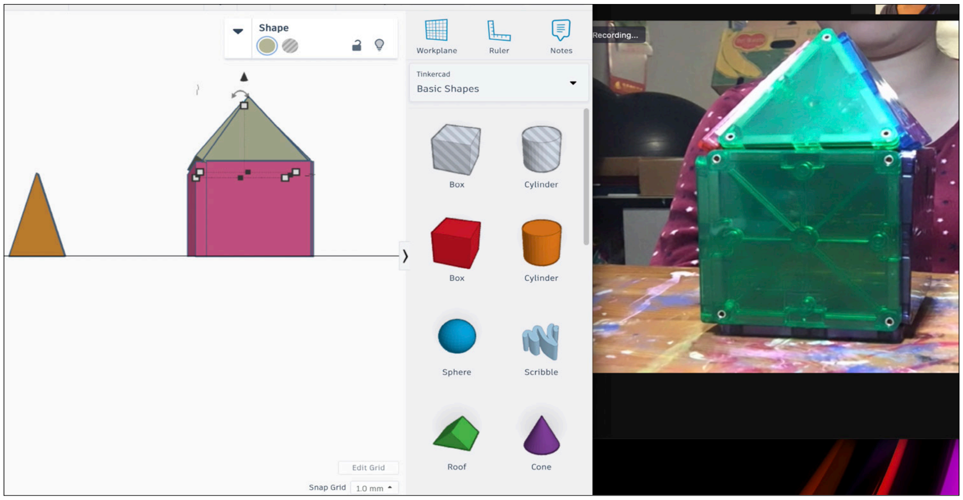


Figure 7b: Screenshot of Wizard of Oz Process showing P1 building a house (Right). CAD Model built to replicate P1's house (Left)

4.5.1 Findings:

1. P1 indicated that creating a 3D house was very easy with the audio feedback because it was beneficial to know that the tiles have been scanned.
2. P1 suggested the use of 3D blocks such as spheres and cones along with a variety of geometric tiles.
3. P1 also suggested adding some flexible materials to the toolkit along with the 3D tiles as geometric tiles may be limited in flexibility.
4. P1 suggested Velcro add ons as an effective way to connect shapes by not limiting them to magnet polarities.

4.5.2 Inferences:

1. Toolkit needs to incorporate flexible materials to create 3D drawings to overcome challenges with limitations created by geometric tiles.
2. Shapes in toolkit should include shapes such as cones and spheres along with basic geometric shapes.
3. Toolkit should have an opportunity to use a compensatory method of attachment in case magnetic component fails.

4.6 Prototype 3

Based on my co-design sessions and findings from the first two prototypes I further developed the analog components of the toolkit. As both participants indicated the need for flexible components, wax sticks and off the shelf components such as Play-Doh were added to the initial concept of geometric tiles. I designed and 3D printed the tiles to consist of shapes that would be useful in building 3D models.

Method: Creating Custom 3D printed shapes and wax sticks. Adding off the shelf components (Play-Doh, Velcro, Loop Scissors)
Aim: To create low fidelity analog component of the toolkit which could be evaluated by participants.

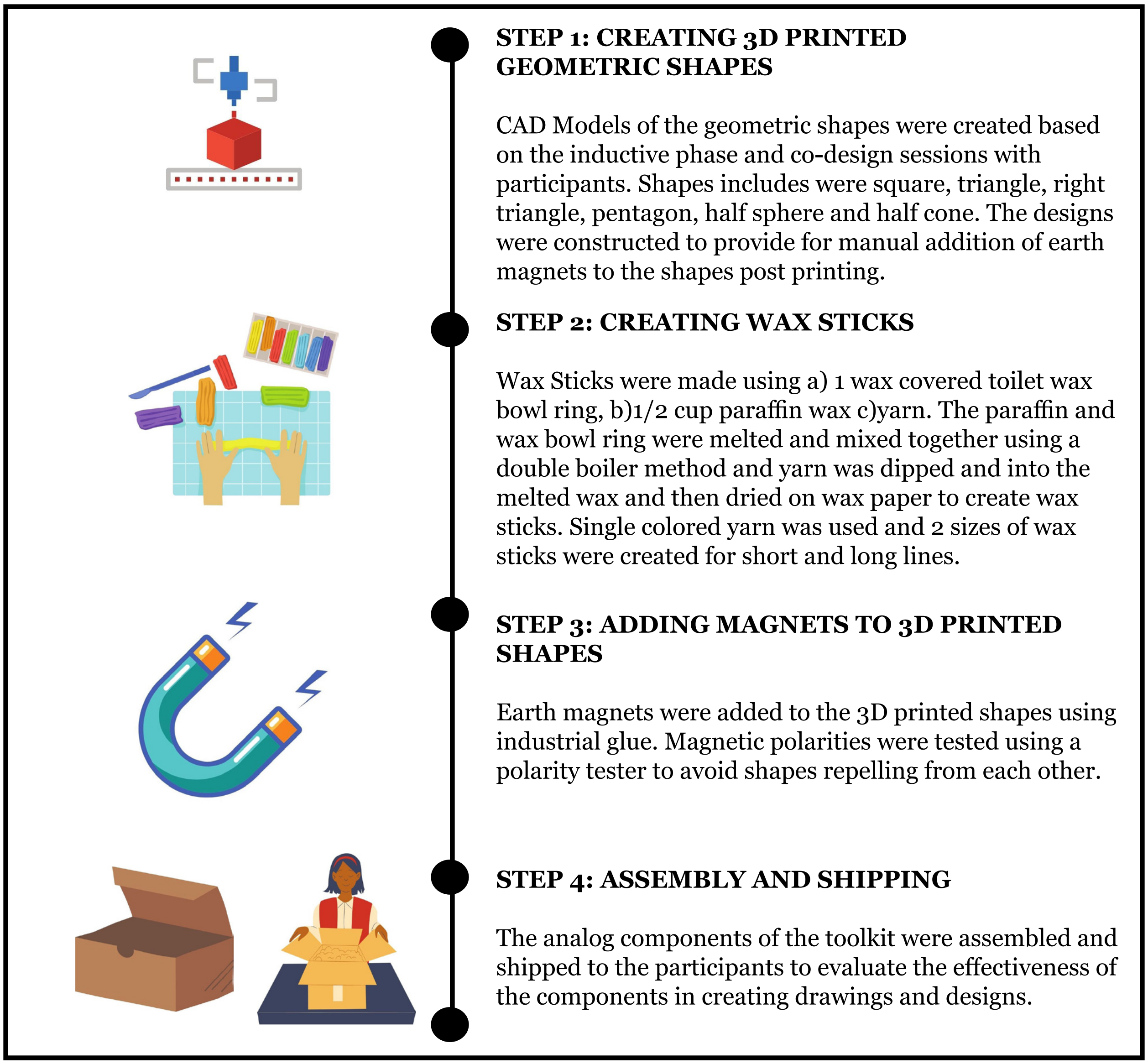


Figure 8a: Steps of building analog components (Prototype 3)

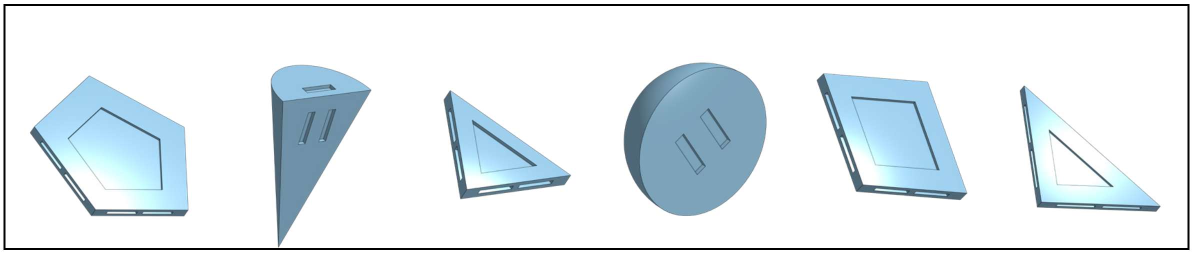


Figure 8b: CAD Models of geometric shapes (Left-Right) pentagon, half cone, triangle, half sphere, square and right triangle

Figure 8c: Custom wax sticks

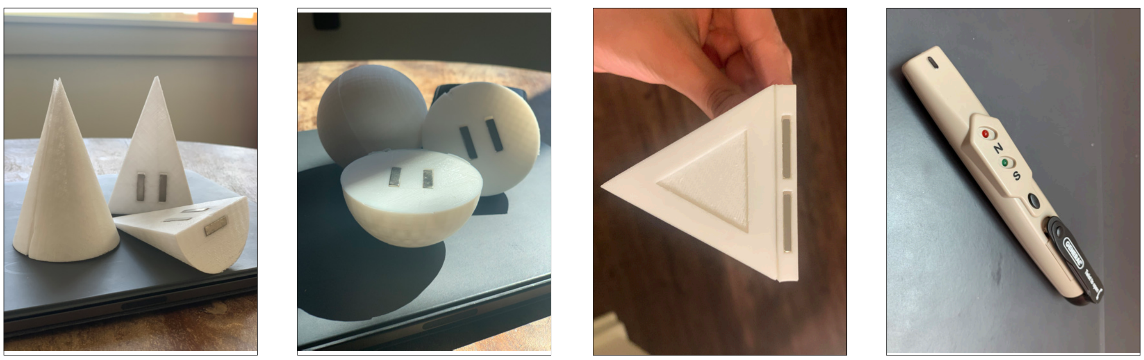


Figure 8d: 3D printed geometric tiles fitted with earth magnets (Left-Right) Half cones, Half spheres, triangles. Image of magnetic polarity tester (Extreme Right)

Figure 8e: Analog components of drawing toolkit (Prototype 3)

4.7 Prototype 4

The scope of this project did not allow for the time to build a digital component consisting of the ability to scan all the materials in Prototype 3. However, we built an app to test the feasibility of scanning simple 3D shapes with QR codes as a starting point.

Aim : To test the feasibility of scanning a simple 3D structure in order to create a digital 3D model. Feasibility testing videos of this prototype are available in Appendix A

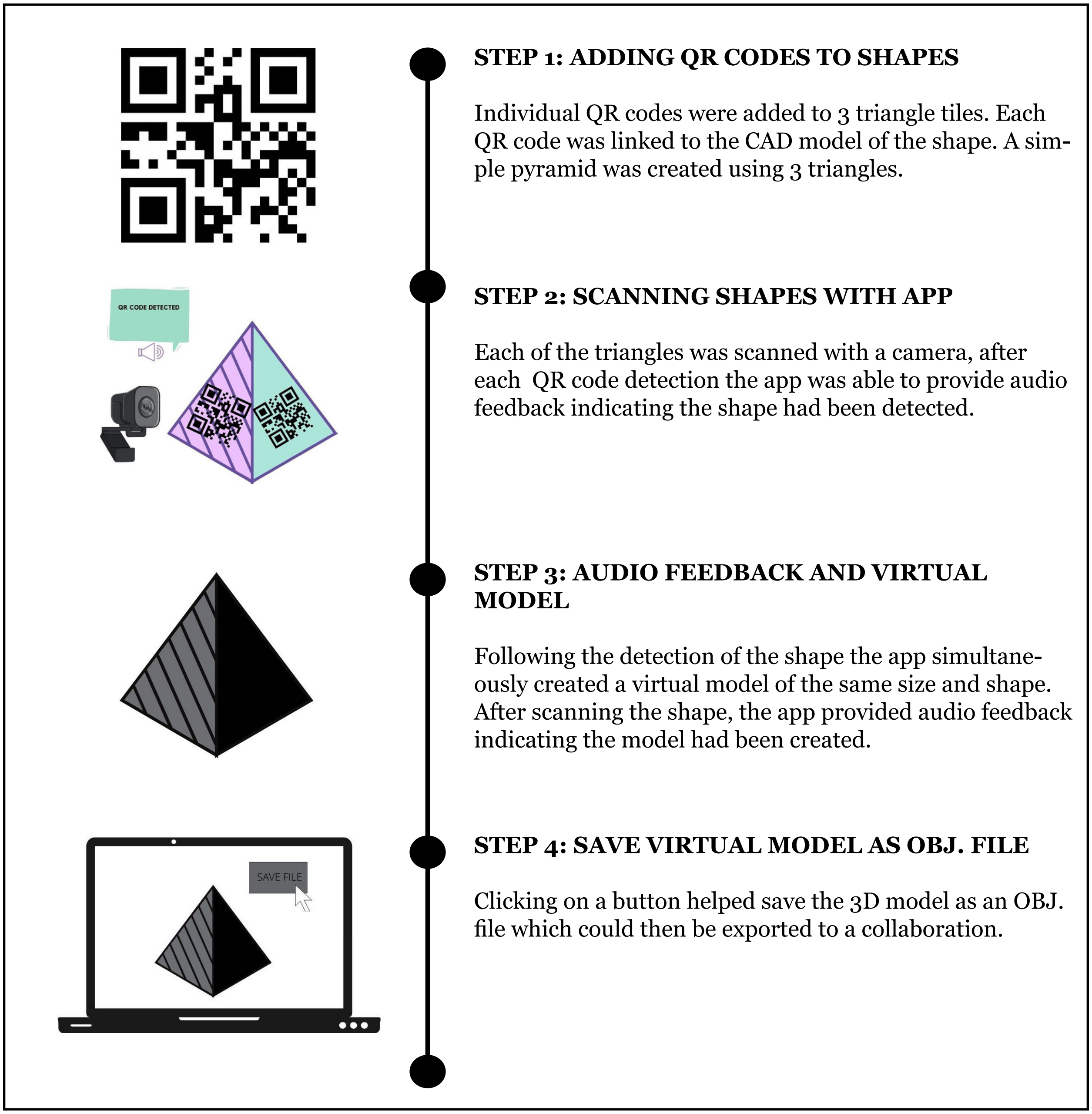


Figure 9a: Steps of testing the feasibility of digital scanning app (Prototype 4)

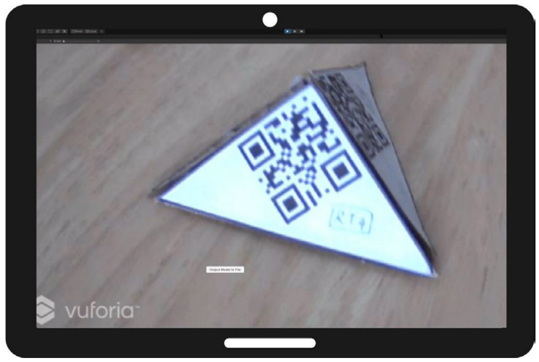


Figure 9b: Screenshot of pyramid made with 3 geometric tiles

Figure 9c: Screenshot of shapes being detected by scanning app with audio feedback (left). Screenshot of entire 3D model with audio feedback indicating model has been generated

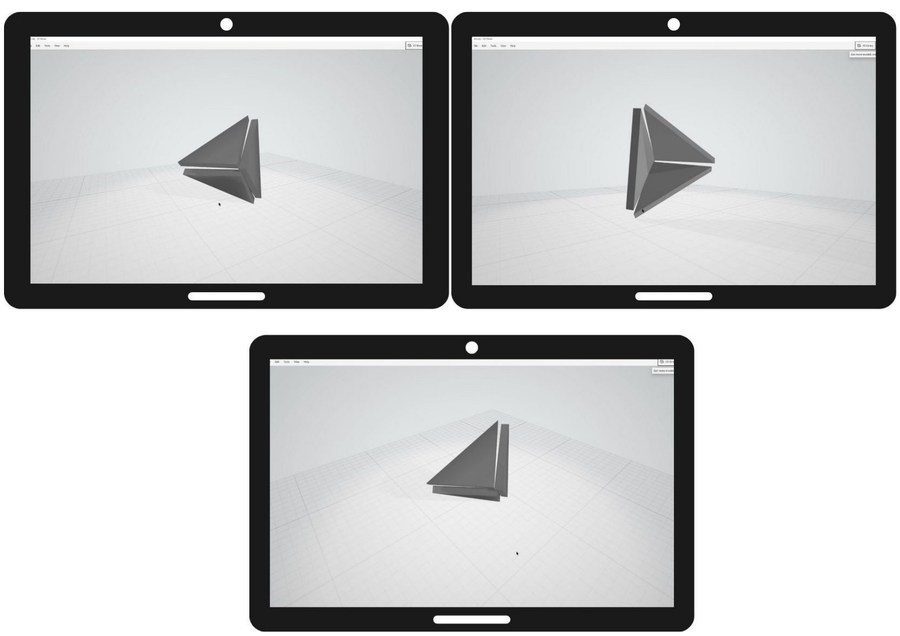


Figure 9d: Screenshot of virtual model of pyramid generated as OBJ.file

Chapter 5

EVALUATION

The analog components of the toolkit (Prototype 3) were shipped to P1 and P2. Components of the prototype were tested by asking both participants to create a variety of drawings. Interview sessions were conducted to analyze strengths and weaknesses in the design.

5.1 Evaluating Analog Components of the Toolkit with P1

Evaluation session with P1 consisted of the following activities:

1. Exploring Components of the Toolkit
2. Creating drawings using the components of the Toolkit.
3. Interview session: Reflecting on effectiveness and challenges with the toolkit components

5.1.1. Exploring Components of the Toolkit:

P1 explored individual components of the toolkit through touch. I provided verbal descriptions of each component of the toolkit while they explored. P1 described how they found the magnetic cones and spheres particularly interesting. They expressed curiosity about how the shapes were made, how they snapped together and what materials were used. While manipulating the shapes, P1 exclaimed: *“ This is cool, fun” and “how did you manage to fit magnets into a sphere?”* Another set of materials that P1 had not used before included the wax sticks and the easy opening loop scissors.

5.1.2. Creating Raised Line Drawings:

Creating Basic Shapes

I asked P1 to create raised line drawings of a circle, square or triangle using the wax sticks. A think aloud method was used (Fonteyn et. al, 1993) to understand P1’s creation process. P1 asked if the drawings needed to be 2D or 3D. I responded by asking P1 to create with the method that is more intuitive for them; the activity in itself was designed to explore 2D drawings. P1 then went on to explore creating a wire frame pyramid using the wax sticks, since they were curious about the material. P1 created a square to form the base of the pyramid and measured equal lengths diagonally to create a pyramid. P1 used the loop scissors to cut the wax sticks.

Figure 10a: Wire frame pyramid made out of wax sticks (Left, middle). Drawing of an umbrella made out of wax sticks (Right)

Creating Simple Drawings

Next I gave P1 the option of creating a key, an umbrella or butterfly using the wax sticks. P1 chose to do a 2D linear drawing of an umbrella. P1 started their creation by trying to imagine a picture of an umbrella, they mentioned that they would have preferred to have a stencil so that they would get a more accurate angle with the curvatures. The started with making the umbrella handle and the top of the umbrella. P1 mentioned that they remember the umbrella image having ribs. P1 used the short wax sticks to make rainbow arcs at the bottom of the umbrella. To make the arc on top P1 mentioned thinking of a turtle shell and to make the short arcs at the bottom they thought of a smiling emoji. P1 mentioned that they have a problem when a drawing has too many lines coming together and it makes them lose focus, they edited their out line by taking out the upper half of the handle. Once the outline of the umbrella was complete P1 went on to add details to her creation with wax sticks and black colored markers.

5.1.3 Creating Complex Drawings:

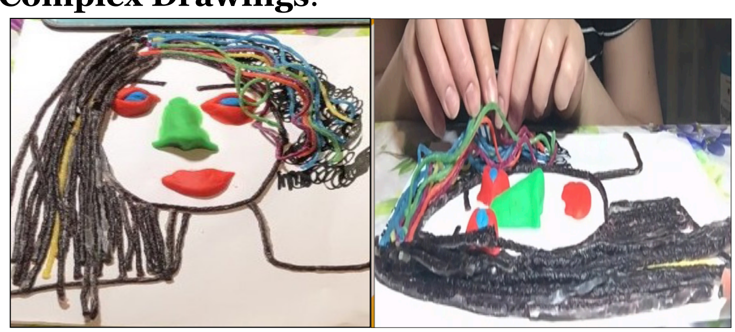


Figure 10b: Drawing of a portrait made out of Play-Doh and wax sticks by P1

For the next task I encouraged P1 to create something that they previously might not have had success with due to limitations of tools or materials. P1 came up with creating a portrait of a person (female with long hair). P1 indicated that they have always had a challenge drawing hair as they were not able to get the texture right with the tools they used. P1 used wax sticks to create the hair and outline of the face, they created layers and added texture to the hair with spirals made out of wax sticks. P1 mentioned that they liked the wax sticks because of their thickness and they are able to capture the 3D nature of the layers of hair as opposed to the high contrast markers they have tried before. P1 had a challenge creating eyes with wax sticks and decided to use Play-Doh instead so they could accurately depict the eyes. They used their own face as a reference point to create the eyes, nose and mouth as a 2.5D structure. They mentioned that they wanted to capture the shadows and highlights of the features of a face which is difficult to do with a line based drawing. P1 used their phone with voice over to capture the images they had created and the phone camera was able to detect their creation as a face.

5.1.3 Creating 3D Drawings:

Creating Simple 3D Drawings

I asked P1 to create simple 3D structures such as a pyramid and an ice-cream cone. P1 chose to use the geometric tiles to create a pyramid and an ice cream cone. P1 was able to easily snap the components together to build the shapes.

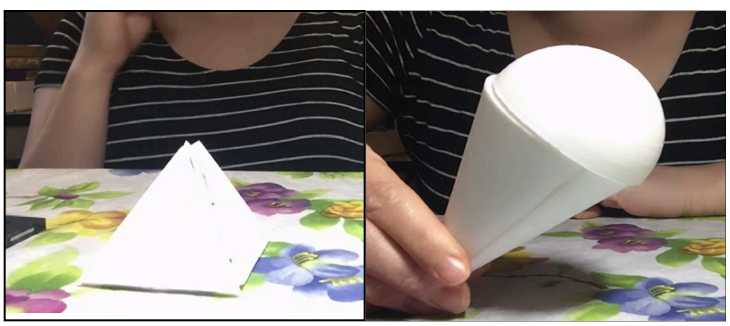


Figure 10c: 3D structures of a pyramid (left) and ice cream cone (right) created by P1

Creating Complex 3D Drawings:

Next I asked P1 to create an airplane. P1 suggested that a cylindrical shape would have been perfect for creating an airplane. They used a can they had at home to create the body of the airplane. They used the half cones to create the wings of the plane and added more details using the Play-Doh. P1 thought about why the airplane has the structure it does in each part in order to create a mental model. P1 used a half sphere to create the head of the plane and added PlayDoh to make it conical, they thought of a short dolphin nose while creating the head. They used triangles to create the back structures of the airplane.

Figure 10d: 3D structures of an airplane created by P1 (side view- left, top view-right)

For their second complex drawing P1 decided to make a modern castle. They used squares, and triangles to create the wall structures of the castle and the pentagons and triangles to create their house. They mentioned that 3D cylinders would have been very useful to create the towers of the castle. They replaced the towers with Play-Doh cans stacked one on top of another and an oil can to indicate where the towers would be. P1 needed more tiles than were available in the toolkit and ended up using some tiles from the set of Magnatiles that they had at home.

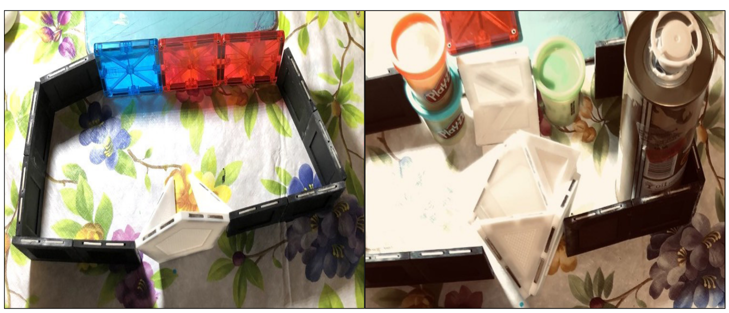


Figure 10e: 3D structure of a modern castle created by P1

5.1.4 Interview Session:

P1 indicated the following strengths and challenges during the interview session

Strengths:

1. Geometric tiles were the easiest to work with when it came to building block-like structures.

2. They liked the flexibility of the wax sticks and they stick very well leading to creating more details.

3. None of the components were challenging to work with in the toolkit.
4. They liked the magnetic component of the tiles *"It was like building a gingerbread house without having it fall down."*
5. Play-Doh was beneficial in adding softness to the structures and adding details.
6. Potential Applications: P1 said they would use the toolkit for 3D models, geometric 3D art and 2.5D art.
7. P1 indicated that the toolkit was definitely a lot easier to use than the tools they have used before.

Components to Improve:
1. Right angled triangles were what they used the least, however it came handy in making rectangular shapes.
2. The cone is probably what they would use the least to create, "It's one of the more odd shapes to use, however they were beneficial while making the wings of the air plane."
3. They suggested adding cylindrical components to the toolkit either in a disc based format or in the form of tall cylinders to make it better.

5.2 Evaluating Analog components of the Toolkit with P2

Evaluation session with P2 consisted of the following activities:
1. Exploring Components of the Toolkit
2. Creating drawings using the components of the Toolkit.
3. Interview session: Reflecting on effectiveness and challenges with the toolkit components.

5.2.1. Exploring Components of the Toolkit:

P2 explored individual components of the toolkit through touch. I provided verbal descriptions of each component of the toolkit as they explored each component. P2 thought it was very interesting that the wax sticks were made at home. P2 was able to identify the geometric shapes through touch. This was P2's first time exploring 3D geometric shapes and the loop scissors.

5.2.2. Creating Raised Line Drawings:

Creating Basic Shapes:
I instructed P2 to create simple shapes using the wax sticks. Options provided: Circle,

Triangle, Square. P2 was able to easily manipulate the wax sticks since they were familiar.

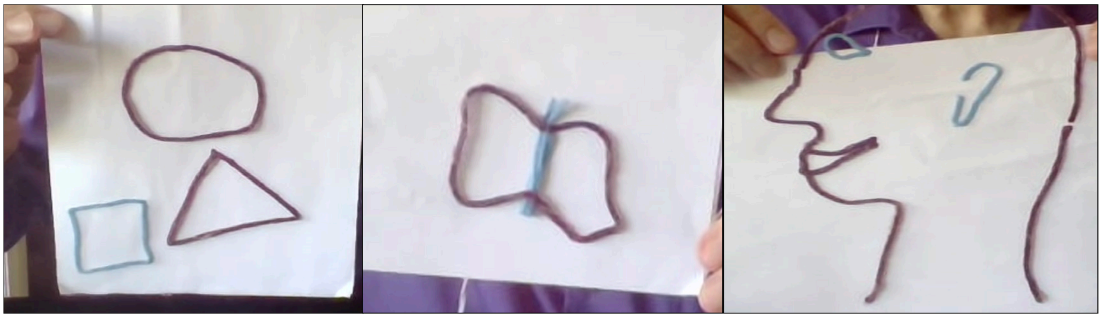


Figure 11a: Circle, square and triangle (left), a butterfly (middle) and side profile of a face (right) created out of wax sticks by P2

Creating Simple Drawings:

P2 was given the option of creating a key, an umbrella or a butterfly using the wax sticks. P2 chose to create a butterfly. P2 indicated that the home made wax sticks did not feel significantly different from the ones that are commercially available.

Creating Complex Drawings:

I encouraged P2 to create something they haven't tried to create in a while. P2 was given the example of P1 having created a portrait of a face. P2 said that they haven't drawn a face in a while and would like to try drawing a face. P2 decided to create a side profile of a face using the wax sticks. They thought of cartoon faces while creating their drawing. P2 said that they were never good at drawing faces with or without sight. P2 said had some challenges coming up with ways to create the eyes. P2, *"I have no idea how to do the eyes."* They decided to go with a wire frame almond structure for the eyes.

5.2.3 Creating 3D Drawings:

Creating Simple 3D Drawings:

P2 was instructed to create simple 3D structures such as a pyramid and an ice-cream cone. P2 used the geometric shapes to create a pyramid and an ice cream cone. P2 was using geometric tiles to make structures for the first time. P2 was able to easily manipulate the magnetic tiles to create simple 3D structures.

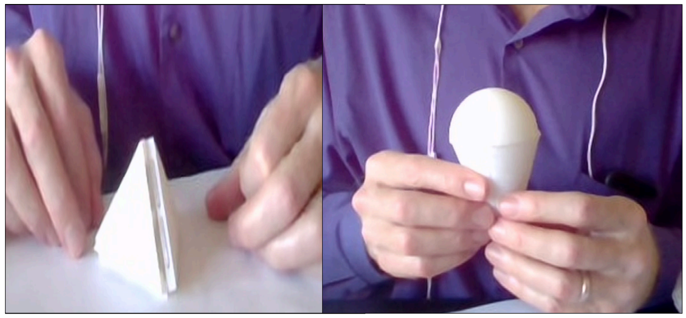


Figure 11b: 3D structures of a pyramid (left) and ice cream cone (right) created by P2

Creating Complex 3D Drawings:

I asked P2 to create an airplane using anything they find useful to create out of the toolkit. P2 said, "That is something I haven't drawn in an awful long time." P2 initially tried to use the wax sticks to create a line based drawing of an airplane since it was most familiar to them. P2 explained that while exploring the geometric shapes they did not find a cylinder in the shapes and could not get past that, hence they moved to the wax sticks. P2 said, " I had forgotten about the Play-Doh, I might switch to that." P2 then started using the Play-Doh to create the cylindrical body of the airplane and then added further details with the wings and the tail. P2 found the Play-Doh to be extremely soft and a little hard to hold it's own shape.

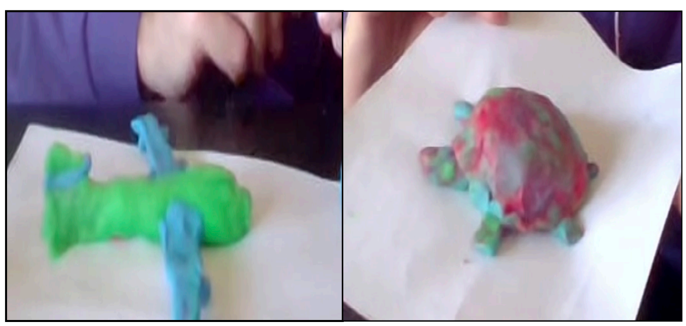


Figure 11c: 3D structures of airplane (left) made out of Play-Doh and a turtle (right) made out of a half sphere and Play-Doh by P2

For their second complex drawing I encouraged P2 to create something that they have been curious about. Being an architect P2 came up with " The Bean" structure from Chicago which is a bean shaped sculpture. P2 did not have a visual memory of this structure and had explored it using their stick. P2 said , *"That is a structure I can't draw with wax sticks. I have been interested in how you can use that form and shape to sculpt different acoustic phenomena. It was a fun thing to explore."* P2 tried making the structure of "The Bean" using the Play-Doh. P2 tried reinforcing the Play-Doh with the wax sticks however found it too soft. They modified what they wanted to create by creating a turtle instead. They used the half sphere to create the structure of the turtle shell and added details to it using the PlayDoh.

5.2.4 Interview Session:

P2 listed the following strengths and challenges with the prototype

Strengths:

1. P2 listed wax sticks as easiest to work with (due to familiarity, followed by PlayDoh and geometric shapes
2. P2 suggested that to build free form and 3D, the Play-Doh would work best so long as you can get enough structure (e.g. half dome used with Play-Doh to build turtle)
3. Potential Applications: Wax Sticks for 2D Drawings, geometric shapes could be useful to create spatial architectural models if the square and rectangular pieces were available in a wider variety. Per P2 it is helpful to get inside a space with the current size of square. For P2 having the ability to work in a 3D space would be a welcoming change.

Components to Improve:

1. Shapes were limiting in their size and type.
2. Magnet aspect is ingenious but poses some challenges as well with the polarities.

Chapter 6

DESIGN IMPLICATIONS AND FUTURE DIRECTIONS

This study aimed to explore non-visual drawing for blind and partially sighted individuals by limiting sighted bias through co-design with two blind and partially sighted drawers. The study involved participatory research through the stages of induction, iterative co-design, prototyping and evaluation.

The induction phase enabled me to develop an understanding of challenges facing blind and partially sighted drawers when they are using currently available tools. Video observations informed my inferences about the needs of blind drawers, revealing the importance of continuous perceptual feedback through bimanual manipulation of 3D objects to scaffold their construction of mental models.

The literature review revealed a need for affordable and intuitive drawing tools for non-visual drawers. It showed how most advances are in 2D (such as raised line) and 2.5D (bas-relief) technologies. Absent from the literature was work in 3D construction kits for 3D drawing, the possibility suggested through my video observations. Semi-structured interviews with both participants revealed their preferences for tactile feedback and their desires for capabilities to share drawings digitally.

The process of iterative co-design and prototyping with both participants informed my understanding of their needs for 3D objects, and the role these performed for their construction of 3D mental models by iteratively interacting with materials. I observed how this was enabled through continuous bimanual haptic feedback.

Prototype 3 consisted of analog components of the toolkit that both participants evaluated. It consisted of 3D-printed custom geometric shapes with magnetic edges for assembling more complex objects from the geometric shapes, custom wax sticks and off-the-shelf components such as Play-Doh, Velcro tabs and loop scissors.

6.1 Specific Insights from Evaluation

During the evaluation phase, I found that the 3D drawing toolkit could be used by P1 and P2 to create both simple and complex line-based and 3D drawings. Overall, I found that a drawing toolkit for blind and partially sighted individuals needs to provide opportunities for 3D spatial along with 2D raised line drawings. Future directions would consist of adding an additional variety of shapes and sizes in the toolkit and testing the prototype with a larger sample size. Specific findings follow:

6.1.1 Strengths: Geometric tiles and wax sticks

P1 found geometric tiles easiest to work with when creating block-like structures and liked the flexibility of the wax sticks for more free form shapes such as those of hair represented with wax sticks in portrait drawing. P2 found wax sticks easiest to work with due to their familiarity with them, followed by Play-Doh and geometric tiles.

6.1.2 Limitations: Not enough variety in geometric shapes

P1 and P2 both listed limitations when creating free form structures using pre-set geometric shapes. P2 suggested that further variety in shapes is needed to create complex structures. Both P1 and P2 suggested a need to add a cylindrical shape to the toolkit.

6.1.3 Raised lines versus 3D

Preferences for line-based versus 3D components may depend on the type drawing being created (relative to its purpose) as well as flexibility and structure afforded by the materials. P1 and P2 both found line-based drawing limiting when creating certain structures (such as in the foreground) and leaned towards materials that provided the opportunity for volumetric spatial representation (e.g., P1 used Play-Doh to form nose, lips, and eyes for a 2.5D structure; P2 started making an airplane with wax sticks but changed their approach to make it with Play-Doh). P1 found raised lines to be effective for background scenes.

6.1.4 Digital interface for social distancing and remote collaboration

The Covid-19 pandemic highlighted the importance of accessible virtual environments for education and work. Due to added barriers of virtual environments for blind and partially sighted individuals, it is critical to consider methods to create and share digital models of drawings and designs that work for BPSI. Although the scope of this project did not allow for creating digital models from all the components developed in Prototype 3, a scanning application was developed as a starting point to create simple 3D structures with the use of geometric shapes, QR codes and augmented reality. By testing the feasibility of Prototype 4, I found that QR codes and AR may provide opportunities to create and share simple 3D models. However, this approach may be limited in sharing complex structures such as the ones created by P1 and P2. Advances in 3D scanning technologies have allowed for scanning 3D models. However, since these applications may be limiting for BPSI due to the significantly visual nature of their design i.e., continuous visual feedback needs to accurately scan an object, future directions may include developing an accessible 3D scanning application which can be used with the 3D drawing toolkit as well as other materials. Future directions would include building a prototype of an accessible scanning app. The app will allow users to create digital representations of 3D structures using a variety of materials beyond geometric shapes.

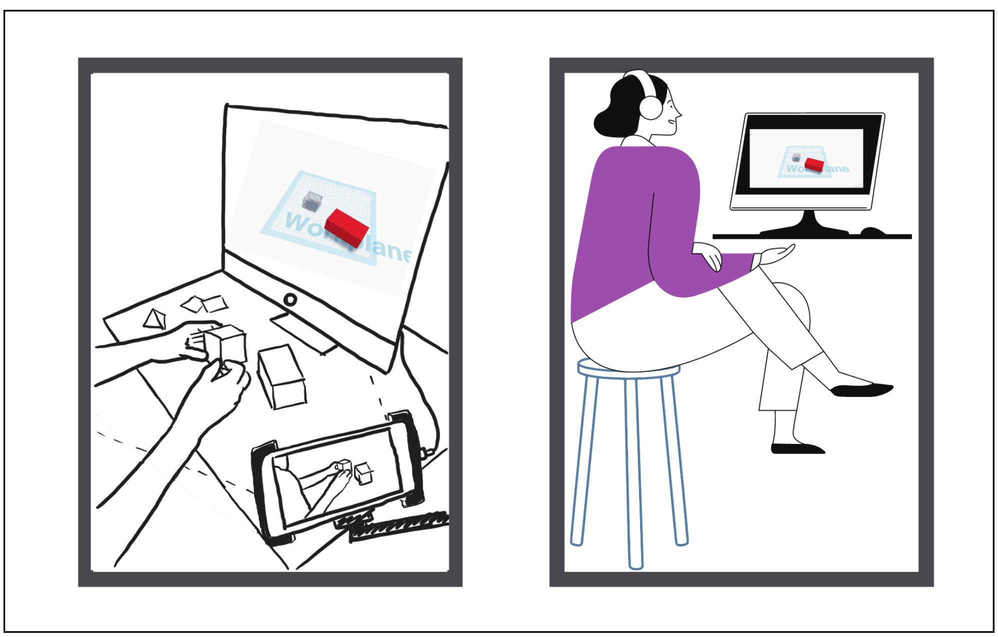


Figure 12: User experience sketch of using 3D Drawing Toolkit to share designs such as between a blind student and a professor.

Chapter 7

CONCLUSION

The aim of this research is to develop drawing tools and techniques that avoid importing visual assumptions and biases about drawing that might be less effective for blind and partially sighted drawers. Findings from semi-structured interviews and participatory design sessions with two blind and partially sighted drawers informed the development of prototypes for an analog 3D drawing toolkit and a digital scanning app to import the 3D analog drawings created with the kit into 3D digital formats for collaboration and sharing.

Findings from the evaluation sessions support the possibility (informed by interviews and co-design sessions) that non-visual drawing is afforded by continuous bimanual haptic feedback while assembling 3D objects from primitives. The 3D drawing toolkit prototype developed in this project explored this possibility to create simple and moderately complex 3D and raised line drawings. However, the toolkit impedes the creation of highly complex drawings due to its limited variety of geometric shapes (participants augmented the kit with geometric shapes afforded by household materials in response to this limitation). Increased varieties of shapes and sizes is recommended to provide additional flexibility. The digital component of the tool (Prototype 4) currently allows for importing drawings of the kit into 3D digital formats, which may be beneficial in learning geometry concepts for blind and partially sighted individuals in K-12 learning environments. However, the application needs to be developed further in order to create accurate 3D models of complex structures, such as the ones created by P1 and P2.

Developing an accessible 3D scanning application will provide non-visual drawers with a capability to use both geometric and flexible materials to create and share 3D drawings. It might allow for blind learners to access both K-12 and higher education in science, technology, engineering, mathematics, art and design fields.

Chapter 7: Conclusion

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APPENDIX A

Digital Links

Videos of feasibility testing for the digital app developed in the project (Prototype 4) can be accessed through the links below:

1. Prototype 4 Feasibility Test : Video 1 (Pyramid)

2. Prototype 4 Feasibility Test: Video 2 (House)

In order to access additional information about this ongoing project in another format you can access the website link