

University of Nevada, Reno

**Making Spatial Information Accessible on Touchscreens for Users who are  
Blind and Visually Impaired**

A Dissertation Submitted in Partial Fulfillment  
of the Requirements for the Degree of Doctor of Philosophy in  
Computer Science and Engineering

by

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**THE GRADUATE SCHOOL**

We recommend that the dissertation prepared  
under our supervision by

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## ABSTRACT

Touchscreens have become a de facto standard of input for mobile devices as they most optimally use the limited input and output space that is imposed by their form factor. In recent years, people who are blind and visually impaired have been increasing their usage of smartphones and touchscreens. Although basic access is available, there are still many accessibility issues left to deal with in order to bring full inclusion to this population.

One of the important challenges lies in accessing and creating of spatial information on touchscreens. The work presented here provides three new techniques, using three different modalities, for accessing spatial information on touchscreens. The first system makes geometry and diagram creation accessible on a touchscreen through the use of text-to-speech and gestural input. This first study is informed by a qualitative study of how people who are blind and visually impaired currently access and create graphs and diagrams. The second system makes directions through maps accessible using multiple vibration sensors without any sound or visual output. The third system investigates the use of binaural sound on a touchscreen to make various types of applications accessible such as physics simulations, astronomy, and video games.

This is dedicated to my wife, Allison, who has been with me and helped me through the difficulty of the dissertation and the Ph.D. classes.

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## CHAPTER 1

### INTRODUCTION

According to the World Health Organization, 285 million people are visually impaired (either completely blind or low vision) in the world [106]. In the U.S., there are approximately 7 million people who are blind or low vision. Approximately 500,000 (13.4%) of those within the 21-64 age range have a bachelors degree or higher. Further, in the U.S., only 26.4% are employed full time.

Mobile screen reader usage for the visually impaired has gone up dramatically from 12% in 2009 to 82% in 2014 [105]. The majority of these mobile screen reader users report VoiceOver as their primary screen reader, which is part of Apples iOS for their touchscreen devices [3]. VoiceOver was first included in iOS 3.0 on iPhone 3GS in 2009. VoiceOver was also included in every iPad starting from the first generation released in 2010. But this usage of touchscreen devices by visually impaired people remains limited to the reading of textual elements and items on the screen along with some limited ability to enter text. There are many graphical apps that people who are blind and visually impaired cannot access such as scientific simulations, video games, maps, and drawing apps.

There has also been an increase in touchscreen usage in the general population over the last several years. Tablet touchscreen devices are projected to reach sales over 200 million by 2018 [97]. A smaller fraction of those sales are predicted to be in business and education while a larger fraction remains as household or personal devices. Furthermore, tabletop and wall sized touchscreens are increasingly used for business and education, while household sales for large touchscreens are becoming increasingly viable as the price of this technology drops and household applications become more apparent [100, 46, 79]. Small sized touchscreens are also

coming on the market in terms of home appliances and wearable computing, such as, smart watches and head mounted displays [24, 41]. Smartphones with touchscreens have the largest sales with over a billion units sold in 2014 [36]. Because of these trends in both mobile touchscreen usage by people with visual impairments and touchscreen usage by the general population, it is more vital than ever to research effective and practical methods for people with visual impairments to enjoy full access to this technology.

This dissertation presents research into three systems that make various types of spatial information on touchscreens accessible to people who are blind and visually impaired.

First, AudioDraw is a system to use text-to-speech on the drawing surface of an iOS touchscreen to assist people who are blind or visually impaired to draw geometry and diagrams. An open-ended interview study was conducted to understand how people who are blind and visually impaired are currently accessing and creating graphs and diagrams in school and work. This study showed many low tech solutions are still being used with some higher tech solutions being used by more advanced computer users such as software engineers. The study shows the need for an advanced and easily accessible system to all users who are blind and visually impaired to create their own diagrams and spatial information.

After this initial study, two prototypes were made. One with geometry that was tested only on a preliminary set of test subjects and one with more general diagramming capabilities that was tested on several test subjects in a formal user study. In these prototypes, the users are able to pre-select different shapes, place them on the screen, hear where they were placed, and specify their directions and dimensions using gestural input. The second prototype, informed by the first test,

is more general and allows placement of shapes for not only geometry but many other diagram types.

The second system is a system for people who are blind and visually impaired to find their way through the directions on a touchscreen map. Currently, maps such as Google Maps or Apple Maps are not accessible in their visual content to people who are blind and visually impaired. In order to understand the spatial directions through a map, this system uses two vibrators, one from an Android smart watch and the other from an Android tablet. The two vibrators together create eight different vibrational patterns to tell the user which way to move their finger on the touchscreen as their finger traces the map. There is no audio feedback or visual feedback in this system, which makes it useful also to people who are both blind and deaf. First, the users who are blind and visually impaired were tested to find their accuracy of tracing vibrational lines on a touchscreen, and this was compared with results from sighted subjects as a control group. Then, six users who are blind and visually impaired were tested with the map system for timing results and qualitative feedback. Timing is compared to previous systems in the research literature.

The last system presented in this dissertation is a system to find and listen to objects on a touchscreen using binaural sound. This system allows for the access of moving content and graphics heavy apps as many objects can be heard at the same time with binaural sound in headphones. Apps such as video games, physics simulations, and astronomy can be made accessible with this technique. A prototype was made on an Android tablet, and a user study was conducted. The prototype shows to the user where an object is on the screen through binaural sound. As their finger gets closer to the object it becomes louder. Two variables were tested in this

study: the mapping of the x and y axis of the touchscreen to the x and y axis of the binaural sound engine versus the x and z axis of the binaural sound engine. The second variable tested was using volume to find the object versus using volume and pitch increases to find the object.

## 1.1 Publications

The work presented in chapter 2 has resulted in the following publication:

1. William Grussenmeyer and Eelke Folmer. 2017. Accessible Touchscreen Technology for People with Visual Impairments: A Survey. *ACM Trans. Access. Comput.* 9, 2, Article 6 (January 2017), 31 pages.

The work presented in chapter 3 is still being revised for submission to a journal.

The work presented in chapter 4 has resulted in the following publication:

2. William Grussenmeyer and Eelke Folmer, AudioDraw: user preferences in non-visual diagram drawing for touchscreens, Proceedings of the 13th Web for All Conference, April 11-13, 2016, Montreal, Canada

The work presented in chapter 5 has resulted in the following publication:

3. William Grussenmeyer , Jesel Garcia , and Fang Jiang, Feasibility of using haptic directions through maps with a tablet and smart watch for people who are blind and visually impaired, Proceedings of the 18th International Con-

ference on Human-Computer Interaction with Mobile Devices and Services,  
September 06-09, 2016, Florence, Italy

The work in chapter 6 is currently being prepared for submission to a conference.



## CHAPTER 2

# A SURVEY OF ACCESSIBLE TOUCHSCREEN TECHNOLOGY FOR PEOPLE WITH VISUAL IMPAIRMENTS

### 2.1 Traditional Touchscreen Interaction Techniques

We provide here a brief overview of traditional touchscreen interaction techniques in order to provide a background as to what objectives need to be reached for non-visual touchscreen access.

There are several different sizes of touchscreens that are commercially available and have been researched. There are watch sized and appliance sized touchscreens, smart phone sized touchscreens, tablet sized touchscreens, and much larger touchscreens on tables and walls. For example, the Apple Watch is a small sized touchscreen [4]. Small sized touchscreens have the problem of low precision of target acquisition because of the large size of the finger compared to the small size of the target [6]. A further problem is that the finger or thumb occludes the object being touched. The former problem has been researched as to the optimal size of targets for one thumb interactions on small sized touchscreens such as a watch [84]. They discovered that target sizes between 9.2 mm and 9.6 mm are optimal for comfort and usability in performing targeting tasks.

Smartphones have bigger touchscreens, but their limited form factor also causes problems. For target acquisition, Gesture Avatar was a research project that created the ability for users to trace shapes or characters on the screen that best match a widget or text on the screen that they want to activate [71]. If there was a match with the wrong widget, the user could correct the problem. Results showed good

performance and user satisfaction.

Potter et al. had one of the earliest evaluations of touchscreen interaction techniques that have been adopted in various forms for all sized touchscreens [90]. They compared three techniques: land-on, first-contact, and takeoff. The land-on strategy activated whatever was first touched on the screen, and if no targets were touched then nothing was activated. The user would then have to lift their finger and try again as there was no continuous logging of touch data. The first-contact strategy worked like land-on except if nothing was immediately touched, the user could slide their finger to the target they wanted and whatever target was first touched would be activated. This would lead to problems if another target was in the way of the one they wanted. In the take-off method, there would be a cursor in the shape of a plus sign above the user's finger, and the user would move the cursor around the screen until it hovered over what they wanted. Then, they would lift their finger to activate that item. The item would also be highlighted. They discovered that the performance time for the first-contact strategy was faster than land-on or take-off. The results also showed that the take-off strategy had far less errors than the first-contact or land-on strategies.

These different interaction techniques have been used in commercial touchscreens of various sizes such as tablets, smartphones, and smart watches. For example, iOS uses a land-on technique mainly. If the user misses the target and tries to move the finger to the target, various things will happen like the page scrolling up and down or left and right. The take-off strategy is also used by iOS in their QWERTY keyboard. Because it is more difficult to land precisely on smaller targets on the keyboard, the take-off method allows the user to correct their error by moving their finger to the desired letter and lifting off. This is far less error prone.

While these strategies looked at finger touch interactions, there are also commercial implementations of soft touchscreens that use styluses for their interaction rather than the finger. It was found to be more accurate when trying to touch smaller targets on the screen as the stylus tip is smaller than the fingertip [92]. Ren and Moriya also found that stylus target size was limited to 1.8 mm diameter circles. But as we discuss later, people with visual impairments typically do not use stylus interaction, and there has been no research done on it.

Another important aspect of commercial implementation of touchscreens is their use of multi-touch technology. Multi-touch allows more than one finger to be sensed at once by the touchscreen. This allows for more complex gestures such as swiping with two or three fingers or tapping with two or three fingers. There have been many research projects on multi-touch previous to these commercial implementations [13, 28, 66]. Dietz and Lee, in particular, looked at multi-touch surfaces for collaborative work between multiple users on a large touchscreen in a project called DiamondTouch. As we will see, there have been no studies that look at collaborative touchscreens between visually impaired and sighted users.

Larger touchscreens create the challenge of being able to drag and drop items across larger distances. It can be easy for the drop target to be out of reach of the user's arm. In Drop-and-drag, Doeweling and Glaubitt created a technique for dragging and dropping items on a large touchscreen [29]. The users move the item to a nearby location and leave it there in paused suspension. They then resume the dragging when they are in reach of their target. User studies showed that this technique performed faster than traditional drag and drop techniques for large distances while the reverse is true for very close targets.

## 2.2 Non-visual User Interface Navigation

There have been several research projects tackling general non-visual gestural input [1] citeVanderheiden, Kane2008, McGookin2008. Vanderheiden's talking fingertip allows the user to scan through a list on a kiosk by sliding their finger around the screen and hearing each item spoken aloud [103]. They could then lift their finger without activating anything and press a hardware button to activate the last item they were at. The system had, at the top of the screen, a button that could be pressed to provide a spoken overall description of the screen layout. Further, the system could turn the whole screen into a list, subsuming into it any lists that were also on the screen. Kocielinski and Brzostek used a similar technique of turning the whole screen into a list, but they added a new twist by allowing the user to move into a sub list of the main list [62]. They could select an item and, from that point, the list would become 25%, or whatever the parameter was set to, of the main list. Participants were able to find things faster.

Slide Rule was similar but used multi-touch gestures on a mobile device rather than single touch gestures on a kiosk [55]. They implemented software on an iPhone. Instead of touching a hardware button to activate an item, they held down a finger on an item and then they tapped with a second finger to activate the item (split tapping). Kane et al. also included complex gestures. They had subjects perform an L shaped gesture to select a musical artist and then slide right and up to activate the list of songs by this artist. McGookin et al. took a different approach by requiring the user to swipe with one finger left or right to move up or down the list respectively and then double tap anywhere on the screen to select the last item they were at [74]. Ahmed combined both techniques to browse tables on a webpage [1]. They could slide up with their finger or flick up to move one row

up or they could slide left or right or flick left or right to move one column left or right. In these studies, most of the participants gave favorable feedback to all these techniques.

Commercial screen readers have adopted most of these techniques in one form or another. In particular, swiping left or right with one finger to move one element to the left or right in a grid of icons, which wrap around when the user is on the edge is a well-known and well-used technique by people with visual impairments. The technique to swipe left or right is also used to move up or down one item in a list. Swiping up and down are typically reserved for other actions such as moving up or down a heading. Multi-touch gestures and split-tapping have also been implemented along with a special amount of taps to hear an overall description of all the elements on the screen from top to bottom. A couple of commercial implementations include Apple's VoiceOver for iOS and Android's TalkBack [3] [21]. As mentioned before, VoiceOver was added to iOS in July 2009 to the iPhone 3GS. TalkBack was officially released in October 2009 on Android Donut.

Android's Eyes-Free Shell, released previous to both VoiceOver and TalkBack in April 2009, and included a different type of touchscreen access [22]. Instead of moving a fingertip around the screen, different applications would be entered or activated by selecting a number on the keypad. The keypad would be relatively oriented so that wherever the user placed their finger would designate the 5, and then they could move their finger up to get to 2 or northwest to get to 1. This interaction technique used the take-off method as discussed before, and the user would activate their item by only lifting their finger and not needing to double tap such as in Slide Rule. This was used for entering phone numbers and for activating different buttons that launch apps or different parts of apps. To scroll

through items, they would use a physical D-pad or track ball on the phone.

## **2.3 Touchscreen Text Entry**

### **2.3.1 Traditional Text Entry on Touchscreens**

For sighted people, visual on-screen software keyboards have many benefits. They do not have to be physically carried around. They can be made smaller or bigger as needed. The keyboard can be switched to multiple different modes for different keys, such as symbols or numbers. But there are also many challenges. They are typically smaller and harder to type in [94, 31]. On mobile phones, the typing cannot be done with both hands but with one or two fingers or thumbs. A new type of keyboard designed around two thumb text entry has been researched and provides performance enhancements over QWERTY touchscreen keyboards [82]. Another problem arises with the problem of lack of tactile feedback making it hard for the user to know where their hands are and what keys they are typing without looking. Without the tactile feedback of the physical buttons, it is also easier to make errors while typing. Occlusion is another problem. Because there is no tactile feedback, users have to look more at the screen to know what they are typing, and their hands and fingers can obscure the keys. This is not such a problem on physical keyboards because people have little problem typing without looking after some training and practice.

For small QWERTY touchscreen keyboards, typical typing rates can vary from 21 WPM to 32 WPM depending on the size of the keyboard and the practice of the user [94]. This is much slower than large sized physical keyboards in which

experienced typists can have speeds up to 135 WPM [31]. Predictive text entry and word completion, where the most common words are presented to the user as they type, can speed up touchscreen text entry by anywhere from 30% to doubling the typing rate [30].

Hand drift is another problem for touchscreen keyboards. Because of the lack of tactile feedback, users' hands and fingers drift away from the keys. Adaptive keyboards that customize to the users typing patterns and drift have shown some increase in performance [47, 70]. There are also hand writing recognition systems, which are slower, require more space, and cannot recognize unknown words [31]. There are also systems such as SHARK and swype that combine tapping keys with shorthand gestures for common words or letters [115, 59]. While no expert typing rates were done in the initial tests of SHARK, it was shown that the users were able to quickly learn SHARK shorthand gestures quickly and that their learning rate went up faster with each new session. Qualitative feedback was also positive.

Another challenge for text entry on mobile touchscreens is the distractions and difficulties brought on by mobile environments and situations [38]. Walking and typing at the same time can slow down speeds, and solutions to this problem with drift correction through accelerometer information have proven to increase accuracy and speed in mobile situations [38].

### **2.3.2 QWERTY Keyboards for People who are Visually Impaired**

For people with visual impairments, typical commercial implementations of the screen reader will read each letter of the on screen QWERTY keyboard or number of the numeric on screen keypad as the user moves their finger around. Once they

get to a letter or character they want, they can double tap anywhere on the screen to select it. This is similar to the gestural techniques as described in the previous section, but there are some important differences. One is that settings allow the letter or character to be selected when the user immediately lifts their finger off the screen with no need to double tap. This lift-off method is used typically for sighted interaction, as mentioned before, but it is more specific to keyboard usage when it comes to non-visual interaction techniques. The other important difference is the keys on the keyboard are smaller than other icons and buttons and can be easily missed or difficult to find. Typing rates for people with visual impairments tend to be very slow at around 4 words per minute [11].

With large tabletop screens, it is possible to have a full sized keyboard where the user can place their hand in a standard position. A multi-part research project looked at increasing touch typing rates, on large touchscreen surfaces, for sighted users but which requires little or no visual attention [34]. They developed keyboards, which adapt to the individual as they type. They tested three different touch keyboards: standard, adaptive but with no visual difference from standard, and adaptive with visual adaptation. Surprisingly, they found that the keyboard that adapted but had no visual change worked the best, and that the keyboard that visually changed did not offer any performance increases. None of this was done with visually impaired people, and it is an interesting direction for research.

A more recent project attempted to make QWERTY keyboards faster with bi-manual interaction and simultaneous stereo speech, but it had limited results [44]. They used a large sized touchscreen, and the user could place two fingers on the screen (one finger on the left half of the keyboard and the other finger on the right half of the keyboard). Then the user could explore around with concurrent TTS



in the left speaker for the left side of the keyboard and in the right speaker for the right side of the keyboard. Results showed that users were able to enter text at similar speeds to touch by exploration on QWERTY keyboards, i.e., around 5 WPM. But results also showed that users were able to leverage their spatial knowledge of the QWERTY keyboard to land their fingers closer to the target keys and to find paths that were more direct to the target key.

### **2.3.3 Braille Touchscreen Keyboards**

A Braille keyboard has six keys, one for each Braille dot, which makes up one Braille cell that represents a character, and the user types with chords, or pressing multiple fingers at the same time. In contracted Braille, a single character can stand for multiple letters, which makes typing even faster. Chording is a type of input that uses multiple key presses at the same time such as a piano. Twiddler, for example, uses a one handed chording text entry approach on mobile phones [72]. User studies show that the Twiddler approach with an experienced user can achieve up to 60 WPM. With two handed physical keyboards that use chording, professional typists can reach up to 225 WPM [31].

Braille soft keyboards have now been built into iOS 8 and later based on BrailleTouch and Perkinput citeAzenkot2012a, Southern2012. In screen away mode, the user holds the phone away from herself and types by wrapping three fingers from each hand around the edges to touch the screen, which is a useful technique if no flat surface is available on which to lay the touchscreen. In tabletop mode, the user places their six fingers on the screen as in a Perkins Brailier. In the BrailleTouch studies, typing rates using the screen away method, the tabletop method,

and a physical Braille keyboard were comparable at around 20 words per minute and had comparable error rates around 10% on average [96]. Perkinput showed that the tabletop method could be averaged up to 38 WPM using different algorithms to detect finger drift and touch inaccuracies [11]. Perkinput also tested Braille input with three dots at a time on a smaller touchscreen. Dots one through three would be entered, and then dots 4 through 6 were entered. These results were not as good as the tabletop method. Further, Perkinput tested two phones, one for the left hand, and one for the right hand with similar results to the tabletop method. There is still a problem with high error rates on Braille input, and there has been one attempt called B with some success to provide word level error correction Nicolau2014.

Educational games called BraillePlay for children who are blind were developed that could allow them to write Braille characters using vibration feedback [76]. The touchscreen is divided into six sections, and each section represents one of the dots of a Braille character. They could write by tapping the section of the screen to raise that dot. While this is slower than other Braille input methods using all six fingers at once, it is easier for children who have lower dexterity and are unable to hold the phone in the BrailleTouch manner or use the chording method on tabletop mode. It is also helpful for children to learn Braille this way.

TypeInBraille is a much simpler Braille keyboard layout where only two Braille dots are shown at a time [73]. The user selects either one dot or both dots to be raised for dots 1 and 3, then for dots 2 and 4, and then for dots 3 and 6. No user studies were done, and it is unknown what the WPM is for this approach.

A single tap braille keyboard was developed and tested that allows placing the dots of the braille cells anywhere on the screen and analyzes the relationship

between them to determine the braille character [2]. This allows the user to hold the smartphone with one hand and tap the dots of the braille character with a thumb or single finger. There are no pre-determined areas on the screen to touch, and it is up to the user to place the dots in such a way as to represent the braille character. For example, if a user places two dots next to each other and waits, the letter c is typed. In a user study, the single tap braille keyboard was shown to perform better than the QWERTY keyboard and that it was easier for users to correct their errors. Qualitative feedback was also positive.

### **2.3.4 Non-Standard Keyboards**

Several types of non-standard text entry methods have been researched, but many of them have not been tested with people with visual impairments.

An eyes-free graffiti input alphabet was tested on sighted people [101, 102]. They were able to achieve up to 7.6 WPM while sighted participants held the touchscreen device under the table. With auto-prediction algorithms, they were able to achieve up to 10 WPM. But tests still need to be done on people with visual impairments to see if they can type as fast with the graffiti gestural alphabet.

SlideType was a different approach for visually impaired subjects with a sequential keyboard [107]. The alphabet was laid out in a line across the screen where the letter in the center was highlighted and zoomed in. There was also audio feedback stating the current letter. Users could move along the alphabet by sliding their fingers or tapping once on arrow keys on the left and right sides of the tablet. 5 visually impaired subjects were tested and gave positive feedback, but no quantitative studies were done. The benefit of this approach in terms of WPM

is unknown.

NavTap, or NavTouch on touchscreens, is a completely novel technique and was researched with visually impaired test subjects using quantitative data [45]. The users could move through the alphabet by performing left to right gestures, similar to the sequential keyboard mentioned earlier, but they could also jump to different vowels in the alphabet by performing up and down gestures. Results showed that after some training, it only took on average 4.6 gestures to find a character, and the error rate was comparable to other methods at around 13-14%.

### **2.3.5 Numeric Entry**

Numeric entry is a subset of text entry, and techniques were developed for optimizing it with relevant applications such as entering phone numbers or personal identification numbers.

DigiTaps was a system devised to provide minimal or no audio feedback [8]. A set of gestures, and combinations of these gestures, were mapped to each digit 0 through 9. For example, a single tap is 1 and a three-finger tap with a single finger swipe is a 3. Haptic feedback can be given by the system. In the case of a successful swipe, two vibrating pulses are given while tapping gestures give one vibration. Overall, participants were able to enter digits at 0.87 per second with a low error rate.

Similar to the previous technique, PassChords is a password entry technique that allows users to enter passwords using a series of one to four taps [10]. Users were able to enter passwords two to three times faster than using the VoiceOver

method with the QWERTY keyboard. There was no audio feedback to confirm results for security reasons.

A text entry system was developed around the numeric keypad [19]. Different haptic effects along with audio output were designed to allow the user to tell which number of the keypad their finger was on. In order to enter text, the user moves to a number on the keypad, such as 2, and then taps the number of times necessary to get to the standard letter, e.g., tap once for a, twice b, three times for c on the number 2. Pausing automatically enters the letter into the message, and there are gestures for editing such as swiping left, right, up and down for deleting. A qualitative study was done with positive feedback, but no quantitative data such as words per minute was logged.

A couple of less recent studies (No-Look Notes and Mobile Messenger) were also researched around the numeric keypad [14, 95]. Mobile Messenger entered letters by the user moving their finger to one of the numeric keys on the keypad and then waiting for the letter they wanted to be spoken, e.g., leaving their finger over the number one and hearing a, b, and then c spoken out loud. Then, they would lift their finger to select the character. No-Look Notes took an approach where the user had to split-tap to move through the letters and then double tap to select the desired letter, but this had no haptic feedback as the previous study by Buzzi et al.

## **2.4 Graphical Information Access**

While there is general access to touchscreens through gestures and touch by exploration and there is text entry gestural access, these techniques do not work for

graphical information. For example, exploring a map through the use of touch exploration would be slow and tedious. Also, drawing items on the screen is a very different type of gestural input from trying to tap a button.

### **2.4.1 Graphical Information Navigation**

Access Overlays are guidance techniques that help the user navigate the screen and understand spatial relationships in a faster way [56]. They provided three techniques: edge projection, neighborhood browsing, and touch and speak. Edge projection would place all the items on the screen along the edges of the touchscreen. The user then could touch the edge to find the item they are looking for and then move their finger vertically or horizontally to find the location on the screen. Neighborhood browsing would be activated by a gesture and tell the user the nearest item location in inches. Touch and speak would allow a user to tap the screen and give voice commands which would be centered around their finger placement on the screen. Voice commands included directions to a target, speaking all targets on screen from left to right, or reading all nearby targets. In usability studies with a map application, users were able to perform better most of the time than using Apple's VoiceOver techniques. These techniques were used on a large tabletop touchscreen and included bimanual interaction, e.g., a user could touch a target with one hand while browsing a menu for actions on that target with another hand.

AudioGraph was another approach that focused on diagrams [60]. Everything around the user's finger in a square would be spoken aloud sequentially, and the user could change the size of the square. Objects and their relations to each other

would be described, and by touching with more pressure, attributes of the elements of the diagram would be spoken.

A different study looked at how panning around a map or other graphical information can be performed on a touchscreen [83]. They tested several gestures to allow panning around a map, and they found multi-touch gestures were preferred. They also found that there was even better understanding of the map through panning. They tested them on blindfolded sighted subjects. There are other methods for exploration of graphical information, which are dependent on other output modalities, and these will be discussed later with their specific non-TTS output modality sections.

## **2.4.2 Graphical Information Creation**

Instead of the exploration of graphical information, TDraw was a research project that focused on the creation of graphical information by visually impaired subjects on touchscreens [63]. The system used a graphics tablet and pen, and the subjects were able to draw lines and polygons in a free hand style. The free hand style resulted in wiggly lines rather than straight lines, but the subjects were able to draw some pictures such as chairs and tables. As the pen went over a drawn line, a verbal tag was spoken which the subject had provided using voice. The voice input was simulated through a Wizard of Oz interface. The subjects showed enthusiasm for the system and a desire to draw the pictures.

Using gestures to create graphical information such as pictures, games, and diagrams is a little explored area of research. New research in this area could include drawing of circles and curved lines rather than only straight lines and the

placement of pre-created shapes and objects on the screen in specific relationships.

## 2.5 Non-visual Speech Input

People with visual impairments are using speech input more and more for touch-screen mobile devices. Azenkot and Lee found that 90.6% of blind and low vision users have recently used dictation on their smart phones, which was 35% higher than sighted people [9]. Azenkot and Lee further found that typing rates were 5 times faster with dictation than the keyboard for the visually impaired subjects, that the visually impaired subjects were more satisfied with speech input than sighted people, and that they spent 80% of their time doing error correction by editing of the text after speech input. Azenkot and Lee identify several new research issues including better text selection with copy and paste, better movement around text, easier ways to detect errors in dictated speech, and a study of auto-correcting errors.

While three platforms contain voice-controlled systems (Siri [5] on iOS, Google Now [40] on Android, and, most recently, Cortana on Microsoft mobile phones [75]), it is unknown how much visually impaired people use these systems to interact with their mobile devices, nor how effective it is when they do use these systems. JustSpeak was a research project to expand and improve these types of voice control systems on mobile devices for visually impaired people and people with motor impairments [117]. JustSpeak is different in that it allows access and control to any application that already has accessible tagged UI elements made for screen readers. The user can speak a word or words and the system will try to find the matching accessibility tag on the screen and click that button. It is also



different in that it allows for multiple words to be spoken at the same time such as 'open and refresh' which will open an app and then refresh it. No user studies were done on this system to test its effectiveness and quality.

A research project tested voice input compared to gestures and keyboard with visually impaired users [61]. The researchers offered gestural input, on-screen keyboard input and speech input for browsing the web. They tested the system on a weather map. Gestures allowed the users to find weather in a given direction and distance. Voice input allowed the users to search for specific time and date. Keyboard input allowed them to enter information in text fields to search for the same. Most users found speech input to be fastest and easiest even though it was more error prone. Gestures were not as useful though the users liked them. On screen keyboard was found to be slow and tedious.

## **2.6 Non-visual Sensor Input**

Many smartphones and tablets with touchscreens come equipped with sensors such as compasses, accelerometers, gyroscopes, cameras, microphones, and GPS. These sensors provide input to many types of apps such as exercise, navigation, and games. These sensors can provide people with visual impairments better access to touchscreens by allowing them to access apps without the need of touch or voice, e.g., step detection.

Virtual Shelves is a research project to leverage users' ability to remember different spatial locations in front of them and use them as a bookmark or to send a text message or another function [68]. The users held the phone in front of them and pointed it at a location such as to the left and down to select one of

the 'items' on the virtual shelves. The sighted users performed these tasks blind-folded. When performing the tasks visually with a mobile touchscreen phone as compared to the blind-folded method, the users performed faster with virtual shelves but had a higher error rate. Li et al. continued this research with users who are blind and visually impaired [69]. They discovered that these users performed with less accuracy than sighted users. But the system with the blind and visually impaired users would speak the shortcut out loud as they passed over it with the smart phone. A further test was done with the users being allowed to customize what shortcuts went on the virtual shelves and where they were located. In this study, the users performed with even better accuracy and faster time. The subjects reported that they felt virtual shelves was even faster than their current user interface for their smart phones.

The sensors can also make smart phone games accessible to people who are blind and visually impaired. Mobile game sales are taking over gaming and are starting to sell more than console games [35]. Virtual reality and augmented reality games on mobile touchscreens are being made accessible with sensor input with the compass, gyroscope, and accelerometer. Several popular games for iOS have been made using this technology. One of the more popular, even for sighted users, in which there was no visual feedback but only audio, is called Papa Sangre [33]. It is a game in which the user moves around a virtual world by tapping on the bottom of the screen to move and tapping on the top of the screen to use their hands. The objective is to escape the levels and obstacles put before the user. One limitation was that users could not both move and use their hands at the same time. More complex game interactions on touchscreens are a promising area of research for creating multi-player social games, educational games, and exercise games. There is a vibrant community of blind and visually impaired game enthusiasts for mobile

games. AppleVis and AudioGames.net contain many examples of accessible and not so accessible touchscreen mobile games

## **2.7 Audio Output**

Audio is the main form of output used by people with visual impairments to access touchscreens. There are two main forms of audio output: speech and data sonification.

### **2.7.1 Speech**

Accessibility technology such as screen readers use TTS or pre-recorded human speech as their main form of accessibility output modality.

#### **Human Speech for Touchscreens**

There is accessible technology that uses pre-recorded speech. Some examples include products from MarvelSoft. They have pre-recorded speech for digital music players, learning typing and math skills [?]. There is also narrated movies and television for the blind and visually impaired with pre-recorded human speech [80]. For touchscreens, the voice of Siri is partly pre-recorded human speech [5].

Brady et al. investigated the frequency and type of speech output for navigation applications such as directions through an indoor mall [15]. They used a Wizard-of-Oz technique with the output as the live voices of the researchers giving

directions. Although they did this without a touchscreen, these navigation apps are typical of touchscreen mobile phones, and the results are applicable. They tried various frequency and amounts of information such as updates on distances every 30 feet or every 10 feet and with and without landmarks, and they compared this to data sonification (beeps playing faster as they got nearer to a landmark). All subjects in the user study felt that they could use even more information when navigating. They also felt that the interface was better with speech than with data sonification because it gave them a better descriptive picture of distances.

### **TTS Screen Readers for Touchscreens**

TTS refers to translating text into synthetic speech very quickly. TTS can be distinguished from pre-recorded audio, e.g., an audio book or snippets of words being spoken by a person. TTS interprets words and pronounces them on the fly through synthetic speech. This allows apps to be spoken aloud without the app developer needing to provide their own recorded audio.

The most common use of TTS for people who are blind and visually impaired is screen readers. There are both screen readers for desktop or laptop computers, which take keyboard input as their main form of access, and screen readers for touchscreens, which take gestural input as their main form of input (voice input does not typically go through the screen reader).

In one commercial implementation of a screen reader for a touch screen, Apple's VoiceOver, which we have previously described, can be used in such a way that moving one's finger over some text will read the text aloud from beginning to end. The user can change from reading the whole container to reading one char-

acter, one word, or one line at a time. Simply by swiping down, in the case of line reading, the screen reader will move to the next line and read it. If the user swipes down again, the next line will be read aloud. In this way, users with visual impairments can read large chunks of text in small bites or spell out words with a set of swiping gestures.

The screen reader also has configuration settings to allow changing the speed of the speech, whether to read punctuation, and the ability to change the voice itself, e.g., a female voice or male voice or a different accent.

Stent et al. tested the ability of early blind (blind before the age of 6) to understand very fast synthetic speech [98]. For the measurement tasks, the users had to transcribe semantically meaningless sentences. They discovered that the users could understand 500 words per minute with 50% transcription accuracy. 500 words per minute is approximately 2.5 times real time human speech.

Guerreiro and Gon'alves investigated concurrent synthetic speech with blind and visually impaired users [42]. The users had to identify and understand snippets from news articles with 2, 3 or 4 synthetic voices speaking. The voices were localized with binaural sound. Binaural sound simulates the real acoustics of the ear. It uses inter-aural time differences, which is the difference in time that a sound reaches one ear rather than the other ear, e.g. a sound from the left will reach the left ear first before the right ear [25]. Binaural sound also uses inter-aural level differences (ILD), which are the differences in volume of distance from one ear rather than another ear, e.g., a sound coming from the left side of a listener will be louder in the left ear than the right ear. These binaural sound cues can be recorded with two microphones in the ears of a dummy head with the same dimensions of a typical human head, or they can be created through simulators using a head-

related-transfer function such as OpenAL [?]. This is different than 3D sound, which only uses left and right panning for sound localization. They discovered that users were able to still understand hearing two voices at approximately 278 words per minute. They also discovered there was no statistically significant difference between blind and sighted when understanding concurrent speech [43]. They further tested concurrent speech on touchscreens (see section 3.2.1) citeGuerreiro2015.

Prosody, which is the natural rhythm, stress, intonation and pitch of spoken language, has a beneficial effect on TTS systems, especially for the use of spoken mathematical equations [12]. When the TTS speaks the equation, each different level of nested equations will be spoken 6% faster, Furthermore, there are extra beeps to denote parenthesis. To further make the equation easier to understand, this system uses spearcons, which are compressed words spoken very fast, and they are only understood through the sound and inflection. For example, begin fraction and end fraction are turned into spearcons to quicken the speed and better understand the equations.

### **2.7.2 Data Sonification**

Many screen readers for touchscreens incorporate non-verbal sounds. Flicking, swiping, and tapping can be accompanied by sounds that designate successful completion of the gesture. They are also used in menu navigation. If the user comes to the end of a list, typical screen readers will make a negative noise denoting the bottom of the list and perhaps a different one denoting the top of the list. A sound may also be made to designate focus movement to a new item in the list.

There has been research into how to make menu and movements through lists easier for people with visual impairments on touchscreens [109]. Auditory scroll bars for menus were tested using pitch polarity and four designs: single tone, double tone, proportional grouping, and alphabetical grouping. In each of the four designs, pitch polarity would cause the tone to increase or decrease in pitch as the user goes higher or lower in the menu. Both conditions higher pitch for higher menu items and lower pitch for higher menu items were each tested. Single tone design plays a single tone for each item in the list, with a distinct tone, and then the TTS item is spoken. Double tone plays one distinct tone for each item in the list a one tone of the last or first item in the list (first if they are scrolling up and last if they are scrolling down to tell them how far away from the end of the list they are). The proportional grouping plays a musical note on a scale of 8 notes and breaks the menu up into groups of eight. If the user is on a group, then that one musical note will play as they scroll through all items in that group. Alphabetical grouping is the same as proportional grouping except that it assigns a musical note to each letter in the alphabet and plays that note for each grouping of words that start with that letter. The first three types of scroll bars were tested on people with visual impairments (the alphabetical grouping was left out as it did not do well in studies with sighted users). They tested the different designs and polarities on menus with 8, 24 and 48 menu items on a mobile phone with a touchscreen. The results showed that the users performed best and had lowest error rates with proportional grouping scroll bars. They also gave the best subjective feedback for proportional grouping, but 3 of the participants did prefer single tone. Double tone performed the worst out of all. This suggests designing auditory menus around the proportional grouping menus would provide people with visual impairments the best performance and user experience on average.

Another research project looked at how to speed up navigation through alphabetically ordered menus or lists of items, Jeon and Walker invented the idea of spindex [50]. A spindex is the first letter of a word pronounced by itself and possibly sped up using synthetic speech. On touchscreen mobile phones, spindexes were tested to scroll through address books. It was shown that the spindex TTS increased the performance of the sighted users on average over the TTS only version of scrolling through the items. Further, an attenuated spindex, where successive spindex cues decreased in amplitude, allowed users to perform even faster at the list search task than the non-attenuated cues. These two experiments were done with sighted participants while the third experiment was done with people who have blindness or a visual impairment. The third experiment showed that people with visual impairments performed better with the spindexes than with the TTS only, and they rated the spindex condition as more helpful than the TTS condition. Furthermore, qualitative responses showed that all users preferred using a spindex over TTS only. This research was continued testing different types of gestures in combination with the spindex, but people with visual impairments were not involved [51].

Besides making menus more accessible with data sonification, there have been several attempts to make graphical information accessible with data sonification. PLUMB was a research project to make graphical information accessible with a pen and data sonification [26]. It is similar to games in that it plays a sound over a line, and the sound gets lower in volume as the pen moves away from the line. A text to speech designation is played when a user reaches a vertex, and the user can right click on the vertex in order to hear information about it such as how many edges are connected to it and in which directions. There was a small user study with good results on some simple, custom-made graphs.



EdgeSonic was an attempt to automatically sonify general graphical information presented in any app or image [113]. After the graphical information was processed, sounds were played when users put their finger over the lines of a shape in an image, and when they were off the outlines of shapes, a pitch played which went up higher as they moved towards the nearest edge. With training, test subjects were able to reproduce some of the shapes in the images.

### 2.7.3 Stereo Sound

Earpod [116] used stereo sound to help the user remember where the menu item was placed in a clock around the center of an iPod. The researchers hypothesized that this was a helpful feature to remember where the item was on the screen but no specific analysis on this feature was performed.

In a similar project unrelated to touchscreens, researchers found that using spatial sound cues for tables on webpages, e.g., hearing a beep in the left ear to designate a far left column and in the right in to designate a far right column, along with pitch going up and down to designate different rows, showed no improvements and sometimes worse performance in sighted subjects when compared to navigating tables without the sound cues [87]. No tests were done on people who are blind and visually impaired.

Instead of items in a clockwise menu with static stereo sound, GUESS was a project that used the location of shapes and identifying different shapes through panning stereo sound on touchscreens [54]. The stereo sound would play the shape as if the sound were tracing the shape. For example, a right triangle's base would be heard as a sound going from the left speaker to the right speaker. The

vertical side of the triangle would be a sound heard going from the bottom right to the top right, which is represented by a lower pitch to a higher pitch. This technique was not used on more complex shapes, and mono sound was used to locate the shapes on the screen.

A more complex shape-learning interface called Timbremap was made and tested on participants who are blind [99]. The application was used to learn maps, but non-trivial geometrical shape learning was also tested. When on a path or line, no sound is played but as the user moves off the line, audio hints in stereo are made to let the user know which direction to go in order to get back to the path. Only four compass directions were used, and to designate north or south, high pitched and lower pitched earcons were played respectively. The interface also had another exploration mode for large scale learning areas by the user running their finger over the map quickly in wide strokes. Paths were silent, and areas that were empty played various sounds. Usability study results of learning the shape and learning directions were good.

Follow That Sound used stereo sound to teach people who are blind to learn gestures, which require some spatial understanding of the shape of the gesture Oh2013. In a stereo headset or speakers, the users hear a sound in the direction they need to move their finger along the touchscreen. Some of these gestures make shapes such as triangles.

## **2.8 Haptic Output**

People with visual impairments use haptics mostly as a secondary form of access to touchscreens. Haptics can be vibrations, tactile overlays, or friction on the surface.

### 2.8.1 Vibrations

Tactile vibrations on text entry with soft keyboards have been shown to increase performance for sighted users [16], and tactile feedback for soft keyboards have become standard for android accessibility for people with visual impairments. A slight vibration occurs as the user's finger moves from one key on the keyboard to another key while TTS speaks the key itself. No user studies were done in the effectiveness of this haptic feedback.

In BraillePlay and V-Braille, vibration only feedback to make Braille accessible on touchscreens has also shown some promising results [49, 76]. The touchscreen is divided into six sections, one for each of the Braille dots. This allows distinguishing between different Braille dots with no audio feedback. The time it took to read characters and a sentence was much slower than physical Braille reading.

Another project presenting the reading of Braille characters used a faster and more localized vibration method called a piezoelectric actuator [91]. The experimenters had the subjects read one Braille character at a time and one Braille dot at a time in the Braille character. The vibrations were localized on the screen to give a better spatial feel of the Braille. Raised Braille dots were represented by higher amplitude vibration while lowered dots were lower amplitudes. Three methods were used. The first divided the screen into six sections, one for each Braille dot. A stylus was used to explore the Braille character. A single gesture going up and down in one scan was used to read the character. The second method laid the dots out as in a Braille typewriter, and the users made a sweeping gesture across the screen to read the character. The third method was temporal encoding in which the users felt patterns of vibrations at the same location on the screen in intervals

for each dot of the six cells. All three methods had over 90% recognition accuracy, and the mean reading time of the rhythm method was fastest while the other two methods were comparable to each other. The mean times were much slower than printed Braille, 0.2 characters per second (CPS) and 5 CPS respectively.

Instead of augmenting Braille reading, PocketMenu looked at using vibrations alone to move through a list. Vibrations were made to occur when moving to new items in a list on a touchscreen, and it was shown that people can memorize the order of list items and only need the vibrotactile feedback to move around the screen and select the desired menu item [86]. In comparisons done with Apple's VoiceOver, which uses many of the above TTS list based interactions, the selection time, error rates and satisfaction were higher with the vibration only feedback than with the VoiceOver feedback.

Even more complex haptic output has been used to identify different lines, shapes, differences between shapes, and spatial relationships through purely haptic feedback [7]. The success rates were around 50% to 60%, and further modifications need to be made to increase success rates and speed of learning.

## 2.8.2 2nd Generation Haptic Devices

Current commercial vibrators have many limitations such as long delays, non-localized vibrations, and too much power consumption, but new vibrators in research labs have been invented which take lower power, provide faster response time, and have localized vibrations. People who are blind have tested such feedback for the identification of shapes and the freehand drawing of shapes on touchscreens in TeslaTouch [108]. The users expressed satisfaction for the new feedback

but the speeds were slow and success rates not so good.

Another research project that used more advanced vibration technology divided the screen into different semantic sections and gave haptic feedback to let the user know which section they were in [18]. Semantic sections of an app have different meanings and uses to the user. For example, they divided the Gmail email client in Android into different semantic sections such as email lists, header content, editing sections and so forth. Each section had its different vibrational effects to let the user know where they were in the app. There were no user studies done on this interface.

The TPad is a project that gives Friction feedback through ultrasonics on the surface of the touchscreen Mullenbach2013, Mullenbach2014. It can give the feel of textures. It was initially integrated with a Kindle tablet and then a Nexus 7. User studies showed the effectiveness in communicating with friends and strangers through the friction feedback. The TPad was used for accessibility in another project through integration with the Android OS [52].

### **2.8.3 Tactile Overlays**

Kin'touch used tactile overlays for map exploration on a large tabletop that could sense up to ten finger touches at the same time and also combined motion detection for more accurate finger touch readings [17]. They were able to detect finger motions that never touched the screen, allowing faster exploration by the users, while also ferreting out accidental finger touches or palm touches.

Touchplates is a less expensive approach [57]. They only require paper or

plastic cut into various shapes possibly with holes cut in them. These different shaped pieces of plastic are then placed and moved around on the touchscreen by the user, and the touchscreen will then recognize the shape and perform different functions accordingly. For example, a round piece of plastic with two holes next to each other act as a mouse where the holes are the buttons. They performed an exploratory user study on a map application running on a tabletop touchscreen. Users dislike some of the touchplates, including all users disliking the mouse touch plate. They liked other ones, such as various shaped ones that they could place on the touchscreen and ask the application to save that location and attach it to that touchplate, and then the users could simply place the touchplate on the screen to return to that location.

Instead of a maps application, tactile overlays to augment reading of large amounts of text such as a book were created and studied [32]. Pieces of plastic with horizontal lines spaced apart similar to a ruled piece of notebook paper were created and placed over an iPad. Visually impaired participants were then asked to read text using the overlays and qualitative feedback was elicited. One difficulty of their approach was that many applications had different layouts where large chunks of text might appear. This would require the making of many custom overlays for each app.

## **2.9 Multimodal Input**

Data sonification and vibrations have been used together for people with visual impairments to learn the spatial layout of graphical information on a touchscreen [37]. People with visual impairments attempted to identify bar graphs, letters,

and orientations of geometric shapes through a vibro-audio interface. When the user's finger touched the lines, a vibration occurred and when tapping on the screen audio information was given such as their location in the graphical information. While results were promising with high success rates of identification, the speed was much slower than physical tactile diagrams, and a technique to speed up performance needs to be investigated.

In another prototype, a maps application was made which allowed accessibility through stereo sound, vibrations, and TTS [53]. As the user moved their finger along roads, the tablet vibrated, while stereo sound was used to designate the existence of crossroads. TTS gave further information about the roads such as names. But it was unclear how they represented distances, and further they performed no user studies on the application.

SemFeel was a project that used multiple vibrating motors attached to the back of a mobile phone [111]. They included a sleeve on the back of the device which touched a user's palm for better feel of the vibration. They also tested circular vibrating patterns. In one user study, the participants were able to distinguish the vibrating patterns but were confused by multiple different circle vibrating patterns. Their second study was eyes-free (but did not include blind participants). In this study, the subjects were allowed to support their dominant hand with their non-dominant hand as the device was heavy due to the motors. The users placed their thumb on a keypad to enter different numbers and each key vibrated differently. The results showed better eyes-free usage of the numeric keypad as compared to without vibration or with only one single vibrating motor.

SpaceSense continued the research of SemFeel with blind subjects [110]. An app was developed using TTS and 9 vibrating devices attached to a touchscreen.

Each vibrator represented one of eight directions on the compass while the 9th vibrator was in the middle. The user would hold the touchscreen in their hand, and then flick to hear directions spoken out loud. If the direction said to go north, then the top of the device would vibrate and so forth. The results of the study showed that users with visual impairments were able to get a better spatial sense of an area with the app than without. But further research needs to be done with second generation vibrational devices as current vibrators used in this study could wear out the batteries very quickly, could cause too much heat, and could be bulky in its form factor. It still needs to be seen if this could be made commercially available.

A similar technique called TGuide with 8 vibrators attached to a stylus for a touchscreen tablet was devised and tested but only on simple target acquisition with no complex maps [64].

## **2.10 Multiple Device Input and Output**

In Duet, Chen et al. showed that multiple devices can be coordinated together for new interactions [23]. One device can serve as input while the other serves as output or vice versa. Or both devices can serve as input or both as output. In their example prototype, they used two touchscreens, one on a smart watch and another on a smartphone. Users performed gestures such as swiping starting from the watch screen onto the phone screen and vice versa. Their user studies with example apps showed promising feedback and usefulness.

This research can be furthered with the idea that multiple devices can be connected to touchscreens to make them more accessible. For example, Apple Watch provides both input and output to their smartphone along with the input and out-



put to the smartwatch touchscreen itself. The smaller screen on the Apple Watch might make existing app interfaces such as Pandora easier to navigate as there is less screen clutter, but this has to be researched to be confirmed. Unlike android smart watches, which only have larger print access for people with low vision, Apple Watch comes equipped with the full-blown VoiceOver screen reader. But currently there has been no study looking at the effectiveness and usefulness of small touchscreens on people with visual impairments.

### **2.10.1 Multiple Device Input**

Perkinput was also attempted on two different smartphones at once. The user places their hand on one phone for dots 1 through 3 and their other hand on another phone for dots 4 through 6, which achieved up to 20 WPM [11].

A wristband type device, without a touchscreen, was made to pair with an iOS device and to be used to operate the VoiceOver screen reader [112]. The device has raised buttons and tactile guidelines separating the different buttons. There are only three types of buttons: home, select, and navigate left/right. Touching the home button will take the user back to the home screen, select will select the current app or button that VoiceOver is focused on, and the navigation button moves accessibility focus one to the left or one to the right in the list. The users do not interact with the iOS touchscreen. In interviews, the participants found the device easy to use and had a willingness to use it in the real world.

Porzi et al. developed a smart watch app that would recognize arm movements through the accelerator of the watch [89]. First, the smart watch is tapped to start the app, and after the gesture is performed, the user's smartphone then activates

the desired function. One example app was to perform a gesture that activated the phone's camera to identify wet floor signs. The watch and phone were able to process and recognize some of these gestures with good success rates.

### **2.10.2 Multiple Device Output**

A smart watch was made to provide eyes-free interaction for sighted people with haptic feedback that would allow them to count the number of emails or messages they had in their inbox [85]. The number of vibrations was equal to the number of emails. The users expressed that they did not want to count the number of emails but would rather be given notice if there were lots of emails or few emails. In this case, the numerical counting with vibrations from the watch did not seem to give much benefit to the users and was difficult to perform. Also in their paper, they suggest the use of both the vibrator on a smartphone and the vibrator of the watch to receive two levels of information. Their example was to use the watch vibrator for high priority notifications and the smartphone vibrator for low-level notifications. But they did not suggest interaction with the mobile device's touchscreen for non-visual haptic interaction from both devices nor did they have a more complex example. They also did not perform any user studies on this, nor did they make a prototype to do this.

In another project using multiple output devices, Nicolau et al. attached six small vibrators to the fingers of users with visual impairments to see if haptic feedback to confirm their Braille input on the touchscreen would increase productivity and reduce errors Nicolau2013. Results showed that single vibrations were easily distinguished with 100 accuracy on each finger, but multiple vibrations to multiple

fingers only had about 80% success rate. No studies were done with people with visual impairments.

GraVVITAS was a research project that used vibrators attached to the fingers in order to support bimanual interaction to explore spatial information such as line graphs and floor plans on a touchscreen [39]. When a finger touched the screen, it would vibrate differently depending on whether it was on a line, inside a shape, or on a vertex. They complemented this exploration technique with stereo audio sound with bimanual interaction and text to speech descriptions. In the stereo audio, there were two modes: 1) stereo sound was played around a single finger limited by a small circle as not to play the audio of the whole screen at once, and 2) stereo sound played describing lines and shapes between two fingers that were on the screen. The text to speech was spoken about a line or shape when activated by a gesture. Most participants expressed satisfaction with the tool, but the times of exploration varied greatly.

## **2.11 Accessibility for People with Low Vision**

The Apple's iPhone has zoom to make apps and print larger for people with low vision, along with larger text and bold text settings. It allows inverted colors, along with changing the contrast settings, to make contrast of text stand out more, e.g. switching black text on white background into white text on black background. There is also a setting to turn all the colors to gray. Low vision users can change button shapes allowing for larger boxes to be put around buttons. There is also a setting to reduce motion of icons that float around.

There have been a few research projects that looked at low vision technology for

touchscreens. A research project looked at adapting touchscreen target sizes and font size automatically for people with low vision [Montague2012]. They tested three apps on an iPod touch with 5 low vision users. During the first session, they had the participants touch targets, learn indoor navigation (through a map on the touchscreen), and move through television listings. On the second session, they adapted the interface based on the previous session. They found subjects committed less errors while touching targets than without the adapted user interface.

Another study focused on gestural magnifiers [65]. A gestural magnifier is one in which the zoom is changed through pinching or swiping while another gesture is used to move the magnifier around the screen. They compared the iOS gesture magnifier to that of magnifiers on mobile devices that use knobs or buttons to zoom in and out and move around the screen. Their study concluded that people with low vision overwhelmingly preferred the gestural magnifier. None of the participants had experience with gestural magnifiers before.

## **2.12 Understanding the User's Needs**

In this section, we look at studies that investigate the preferences and needs of the users. These studies do not introduce any new techniques nor any new prototypes. Instead, they evaluate current technology with blind and visually impaired users and try to understand better the problems and preferences of the users. The studies address the issues of what accessibility problems may still arise in current touchscreen technology.

One important issue is the inclusion of the target users in the evaluation and design of new touchscreen technology. Research into assistive technology can have

an impact when people with disabilities are included in the design and evaluation of the technology [94]. This does not guarantee success, but research into technology that does not include representative users is likely to fail. It is important, then, to evaluate touchscreen research with people who are blind and not with people who are blindfolded. But evaluating people who are blind is not enough. As Sears and Hanson pointed out, differences in people's level of blindness and age of onset of blindness can be very important. A thorough description of the people with visual disabilities is necessary in order to substantiate claims of generalizability. Things are further complicated by the fact that diversity between individuals with disabilities affect technology usage much more than individual differences between people without disabilities. Memory, for example, may have a bigger impact for people who are blind than people who are not blind because people who are blind must remember things that are typically conveyed visually, e.g., the location of a button. Therefore, levels of blindness, age of onset, and diversity of different characteristics must be taken into account for new touchscreen technology as for any accessible technology.

A study focused on understanding the preferences and usability of gestures on touchscreens by people with visual impairments [58]. Two studies were performed that compared people with visual impairments with those who are sighted and how they perform gestures differently. The first study had the participants invent their own gestures for actions provided by the researchers, e.g., copy and paste. This experiment found that people with visual impairments invented significantly different types of gestures than people who are sighted. Differences included more often creating gestures that used two hands, that were based on a QWERTY keyboard such as CTRL-V gesture for paste, and that used corners or edges of the screen. In the second study, the participants were asked to perform a

set of gestures as described by the researchers, e.g., draw a circle. This study found that people who are blind take more time to perform gestures, perform larger gestures, and performed gestures with wider variation in size. The researchers concluded with a set of guidelines for creators of touchscreen apps, e.g., favor corners and edges.

A similar study also looked at preferences of people with visual impairments for gestures on a touchscreen [20]. They conducted their study with 36 visually impaired subjects, and they ran 3 studies concurrently with 3 different researchers. Their results showed that people with visual impairments overall preferred simpler gestures to more complex ones and preferred rounded gestures rather than straight or angled gestures. A straight gesture would be swiping up in a straight line across the screen, and an angled gesture, for example, would be making a z shape across the screen or an L shape. Simpler gestures included gestures with only one finger, and gestures that would include one stroke. The researchers also noted that the subjects would sometimes run their gestures off the edge of the screen, which would cause the touchscreen to believe that they were finished with the gesture. This would slightly contradict Kane et al.'s study that encourages gestures designed around corners and edges of touchscreens.

Another study looked at eyes-free absolute positioning of fingers on the touchscreen in order to control the smart phone [104]. While not using visually impaired participants, the study showed that eyes-free interaction was worse at the middle right and had higher error margins along the vertical rather than the horizontal.

A more general study was done on Apple's VoiceOver to find existing issues that people with visual impairments are still encountering [67]. They discovered that many times links or buttons were not being announced, that navigation se-

quentially through the screen was not always logical, and when editing text, the user lost focus and knowledge of the edit field that was being typed into, which causes problems for verifying what was typed. One blind subject did this inspection of VoiceOver and 2 sighted subjects with the screen curtain on.

Another study looked at more general touchscreen use by people with visual impairments in the wild [93]. The researchers provided 5 visually impaired subjects with android touchscreen smartphones with TalkBack installed and enabled on them. The 5 participants never used a touchscreen before. They tracked their learning, adoption, and usage of these touchscreen phones over 8 weeks. First, the researchers found that the built-in tutorial for TalkBack was difficult for all participants to complete and learn from. Second, the subjects struggled to use all the gestures on android consistently, and many did not use complex gestures such as L shape even after 8 weeks. Third, many subjects found the device slower than their previous device even after 8 weeks of learning, and lastly, the subjects had many problems with the inconsistency of screen layouts even within the same app. Many of the subjects wish there had been a manual to learn from or a person to rely on when they needed to do something like send a text message. This study only looks at android when it is known that most visually impaired people have adopted iPhones, and this study could be further extended out to other smartphone evaluations. Furthermore, this study only looked at early adoption experiences, which is important, but further insights could be gained from the problems encountered and discussed by long term users of touchscreens.

There have been some evaluation studies that looked at current text entry on touchscreens. A recent study recorded the learning of typing on a mobile touchscreen by novice users Nicolau2015. They discovered that novices learn touch-

typing rates 0.3 WPM on average per week during an 8-week period and still improve their typing rates after that time period. They also discovered there was a lag between the character of the keyboard being spoken and the location of the finger depending on the current speed of the TTS engine. This would cause subjects to accidentally enter a character they thought they were on. By week 8, subjects were landing on or near keys much more often at 91% success. The researchers did not specify the activation of the particular key on the keyboard. There is lift off activation where the key is immediately pressed when the lift off of the finger occurs, and there is double tap activation where the user double taps anywhere on the screen to activate the last key entered.

A less recent study of text entry typing of touchscreens with visually impaired people was done Oliveira2011. The study compared four different typing methods: traditional QWERTY keyboard layout, a keypad type layout, NavTouch (a directional movement between the alphabet as described before in section 3.2.4), and a Braille typing method with the screen divided into six Braille dots and a long press activates one of the Braille dots. The purpose of the study was to demonstrate that different people desire different typing methods, and one typing method does not fit all people.

## 2.13 New Research Directions

In this section, we look at research issues:

1. **Creation and editing of 2D and 3D content.** There are many apps on touchscreens that allow sighted people to manipulate and create 2d and 3d graph-



ics such as simply painting apps to more complex apps. The majority of accessibility research on touchscreens has focused on making textual content accessible using speech or haptic feedback, yet little research has been done in the area of visual content creation. Only two research apps look at visually impaired and blind people drawing 2D graphics on a touchscreen. The creation of static and dynamic information is important for such tasks as educational class projects like geometry or chemistry, art for enjoyment, work presentations and documents.

2. **Navigation of 2D and 3D graphical information.** Much of the content presented on touchscreens is graphical in nature. There have been several research projects on making graphical information accessible through various navigation techniques, but many of these techniques remain slow and error prone. More research is needed in order to create faster navigation techniques that are easy to use. Furthermore, no projects have looked at making 3D graphical information accessible. Such improved navigation techniques could be implemented into a new type of screen reader that can navigate graphical content.
3. **Collaborative work between sighted and blind users.** There have been research projects on collaborative large sized touchscreens for people with vision, but making collaborative work on touchscreens accessible to people with visual impairments has not been researched at all. Given that people are often required to collaborate it should be possible for visually impaired people and sighted people to efficiently work together on different sections of a tabletop sized touchscreen for work or education.
4. **Accessibility of large size touchscreen devices.** Table and wall sized touchscreen devices have become more common but existing accessibility research

has mostly focused on smaller hand held touchscreen devices. Only one research project has looked at large touchscreens [56]. Existing accessibility techniques don't seem to scale up very well to larger screens. It is much more difficult to find items on larger screens and especially when multiple movable objects are present, remembering their locations becomes quite a challenge, due to the limited size of human spatial memory and the fact that spatial memory tends to fade over time.

5. **Editing of text.** As demonstrated by Azenkot and Lee's study [9], editing of text can be difficult and time consuming for people with visual impairments. The problems include moving around the text efficiently, deleting text, copy and pasting text, and auto-correction accessibility.
6. **Accessibility of text entry.** While Braille input has been researched and implemented commercially, vastly increasing typing speeds for visually impaired people, many of them do not know Braille and thus still rely on the QWERTY keyboard input method. A new direction of research is large QWERTY keyboards that can be placed in full sized mode. Research has been done on these full sized QWERTY keyboards with sighted people but not blind people. Further research is also needed on text entry for small devices for people who do not know Braille.
7. **Video game accessibility.** The past decade, video games have increased in popularity and mobile devices have become a major platform for games. Most game accessibility research has only focused on the PC/console market [114]. While there have been a few games made for people with visual impairments on touchscreens such as Papa Sangre [33], this area remains largely unexplored. One promising area could be augmented reality games where blind people could navigate virtual reality by taking real steps. Fur-

thermore, there is also the possibility of making top down computer games accessible such as real time strategy games. Making such games accessible could be achieved using spatial sound.

8. **Understanding the users' needs.** There have been no studies looking at general touchscreen use in the wild by people with visual impairments. One study has looked at touchscreen adoption by novice users, two studies investigated preferred gestures while another study looked at accessibility issues of Apple's VoiceOver (see Section 11). We believe there is still room for doing interview or observational studies on the use of multiple different touchscreens that people with visual impairments have been using on a regular basis. This would help identify accessibility problems and could lead to new accessibility solutions.
9. **Using multiple devices to create assistive technology.** The emergence of wearables, such as smart watches, creates new opportunities for multi-device interaction, with potential accessibility applications. Using multiple devices for creating assistive technology has barely been scratched as illustrated by Table 1. The learning of spatial information using a pairing of a smart watch with a tablet or smartphone is a potential research area. Further, multi-part gestures using two or more devices could create interesting interactions. For example, the exploration of graphical information through the use of a smart watch and tablet.

## CHAPTER 3

### A STUDY OF BLIND PEOPLE'S USE OF GRAPHS AND DIAGRAMS

#### 3.1 Introduction

Diagrams and graphs are an integral part of people's work and school on a daily basis. Every discipline from physics and chemistry to software engineering and economics uses diagrams and graphs to visually convey important information. For example, the trends in the stock market might be shown in a news paper with a bar graph, or the ethnic make up of a population might be displayed in a pie chart in an academic article. These diagrams and graphs are necessarily visual forms of information, and hence are not accessible to people who are blind and visually impaired. While some of these diagrams and graphs have current accessibility solutions for this population, many of these solutions have problematic limitations. For example, raised line or tactile forms of these diagrams and graphs suffer from taking up more space and have coarser granulation than their sighted versions. Furthermore, the creating and editing of diagrams and graphs have almost no accessibility solutions. 3D CAD tools for example are not accessible in either input or output.

In order to better understand this problem, we conducted 21 semi-structured interviews with blind and visually impaired people. We asked them what types of diagrams and graphs they were attempting to access or create, how they were trying to solve this accessibility problem. We categorized and analyzed the types of diagrams and graphs they were attempting to access and create. We looked at common features and problems that cut across these different diagrams and graphs. We present an analysis of these common features and how researchers

might leverage these commonalities to create better accessibility solutions.

## **3.2 Methodology**

### **3.2.1 Participants**

There were 21 participants in the study. 18 of them had no functional vision. Three of them had low vision but used a screen reader on a regular basis and did not use magnification software. 9 of them were blind from birth, and the other 12 were blind later in life. 7 were female and 14 were male. The average age was 30.2 with a standard deviation of 9.8, and the range was 18 to 50. The participants were recruited through several mailing lists and through local organizations for people who are blind and visually impaired. The participants were given a 20 dollar gift card for participating in the study. Table 3.1 shows the overall demographics with numbers for each participant.

### **3.2.2 Procedure**

The participants were interviewed over Skype or over the phone. The interviews lasted around 20 to 30 minutes. The questions were grouped into two different categories. The first set of questions involved what kind of diagrams and graphs the participants were being asked to access and create. They were asked what classes or jobs these diagrams and graphs were for. They were also asked to describe what the diagrams and graphs involved in terms of components, meanings, and relationships. They were further asked what these diagrams or graphs looked like

Part.	Sex	Age	Residual Vision
P1	M	50	light
P2	M	37	light
P3	M	29	no
P4	F	27	no
P5	F	21	light
P6	F	21	light
P7	M	24	No
P8	F	18	no
P9	M	35	light perception
P10	M	18	light
P11	M	19	low
P12	M	40	no
P13	F	19	light
P14	M	20	no
P15	M	46	low
P16	F	40	light
P17	M	33	low
P18	M	36	light
P19	M	40	light
P20	M	28	no
P21	F	34	no

**Table 3.1:** Participant Demographics

as far as they knew. The second set of questions revolved around how the participants were solving the problem of accessing and creating diagrams and graphs. They were asked in general what technology they were using and if they had sighted help. They were also asked what problems they were encountering and what solutions were successful.

### 3.3 Results

#### 3.4 Types of Diagrams and Graphs and Their Commonalities

There were several types of diagrams and graphs that the subjects mentioned having to access and create during their school and work careers. Table 3.2 provides a brief overview of these types of graphs and diagrams and their associated fields. Unsurprisingly, most of the fields are STEM related.

Many diagrams and graphs have common features which cut across their respective fields. UML class diagrams and entity relationship diagrams were the most commonly mentioned, but state machine diagrams, UML use case diagrams, and work flow diagrams were also mentioned. These diagrams require placing shapes (rectangles, circles, etc.) on the screen and drawing different types of lines between them. Further, the diagrams require many textual labels in and around the shapes and lines.

Mind maps, linguistic syntax trees, and computer science graph and tree diagrams all share common features. Visually, they all have nodes and lines going between the nodes. Semantically, these types of graphs and diagrams visually describe multiple relationships between multiple objects, and they also have overall meanings and properties. Types of relationships are typically abstract such as “Greg supervises John, Mary, and Jeff,” or “Node A has three neighbors.”

Computer engineering perhaps presented the most complex diagrams. The circuit diagrams required many wire connections to go between many different circuits or gates with splits in the wires. It was very difficult to explain or trace

Field	Types of diagrams	Graph types
Software Engineering	UML Diagrams, Use Case Diagrams, Entity Relationship Diagrams, Work Flow Diagrams, Tree diagrams, State Machine Diagrams, Encryption Diagrams, Security Architecture	Firewall Graphs, Automata
Computer Engineering	Circuit Design Diagrams, State Machine Diagrams, Block Design Diagrams	None
Chemistry	Molecule and Reaction Diagrams	None
Astronomy	Star Charts and Constellations	None
Physics	Internal Combustion Engine	none
Biology	Anatomy Diagrams	None
Math and Statistics	Venn Diagrams	Line Graphs, Histograms, Bell Curves, etc.
Economics	Bar Graphs, Pie Charts	supply and Demand Curves
Creative Writing	Maps	None
Languages and Linguistics	Phonetic diagrams, syntax trees	None
Cross-Disciplinary	Presentations, Gantt Charts, Brainstorming maps or mind maps, Maps, Organizational Charts	Line Graphs
Visual art	Drawings and sculptures	None

**Table 3.2:** Types of diagrams and graphs.

dozens of wire connections between one circuit such as an adder to another circuit such as a register file. The state machine diagrams were also complex, requiring many transitions between states and complex labeling.

While most diagrams and graphs are in 2D forms, there were some participants who expressed the need to work with 3D objects and images. Engineering in general required the use of 3D CAD tools. One participant mentioned needing to use SolidWorks for much of one engineering class. In math, too, geometry at higher levels requires working with 3D objects such as spheres and pyramids. P1



expressed a desire to understand and create 3D and 2D diagrams of his desktop, laptop, and keyboards. He wanted to be able to understand other designs before purchasing them, and he wanted the ability to design his own computer to his own customization without having to use verbal descriptions.

Biology was another area where diagrams were required to be understood. These diagrams were typically anatomy of a plant, animal, or part, e.g. the eye, human body, digestive system, cell or DNA. Unlike the computer diagrams with well-defined rectangles, squares, and circles, etc., these biology diagrams involve many curved lines and non-circular curved shapes. The diagram of the eye might have many ovals and ellipses while also containing many lines with labels pointing to different parts of the eye, e.g. retina, cornea, etc. These diagrams, too, might be in 3D form while also being a sideways slice of an object such as looking at the eye from the side rather than straight forward.

Similar to the complex biological diagrams, one participant mentioned having to understand a complex physics diagram. The diagram was of an internal combustion engine with many moving parts. Each part was labeled, and many of the parts were shown to have relationships to other parts. The participant described this as very difficult to understand and finally gave up on it. Another physics diagram was an astronomy diagram of star charts and constellations. These astrophysical charts were complex and required much effort to be made accessible, but the teacher was deaf and understood the needs of disabled students. He went out of his way to make the star chart accessible to his blind student.

Chemistry also provided difficult diagrams. These diagrams showed molecular reactions, molecular structures, and atomic relationships. The diagrams had lines going from electrons of one molecule to another molecule showing the changes.

Sometimes, there would be many lines and many electrons moving around, making the diagram complex and difficult to follow even for a sighted individual.

The participants required access to maps for work, school, and personal use. For example, one of the participants was a zoology major and required learning a map of the stables for an internship. This map was a non-standard type of indoor map with large spaces and different sections of the barn. Another participant wanted to access maps and create maps for his fictional stories he was writing. He needed to know what streets were in a given city and the relationships to other streets so he could describe how his characters moved and chased each other around the city. While many street maps are laid out like grids, others have diagonal streets and curved streets not laid out in a grid. Another participant expressed a desire to understand maps of malls and other indoor buildings.

In languages and linguistics, there were also a few diagrams. One interesting type of diagram mentioned by a participant was grammatical diagrams in which words and phrases would be circled, underlined, and lines would be drawn between different words on the page. Another type was a syntax tree to show how roots of words are derived. This diagram would be similar to a binary tree in computer science with the root word at the top of the tree and branches moving down to the derived words.

There are also many cross-disciplinary diagrams and graphs worth mentioning. For example, bar graphs and pie charts are used in many fields such as economics, cyber-security, statistics, and research in all fields. Gantt charts and organizational charts were mentioned as a form of project management in, for example, software engineering, accounting, and economics. Some participants mentioned the importance of color in many of these diagrams and charts and were worried about the

accessibility of colors. Many fields use line graphs and statistical graphs such as bell curves, histograms, and scatter plots. Another major type of cross-disciplinary diagram is brain-storming diagrams or mind maps where there are many, usually hierarchical, levels connecting different concepts and people together through many different lines. Putting charts, pictures, and words together to create presentations gives another level of challenge to people who are blind. This requires using multiple diagrams and graphs and creating a visually appealing and understandable presentation.

Some diagrams were interactive and moving. For example, some diagrams were created by sighted people to teach operating system and algorithm concepts to students. One diagram was made in a PowerPoint and could be stepped through frame by frame to see the algorithm work. Another program was created in java, was web based, and taught operating system concepts through moving and interactive parts.

### **3.4.1 Types of Solutions**

The participants used many common solutions such as tactile Braille diagrams that were made for them and printed on an embosser. Table 3.3 provides an overview of the different solutions. Tactile braille diagrams and graphs are built by sighted people on a computer with specialized software. The diagrams and graphs are raised up in lines that could be felt with a person's fingers without the need of sight. The tactile printout may also have braille labels to describe many parts of the diagram.

Another common solution are raised line drawing kits. These allow both blind

and sighted people to create diagrams and graphs. These kits have a pen, plastic, and a special board. When a person presses the pen into the plastic sheet which is fastened on top of the board, a line is raised up on the paper while there is also visible ink on the line. A blind person can then feel the lines while a sighted person can see the diagram or graph. These allow some independence on the part of people who are blind to create their own diagrams and graphs. Some of these raised line drawing kits allow for the erasing or smoothing of lines, effectively allowing some editing and modification in a limited fashion.

Only one participant reported using a graph board with pins and rubber bands. She would press the pins into different places on the board to make data points in a graph. Then she would connect the pins together with rubber bands to create the lines of the graph. Afterwards, she could follow the rubber bands and pins to get an overall visual feel for the graph she had created.

Office productivity tools were used, such as MS Excel and Office, to create many different types of diagrams and graphs. With MS Excel, users who are blind can use screen readers to input data into the spread sheet which then can be automatically converted into diagrams such as pie charts, bar graphs, graphs, Gantt charts, etc. Some participants reported, though not all, that some diagrams and graphs could be then converted into an HTML representation using a short-cut key. They then could explore the diagram or graph in HTML format with the screen reader. With Microsoft PowerPoint, one participant reported being able to select pre-defined shapes and move them around the screen while hearing x and y coordinates of the locations of those shapes. She was able to hear the type of shape she currently was dragging around. She used the screen reader JAWS with MS Office to accomplish this diagram creation. She could also add alt tags to different

groups of shapes. Another couple of productivity tools used by participants were called Logger Pro and TI Interactive. They used them for math and statistics class. Inputting the data was accessible.

Sighted assistance was reported most commonly for accessing and creating of graphs and diagrams. Students in college would have diagrams or graphs described to them on tests or from books while they describe back a diagram or graph that they needed to have drawn on a test or homework. This was very common for testing as other software or physical means could not be used during tests, such as 3D printing. P2 reported that his employer started having everyone create their UML diagrams in teams because it would be easier on him. The other person could operate the software while he contributed ideas and content. P1 also reported a similar experience with group projects for school. P20 would have a sighted assistant many times describe graphs or diagrams to him from articles or textbooks despite access to 3D printing and other such high tech solutions. It was faster and he could ask the sighted assistant questions for clarification. P5 had a sighted assistant help her draw an accessible map of the stables that was part of her internship. Sighted assistance was the only way to describe moving diagrams or 3D diagrams.

Many of the people interviewed in the study were low vision before they became blind, and they reported using magnification software at one point to help them access diagrams and graphs. P2 attempted to use magnification software to create charts in MS Excel and UML diagrams in other software. He said, "I was unable to create professional looking diagrams this way and had to always do simple things or ask for sighted help." He also reported that UML diagrams were very complex and difficult to create with magnification software because he could

not really see the whole picture at once and had to remember many details. P9 reported using a CC TV to understand diagrams and graphs in text books and this only worked well for the brief time he was low vision.

But there were also a variety of uncommon, creative solutions being used, especially to create diagrams and graphs. Several participants used their own natural English descriptions of diagrams to turn in for homework or for tests. P6 regularly made her own textual descriptions of biology diagrams such as the eye and ear. She also described organizational charts such as Gantt charts in text. She said it was much easier for her to understand this way. Another interesting example is a participant who created their own ASCII diagrams with words, punctuation and dashes. He would create ERDs by connecting two entities on the same line with dashes and words at the ends. The multiplicity of the connections would be designated by letters and numbers, e.g. M stands for multiple and 1 stands for only one connection. See below for two examples of these ASCII diagrams provided by the participant. The common language was decided on between the student and the teacher for a database class, and the participant expressed effectiveness and satisfaction with the setup. He could then create his own diagrams or transcribe other diagrams created by others into his language as long as someone described the already existing diagram to him. He stated, "Text diagramming works wonders. We covered it in one of our Java courses, and I used it during both my SQL Server database course and Oracle DB course. My SQL Server database professor said that she has even seen text diagramming with sighted people. It completely does the job when the only possible app to write with is notepad. I got an A in both courses, so it will work as an alternative. It will depend on how much your professor is willing to bend."

Solution	Description	Accessibility
Sighted assistance	co-workers, other students, family, etc.	oral descriptions for both input and output
Magnification software	Zoom text, magic, and others	Input and output accessible
Scripting languages	PlantUML, Latex, LatexAccess, TextDiagram, TextUML, and Event Studio	Input Accessible, Output typically inaccessible without other tools
Raised Line Drawing kits	Easy Graphics, imagine Board, Edge Board	Input and Output Accessible
Text Diagramming	Drawing diagrams with ASCII plain text and lines with dashes	Input and output accessible
Data sonification	Data sonified graphs (calculators and other software), the vOICe for images and video	Input and output accessible
3D Models	3D printed models, 3D physical models with moving parts	Input inaccessible, output accessible
Graphing software	Maple, SPSS, R statistics	Input accessible, output inaccessible
MS Excel	Pie Charts, Bar graphs, line graphs	Input accessible, output partially accessible
MS PowerPoint	Shapes placement, labels and lines	Input accessible, output partially accessible
SVG	Scalar vector graphics with coordinates description	Input accessible, output inaccessible
3D CAD Tools	OpenCAD, descriptions in text	input accessible, output inaccessible
Tactile braille print-outs	diagrams and graphs printed and embossers and made by sighted people	input inaccessible, output accessible
Strings, felt, glue	Be able to feel diagrams and graphs with strings, flexible sticks, and glued on felt to paper and posters	Input inaccessible, output accessible

**Table 3.3:** Current solutions to inaccessible diagrams and graphs.

// From an ER diagram. The employee must work in an office and can only work in a single office. // However, an office can have multiple employees, but

must have at least 1 employee. Employee M:1 — Works in — 1:1 office

//A simple activity diagram where a user must login to a system. //Two paths are taken: signed in and sign in failure. [start] user — login —>login screen[y:n] [N]: login screen — failure notification —>user [repeat from start] [Y]: login screen — request home screen —>home screen [stop]

Physical objects were also used by the participants to make diagrams and graphs accessible. One participant had to give a poster presentation with population change over time. In order to be able to give the presentation by pointing to different populations on the poster, the student received help to put felt and Velcro on the poster. A sighted assistant would glue different tactile objects to the graphs on the poster in such a way that the student could feel them during the presentation. Thus, the student was able to give the presentation and point to different populations on the poster for sighted people to understand better what was being referred to. A different participant reported having a sighted assistant use a hot glue gun to trace lines on graphs and pictures. Once the hot glue dried, he was able to trace the lines with his fingers and feel what the diagram or graph looked like. Wiki sticks were used by P3 to show shapes of graphs to sighted assistants on tests. Wiki sticks are waxed covered strings that hold their shape when bent, and they stick to paper. He showed the general shape of the graph, and the sighted assistant was able to draw it on the already plotted points. P6 used pipe cleaners and strings to accomplish similar tasks. P4 used a paper clip and graph paper to cut out lines in the graph that she could then feel. P8 modified a compass with a stylus in order to push lines into a graphing paper so she could draw circles that she could then feel. P20 reported using a tracing wheel on the back of pieces of paper to create raised up lines.



Another form of accessible technology for math and statistics were scripting and command line languages. For example, in a software called Maple, one participant reported he could easily type entire equations on the command line and had enough confidence that the output created the graph correctly. He never checked the output with a sighted person. Another two programs were SPSS and R statistics. They both have accessible input in the form of text and command line input equations could be written out in their languages, variables defined and specified, and data written to output files. Further, Latex and Latex Access offered many different forms of accessible math and statistics provided in a complex scripting language. PlantUML, which is a Latex package, offers the ability to create UML class type diagrams using the Latex language with its typesetting and escape sequences. The participants were able to define many parameters such as length, distance and direction of arrows from different classes to other classes.

Data sonification was used by some of the participants. They could enter equations into a graphing calculator. Then the calculator would create the graph, and by pressing a button, a data sonified version of the graph would come out through the speaker. Higher pitch would be used for higher y values and lower pitch for lower y values. The x-axis would be traversed over time, e.g. higher and lower pitch sounds would play out in a constant up and down stream as the sound went along the x-axis. Similar software with data sonification was used on the computer by other participants. One interesting program some people reported using was called vOICe ([www.seeingwithsound.com](http://www.seeingwithsound.com)). This software can give a soundscape of a video stream. For example, a person can walk with their iPhone video camera and the software would convert the stream into a soundscape that would try to replicate objects in the environment. For example, a beeping to the left would mean an object on the left side and so forth. Participants reported also using this

software for making still diagrams and graph pictures accessible. P7 reported that this was very useful for simple graphs and diagrams.

A few participants used 3D models to understand diagrams. P20 reported using 3D printing to create 3D molecules for him to understand molecular structures that were drawn in 2D on the page. The user would create the 3D printer files needed by running a script through already existing log files of molecular structures and converting them to a 3D printing SGI file. Another participant reported using 3D CAD software through both text based input files and sighted assistance. He would attempt his best to write coordinates and other information that the CAD tool needed and ask the sighted assistant to describe the output. A third participant did not use CAD or 3D printing at all. Instead she used already existing 3D models that had moveable parts. These models were created for sighted people, and her teacher already had these models in the classroom. The teacher allowed the blind student to use the models for understanding molecular structures, bonding, and formation by both feeling them and moving around the different parts of the molecule. P5 reported making her own 3D models out of paper such as a horse. P8 reported using a rather unusual 3D model to help her understand algebra. While algebra equations are not diagrams or graphs, they can be very visual, and the participant's solution was interesting enough that we decided to include it here. P8 would use a scale, and balance objects on each side of the scale, in order to understand that she had to do the same thing on each side of the algebra equation. One rare solution that only one participant mentioned was a software called SVG Draw. This software allowed a blind user to input coordinates for scalar vector graphics and create diagrams and graphs in this way. There was also a touchscreen app for tablets that made the output accessible.

### 3.5 Problems with Existing Solutions

While tactile embossed printouts of diagrams and graphs are very common, they suffer from needing a sighted user to create the diagram or graph. This process is done by hand and is time consuming. The tactile diagrams or graphs cannot handle large amounts of labels and text so a key or legend is usually required. For example, the number one would be put in place of an x-axis label, and the user who is blind would have to refer to a secondary braille page or text file to find out what the number one stands for. Once the embossed tactile diagrams are created, they are unable to be modified. They cannot be corrected or added to. Corrections or additions would have to be done on the software and re-printed. P10 reported that tactile diagrams were ineffective for her. Blind from birth, she reported having a low spatial ability to understand diagrams and had lots of difficulty using tactile line printouts: "It would take me a half an hour sitting there feeling the angle of a triangle to understand what was going on." She reported that 3D models had been most effective in helping her understand diagrams.

There is a similar problem with the gluing, taping, and attaching of physical objects such as string and felt onto paper and, posters, and plastic. The end result is pretty good for the user who is blind, but they have to be created by a sighted person. This is again time consuming and problematic in terms of feedback and corrections.

Sighted assistance in general spans across many of the solutions. Sighted assistance is needed to create tactile diagrams for embossers, to create 3D printing models, and creating of physical attachments to paper or plastic. Cost effectiveness, extra time consumption, and difficulty of verbal communication are the problems

with sighted assistance in all these cases. A feeling of independence and pride in self-accomplishment are also taken away by the need for sighted assistance.

Raised line drawing kits solve one of these problems in that they allow people who are blind to create their own graphs and diagrams by touch with a pen or stylus, but they suffer from the same problem of being more difficult to label with braille or non-braille labels. There is not enough space to create the labels, and it is almost impossible to make a braille label on them, leaving those users who cannot print words in a difficult position. Furthermore, many participants reported the difficulty of scaling their diagrams and graphs to both fit on the page and to look proportional and correct. These plastic or paper diagrams cannot be saved digitally and must be carried around and kept track of physically. After a while the lines can wear down as they are stored in folders or backpacks. Fine grained detail coming through on these plastic sheets of paper was also reported as a difficult problem. They give coarse granularity at best with more complex diagrams. This would happen, for example, in statistics classes with many small lines and data points connecting them.

One problem with both tactile print outs and raised line drawings is that they have a difficult time representing and conveying 3D images. P13 reported that she had an impossible time trying to understand a 3D tactile print out of a cube and prism. She said, "There were lines everywhere and I could not figure out what the lines meant."

Magnification software, only mentioned by a few of the participants which they used when they had low vision, was described as difficult to use to create diagrams and graphs. The problem was that there was an inability to see the overall diagram or graph while editing. The problem was less when simply trying to understand

the graph or diagram as that required less cognitive energy.

Some people found some drawbacks with their invented natural language descriptions of their diagrams and graphs. For example, P11 reported that some diagrams would take almost a page to describe in full detail and that this was tedious both for him and his instructor. It was also difficult to find a way to be as specific as possible using words to describe a diagram or graph. Sometimes there was ambiguity in the descriptions.

The 3D printing and modeling tools suffer from the problem that the visual output of the design tools is inaccessible. The input text files that were used by some subjects to define the 3D objects were time consuming and difficult to write. Although P20 was able to find a way to automate the creation of 3D printing files from his molecular logs, he reported that this only worked with the custom software of his particular research lab and they had many difficulties trying to use it with other software log files. While many participants reported that the resulting output was very impressive and useful, it was difficult to use different 3D printouts together to create a large diagram, e.g. molecular reactions. Furthermore, once printed out, they could not be changed or modified. One of the participants reported using movable 3D models, which were not from 3D printing but commercial retail models for sighted people to use as examples in the classroom. 3D CAD tools, such as circuit design tools, could not be printed out, and their output was completely inaccessible. Although some participants reported that the input on 3D CAD tools could still be textual and accessible. This required a sighted assistant to look at and describe the output for correction and clarification of the design.

Scripting languages, like Latex, are very powerful, and their output could be put through other software like vOICe for accessible understanding of the out-

put. But in general, the output of such scripting languages is inaccessible, and many times a sighted person has to confirm it. Furthermore, these scripting languages, while popular in STEM fields, can be difficult for non-technical people to learn, understand, and use. For example, a business student who wants to create a simple diagram showing work flow in a business on a presentation would find it extremely difficult if not impossible to spend time learning a language like LaTeX. Even in STEM fields, people expressed concerns at having to learn such languages at early stages while still struggling to learn other languages such as Java or C++ at the same time. P7 reported that while he was a junior in college and could easily learn Latex, he did not try as he only needed to make a couple of diagrams for only one week of the class. He felt the time investment was not worth it, and he reported that his classmates were able to draw the diagrams with quick and easy to learn visual tools. P7 reported that while there were programs to translate Latex into braille, it was not possible to translate the other way around. He thought this would be useful for him to create math in braille and translate it into Latex automatically.

Similar to scripting languages and 3D printing or CAD software, the SVG Draw solution also suffered from the problem of time consuming and difficult to learn text input. Files with specific coordinate input need to be created for SVG Draw in order for the software to create a diagram or graph. Accessibility of output was another issue, but the SVG Draw came with a touchscreen app for tablets that made the output more accessible.

Office productivity tools such as Open Office, MS PowerPoint, Excel, and TI interactive, which were mentioned by the participants, had little accessible output. While some charts or graphs in MS Excel, could be converted to an accessible

HTML format, this format does not give a real accessible spatial feel for the data. Complex graphs with many data points were not accessible at all. It was reported that trying to make sure data points were visually readable and labels far enough apart and not overlapping was difficult. Making sure labels of different bar and pie charts were readable was also difficult and required sighted assistance. TI Interactive and Logger Pro had no accessible output options. P4 mentioned that while she could underline things in MS Word, she would have liked an option for MS Word to circle things for her, which was not possible. P4 also reported not being able to hear orientation changes in the direction of the different shapes in MS PowerPoint. Once she changed a triangle to 45 degree angle for example, it would not say if it was overlapping another shape or what the orientation was.

Many participants reported being excused from having to create or understand diagrams, even though they felt this resulted in a lower quality educational or work experience. This is not so much a solution but an anti-solution that gets people by as a necessity. For example, P7 said that he was excused from learning to create finite automata from a computer theory class and feared he missed understanding a lot.

Data sonification was problematic for many of the participants who used it. P8 reported that she had a data sonified graphing calculator but that it was not intuitive and she could not figure out how to interpret the sounds. She could not find anyone who could explain to her how to interpret the sounds. Another participant reported that a major problem with vOICE ([www.seeingwithsound.com](http://www.seeingwithsound.com)) was that it could not describe and read labels while giving the data sonified version of the graph or diagram picture.

### 3.6 Conclusion

This research provides a comprehensive overview of how a wide variety of people who are blind and visually impaired are trying to access diagrams and graphs, which has previously only been provided in fragments or partially in previous research studies. This research provides a basis for future research studies that wish to work on diagram and graph accessibility. We conducted 21 semi-structured interviews with people who are blind and low vision in order to better understand their requirements and problems with accessing and creating diagrams and graphs. We asked what types of diagrams they have been asked to access and create throughout their school and work careers, what solutions and problems they were encountering. We discovered that there were many types of interesting and complex diagrams and graphs that these people were trying to access or create. For example, some participants were trying to understand and represent complex molecular reactions and bonding. We also discovered that many participants were working around their accessibility issues with interesting and innovative solutions such as their own natural language descriptions and physical objects attached to paper such as strings. There are many problems with existing solutions still such as the inability to access 3D and 2D digital output on computer screens and the necessity of a sighted person to create printouts whether 2D or 3D. This research shows a great need for new digital solutions to accessing and creating diagrams and graphs and. It highlights some of the important aspects of these diagrams that need to be tackled such as 3D diagrams and curved diagrams.



## CHAPTER 4

### AUDIODRAW

#### 4.1 Introduction

Many people use and work with productivity tools such as MS Word or Pages on a daily basis. These tools have many features allowing the user to create visual diagrams with rounded rectangles, circles, lines with arrows, and labels, to name a few elements. There are also more specific productivity tools that allow the fast creation of visual diagrams such as software engineering UML diagram tools, wire framing tools, and many others. But for people who are blind and use screen readers on a regular basis, the techniques of these diagram-building features of productivity tools are mostly inaccessible. The techniques typically rely on pointing and dragging objects and lines with a mouse while receiving constant visual feedback.

Some tools use accessible techniques such as MS Excel where users who are blind can create bar graphs and pie charts by entering numbers and headers in the work sheet area and selecting automatic creation. But these techniques only work with specific, standard type diagrams where as general non-standard diagram techniques are inaccessible. Another technique that is accessible is LaTeX type setting language, which users can provide textual code describing placement of objects and images and automatically create a PDF file from these instructions. But the LaTeX language is oriented toward STEM fields. Furthermore, only visual feedback is given using the LaTeX language in the resulting created file.

There is a need for people who are blind to use such tools in classes in school or

presentations at work, which was demonstrated in Chapter 3. We created an initial prototype to use as a design probe to discover the potential of people with visual impairments using touchscreens to create diagrams. Based on initial feedback from a few users, we created a new revised design probe and conducted interviews with 8 participants with visual impairments using this new design probe.

Based on the feedback from the interviews, we discovered that the participants were very enthusiastic and excited about the possibility of using a touchscreen to create diagrams. They generally felt touchscreens were being used more and more, and this possibility would be on the cutting edge of current technology use in the classroom.

## **4.2 Design of Initial Prototype**

Based on the fact that tablets are becoming more popular in school in general and also becoming more popular among people with visual impairments and blindness, we decided to create a design probe with a tablet app. One type of class that requires diagrams is math, and we decided to create a geometry app that allows the users to create shapes based on geometric properties.

The app was built on an iOS Mini iPad first generation, and it was made compatible with the VoiceOver screen reader. Most of the screen, except the bottom buttons, was programmatically set to not use VoiceOver. This way the touches of the user can be directly interpreted by the app instead of being intercepted by VoiceOver. The app was laid out with an x and y axis filling most of the screen. The origin of the coordinate system was placed slightly off center of the tablet as a whole as we needed to place menu buttons as the bottom, and also the time and

status bar at the top could be hidden, but the space could not be removed.

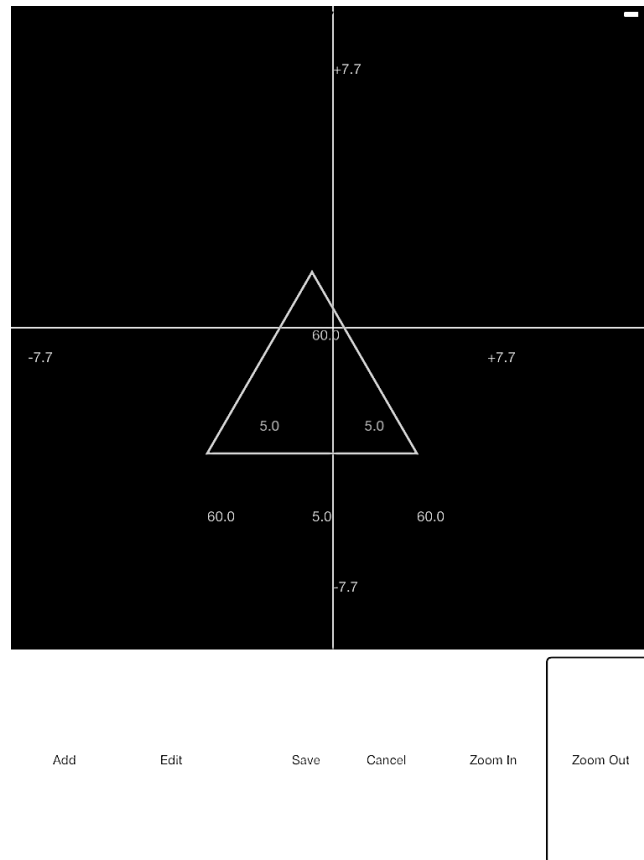
Users could go into the menus and select what type of shape they would want to place on the plane. For example, if the user selects a circle, the user will place it by specifying the properties of the circle with gestures on the touchscreen. The user drags their finger around the screen to set the x and y center of a circle on the Cartesian plane and then drag out the radius in any direction. The app speaks the x and y coordinates of the center of the circle as the user is placing it and then speaks the length of the radius as the user drags out the line in any direction they want. The coordinates are spoken with one decimal digit, e.g., 1.2, 2.4, etc. To drop the center of the circle, or choose the length of the radius, the user double taps anywhere on the screen. There is a delay between when the finger touches the screen and the app deciding on what type of gesture is being used. The delay is about 250 MS, and the users did not complain about any lag as they initially dragged the shape. If the finger was lifted before 250 MS, then nothing would happen, and if there was another tap within another 250 MS, then the center of the circle would be placed, or the radius length chosen. If the finger stayed on the screen longer than 250 ms, then it was determined to be a dragging gesture. This made sure that the user did not accidentally re-locate the center of the circle as they were trying to double tap. These time delays were determined to be usable in preliminary testing on a few sighted subjects.

The app would then automatically draw a point for the center of the circle, a line stretching out to the right parallel to the x axis for the radius and then automatically draw the circle with that radius and center. The built in libraries for iOS basic shape creation were used for this automatic drawing of the shapes. The radius and coordinates of the center would be automatically labelled with lengths

and coordinates.

The lengths and x and y coordinates are not in any unit lengths because geometry classes typically do not rely on unit lengths in classes and textbooks. They do not want the students measuring the length and width of shapes, but instead they want the students to use the geometric theorems for calculations. The other two shapes that were implemented in the design probe were a triangle and a rectangle. For the rectangle, the user places a point of a corner anywhere on the screen and then drags out the diagonal of the triangle in any direction they want. The app speaks the length and width of the rectangle as the diagonal is moving.

The diagonal is placed in the same manner as the circle with a double tap and then the app automatically draws the rectangle using the built in iOS drawing functions. The length of the sides are automatically labelled. Again, the lengths are abstract as geometry textbooks and classes do not want the students measuring the lengths but use the theorems to calculate lengths and degrees. The triangle is a little more complex. The user places one point of the triangle where they want and then places the second point of the first line where they want. A line is then drawn between the two points. The user then selects the third point and then drags the point around, which moves two lines around, each one attached to a point of the first line. The app speaks the length of the lines out loud. Once the third line is placed, the app completes drawing the triangle. This time the sides of the triangle are labelled with lengths, and the angles are labelled with degrees. Because it can be difficult to draw a triangle, we also included a mode where the user can enter the lengths of the sides of the triangle with the keyboard. See Figure 4.1 for a screenshot of the app.



**Figure 4.1:** Triangle placed with prototype 1.

### 4.3 Testing and Revision of Design

A few blind test subjects initially tested the prototype and gave valuable feedback on the design which led us to revise the prototype before we did a full interview and user study. The two test subjects were 23 and 30 respectively, both completely blind with no light perception, were both male, were later blind, and had many years of technology use. The test subjects were taught how to use the app, placing points on the screen and dragging out the radius of the circle, diagonal of the rectangle, and placing three points on the screen for the triangle. The two users were then asked to place a few of each of the shapes with different sizes and location. Each shape was placed by itself on the screen, and the last shape was erased. Initial

feedback showed that the design probe was intriguing to the users, but there were several problems. The users wanted to be able to change the labels of the numbers on the x and y axes and also label the lengths and degrees of the shapes themselves as they would do in a geometry class.

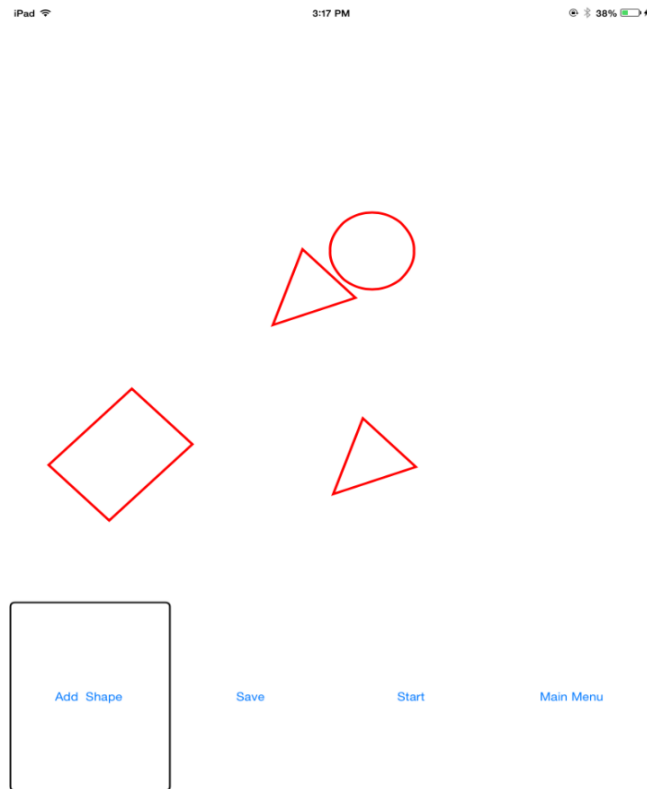
Furthermore, the users felt the app was limiting in that it only allowed for use in a geometry class, and they wanted to be able to place shapes in a general app for creating not only geometry shapes but diagrams in general. They were unable to move the shapes after they placed them, and they were unable to change the direction of the shapes. They also reported that the triangle was the hardest to place on the screen and difficult to visualize its shape.

#### **4.4 2nd Design of the Prototype**

Similar to the last prototype, the user can select what type of shape they want: circle, rectangle, or triangle. They then can drag around the shape anywhere they want on the screen. In order to make the app more general and usable, we used shapes with pre-defined sizes so the users did not have to drag out the size of the shapes on initial placement. Instead of a coordinate system to tell them where they were on the screen, information in the form of text to speech is given to them in which they were told where they were in compass directions (north, north east, east, south east, etc.) in relation to the center of the screen and also given the number of inches they were away from the center of the screen. This made the app more general than simply being used in a geometry class. See Figure 4.2 for example of objects placed in the app. Once they have decided a spot to place the object, they double tap to drop the object at that location. The gestures have

the same time delay for recognition as the previous app so that the users do not accidentally move the shape when they are trying to double tap. After placing an object, they are given the choice of centering objects on an already placed object using a three-finger tap. Instead of the center of the screen, they are given compass directions and inches away from that particular object.

After the object was set in place, the user could place their finger on the object and receive TTS feedback on the type of object. Once the object is in place, the user can then select the object by placing their finger over it and then double tapping anywhere on the screen. The object is then selected for direction selection. The user can then move their finger around the object in a circle at any distance and text to speech feedback is given. The text to speech information tells the user in which direction the object is now facing. The direction changes at 45 degrees around in a circle at each compass direction. Once they select a direction they are able to double tap to set it in place. This technique was based upon similar techniques that sighted users perform in editors that allow them to not only drag and drop objects with a mouse but also change their facing direction. No other drawing or navigation research projects on tablets or otherwise has looked at direction changing or orientation descriptions for people who are blind. After a diagram has been created it can be saved and explored later using the same technique.



**Figure 4.2:** Many shapes place with prototype 2.

## 4.5 User Study

### 4.5.1 Participants

There were 8 participants in the study. They were recruited from local organizations for the blind. Three were early blind (from birth or close to birth) and 5 were blind later in life.

The average age of the participants was 45.4 with a standard deviation of 9.5 and range of 33 to 58. Most participants were experienced in the use of technology and the use of touch screens. On a 5-point Likert scale (1 = strongly disagree and 5 strongly agree), the participants reported for experience with technology



Part.	Sex	Age	Age onset	Residual Vision
P1	M	56	42	no
P2	F	48	birth	no
P3	M	33	birth	no
P4	F	40	23	light
P5	M	35	17	light, color, shape
P6	M	52	26	No
P7	M	58	birth	light
P8	M	41	28	No

**Table 4.1:** Participant Demographics for Study

in general an average of 4.25 with a standard deviation of 1.04. With regards to experience with touchscreens, the participants reported an average of 3.75 and a standard deviation of 1.16. Two participants were female and 6 were male. See Table 2 for the full demographics of the subjects.

#### 4.5.2 Procedure

The participants were given basic instructions in the use of the app. They were told how to select a shape, position it on the screen, and change the orientation. They were instructed on the meaning of the TTS feedback. One participant had not used touchscreens before, and he was given instructions on how to use the VoiceOver screen reader on the iPad and allowed time to accustom himself to it. The users were then asked to select and position several shapes on the screen. Once they had positioned those objects, they were then asked to change the orientation of a few objects. After this trial, qualitative experiences were collected using a questionnaire to assess the ease of use of the various feedback elements of our design probe using a 5-point Likert scale that ranged from 1 (strongly disagree) to 5 (strongly agree).

## 4.6 Results and Discussion

The participants felt the ability to drag and drop shapes on a touchscreen was intriguing. The participants felt strongly that the techniques were easy to use, especially the positioning technique and the compass directions.

Many participants gave feedback in the form of comments and suggestions, and all except one of the participants felt the techniques and the ability to create diagrams on touchscreens was important to be made accessible.

1. **Positioning Technique.** To the statement "I found the positioning technique easy to use", on the 5-point Likert scale, the participants rated the positioning technique an average of 4 with a standard deviation of 0.93, which shows that the technique was effective and easy to use. Participant 1 said the app was "fun to use" and used the app the longest out of all participants. P1 wanted to connect the objects together and form one bigger object but was unable to do so. As a result, P1 tried to get the objects as close together as he could. Once he placed his first triangle, P1 selected it to position all other objects around it within .2 or .3 inches in different directions. Some participants wanted to know the size of the shapes. The shapes were approximately a little bigger than their fingertip. They wanted to hear descriptions of those dimensions, whether shapes or outlines or filled in with colors. P8 stated that relative size information between the dimensions of two different objects would be helpful. He also wanted to know more about the overlap of shapes, such as the overlapping of circles for a Venn diagram. Many participants wanted the ability to resize the shape, changed the line thickness of the shape, and be allowed to shade the shape.

2. **Direction facing technique.** In response to the statement, "I found the direction facing technique easy to use", the participants rated the orientation technique with an average of 3.63 and a standard deviation of 1.19, which is less than the positioning technique and still shows some ease of use and effectiveness. P1 also wanted to change the orientation of all the objects so they were facing southwest. P1 was able to do these tasks with relative ease. P1, and other participants, suggested the rotor gesture that is typical of the iPad. Some participants also wanted to hear direction information after placing an object on the screen. Instead of "facing west", they wanted something like "portrait and landscape" view for the rectangle. P6 wanted to set the degrees of orientation such as five degrees instead of it automatically jumping by 45-degree increments.
3. **Compass Directions.** Most participants felt that the compass directions were very helpful and easy to use (rating, in response to the statement "I found the compass directions easy to use," with the second highest average of 4.13 with a standard deviation of .64). P7 stated that the compass directions were very helpful because "that is the kind of stuff you learn during mobility training" learning the compass directions to walk in." More than one participant mentioned wanting to hear some sound effects such as when objects bump into each other or different pitch sounds for different parts of the screen instead of compass directions. P8 mentioned that different voices and different pitches for different objects and directions might be helpful.
4. **Inches Information.** Some of the participants did not like the inches" information and found it difficult to use. In response to the statement, "I found the inches" information easy to understand," they rated it 3.13, the lowest out of all ratings, with a standard deviation of .99. One participant stated that the

feel of the screen was enough to tell distance. Only P1 ended up using the inches" information, but this could be because he became blind at a later age and had been more familiar with using inches. Some participants felt the feel of the screen itself allowed them to tell how far they were from the center of the screen, but this did not tell them distance while positioning around an object at a random place on the screen. Providing inches information could be provided as an option.

5. **Gestures and Screen Layout.** All participants found the gestures easy to use. In response to the statement, "I found the gestures and screen layout easy to use," they rated it the highest with an average of 4.63 with a standard deviation of .63. But there were a few problems. P8 had trouble once he had set a triangle on the southern border near the menu buttons. P8 was unable to put his finger over the triangle even though it seemed to be there according to the sighted assistant. P8 suggested putting the menu buttons at the top of the screen or get rid of them altogether. P8 also wanted to typically double tap anywhere on the screen to activate the menu buttons on the bottom, but the drawing screen was separate from the iOS VoiceOver software and double tapping on that screen did not activate or interact with the VoiceOver software. P1 also attempted to determine where the objects were after setting them in place by tapping with three fingers, which is also a typical gesture on iOS to describe accessibility focus location on the screen. Interestingly, P8 stated the possibility of using two fingers at once to set a line in place or to place two objects at the same time. This would give more of a feel for distance and relative positioning of objects and lines.
6. **Tactile Feeling.** Most participants found the surface of the tablet easy to use in order to move around objects and change orientation of objects. In

response to the statement, "I found the spatial layout of the screen easy to use," they rated the effectiveness of the surface with relationship to diagram creation with an average of 3.88 with a standard deviation of .35. They liked the tactile smooth feel of the tablet. But some participants (especially the early blind) stated that they wanted more tactile feedback. For example, P8 also mentioned the possibility of using a tactile grid layered over the iPad to help feel distance. Two other participants also mentioned wanting to integrate tactile feeling into the app and wanted to see the possibility of a braille display being used. P2 stated, "I'm a big tactile person... for me a drawing program is a great idea but I think that for me anyway part of it is I want tactile feedback." P2 also mentioned wanting braille labels along with visual labels. Interestingly, p4 mentioned that the app could potentially be used for other disabilities such as dyslexia because it gave TTS feedback on the directions of the shape, which would help in understanding the diagram. More than one participant mentioned wanting more shapes and wanted to try out 3D shapes too. P8 also mentioned the possibility of using a bigger touchscreen. The iPad mini was used, but P8 suggested an even larger tabletop touchscreen.

## 4.7 Future Work

While most participants liked the design probe, they offered some different directions of further research:

1. **Resizing of shapes.** Some participants wanted to change the size and dimensions of the shape just like a sighted person would be able to do in editing

software with a mouse, clicking on the edge of the shape and dragging the edge further away. A technique to allow a person who is blind to select a particular side or vertex of a shape and then drag their finger closer or further away from the shape would be needed.

2. **Being able to connect shapes together to make a bigger shape.** Connecting a triangle to the top of a rectangle or the circle being placed inside a rectangle would be useful to users so that they can create more complex diagrams.
3. **Inclusion of lines and being able to create parallel lines, vertical and horizontal lines and curved lines.** The drawing of lines was not included in testing, but it would be very important in the creation of diagrams to draw a line with an arrow from one shape to another shape with a label on the line. Some important problems here would be to give the user the ability to draw exactly horizontal straight and vertical straight lines by selecting two points. Also, it would be important to allow the user to create lines that are somewhat parallel to each other.
4. **Bi-manual interaction to place shapes and lines at different distances at the same time with two fingers.** Interestingly, P8 suggested the ability to select two points of a line with two different fingers at different places on the screen. This could also be extended to allow the user to place two objects at once on the screen with two fingers. This would give some more spatial sense of distance of lines and distance between objects.
5. **Quantitative measurements of real world diagrams.** We will also include the measurements of times and successful drawing of real world diagrams such as flow charts or UML diagrams in the future.

All these research directions will require new interaction techniques. Other things mentioned by participants, such as visual labels, would use the same placement techniques.

## CHAPTER 5

### HAPTIC MAPS ON TOUCHSCREENS

#### 5.1 Introduction

Graphical maps displayed on touchscreens and computer screens are inaccessible to the blind and visually impaired population. In order to address this inaccessibility, textual descriptions for directions through a map are provided using automation such as Google maps or constructed by hand by a mobility trainer. Another solution is to provide tactile maps which are typically made by hand and printed with a special printer. Because they are hand-made by a sighted person in a time consuming manner and require a special printer which is expensive, people who are blind and visually impaired generally do not have access to these maps as much as they have to textual descriptions. A non-visual, cheap, off-the-shelf system using a touchscreen would allow access to many different maps for the blind and visually impaired without the need of human intervention.

This research provides the following contributions: (1) a prototype with two cheap, off-the-shelf devices (a smart watch and a tablet) to determine distances between vibrating lines; (2) a comparative user study with this prototype between blind and sighted individuals that shows blind users have a better ability to determine distances through vibrational feedback from two devices; (3) a second prototype that uses more complex vibrational patterns from the same two cheap, off-the-shelf devices to perform map tracing; and (4) a second user study showing both the feasibility and usability of the second prototype with blind and visually impaired users.



## 5.2 Prototype One

The first prototype was designed to measure the ability of users who are blind and visually impaired to determine distance between two lines on a touchscreen using vibrational cues. An Android smart watch (Galaxy Gear Live) and an Android tablet (Nexus 10) were used to provide directional vibrational cues. Android was chosen over iOS because iOS tablets do not have haptic feedback. Besides the use of the tablet to provide directional vibrational cues, the touchscreen tablet was also used as the screen where the lines were traced.

In order to designate different distances, the vibrations pulsed at different speeds. Slower pulsations were used to designate further distances, and faster pulsations were used to designate shorter distances. The duration of the pulsations was a function of the distance from the finger to the end of the line in pixels of the touchscreen, defined in milliseconds as  $t = distance \times 0.1$ . For example, if the distance from the user's finger to the end of the line was 1000 pixels, then the vibration would pulse for 100 milliseconds on and 100 milliseconds off. Pulsating vibration was simulated in the software by sending signals at exact times to turn the vibrator off and on. The maximum pulsation duration was 150 ms given the longest line was 1500 pixels. The minimum vibration pulsation duration was 1 millisecond. The user would start with their finger in the bottom left corner of the screen, and the pulsations would be slower for the longer line and faster for the shorter line. The pulsation rate became the same between the short and long lines when the user's finger reached the end of the lines. The width of the lines was 8.99 mm, which has been shown to be the optimal width for line tracing according to psychophysical studies [37]. It

Three types of lines were traced: vertical (along the left vertical edge of the tablet), horizontal (along the bottom edge of the tablet), and diagonal (along a 45 degree angle). The lines were not graphically rendered for this prototype. All lines started in the bottom left corner, and paper guidelines were taped on the bottom and left edge of the screen to guide the user's finger along the line. When the diagonal line was traced, the paper guideline was placed at a 45 degree angle from the bottom left of the tablet to the top right (northeast, see Figure 5.1). The guidelines were necessary as the bottom part of the tablet contains software buttons such as back and home, which could be accidentally pressed. This test was not looking at the ability of the blind subjects to trace lines in a straight manner but was testing their ability to judge distances.

The smart watch was placed on the user's non-dominant hand. Users used one finger of their dominant hand to touch the tablet screen. The tablet was taped down to a desk to prevent it from moving during the test. The bottom edge of the tablet was lined up with the edge of the desk, and the desk was raised up or down for the comfort of each user.

The tablet vibrated for the vertical lines. The watch vibrated for the horizontal lines. Both watch and tablet vibrated for the diagonal line. Note that for prototype one, the alternative combination with the tablet vibrating for horizontal and watch for vertical was not tested. The alternative combination of vibrational patterns was tested for Prototype Two (see User Study Two section).



**Figure 5.1:** Setup for User Study One showing the smart watch and the tablet with paper guidelines attached.

## 5.3 User Study One

### 5.3.1 Participants

A total of 6 visually impaired and blind users (3 males,  $43 \pm 8.63$  years old), and 6 sighted users (2 males,  $47 \pm 18.7$  years old) participated in this user study. The demographic data for blind and visually impaired users along with their causes of blindness are summarized in Table 5.1. Both sighted and blind participants with

Part.	Sex	Age	Age onset	Cause	Residual Vision
P1	M	56	42	Uveitis, glaucoma	no
P2	M	35	1	Scarlet fever	Few shapes, colors
P3	F	35	21	Macular degeneration retinitis pigmentosa	Some peripheal vision
P4	F	46	12	Retinitis pigmentosa	some peripheal vision
P5	F	40	21	Retinitis pigmentosa	light perception
P6	M	34	Birth	Retinitis pigmentosa	No

**Table 5.1:** Participant Demographics for Study 1

residual vision were blindfolded for this study.

### 5.3.2 Procedure

Participants were asked to compare two lines of different length and determine which of the two lines is longer. The participants were notified by a sound when they reached the end of the line. Once both lines had been traced, text to speech asked users for a response. Responses were recorded by swiping left if the first line was longer and swiping right if the second line was longer. The answering mechanism was made very insensitive to avoid accidental responses. The users were required to slowly move their finger left or right for a good distance to indicate which line was longer. To minimize potential overlap, they were asked to answer on a different section of the tablet than where they traced the two lines.

Three conditions were tested: vertical lines, horizontal lines, and diagonal lines. Each condition had a block of 50 trials. For each condition, participants were given 5 trials to learn the system before the start of the test. The order of the three conditions were counterbalanced across participants.

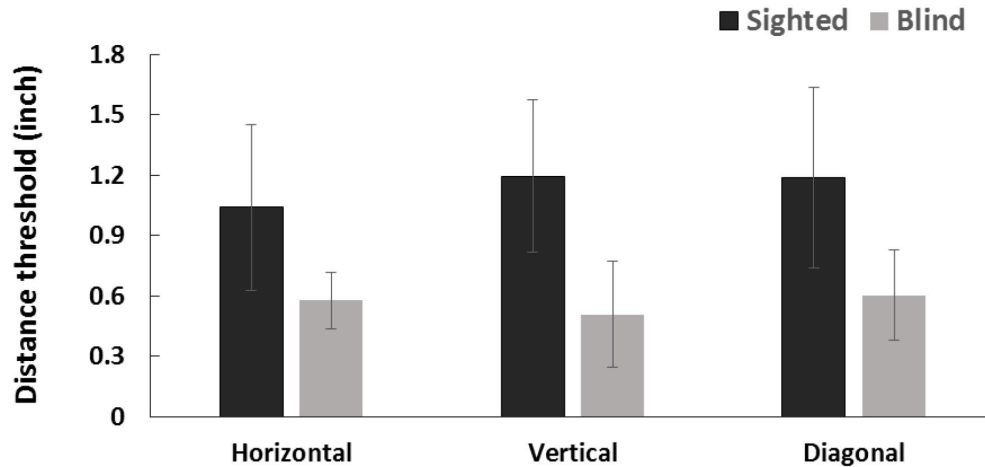
A staircase method [27] (3 down 1 up) was used to determine the distance

threshold. A static short line of 2 inches was used during all trials. The second line started out at 5 inches. The order of the two lines was randomly assigned for each trial. If the user answered correctly three times in a row, the longer line would have its length decreased by half the distance between the long line and the short line. For example, if they got the first three trials correct, then the distance between the lines would be reduced from 3 inches to 1.5 inches. If they got the next three correct, then it would be further reduced to .75 inches and so forth.

### 5.3.3 Results

The blind and sighted participants' ability to determine the distance between two lines were measured using a staircase procedure (3 down 1 up; 50 trials per condition). Thresholds were calculated by fitting the data with Weibull psychometric function and targeting 79.4% level on the psychometric function. These thresholds correspond to the distance in inches at which the participants can correctly detect the presence of length difference between two lines on 79.4% of the trials. As shown in Figure 5.2, distance thresholds were reported for all three conditions.

Two-way ANOVA comparing the effects of subject group and condition found a significant effect of group ( $F(1, 32) = 4.85, p < 0.05$ ), with no significant effect of condition ( $F(2, 32) = 2.27, ns$ ). As predicted, the overall threshold across all 3 conditions was significantly lower in blind than in sighted group ( $t(34) = 2.27, p < 0.02$ , one tailed). The lower distance thresholds in blind individuals suggest their enhanced ability to form representations of spatial distance from tactile vibrational cues.

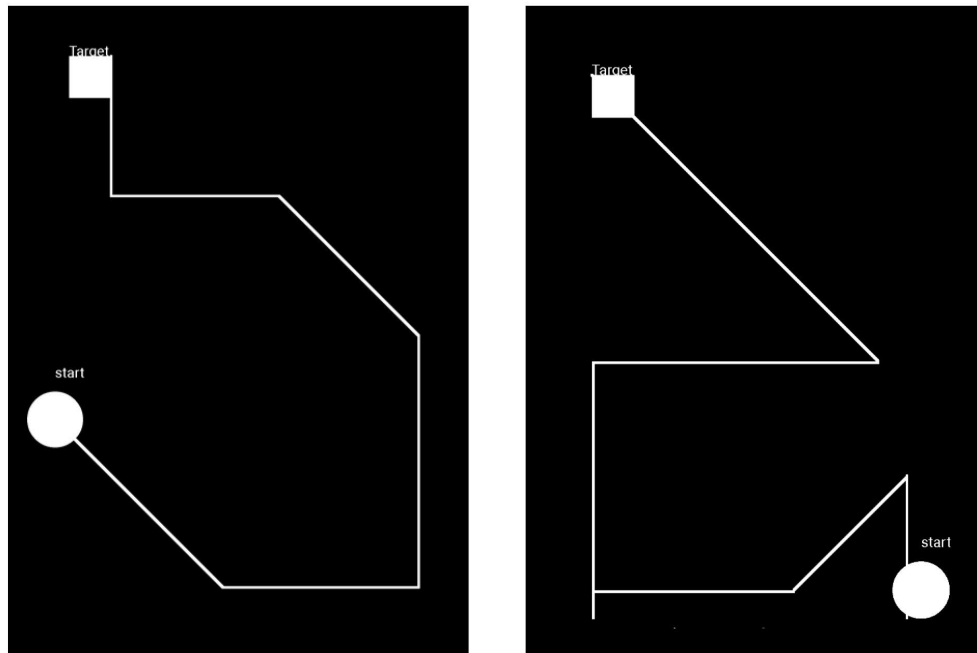


**Figure 5.2:** The distance thresholds for blind and sighted subjects for all three conditions: vertical lines, horizontal lines, and diagonal lines.

## 5.4 Prototype Two

Similar to the first prototype, the second prototype also consisted of an Android smart watch and an android tablet. It was designed to test a practical application in which the users trace maps using vibrational cues from two vibrating devices. A real-world application I envisioned for the system would be blind users tracing Google Maps on their smart devices using haptic cues as they walk down the street to find their destination.

6 training and 6 test maps were manually constructed in Java on the Android tablet. The six training maps were made easy to familiarize participants with vibrational patterns. They were 5-10 inches long, with 3-4 short segments including one diagonal line. The six test maps were made to have higher complexity than the training maps. They were 15-18 inches long, with 5 to 6 segments including 1 to 2 diagonal lines (see Figure 5.3 for two test map examples). Due to the limited amount of space on the Nexus 10 touchscreen, test maps could not be made with



**Figure 5.3:** Two test maps used in User Study Two: test maps were made to have similar complexity. They were around 15-18 inches long, with 5 to 6 segments and 1 to 2 diagonal lines. The starting and ending locations were indicated by white circles and white squares, respectively.

the exact same complexity. All maps were constructed from vertical lines, horizontal lines, and diagonal lines. Note that lines were graphically rendered on the screen for Prototype Two. Similar to the first prototype, the line width was 8.99 mm and all diagonal lines were rendered at exactly 45 degree angles. Unlike the first prototype in which the diagonal line only went to the northeast direction, the second prototype used diagonal lines going in all four directions (i.e., northeast, southeast, southwest, and northwest).

Two conditions were tested. Condition 1 involved the tablet vibrating for vertical lines and the watch vibrating for horizontal lines, whereas Condition 2 involved the tablet vibrating for horizontal lines and the watch vibrating for vertical lines. Note that for Prototype 2, the duration of the pulsation was kept constant

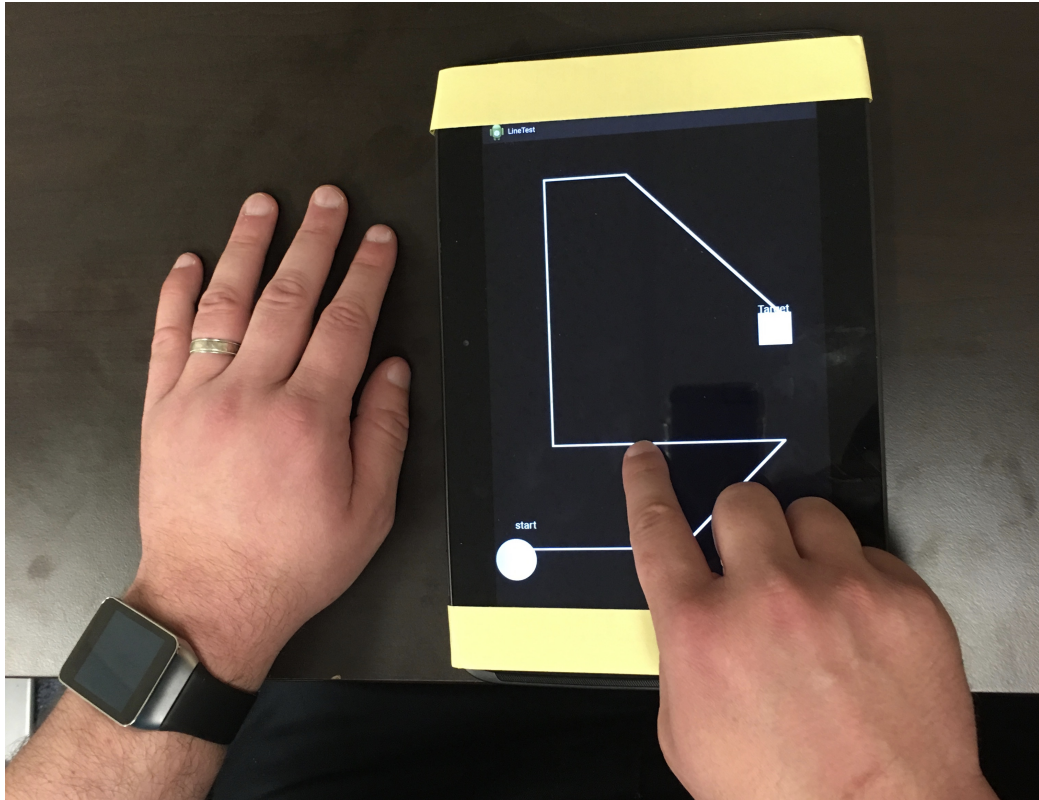
(300ms on and 300ms off). We used different vibrational patterns to distinguish between lines going north and lines going south, with lines going north vibrating solid and lines going south pulsating. Similarly, different vibrational patterns were used to distinguish between lines going east and lines going west, with lines going east vibrating solid and lines going west pulsating.

The vibrational patterns of horizontal and vertical lines were combined to create vibrational patterns for diagonal lines. For example, diagonal lines going northeast would have both tablet and watch vibrating solid at the same time, regardless of conditions. The lines going northwest would have the tablet vibrating solid and the watch pulsating (Condition 1), or vice versa (condition 2).

Map starting and ending locations were determined and placed visually on the screen. To increase the difficulty of the test, the starting and ending locations were made different for each map. Their finger would be guided to the starting location. Timing was started once the user's finger touched the starting location. When the user reached the ending location, the timing was stopped and recorded in a log file. TTS would then provide the name of the next map (e.g., map 2 would be announced once they finished map 1). In order to prevent accidental starting of the recording, a 3 second delay was put in between two test maps.

The setup of Prototype Two was identical to that of prototype One. As shown in Figure 5.4, the smart watch was placed on the user's non-dominant hand. Users used one finger of their dominant hand to trace the map on the tablet screen. The tablet was taped onto a desk to prevent it from moving during the test. The desk can be raised up or down for the comfort of each user.





**Figure 5.4:** Setup for User Study Two showing a real user tracing one of the test maps based on vibrational cues from both the tablet and the smart watch.

## 5.5 User Study Two

### 5.5.1 Participants

6 visually impaired and blind users (5 males,  $41.8 \pm 12.5$  years old) participated in this study. The first two participants (P1 and P2) also participated in the first user study. The demographic data for blind and visually impaired users and their causes of blindness are summarized in Table 5.2. Blind participants with residual vision were blindfolded for this study.

Part.	Sex	Age	Age onset	Cause	Residual Vision
P1	M	56	42	Uveitis, glaucoma	No
P2	M	35	16	Scarlet fever	Few shapes, colors
P3	M	58	36	Cone rod dystrophy	Light perception
P4	M	41	28	Bechets syndrome	No
P5	F	33	Birth	Leber Congenital Amaurosi	No
P6	M	28	Birth	Microphthalmia	No

**Table 5.2:** Participant Demographics for Study 2

### 5.5.2 Procedure

The participants were told how the prototype works and were then given 6 easy training maps to practice. If they could not remember the meaning of the vibrational patterns during practice, they could ask the researchers for instructions (see Prototype Two Section above for explanation of vibrational patterns). Training maps were not timed. Then, the participants were given 6 difficult test maps to complete. The two testing conditions were counterbalanced: half the participants were given Condition 1 first (tablet vibrating for vertical and watch for horizontal lines) and the other half of the participants were given Condition 2 first (watch vibrating for vertical and tablet for horizontal lines).

Testing maps were timed. During testing, instructions were given again if participants had difficulty remembering vibration patterns.

After the testing maps were completed, participants were asked about their preference for testing condition. They were also asked to rate three statements on a 5 point Likert scale where: 1 = strongly disagree, 2 = disagree, 3 = neutral, 4 = agree, and 5 = strongly agree. The three statements were: "I did not like the tablet vibrating for vertical and watch for horizontal", "I did not like the watch vibrating for vertical and tablet for horizontal", and "It was difficult to switch between

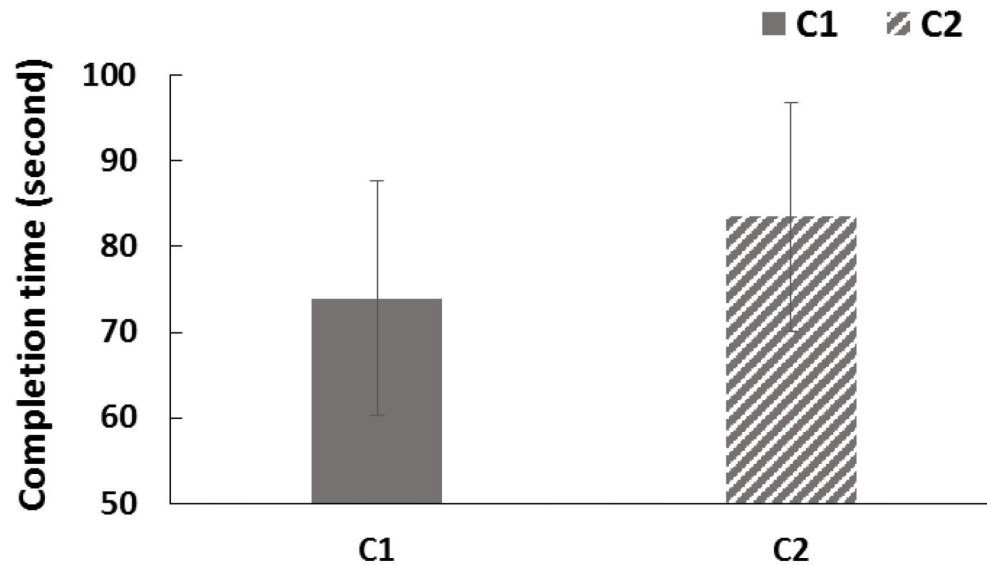
the two conditions". The statements were asked in the negative to avoid positive leading bias that tends to exist in research on assistive technology [?]. Then, the participants were asked if they had additional feedback regarding the prototype.

### 5.5.3 Results

It was feasible for users to trace maps on a touchscreen using vibrational cues. All users were able to complete 12 testing maps (6 per condition) in a timely manner. As shown in Figure 5.5, it took blind users an average of 74 seconds to complete a map in Condition 1 (tablet vibrating for vertical and watch for horizontal lines), and 83 seconds to complete a map in Condition 2 (watch vibrating for vertical and tablet for horizontal lines). There was no significant difference in map completion time between the two testing conditions ( $t(5) = -0.53$ , ns, 2 tailed).

All users were able to understand and utilize complex vibrational patterns. It was easy for them to learn the vibrational patterns for horizontal and vertical lines. Only a few times did a few participants have trouble recalling vibrational patterns for certain diagonal lines. For a real-world application, a good built-in tutorial and the functionality allowing users to relearn complex vibrational patterns would be beneficial.

As a group, blind and visually impaired users showed no overall preference for testing condition. The Likert scales for the first two statements were not statistically different ( $t(5) = -1.46$ , ns, 2 tailed). Furthermore, participants had no trouble learning different vibrational patterns and switching from one testing condition to another. This was supported by their Likert scales for statement three (2.3 with standard deviation 1.4). Interestingly, two participants did report a preference for



**Figure 5.5:** Average map completion time in second for Condition 1 (C1: tablet vibrating for vertical and watch for horizontal lines) and 2 (C2: watch vibrating for vertical and tablet for horizontal lines).

Condition 1 (tablet vibrating for vertical and watch for horizontal lines).

After the test the participants were given the opportunity to provide feedback on the prototype. Overall, participants enjoyed using the prototype. One participant said the prototype was 'challenging, fun, and interesting', and it reminded him of a video game he had played in the past. They thought the prototype was 'very cool', 'really good', and 'has potential for a lot of practical applications'. They believed that this prototype would be especially useful in a noisy environment (e.g., on a busy street or bus) where you can rely on vibrational rather than auditory cues.

Participants also provided constructive criticism of the prototype. Two participants mentioned that it was easy for them to swerve off the lines, and it took a while for them to learn how to backtrack with their finger and find the line again. One participant thought that the lines were too thin. About half the participants

commented that the watch vibration on the wrist was relatively weaker than the tablet vibration on the finger. It was therefore harder for them to sense the vibration from the watch when both devices were vibrating. One participant suggested the prototype should have the ability for TTS to indicate how far the end of the line is in scaled miles or yards. These comments would allow improvements in the prototype for real-world applications.

#### **5.5.4 Discussion and Comparison**

Compared to Spacesense [110] in which users took on average 201 seconds to learn map instructions, the average map completion time of our system was shorter (74 seconds in C1 and 83 seconds in C2). This is despite the fact that test maps in our system had more streets and turns than maps in Spacesense. However, in Spacesense users were allowed to explore the map more than once until they felt they had learned the route. Also Spacesense provided information through audio and tactile cues based on Google map directions but did not allow users to trace the maps with their finger.

In Timbremap [99], the users were given as much time as they needed to explore and learn the maps through sonification. One participant took 14 minutes to learn a map and 10 minutes to learn another. They used more complex maps than ours and were aimed at examining users' ability to understand maps as a whole rather than their abilities to follow specific directions. Similarly, TouchOver Map allowed the users 15 minutes to explore and learn a map [88]. Giudice et al. [37] tested users' accuracy of identifying shapes after spending a certain amount of time learning them, but they did not report average learning time.

It has been shown in previous studies that learning through touchscreen with audio and tactile feedback of maps is feasible and effective. This study mainly looked at how blind users can perform map tracing on touchscreens based on vibrational cues alone. While it is hard to directly compare our results to those from previous studies, our system did show promising map completion time.

## 5.6 Future Work

Blind and sighted individuals were not compared against each other in the second study. Given that blind and visually impaired users were better at determining distances between vibrational lines (User Study One), it is likely that they would be faster than sighted users to complete map tracing on a touchscreen through vibrational cues. This prediction can be tested in future user studies.

When using tactile maps, blind and visually impaired users might prefer to get street and landmark information such as street names and nearby grocery stores through TTS. Adding this information would allow us to test our prototype with real maps. It would be interesting to examine users' ability to follow both vibrational and auditory feedback. For example, how much speech information could they process while attending to the vibrational cues, and what is the optimal speed for speech to be effective.

While at group level there was no statistical difference between two testing conditions in User Study Two, two users reported a preference for condition one (tablet vibrating for vertical and watch for horizontal). A user study with more blind participants would allow us to further test this potential preference.

Lastly, participants sometimes would swerve off the lines and had to trace their finger back to the line. In future work, we could alert them by reducing the intensity of the vibration instead of simply stopping the vibration. We could test whether such information is beneficial in facilitating the completion of map tracing.

## CHAPTER 6

### ACCESSIBLE BINAURAL SOUND ON TOUCHSCREENS

#### 6.1 Introduction

There have been no attempts to make spatial information accessible on touchscreens using binaural sound. This differs from text-to-speech and haptics in that binaural sound can give accurate spatial information through headphones or stereo speakers without the need for slower text-to-speech or limited vibrational patterns where only one thing can be rendered at a time. With binaural sound, multiple visual objects on the screen can emit binaural sounds at the same time quickly and efficiently giving spatial information. Furthermore, binaural sound can be used to render accurate spatial information for moving objects in a non-visual manner. This makes binaural sound optimal for making graphics heavy applications accessible on touchscreens to people who are blind or visually impaired. In this research project, the efficacy of finding targets through binaural sound on touchscreens using different coordinate systems and available cues (volume alone versus volume and pitch together) is tested on users who are blind and visually impaired.

#### 6.2 Binaural Sound

Binaural sound is different from stereo sound in that stereo sound only uses the left or right speaker to tell left or right direction of the sound while binaural sound uses more complex sound cues. Binaural has inter-aural time differences, which is the difference in time that a sound reaches one ear versus the other ear [25]. For



example, a sound coming from the left will reach the left speaker first and then the right speaker afterwards. Binaural sound also includes inter-aural level differences (ILD). Sound coming from the left will be heard louder in the left speaker and quieter in the right speaker. Furthermore, as the user gets closer to the object, the volume increases and as they get further away, volume decreases.

This project uses the OpenAL binaural sound library. As the volume of the sound changes with distance (called attenuation), there is no set volumes or pitch discussed in this project. Instead, the volume and pitch follows the IASIG I3DL2 models of OpenAL [48]. The default model called the inverse clamp model in OpenAL was used with a default roll off factor of 1. The formula is as follows:

$$\text{gain} = \text{AL\_REFERENCE\_DISTANCE} / (\text{AL\_REFERENCE\_DISTANCE} + \text{AL\_ROLLOFF\_FACTOR} * (\text{distance} - \text{AL\_REFERENCE\_DISTANCE}))$$

where *AL\_REFERENCE\_DISTANCE* is a unique number assigned to each sound target internally by OpenAL according to its coordinates, *AL\_ROLLOFF\_FACTOR* is used to determined how fast the volume increases, and distance is the Euclidean distance between the listener's coordinates and the sound target's coordinates.

Since the default of 1 was used for *AL\_ROLLOFF\_FACTOR*, the equation reduces to the following:

$$\text{gain} = \text{AL\_REFERENCE\_DISTANCE} / \text{distance}$$

The same formula was used for increases and decreases in the pitch.

The sound used in all the tests of the prototype was a data sonified star Kepler-10b, found from the NASA website, created by Jon Jenkins [77]. This sound file was used because it was free and provided a clear and stable sound for the users.

### 6.3 Prototype

To test the efficacy of binaural sound to make touchscreen graphics apps more accessible, a prototype was made on an Android tablet. As said before, the prototype uses the OpenAL binaural sound library to render sound targets on the screen. The targets are mapped into the binaural sound engine using the x and y pixel coordinates of the location of the object on the screen. For example, a target located at (1000, 200) pixel location on the touchscreen pixel coordinate system is then rendered into the binaural sound engine as (-232, -600). Since the touchscreen has only a positive coordinate system (y values running from 0 to 2464 from top to bottom and x from 0 to 1600 from left to right) and the binaural sound engine has a positive and negative coordinate system, the touchscreen coordinate system was translated into positive and negative by the following equations:  $y = \text{pixelY} - (2464/2)$  and  $x = \text{pixelX} - (1600 / 2)$ . The pixel coordinates of the user's finger was put as input into the OpenAL as the listener position. One purpose of this study was to test the ability of users to grasp the translation of their finger on the touchscreen as their position in space with sound.

Each sound target that emitted sound was rendered logically (as there were no visuals on the screen) with a size of .5 inches by .5 inches. This is a typical average size of icons on a touchscreen such as iOS or Android. Some icons are smaller or larger depending on the size of its graphics and text, but in this project only an

average size of .5 by .5 inches was used.

Once the user's finger reached the target, the icon would buzz to notify the user that they hit the target. Haptics was used so as not to overload the sound channel with text-to-speech. The user then has to keep their finger on the target for 1 second at least before the target moves so as to prevent accidental touches or swipes over the target. In this prototype, the user only finds single, non-moving targets in order to test some basic parameters.

## **6.4 User Study**

### **6.4.1 Participants**

There were 13 blind or visually impaired participants in the study. They were recruited through local organizations for the blind. They were paid 20 dollars an hour for the study, and the study took on average one hour. There were 8 male participants and 5 female with average age of 42.3 with standard deviation of 12.2. The full demographics of the test subjects are listed in Table 6.1.

### **6.4.2 Procedure**

The participants were given four sets of trial blocks one for each condition, with 35 trials in each block. The first five trials were counted as practice. The four conditions were as follows: (1) XY mapping with volume, (2) XY mapping with volume and pitch, (3) XZ mapping with volume, and (4) XZ mapping with volume and

Part.	Sex	Age	Age on-set	Cause	Residual Vision
P1	M	36	6	scarlet fever	shadows, shapes
P2	M	43	28	bechets syndrome	no
P3	F	43	birth	retinitis pigmentosa	light perception
P4	F	41	birth	retinopathy	no
P5	F	39	birth	glaucoma	no
P6	F	34	Birth	Retinitis pigmentosa	No
P7	M	29	Birth	microphthalmia	No
P8	M	35	Birth	retinopathy	low vision
P9	M	56	Birth	retinopathy	light perception
P10	F	64	31	auto accident	no
P11	M	59	birth	cone rod dystrophy	light perception
P12	M	50	42	cone rod dystrophy	low vision
P13	M	21	3	retinoblastoma	no

**Table 6.1:** Participant Demographics

pitch. The mapping refers to the mapping of the touchscreen 2D coordinate system to the 3D binaural coordinate system. XY system mapped the 2D touchscreen XY plane to the vertical XY plane in the binaural coordinate system. In this condition, sounds heard above the finger on the touchscreen are heard physically above the listener in the head phones. XZ refers to the mapping of the 2D XY coordinate system of the touchscreen to the XZ plane of the binaural sound engine. In this condition, sounds above the finger on the touchscreen will be heard physically in front of the user while sounds below the finger will be heard behind the user. Besides the coordinate system, the other parameter that varied between conditions is available cues (volume alone versus volume and pitch together). In Volume conditions, volume alone increased and decreased as the users finger moved closer to the target and further away from the target, whereas in Pitch Volume conditions, pitch and volume changed together. Note that pitch was not used by itself as it has been shown in previous research to be not as good as volume by itself [81]. Previous research has shown, though, that using pitch and volume together on the same parameters, in this case distance to target, to be more effective than a single

sound cue alone [78].

The user's task on each trial was to find the target using the binaural sound cues in headphones. Once a target was found, the tablet buzzed, and the user had to wait 1 sec until the buzzing stopped before the target moved. Each trial was timed, and the 1 sec delay in buzzing was not counted in the timing. After the 35 trials for each condition, the participants were given 5 minutes or so to rest before the next set of trials.

The XY and XZ conditions were counterbalanced, but the volume and pitch conditions were not. Each participant received a different XY or XZ condition first, but every participant received volume first and then pitch second.

After the trials were over, the participants were asked whether they preferred volume or pitch plus volume. Initially, they were also asked whether they preferred XY versus XZ but the first several participants said they could tell no difference. The participants were also asked for any open-ended feedback and comments.

### **6.4.3 Results**

#### **6.4.4 Quantitative Results**

The average time in milliseconds for each trial for each participant can be seen in Table 6.2 with overall averages and standard deviations. One way anova found a significant difference between the means of all four techniques ( $DF=48$ ,  $F=4.2$ ,  $P < 0.05$ ). Posthoc tests found a significant difference between XZ Pitch+Volume

Part.	xy Volume	xy PitchVolume	xz PitchVolume	xz Volume
P1	14913	9250	10312	9078
P2	21305	11854	11854	15773
P3	10917	11854	7294	8761
P4	10700	9099	13161	24800
P5	12930	12683	6596	9096
P6	8308	8155	12438	20181
P7	12309	9275	6062	7154
P8	11651	10961	10816	24140
P9	2281	11925	9606	1594
P10	18468	17606	16469	21576
P11	24339	12027	8016	10626
P12	12916	6635	5749	8241
P13	7628	6979	7904	25800
Avg	14554	10639	9714	15475
Std. Dev.	5469	2903	3187	7071

**Table 6.2:** Average times in milliseconds for all four conditions for each participant with overall averages.

and XZ Volume for a significance level of 0.05. For a significance level of 0.1 in addition to the result for .05, XZ Pitch+Volume is significantly different than XY Volume and also XY Pitch+Volume is significantly different than XZ Volume.

#### 6.4.5 Qualitative Results

All except P7 preferred the pitch+volume tests as opposed to the volume by itself. The participants gave positive feedback for the test. P1 stated, “pitch would be excellent following a moving target for a game,” and “much faster to home in on pitch version than volume version.” P2 stated, “Instantly user friendly.” P5 stated, “second one with pitch much more fun easier to follow, first one with volume kinda boring, did not have to concentrate as much with pitch test.”

## 6.5 Discussion

Table 6.2 shows that the participants were able to find targets within reasonable times non-visually with binaural sound. The table also shows that while the best overall average times were around 9 and 10 seconds, the users became faster with learning, and their fourth condition usually resulted in pretty fast times. Some users were able to achieve around 6 seconds on average to find targets. The users overwhelmingly preferred to use the pitch increases along with volume increases to cue distance rather than volume by itself. The quantitative data backs up the qualitative results, showing that there was a statistically significant difference in speed between XZ Pitch+Volume over XZ volume by itself. There seems to be no statistically significant difference between times on the XY versus XZ mappings of coordinate systems. The qualitative data confirms this as the first several test subjects had no preference for either one and we stopped asking the question as it confused the participants.

The study results shows that both quantitatively and qualitatively the effectiveness of binaural sound on touchscreens to make them more accessible to people who are blind and visually impaired.

## 6.6 Future Work

For future work, the testing of the efficacy of listening to and finding multiple targets on the screen will be tested. Furthermore, moving objects on the screen will be tested to see how effectively people who are blind and visually impaired can follow, find, and interact with moving objects using binaural sound.

## CHAPTER 7

### CONCLUSION

This dissertation presented three new interaction techniques with several prototypes and user studies to demonstrate how, in new ways, spatial information on touchscreens can be made accessible to people who are blind and visually impaired. The first technique, backed up by a qualitative study on how blind people currently access diagrams, presented and tested two prototypes to make diagram creation accessible. It allowed the users to move shapes around with gestures and hear text-to-speech feedback about what graphics were on the screen. The results were positive from the users in a free-flowing qualitative user study.

The second technique was non-visual and non-auditory and allowed access to maps on touchscreens through haptics. The users finger was guided through a map with eight different vibrational patterns coming from two different vibrators: a smartwatch vibrator and a tablet vibrator. Quantitative and qualitative data showed that this technique was effective for the users and was enjoyable to use.

The third technique relies on binaural sound to allow target acquisition of objects on a screen. The objects emit a sound that the user then can locate through headphones by moving their finger around the screen. The sound gets louder as they get closer to the target. Pitch was also tested along with volume. The user study showed that both quantitatively and qualitatively the technique was effective in quickly guiding the users to the target, and the users found the pitch very enjoyable and easier to use than the volume by itself.

These three studies make progress towards making spatial information in many graphics heavy apps accessible to people who are blind and visually impaired. Fu-



ture work will look at graphics and animations that are moving along with many different objects on the screen such as in a video game or physics simulation.

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