

ABSTRACT

Title of Dissertation: **Designing Multimodal Touchscreen
Interactions For Accessible Data
Visualization Supporting Blind Users**

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Data visualization can be a democratizing force for providing advanced data analysis tools and capabilities to everyday users. However, data visualization also creates barriers for blind and low-vision (BLV) individuals, a fact that has long been recognized in the accessibility research community. Assistive technologies such as tactile graphics, data sonification (using audio to convey data), and refreshable tactile displays (RTDs) can be utilized to lower the accessibility barriers to data visualization. Yet it is only recently that visualization research has realized this fact. Since this realization, there have been various efforts from the visualization community, such as data-centric alt-text, accessible tables, and richer screen reader experiences. However, the visualization community, which arguably is best poised to tackle these challenges, has so far only scratched the surface of creating rich human-data interactions for blind individuals.

Commercial touchscreen devices such as smartphones and tablets now have in-built accessibility features, and are thus increasingly being adopted by blind individuals. These devices are also well-suited to support direct data manipulation through touch interactions. I adopted

a mixed-methods approach to design multimodal (audio and haptic) chart representations and interactions that leverage such touchscreen devices by conducting four studies.

The first study involved semi-structured interviews with Ten Orientation and Mobility (O&M) experts who train BLV individuals in non-visual navigation and spatial understanding. The goal was to derive design principles for effective non-visual data interaction. Findings emphasized the usefulness of crossmodal sensory substitution (CMSS)—a strategy where tactile interactions are paired with sonification to enhance spatial awareness. Participants highlighted that BLV individuals have diverse preferences for sensory modalities, necessitating personalized multimodal experiences that cater to different skill levels and cognitive strategies. These insights informed the design of an accessible data visualization system.

The second study explored the lived experiences of BLV professionals in data-related fields through a two-step online survey. Responses from BLV individuals engaged in data analysis revealed persistent accessibility barriers at multiple stages of the data workflow—including data loading, transformation, analysis, and visualization authoring. Despite expertise in programming (e.g., Python, R, and SAS) and GUI-based tools (e.g., Excel), participants reported substantial reliance on assistive technologies, often requiring sighted colleagues' assistance to interpret visualizations. These findings highlight the need for “born accessible” tools that allow independent and efficient data exploration without requiring external support.

The third study introduces TactualPlot, a multimodal data interaction system that leverages CMSS principles to enable blind users to explore data through touch and sound on touchscreen devices. TactualPlot was developed through an iterative participatory design process involving a blind collaborator who provided feedback on early prototypes. The system supports scatterplots, bar charts, line graphs, and pie charts, allowing users to explore data through multi-finger

touch gestures combined with audio cues and spatial feedback. Unlike traditional sonification approaches, TactualPlot employs direct touch interactions (similar to tactile exploration) to guide users through high-level data trends before enabling deeper exploration.

The final study presents an empirical evaluation comparing TactualPlot to other accessibility solutions, including screen readers (Olli) and refreshable tactile displays (Monarch). Ten blind participants, recruited from blind individuals working in data-intensive fields, performed data analysis tasks of varying complexity across multiple visualization types. The study assessed task correctness, completion times, and user preferences, revealing that hybrid approaches combining touch and sound were preferred over uni-modal (audio-only or tactile-only) solutions. Novel multi-line braille displays such as the Monarch offer features that can combine both touch-screen interactions and haptic feedback. To better understand how blind individuals can create charts for and use RTDs in the future, I also conducted a 3-hour long co-design session with a blind participant, providing insights into how blind users conceptualize and create tactile-based charts.

This dissertation contributes to accessible data visualization research by demonstrating the effectiveness of multimodal (touch-audio) interactions and highlighting new design opportunities for refreshable tactile displays. The findings provide practical guidelines for creating “born accessible” data tools for BLV individuals in data-intensive fields. By integrating touch, sound, and personalized interaction techniques, this work helps with the creation of next-generation accessible visualization systems, empowering BLV individuals to engage with data independently and effectively.

DESIGNING MULTIMODAL TOUCHSCREEN INTERACTIONS
FOR ACCESSIBLE DATA VISUALIZATION SUPPORTING BLIND USERS

by

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List of Abbreviations

ADSR	Attack Decay Release Sustain
AI	Artificial Intelligence
AISP	Audio Information Seeking Principles
API	Application Programming Interface
BLV	Blind and Low-Vision
CSV	Comma-Separated Values
GUI	Graphical User Interface
HCI	Human-Computer Interaction
HTML	Hypertext Markup Language
HVAC	Heating, Ventilation, and Air Conditioning
ICAD	International Community for Auditory Display
IRB	Institutional Review Board
JSON	JavaScript Object Notation
LLM	Large Language Model
ML	Machine Learning
NASA TLX	NASA Task Load Index
NFB	National Federation of the Blind
NOMC	National Orientation and Mobility Certification
O&M	Orientation and Mobility
OCR	Optical Character Recognition
PDF	Portable Document Format
PNG	Portable Network Graphics
RTD	Refreshable Tactile Display
SCSS	Simultaneous Crossmodal Sensory Substitution
SDCT	Structured Discovery Cane Travel
SQL	Structured Query Language
STEM	Science, Technology, Engineering, and Mathematics
TTS	Text-to-Speech
TVSI	Teachers of Students with Visual Impairments
UI	User Interface
UX	User Experience
WCAG	Web Content Accessibility Guidelines

Chapter 1: Introduction

Visualizations are largely inaccessible to individuals who are Blind or have visual impairments. Screen readers, the method Blind people most commonly use to transform on-screen text to speech, generally cannot parse pixel visualizations, and few web-based visualizations provide sufficient textual descriptions or the underlying datasets [2]. People with visual impairments are a large population of potential data visualization users. In 2015, globally there were 253 million people with visual impairments, out of whom 26 million were Blind, and this number is estimated to reach around 703 million by the year 2050 [3]. This is also not just a sociotechnical problem, but a potentially legal one; for example, in the United States, Section 508 of the Rehabilitation Act requires that all federal government websites be accessible for people with disabilities, and the Americans with Disabilities Act similarly requires accessibility for most websites of public accommodations [4]. Blind people¹ navigate a 3D world of space and objects, and are therefore equally capable of understanding spatial layouts as sighted individuals. However, despite continuous advances in visualization research, little effort is devoted to accessibility. While our focus is on Blind individuals, inaccessible visualization practices not only affect Blind people, but also those with other impairments such as motor or cognitive impairments [2,5].

The visualization community must work to lower barriers for Blind individuals by focus-

¹While people-first language is preferred by most people with disabilities, much of the blindness community prefers the use of the term “Blind individuals or Blind people”. In this dissertation, I use both the terms interchangeably.

ing on accessible visualization and data analysis. Additionally, collaboration between sighted and Blind individuals in data-rich social contexts such as work and school might still be challenging due to technology that places sighted and Blind individuals in two different silos. Particularly in STEM fields, spatial and graphical reasoning are invaluable skills that are taught and used by individuals for problem-solving and data analysis. Accessible data visualizations can improve data literacy among Blind individuals, equipping them with practical knowledge of data representation, interpretation, and analysis. This empowers them to actively engage in data-driven discussions, make informed decisions, and advocate for their interests in our data-centric world. One of the goals of this dissertation is to follow a unified approach to lowering accessibility barriers to minimize the need for separate or alternate representations of data visualizations—for Blind and sighted individuals. While there are differences in the needs of Blind and sighted individuals, I believe that fostering collaboration between people with different abilities is essential in educational and professional contexts.

Accessibility technologies for Blind users tend to employ a method called *sensory substitution* [6] by conveying data using other senses such as hearing and touch, and even smell [7, 8] instead of vision. Efforts to render visualizations accessible for Blind users have been explored by research communities such as human-computer interaction (HCI), accessibility, and sonification for specific contexts. Of the two most common sensory substitutes—sound and touch—sound is by far the easiest to deploy since it does not require any specialized hardware. While there exist many examples of sonification and auralization [9] (the use of non-verbal and verbal sound), these efforts primarily involve the Blind community only as *users* or *testers*, and not as full-fledged *informants* or *design partners* [10, 11] in the development team. Data visualizations can be made accessible through techniques such as data-centric alt-text [1] or figure captions, screen-reader

explorable tables and lists [12], and rich screen reader experiences [13]. Blind individuals can use sensory substitution techniques, such as tactile charts and data sonification, to improve chart accessibility. They also utilize various assistive technologies for non-visual sensemaking, such as screen readers, refreshable Braille displays, and tactile media.

The sense of touch is critical for most Blind individuals. Bereft of full use of their vision, Blind people often use their hands to explore unfamiliar objects or their white cane to learn about the world surrounding them. Building on this idea, *data physicalization* [14] creates tangible representations of data to enable a Blind person to feel rather than see the physical shape of a bar chart [15], 3D landscape [16], or node-link graphs [17]. However, data physicalizations that are cheap and accessible, such as thermoform paper and 3D printing, are static and require significant time to produce. More advanced data physicalization techniques that enable interactive feedback—such as shape-changing displays [18], haptic touch displays [19], and refreshable Braille displays—rely on specialized technology that is expensive and therefore not readily available to an often underemployed Blind audience with limited purchasing power. Furthermore, the accessibility field is rife with “silver bullet” technologies that have been abandoned by over-optimistic inventors [2], making investing in experimental devices both costly and risky. While these sophisticated technologies may make data accessible for Blind individuals, adoption at scale is not guaranteed because of the aforementioned limitations.

What is readily available, however, are touchscreen devices. Modern smartphones have had a near-revolutionary impact on Blind individuals, putting screen readers into virtually everyone’s pocket [20]. While still costly, smartphones have significant utility for both personal and professional use and thus enjoys widespread adoption—more than 46% [21]—among Blind people, and the number is likely higher for gainfully employed knowledge workers. Touchscreens provide a

tangible and interactive interface, allowing Blind users to engage with data in a more immersive manner suited for data exploration. Through tactile exploration and haptic feedback, individuals can perceive patterns, trends, and relationships inherent in data visualizations. This multimodal experience facilitates a deeper understanding of complex information, enabling Blind users to grasp nuances, detect anomalies, and extract meaningful insights that may otherwise be elusive through traditional non-interactive methods, or through text and other narratives. As opposed to keyboard input in desktops and laptops, touchscreens are better suited for *direct manipulation* [22] of data, while still demonstrating comparable computational power. The overarching goal of this dissertation is:

How can we design a method for perceiving and interacting with complex datasets on touchscreen devices, allowing Blind users to explore data through multimodal (audio and haptic) feedback—leveraging the same touch-based strategies they use for tactile exploration?

1.1 Research Overview and Approach

To design accessible data visualization touchscreen experiences, I adopt a mixed-methods approach to design multimodal (audio and haptic) touchscreen chart representations and interactions that could potentially be utilized in touchscreen devices such as smartphones and tablets. Overall, the following high-level research questions are addressed in this dissertation:

RQ1: How do Blind individuals perceive and retain sound and touch-based information so that spatial layouts such as charts can be effectively translated into non-visual senses, i.e., sensory substitution?

RQ2: How can we effectively employ sensory substitution to support multiple levels (i.e.,

overview, zoom, filter) of visualization-related tasks on touchscreen devices?

RQ3: How can we integrate touchscreen screen reader and multimodal data visualization interactions to support data analysis of multidimensional data and multiple chart types?

1.2 Dissertation Overview

CHAPTER 1. In this chapter, I have described the motivation, problem statement, and research questions for the dissertation. I also provide an overview of the dissertation, list the publications from my research, and conclude with a thesis statement.

CHAPTER 2. I discuss the relevant background literature on mental and spatial mapping; sensory substitution for Blind users; sound perception and sonification; non-visual chart access through sonification, tactile interaction, and multimodal systems.

CHAPTER 3. To answer RQ1, I conducted a qualitative study that explored the potential of accessible visualization design by understanding how Blind individuals perceive the world around them using non-visual senses, i.e., *sensory substitution*. This knowledge enables the design of more efficient audio representations of data that leverage the mechanisms that Blind people already use in their everyday life. My goal was to broadly understand (1) how Blind individuals perceive and retain sound and touch-based information so that visual layouts such as charts can be effectively translated into non-visual senses, and (2) what this means for accessible visualization design so that future tools are robust enough to support multiple levels of visualization-related tasks [23]. To this end, I conducted semi-structured interviews with 10 Orientation and Mobility (O&M) instructors (experts), all of them Blind, to understand how they teach their students

(Blind individuals) to navigate physical space using the sense of sound and touch. This particular population was selected because O&M instructors not only have significant personal expertise in leveraging non-visual senses to navigate the physical world everyday life, but also the knowledge and experience of teaching these skills to others. As part of the interviews, I also conducted discussions with these instructors on how to use sound and touch to convey data, and to translate visualizations. I found that Blind individuals who undergo O&M training engage in *experiential learning* [24]—e.g., hands-on learning followed by reflection—to calibrate their minds to mapping sounds and tactile feedback to real-world aspects such as size, distance, angles, and position. Individuals actively use echolocation and environmental sounds to make sense of physical space, and the importance of sensory integration (e.g., combining audio and tactile feedback) in understanding it. Based on these findings, I derived design implications for accessible visualization design, with a focus on audio—speech and non-speech, and tactile representations, feedback and interactions. And finally, I discuss the importance of training and usability of tools for accessible visualization for Blind individuals.

Role: My contribution to the research study includes 1) designing the interview script based on the research questions 2) conducting the interviews and the thematic analysis, and 3) authoring the research manuscript.

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CHAPTER 4. I explored the current challenges with accessibility and data analysis of Blind and low-vision (BLV) individuals. I conducted a survey to better understand the user context of Blind individuals working professionally with data and visualizations. I found that Blind and low-vision professionals had challenges with creating accessible charts that can be used by both sighted and Blind individuals. Blind individuals often depended on their sighted colleagues to refine charts; and were limited to using tools (e.g., Microsoft Excel, Python) that were used as part of their current data analysis workflow. Additionally, accessibility issues with tools and processes such as data loading and transformation can lead to further challenges with accessible data visualization during chart creation and communication.

Role: My contribution to the research study includes: 1) collaborating with a research team member to design the survey 2) analysis of the survey data, and 3) authoring the research manuscript.

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CHAPTER 5. To answer RQ2, I defined a design space for *simultaneous crossmodal sensory substitution (SCSS)*. We call this approach *crossmodal substitution* because it replaces the expected haptic feedback from such touch-based sensing with another sensory stimulus; in this case sound. Crossmodal substitution draws on *sensory substitution* [6, 25], a common technique from assistive technologies where stimulus for one sensory system is replaced with stimulus for

another, such as a screen reader verbalizing written text on a screen with synthesized speech. A special case of *multimodal substitution* [26,27] because of the use of multiple sensory channels, the approach explicitly “crosses” touch input with sound output. I achieved this by producing audio rather than haptic output in response to touch exploration. To explore and validate this idea, I proposed and implemented TACTUALPLOT, a crossmodal substitution technique that enables a person to “touch data” spatialized in two dimensions on a tablet touch screen, similar to a visual 2D scatterplot. With TactualPlot, a Blind user can use their fingertips to explore the shape of the data, receiving a dynamically changing audio tone in response that conveys the density under the user’s touch using pitch and verbalization. Unlike many other accessible data representations, TactualPlot was designed for scalability, with thousands of data points in mind. TactualPlot was designed using a user-centered approach by engaging my collaborator, who is Blind, in a series of formative design sessions. Our observations yielded several design revisions, including the need for multiple touch interaction and axes manipulation. Our participatory design sessions helped us understand that it is important to develop a touch-based, non-visual graphical perception technique that could be generalized beyond scatterplots. In-depth expert reviews with two Blind professionals helped assess the utility of TactualPlot, and—by extension—the validity of the crossmodal substitution concept.

Role: My contribution to the research study includes: 1) designing and implementing the features of TactualPlot on the iPad 2) conducting the design sessions with our collaborator, 4) performing the data analysis of the task results and analyzing the touch logs, and 5) authoring the research manuscript.

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TactualPlot: spatializing data as sound using sensory substitution for touchscreen accessibility.

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CHAPTER 6. To answer RQ3 and thereby support data analysis of multidimensional data and multiple chart types, I expanding and quantitatively evaluated the crossmodal sensory substitution design space. I compared TactualPlot to other devices that used only one modality—sound (Olli [12]) and touch (Monarch [28]) to isolate differences between modalities for visualization tasks. I compared task performance with bar charts, pie charts, line charts, and scatterplots. The results indicated that TactualPlot generally led to better accuracy. The Monarch often resulted in lower completion times. Qualitative insights from Blind participants offered perspectives on the use of sound versus touch in data interpretation. To better understand tactile chart authoring for refreshable tactile displays (RTDs), I conducted a co-design session with a Blind participant using a pair analytics approach to explore financial data. Finally, I discuss the need for standards and validated audio-visual scales; and explain the implications of the findings from the two studies for expanding established web content accessibility guidelines for multimodal data visualizations.

Role: My contribution to the research study includes: 1) designing and implementing the charts for TactualPlot, Olli, and the Monarch 2) conducting the pilot sessions and the experiment, 3) performing the quantitative and qualitative analyses, 4) conducting the co-design session and analyzing the data from the session, and 5) authoring the research findings and discussion.

CHAPTER 7. In this chapter, I summarize the contributions from my mixed-methods approach, and propose future work for designing multimodal interactions for accessible data visualization supporting Blind users.

This dissertation addresses the critical challenge of making data visualizations accessible to blind individuals by investigating multimodal touchscreen interactions. Through a mixed-methods approach—including interviews with orientation and mobility experts, a survey with blind and low-vision professions, the design and evaluation of the TactualPlot system, a comparative study of accessibility modalities (screen readers, sonification, and braille), and a co-design session with a refreshable tactile display—my work demonstrates the potential of multimodal sensory substitution for non-visual data exploration. The research contributes empirical insights, and practical design guidelines aligned with accessibility principles to inform the development of inclusive data visualization tools.

Chapter 2: Related Work

Much work has been done across communities such as HCI, Accessibility, ICAD, and cognition to make data and charts accessible. We believe that many of these solutions could make specific chart types or data accessible. As newer and more complex innovation in the visualization community grows, there is a need within the visualization community for frameworks or models to guide researchers and technologists to make their innovations accessible. Below we discuss prior work across research disciplines in the use of sensory substitution to aid in data analysis and visualization.

2.1 Mental and Spatial Mapping

Mental maps are cognitive constructs that are used to understand and explain the environment around a person to support spatial thinking and discussions [29, 30]. These mental maps are stored as schematic representations [31], usually based on rectangular grid structures [32], and contains information related to objects, spatial relations between objects, landmarks, intersections, and route descriptions [33].

Research shows that Blind and sighted people construct spatial maps in similar ways [34], and that Blind individuals use a combination of sensory cues such as auditory, tactile, movement, and proprioception to perceive, store and recall spatial concepts [35–37]. Research shows that

the “visual” cortex of the Blind is activated to process other sensory modalities [38]. More recently, Hersh [7] conducted interviews with 300 Blind and visually impaired individuals about perceiving spatial layouts, and identified that these individuals used their hearing, touch, and a combination of both to perceive space.

Orientation and Mobility (O&M) training has been studied in the literature primarily to inform technology development to support O&M training [7, 8]. O&M training teaches perceptual and conceptual abilities to tackle indoor and outdoor navigation tasks. In fact, O&M skills have been shown to be transferable between virtual environments to the real-world and vice-versa [39, 40]. This partly motivated our focus on O&M instructors in our study.

2.2 Sensory and Multimodal Substitution for Blind Users

Sensory substitution refers to the use of one sense to provide information normally provided by another sense [25], and is a common approach for assistive technology in accessibility [6]. Audiobooks are a prime example of assistive technology using sensory substitution; originally invented to help Blind individuals enjoy reading books, their widespread adoption also with sighted individuals showcases a common phenomenon in accessibility: the “curb-cut effect,” where improvements for one population of users end up benefiting many. *Multimodal substitution*, on the other hand, involves combining different sensory modalities to create a richer experience [26, 27]. For instance, combining touch, sound, and smell can provide a more complete representation of an environment for a Blind user. Sensory and multimodal substitution are commonly used also for accessible visualization [20]. This is primarily done through sound and tactile feedback; we describe these research efforts in detail below. However, researchers have also explored the

potential of using smell to make visualization accessible for Blind individuals [41].

2.3 Sound Perception and Sonification

Sonification is the use of non-speech sounds to convey data or information where data are mapped to sound parameters to generate sound [9]. *Auralization* is the process of modeling and simulating the experience of sound in a virtual space [42]. *Audification* [43], a type of *sonification* is the technique of directly mapping all data values one-to-one continuously to audio-samples. The aforementioned data mapping techniques have been extensively used by the International Community of Auditory Display (ICAD). In a typical auditory display, one may have multiple auditory dimensions (e.g., frequency or loudness of a tone) with each dimension bearing a light information load (data), or relatively more number of auditory dimensions, with each dimension bearing a considerably higher information load. The information being represented using sounds range from a low-resolution equivalent of images [44, 45]; to system functionality and actions—auditory icons and earcons [46, 47]; and abstract data such as temperature and pressure [48]. Brittel [49] presents a review of literature on sonification in conveying geospatial data by mappings to non-speech sound dimensions such as frequency and timbre, and to temporal characteristics such as duration and time.

Sonification using spatial sounds—2D or 3D, where the position of the sound source is modeled, helps Blind and partially sighted users explore spatial layouts such as virtual city maps [50]. Nasir and Roberts [51] present a comprehensive review on spatial sound and sonification techniques that are beneficial in conveying spatial as well as non-spatial data (such as pie charts). The authors state that the complete potential of spatial 3D audio is yet to be explored. Du-

raiswami et al. [42] present techniques for creating virtual auditory spaces to aid acoustic source localization. Geronazzo et al. [52] present a spatial sonification system that enables audio-haptic exploration of virtual maps, and show that a 3D spatial audio and tactile combination outperforms just tactile feedback and tactile feedback with 2D audio.

Sound-based substitution has the advantage of being easily available in professional settings to Blind individuals through personal computing and audio devices such as computers, smartphones, and headphones. However, there are disadvantages such as requiring extensive training [44], and varying auditory perception of individuals. Humans find it hard to distinguish different levels of a sound dimension (e.g., multiple frequency levels) and are better able to distinguish between different dimensions (e.g., between two tones with fewer segments across frequency and loudness) [53]. Walker et al. [48] experimentally compared sound mapping ensembles created by sound designers to be “Intuitive”, “Okay”, “Bad” and “Random”; and the “Random” ensemble resulted in the highest task accuracy over “Intuitive” or “Okay” as one would expect. Hence, it is crucial to empirically test the auditory display system with the intended user to define the most efficient mappings. We seek to better understand such variability in sound perception through interviews, and experimentally testing our sound design.

2.4 Chart Accessibility

Visualizations are by definition visual in nature, so making them accessible to a Blind audience is a significant challenge with facets, many of them social rather than just technical in nature [2]. Visualization has long mostly ignored the fact that visual representations are not accessible for Blind or low vision (BLV) individuals [54], but this is now changing [54–58].

However, designing accessible visualization is fraught with complexity, both in terms of technical challenges (e.g., how to represent complex and large-scale data primarily using sound and touch) as well as social (adoption, maintenance, and training) and economical (high cost to an often underemployed user population) barriers [2]. Here we review the literature on accessible visualization, focusing mostly on the aforementioned technical challenges. Non-verbal sound (*sonification*) and speech (*auralization*) have been used in place of visual representations. Early solutions used musical cues to convey shapes and graphs, but required visually impaired users to have musical knowledge [59, 60]. While not directly related to visualization, audio and haptic feedback have been used to help people with visual impairments understand the structure of web pages representing buttons, links, and search features [61, 62]. NASA researchers developed MATHTRAX [63], an interactive graphing software that sonifies mathematical data, functions, and equations for Blind and low-vision students. Visualization-specific audio translations such as sonification of 2D data tables [64], line charts [65], shapes [66], bar charts [67], pie charts [68], and network structures [69] have mapped audio notes to data values as effective non-visual chart equivalents. The aforementioned solutions were experimentally evaluated with Blind individuals; with sighted or blindfolded individuals oftentimes included for comparison. While these chart specific solutions are effective, issues with training and usability due to lack of familiarity with audio dimensions still persisted. Sonification of axes and labels improve point estimation by providing contextual references [70]—leading to improved graphical perception.

Tactile representations are effective in representing data and in translating visual representations such as maps [71] and bar charts [72] into touch-perceivable equivalents. Guinness et al. [73] used miniature robots to convey data, and found that target acquisition was easier using tactile feedback as compared to sound. The sense of smell could also potentially be used as

a complementary modality towards making visualization accessible for Blind individuals [41]. Zhao et al. [74] created a tool that used both sound and speech to enable visually impaired users to explore maps and several other statistical data graphics. Brown et al. [75] propose audio representation guidelines for graphs and tables, and Zhao and colleagues [74, 76] propose audio information seeking principles (AISP) for abstract data. Computational methods have been used to extract semantic information that can subsequently be sonified or read aloud [77], from charts in applications such as accessible floor plans [78], to metadata added to charts generated in R [79]. However, these solutions work only for charts authored in specific tools. Multimodal solutions using a combination of sound and touch have been shown to be more effective than using single modalities, and have inherently focused on chart translation, interaction, and authoring as well [80–84]. Web chart accessibility focuses on screen reader integration leading to solutions that integrate naturally into Blind individuals’ technology ecosystem [5, 67, 84]. In our work, we focus on bridging these disciplines, confirming results from and adding to past work, and broadly focus on sensory substitution for spatial understanding by interviewing experts from the Blind community.

Given the understandable reluctance among the Blind community to adopt untested and poorly maintained technology [2], one strategy has been to target low-hanging fruit. Screen readers may be one such opportunity. Alternate texts (alt-texts) are machine readable descriptions associated with images on the web, and are commonly verbalized by screen readers to help Blind individuals access image content via screen readers. Jung et al. [85] propose a comprehensive set of guidelines for writing alternative text descriptions for visualizations to cater to the diverse needs of Blind individuals. However, the adoption of alt-text on the internet is poor even for regular images [86], let alone chart images. To deal with these situations, Al-Zaidy and Giles

presented an algorithm that uses computer vision and OCR techniques to automatically extract data from bar charts with an accuracy of over 90% [87]. Similarly, Choi et al. [88] proposed an approach to reverse-engineer rasterized several types of charts to make the data accessible for Blind users.

Another approach is to design visualizations to play nice with a screen reader. Zong et al. [1] worked with Blind collaborators to design visualizations whose structure, navigation, and descriptive content are optimized for rich screen reader experiences. The VoxLens [89] integrates with the screen reader to convey a multimodal approach to visualization accessibility, providing voice commands, summarizing data, and sonifying details on demand. Most recently, Thompson et al. [13] worked over a period of five months to develop a chart accessibility engine combining a screen reader, data sonification, and descriptive content generation for web-based charts.

2.5 Sonifying Data

In a state-of-art report written for the U.S. National Science Foundation in 1997, Kramer et al. [90] define *data sonification* as “*the use of nonspeech audio to convey information*” (p. 4), further qualifying it as “*the transformation of data relations into perceived relations in an acoustic signal for the purposes of facilitating communication or interpretation*” (p. 4). Sonification is a form of an *auditory display* [91]; other forms (not necessarily mutually exclusive with sonification) include audification (directly converting large-scale data to the audible domain, auditory icons (short and self-contained sounds representing discrete events), and verbalization (synthesized speech conveying data).

The ICAD community has been the epicenter of auditory display research for the last 30

years, but not all auditory displays are concerned with conveying data; some approaches are mostly artistic in nature, whereas others focus on conveying realistic soundscapes rather than abstract data. Nevertheless, many sonification efforts can be applicable for such abstract datasets; the *Sonification Handbook* [9] surveys the state of the art in the field.

One of the early sonification approaches was the iSonic system [92], where spatialized geographic data is conveyed using sound to support a Blind user navigating and querying a map using physical key mappings. Our work is heavily inspired by iSonic, but draws on the widespread adoption of smartphones where the touchscreen becomes the equivalent to the physical keys. The web-based chart library Highcharts has recently begun distributing an accessibility tool called the Sonification Studio [93], which enables robust and flexible data exploration using sound. Wang et al. [94] performed a study to rank audio channels in the sonification of data, confirming that pitch is optimal for encode data, but that tappings and length can be effective for specific tasks or data types. Finally, Hoque et al. [95] present a study on how the use of natural sounds can enable blending multiple data channels in parallel for increasing the sensory bandwidth of the sonification. Holloway et al. [96] use both sonification and speech to make infographics accessible. While we use sonification in our approach, we do not sonify the data directly, but rather we sonify the spatial attribute of data when visualized in a scatterplot.

2.6 Touching Data

Standard touch-based assistive technology [6] include the ubiquitous white cane, Braille text that can be read using the fingertips, and tactile maps [96], whereas Braille keyboards enable Blind individuals to generate text. However, for representing data, the options are limited. Static

tactile graphics are mostly made through 3D printing, thermal printing (where lines and shapes are raised when heat is applied), or embossing (which press designs into paper).

Digital tactile representations have the benefit of being able to refresh dynamically, but are often specialized or costly, or both. Nevertheless, such refreshable technologies have been proven effective in conveying data from visual representations into touch-perceivable equivalents, as evidenced by studies on maps [96] and bar charts [15]. Guinness et al. [73] found that using miniature robots to convey data through tactile feedback was more effective for target acquisition than using sound. Such data physicalization [14], shape-changing displays [18], and haptic touch displays [19] could well present workable solutions. However, with the exception of the long-awaited Dynamic Tactile Device (DTD)¹ being developed by HumanWare and American Printing House for the Blind, most of these advanced devices are costly research prototypes, and thus are not widely available to the general Blind population. Another option may be the commercially available ultrahaptics display [97], which generates mid-air tactile sensations using ultrasound, but the device still provides a fairly low resolution.

The nearly ubiquitous smartphone [21] may be a better solution since it incorporates both audio output and a touch surface. A recent paper explores the use of touch for exploring 2D visualizations to yield sonified 3D sound output [98]. However, their evaluation uses six blindfolded sighted participants, which is questionable and not an ecologically valid approach [54]. While our work is based on a similar idea, our approach to multi-touch interaction using a sampling region is more robust and was iteratively developed in a participatory design process with a Blind collaborator and tested with Blind experts.

¹<https://www.aph.org/dtd-fact-sheet/>

2.7 Multimodal Data Access

Recognizing the strengths and limitations of individual modalities, researchers have increasingly turned to multimodal approaches that combine different sensory inputs to create more comprehensive and accessible data representations. These hybrid solutions aim to leverage the complementary nature of different senses to enhance overall data comprehension and exploration. The concept of *sensory substitution*, where information typically acquired through one sense is conveyed through another, forms the foundation of many multimodal approaches [6, 20]. Derooy and Auvray provide a comprehensive perspective on sensory substitution, exploring how information can be effectively communicated through alternative sensory channels [26]. Kramer et al. [90] reported that sonification requires users to interpret abstract acoustic cues—such as changes in pitch or timbre—that can impose a high cognitive load if the mapping between the data and sound is not intuitive. Building on this, Nanay introduces the concept of multimodal mental imagery, suggesting that our mental representations of data can integrate information from multiple senses simultaneously [27].

One promising approach is the combination of sonification and tactile feedback. Nikitenko and Gillis explored the potential of combining touch and sound for data exploration on mobile devices [98]. Their work demonstrates how the integration of tactile interaction with sonification can create more intuitive and engaging data exploration experiences. Our TactualPlot system [99], and ChartA1ly [100] are examples of multimodal approaches, combining sound and touch to represent data. Such hybrid systems have the potential to overcome some of the limitations of single-modality solutions. For instance, while tactile displays may excel at conveying spatial relationships, sonification could complement this by providing quick overviews or

highlighting temporal patterns in the data.

Researchers have also explored the potential of other sensory modalities in data representation. Patnaik et al. [101] investigated the use of olfactory display for data communication, proposing “information olfaction” as a novel approach to convey data through scent. While still in its early stages, this work highlights the potential for engaging additional senses in multimodal data representations. This adaptability is particularly valuable in professional settings, where BLV individuals may need to work with a wide variety of data types and complexities. However, care must be taken to ensure that the different modalities complement rather than interfere with each other, and that the cognitive load of integrating multiple sensory inputs does not become overwhelming for the user. Additionally, as we [20] note in our interview study (chapter 3), it’s important to consider the practical aspects of using these technologies in professional settings, where compatibility with existing tools and workflows is crucial. More recently, researchers conducted a wizard-of-oz study on the use of refreshable tactile displays (RTDs) to make accessible charts, and explored how data and charts can be combined with the speech modality—both for interaction and for verbalization. Reinders et al. [102] conducted a systematic review of touch-based accessibility and identified the need for more comparison studies of presentation technique (sensory modalities) for a wide variety of charts. In chapter 6, we use speech (verbalization) to read out labels and data values, and additionally compare the effectiveness of: sound—textual descriptions that use the Olli [12]; touch—tactile graphics on the Monarch [28]; and an audio-touch—sonified charts that support touch interaction using the TactualPlot [99] system. We explore differences across four chart types: pie charts, bar charts, line charts, and scatterplots.

Chapter 3: Understanding Sensory Substitution

3.1 Introduction

Visualizations are largely inaccessible to individuals who are blind or have visual impairments. Screen readers, the method blind people most commonly use to transform on-screen text to speech, generally cannot parse pixel visualizations, and few web-based visualizations provide sufficient textual descriptions or the underlying datasets [2]. People with visual impairments are a large population of potential data visualization users. In 2015, globally there were 253 million people with visual impairments, out of whom 26 million were blind, and this number is estimated to reach around 703 million by the year 2050 [3]. This is also not just a sociotechnical problem, but a potentially legal one; for example, in the United States, Section 508 of the Rehabilitation Act requires that all federal government websites be accessible for people with disabilities, and the Americans with Disabilities Act similarly requires accessibility for most websites of public accommodations [4]. Blind people¹ navigate a 3D world of space and objects, and are therefore equally capable of understanding spatial layouts as sighted individuals. However, despite continuous advances in visualization research, little effort is devoted to accessibility. While our focus is on blind individuals, inaccessible visualization practices not only affect blind people, but

¹While people-first language is preferred by most people with disabilities, much of the blindness community prefers the use of the term “blind people.” In this text, we use both approaches interchangeably.

also those with other impairments such as motor or cognitive impairments [2,5]. We believe that the visualization community must work to lower barriers for blind individuals by focusing on accessible visualization and data analysis.

Accessibility technologies for blind users tend to employ a method called *sensory substitution* [6] by conveying data using other senses such as hearing and touch, and even smell [7,8] instead of vision. Efforts to render visualizations accessible for blind users have been explored by research communities such as human-computer interaction (HCI), accessibility, and sonification for specific contexts. Of the two most common sensory substitutes—sound and touch—sound is by far the easiest to deploy since it does not require any specialized hardware. While there exist many examples of sonification and auralization [9] (the use of non-verbal and verbal sound), these efforts primarily involve the blind community only as *users* or *testers*, and not as full-fledged *informants* or *design partners* [10,11] in the development team.

In this chapter, we seek to add to the growing body of literature on the potential of accessible visualization design by understanding how blind individuals perceive the world around them using non-visual senses. Such knowledge would enable the design of more efficient audio representations of data that leverage the mechanisms that blind people already use in their everyday life. Our goal is to broadly understand (1) how blind individuals perceive and retain sound and touch-based information so that visual layouts such as charts can be effectively translated into non-visual senses, and (2) what this means for accessible visualization design so that future tools are robust enough to support multiple levels of visualization-related tasks [23]. To this end, we conducted semi-structured interviews with 10 Orientation and Mobility (O&M) instructors (experts), all of them blind, to understand how they teach their students (blind individuals) to navigate physical space using the sense of sound and touch. We chose this particular population

because these O&M instructors not only have significant personal expertise in leveraging non-visual senses to navigate the physical world everyday life, but also the knowledge and experience of teaching these skills to others. As part of the interviews, we also conducted discussions with these instructors on how to use sound and touch to convey data, and to translate visualizations. We found that blind individuals who undergo O&M training engage in *experiential learning* [24]—e.g., hands-on learning followed by reflection—to calibrate their minds to mapping sounds and tactile feedback to real-world aspects such as size, distance, angles, and position. We also learned how individuals actively use echolocation and environmental sounds to make sense of physical space, and the importance of sensory integration (e.g., combining audio and tactile feedback) in understanding it. Based on these findings, we derive design implications for accessible visualization design, with a focus on audio—speech and non-speech, and tactile representations, feedback and interactions. We also discuss the importance of training and usability of tools for accessible visualization for blind individuals.

The contributions of this chapter are the following: (1) results from semi-structured interviews with 10 O&M experts that convey how blind individuals perceive spatial concepts using sound and touch; (2) design implications for accessible visualization design with the idea of sensory integration of sound and touch; and (3) a design space on accessible visualization for blind individuals.

3.2 Methodology

To better understand how Blind individuals learn to use sound and touch to perceive and navigate physical space, we conducted semi-structured interviews with 10 Blind Orientation and

Mobility (O&M) instructors. Here we first provide background on O&M training, present our study rationale, and then describe our data collection and analysis process.

3.2.1 Orientation and Mobility (O&M) Training

Blind individuals enroll in Orientation & Mobility (O&M) training to learn to become independent travelers. As part of their O&M training, individuals are taught to use environmental cues to construct mental maps of the space around them. Orientation and Mobility instructors teach Blind individuals—“*clients*” or “*students*”—to travel both indoors and outdoors, and to increasingly rely less on the visual sense. It is often assumed that Blind individuals are a homogeneous user group, but research has shown that the attitudes, needs, and behavior of persons who are Blind vary greatly. In addition to *O&M* or *Cane Travel*, Blind individuals are also able to enroll in programs such as *Braille learning*, *Technology*, *Job Readiness*, and *Wood Shop Training*.

Orientation and mobility experts receive National Orientation and Mobility Certification (NOMC), a certification that is offered by the *National Blindness Professional Certification Board (NBPCB)*. Certified trainers teach under the *Structured Discovery Cane Travel (SDCT)* model; one that focuses on individuals acquiring non-visual travel skills through experiential learning based on personal experiences. The instructors teach concepts such as cane grips, mental mapping, environmental cues; and problem solving [7, 8]. Structured Discovery Cane Travel is one among two primary O&M training models; the other one—*Sequential Learning (SL)*—is a medical model for rehabilitation that was designed in the 1940s for World War II veterans and did not allow Blind individuals to become teachers.

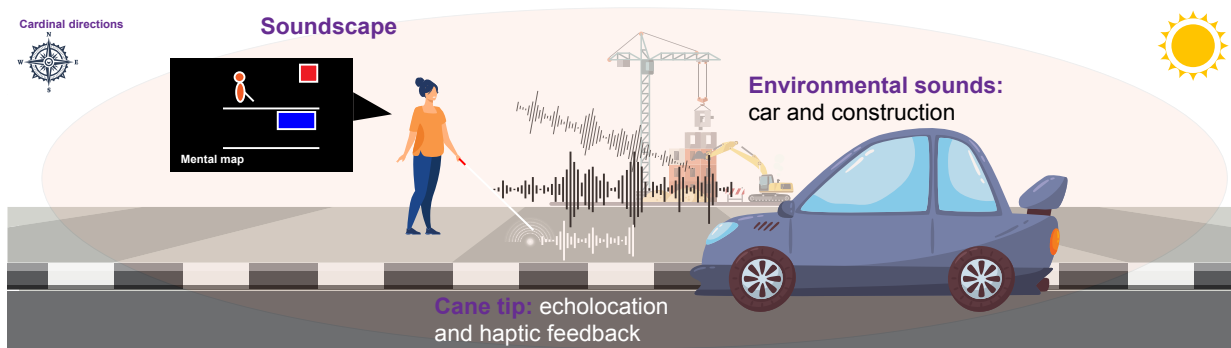


Figure 3.1: **Navigating outdoor space using non-visual senses.** Blind individuals build mental maps (visual thinking) by sensing environmental sounds, and use their cane for performing echolocation and perceiving haptic feedback; in other words, a combination of sound and touch towards non-visual sensemaking of spatial concepts. Our work explores how these capabilities can be used for accessible data.

3.2.2 Study Rationale

While there are potentially many user groups to interview in order to understand sensory substitution mechanism, we chose Blind O&M instructors because they (1) have significant lived experience of using non-visual senses in perceiving space, as well as (2) are competent at teaching these skills to others, and have thus spent a significant amount of time retrospectively thinking about the skills. O&M training is particularly relevant because these skills have been shown to transfer to other contexts and settings in prior work [39, 40].

More specifically, visualizations such as maps, scatterplots, bar charts, and graphs rely on visual semantics such as shapes, size, color, position, labels, and axes to convey data to sighted individuals. Speaking to O&M instructors is a reliable way to explore how to translate a visualization’s visual semantics into non-visual modalities based on how Blind individuals perceive visual semantics of space. Compared to Blind sonification or tactile graphic designers who may use their own experiences, Blind instructors have a broader view from their training and certification to teach other Blind individuals. Prior work also shows that the intuition of sonification

designers may not lead to the best data-to-sound mappings [48]. Blind individuals are also taught mathematics and graphing primarily using tactile graphics such as embossed or Braille charts by Teachers of Students with Visual impairments (TSVI) [103, 104]. TSVI focus more on tactile representations, while O&M instructors focus more on teaching spatial understanding from sound and touch. Tactile charts have several limitations [103] such as cost, information overload, and longer production time. While out of the scope of this work, we do think interviews with TSVI could lead to interesting insights on aspects such as chart authoring, and collaboration in classroom settings. Ultimately, we hope to apply these sensory substitution insights towards accessible visualization design. Additionally, we believe that comprehending fundamental chart concepts such as reference frames, estimating distances, understanding angles, and other visual variables [105] are similar to understanding and visualization navigation layouts and routes in the real world.

3.2.3 Participants

We recruited 10 Blind O&M instructors to learn about their personal and professional perspectives on how Blind individuals use sound to create mental maps, understand their surroundings, and navigate in a physical space. We focused on SDCT instructors because the self-confidence levels of SDCT students are higher than those from SL training.

Table 3.1 provides an overview of the participants. Two of our participants were also itinerant trainers who would visit their students at their preferred locations, while most of our participants conducted classes at institutions. Participants taught students as young as 5 years and as old as 70 years; and also students with other disabilities. OM4 was also a certified TSVI.

Table 3.1: **Demographics and O&M experience of the 10 participants.** *Abbreviations: M—Male; F—Female; NB—Non-binary.*

ID	Age	Gender	Education	O&M Experience
OM1	30	M	High school	3 - 5 years
OM2	32	M	Master’s degree	5 - 7 years
OM3	55	M	Associate degree	More than 7 years
OM4	57	F	Ph.D.	More than 7 years
OM5	66	M	High school	More than 7 years
OM6	62	M	Master’s degree	More than 7 years
OM7	36	NB	Master’s degree	More than 7 years
OM8	25	M	Master’s degree	3 - 5 years
OM9	27	NB	Master’s degree	6 months - 1 year
OM10	30	M	Master’s degree	3 - 5 years

Overall, the participants had a strong expertise in teaching their students to travel using non-visual skills.

Participants were recruited through mailing lists associated with the *National Federation of the Blind* (NFB). The study was approved by our university’s Institutional Review Board, as well as the Research Advisory Council of the NFB.

3.2.4 Data Collection and Analysis

We conducted semi-structured interviews via video and audio conferencing on the internet to collect our data. We then transcribed and analyzed the resulting data using thematic analysis.

3.2.4.1 Semi-structured Interviews

Each semi-structured, audio-recorded interview was scheduled for 60 minutes, and participants—as rehabilitation experts—were compensated with a \$100 Amazon gift card. Broadly, the research goal was to understand the design space to help design and build tools that support data analysis

through sound and touch representations and interactions. This could mean making data representations such as visualizations or charts more accessible, or finding new ways of representing data in using sound—both speech, and non-speech.

To understand O&M training procedures, we asked participants how they trained Blind individuals to rely on sound for creating mental maps of the environment as well their use of auditory interfaces in activities of daily living. Secondly, we asked the participants how Blind individuals perceive and infer different aspects and properties of sound, such as loudness, position and direction, pitch, repetition, moving vs. static sounds, and verbal sounds (speech). Finally, *to brainstorm about the idea of translating a virtual and visual layout (a visualization) into an audio representation*, we introduced our design idea to foster discussion and receive feedback. Participants were introduced to the idea of a web-based interface that allows users to upload a chart image; the tool will then extract text labels, data, and other semantic information from charts—for example, bar charts, scatterplots, maps, and line charts. Next, the tool will translate the visual elements and data into audio representations by simulating spatial audio [106]. Users can interact with the sounds using their keyboard or touch screen. The O&M instructors were not data visualization experts, but this part of the session guided participants to discuss their familiarity with audio and tactile feedback.

3.2.4.2 Transcription

The audio recordings of the 10 interviews—10 hours and 38 minutes, were transcribed using an online service—Rev [107]. On average, each interview lasted 64 minutes.

3.2.4.3 Analysis

We used thematic analysis [108] to open code the transcripts. We started by randomly selecting two transcripts to be open-coded by two researchers. In other words, we each separately tagged text from the transcripts with multiple codes (see below examples) to add semantic structure to our data. After open coding, the two researchers discussed and merged the codes to create an initial codebook. The merging process included a discussion of rephrasing codes, adding missing codes, removing codes that resulted in a codebook that was agreed upon by both researchers to improve reliability of our results. Next, one researcher coded the remaining transcripts using the initial codebook, and added codes as they emerged.

Some examples of the codes that were used are: “*O&M concepts*”, “*Indoor navigation*”, “*Residual vision use*”, “*Multiple sounds*”, “*Technology use in O&M*”, “*Embodied Cognition*”, “*Prior chart knowledge*”, “*Sound Isolation strategies and challenges*”, and “*Sound Mapping and Inference*.” As new codes emerged, we returned to older transcripts to apply the new codes. Overall, 89 unique codes were used, and 258 excerpts were extracted from the coding process. Our codes are included in the supplementary material. Results from our analysis have also been reviewed by one of the co-authors who is Blind, and has long experience in information, data, and knowledge work.

3.3 Findings

In this section, we present three main themes that broadly describe (1) Orientation and Mobility concepts that reveal how Blind individuals perceive elements and layouts of space using non-visual senses, (2) how individuals interact with space using sound and touch, and (3) the

challenges of using non-visual sense in using visualization. We highlight insights derived from this process as follows:

Insight #1. Orientation and Mobility training highlights many audio and touch affordances that may be useful for creating accessible representations of data and visualizations.

The color coding for these boxes signify whether they arise from **perception**, **interaction**, **effectiveness**, **challenges**, or **design guidelines**. We discuss the implications of our insights in detail in section 3.4, but briefly explain how our insights relate to visualization in this section.

3.3.1 Perceiving Space as a Blind Individual

O&M training does not follow a prescriptive approach. Instead, it generally encourages Socratic questioning to help students associate their own meaning to various environmental cues. When asked specifically about different properties of sound, all participants mentioned that while certain properties can have an objective meaning, it is very hard to prescribe a particular threshold when considering the magnitude of these properties. For example, while loudness of sound might increase as someone walks closer to a sound source, estimating precise distances is still challenging. Additionally, participants noted that there is a lot of variability among students in terms of perceiving different sounds. Here we describe specific instances of using different properties of sound and touch in the non-visual sensemaking of physical space.

Participants described the white cane as the primary tool used in the orientation and mobility process. The non-folding version is recommended by the NFB, and is the primary one used in the O&M training process. Other canes, such as folding ones, are also used by Blind individuals, but are not recommended because of the limited haptic feedback that they offered compared to

the non-folding cane. Such haptic feedback is critical; the cane was described as an “extension of the self,” and cane techniques help students actively interact with the environment to receive sensory information. For example, participants described “shorelining” as a technique used by students to understand their position on the sidewalk by walking in “parallel” using the grass or the edge of the sidewalk as a “reference.”

Insight #2. Many white cane interaction techniques help Blind individuals receive haptic feedback while traveling.

Additionally, a sweeping motion of the cane on the ground can also convey tactile information to the students based on the continuous haptic feedback that the hollow stem of the cane transfers to the individual’s hands. *OM4* explained how texture changes in the aisles of a grocery store are perceived during indoor navigation: *“There’s a texture change when you’re in front of the grocery aisle or the refrigerated section, or even the fruit and vegetable sections. Because, that’s a little bit rougher, the texture is a little rough.”* By leveraging the familiar metaphor of actively probing to understand a surface, tactile solutions could strongly couple interaction and representation to improve accessibility.

Participants indicated that the sounds, especially distinct sounds, produced by certain objects in the environment, such as lawn mowers, HVAC (heating, ventilation, and air conditioning) systems, streetcar, and traffic sounds, provide many clues about the environment around them. These ambient sounds, when mapped with concepts that students have stored in their memory, assist in the process of navigation and understanding the shape or layout of the surrounds, especially when walking into unfamiliar routes or buildings. *OM6* explains: *“I think there’s also another thing which is the knowledge that a person has accumulated over the years. When I walk*

into a high-rise building, there's really only a couple possible places that the elevators could be located. And so I'm able to use that knowledge to help me figure out where I need to go to find the elevator." Chart literacy can be challenging for sighted individuals, and is even more for Blind individuals if they are unable to perceive the concepts used in highly customized bespoke charts—i.e., non-standard charts. The importance of concept building indicates a need to effectively represent geometric units used in charts through non-visual senses.

Insight #3. Sounds known to individuals from lived experiences help build spatial awareness.

Many participants mentioned that the loudness is usually associated with the distance between the student and the sound source. For example, OM7 mentioned that they talk to their students about loudness, where a change in loudness indicates changing distance between the two reference points—the individual and the sound source: *"But I'll ask them, "The sound that you hear, does it seem quiet or does it seem louder to you?" [...] And if they say, "Oh yeah, it seems quieter." Then I might say, "Why does it seem quieter?" [...] And if they honestly cannot make that association, then what I will do is have them walk toward the sound and ask them what's happening to the sound as they approach it"*. One participant also indicated that students perceive bigger objects, such as a truck, to be louder than smaller objects, such as a car, indicating that the loudness may also be associated with size.

Insight #4. Loudness is commonly used for perceiving spatial distance, and is also associated with size of objects producing the sound.

Not many participants mentioned the pitch of a sound being directly mapped to a partic-

ular physical property, but indicated that higher pitched sounds were easy to isolate from other environmental sounds. The pitch of the sound was associated with familiar concepts such as the sound of a car engine: *“If a car is idling, I will point out to the student that when the car is shifted into the reverse, the pitch of the engine goes lower because the engine is laboring and that’s something to be aware of because that car could come backing out and you don’t want to be in the way.”* (OM6)

Insight #5. Pitch is used to recognize known objects and their state; higher pitched sounds are generally easier to isolate from other environmental sounds.

OM7 mentioned that their students were cognizant of the *“sound space”* around them, and interestingly described certain aspects using visual space. When students are immersed in auditory environments, multiple sounds, with their different dimensions occupy the auditory capacity. OM7 describes the visual space in front of the students, indicating that sounds are mapped to visual space: *“They should tell me that the sound not only gets louder, but it takes up more of the sound space. It takes up more space in front of them. Like a fountain in the distance, it will sound quieter, but it won’t take up quite as much of the stereo space in front of them, in the same way that a distant fountain won’t take up as much visual space.”*

Insight #6. Individuals map visual space by sampling the various sounds of the environment and interpreting changes in sound dimensions such as loudness.

Participants also mentioned that the sequence of sounds and the duration of a particular sound were important features to interpret to understand sound. Similar sounding tones when played sequentially can also be distracting: *“So as long as there’s a clear enough duration in*

between, like if you're going to play a sound, you want there to be a gap in between.[...] So if they just get distracted for a second, they might miss that there was two clicks instead of one."

(OM8)

Insight #7. The sequential nature of sound dictates that sampling frequency and duration be optimized to improve accuracy of spatial awareness.

Participants perceived the absence of echoes or sounds, and associated the presence of large objects at a certain distance causing sound to be blocked and creating "*sound shadows*"—another visual concept. OM6 describes this phenomenon as follows: "*An individual that has well-developed listening skills can hear those echoes off of telephone poles and even sometimes off of sign poles, depending on conditions. The person can also hear sound shadows from objects in the environment where they're blocking out the sound of maybe a car passing by. They hear a moment where it's blocking out the sound.*"

Insight #8. The absence of sound—*sound shadows*—could be interpreted as being caused by intersecting objects in space.

The soundscape, i.e., the sound space around the individuals, often consists of multiple sound sources at different positions; some louder than others, and at different pitches. Participants mentioned that one of the important skills that students learn is "*sound isolation*." Based on the problem or task at hand, individuals needed to focus their attention on certain sounds, and oftentimes these relevant and necessary sounds would be occluded by environmental sounds.

Prior work on effectiveness of data-to-sound mapping recommends empirical assessment based on end users and the data task [48]. Our findings about loudness, pitch, and lack of sound

being mapped to spatial or geometric properties could be a starting point for accessible sound representations since they are based on Blind individuals' mental models. The idea of *sound shadows* has not been explored in prior work, and could be an interesting design material for audio charts in the future.

Insight #9. Individuals isolate and focus their attention on specific sounds in a soundscape based on the task at hand.

Participants also mentioned that some important sounds such as the “*buttons at the (road crossing) intersection*” sounded very similar to environmental sounds such as the sounds of “*birds chirping*.” The ability to isolate different sounds when needed was a skill that depended on the person because “*people have (had) different levels of hearing ability, and then being able to discriminate [...] used judgement on the cues that they're getting*.” (OM3)

Participants mostly agreed that familiarity of sounds make sound isolation much easier. Participants also describe how triangulation is used to establish their position with more confidence: “*You usually have to have more than just one source of information to make a solid deduction as to where you are. You might need to feel the direction of the sun at that particular time of day, hear where the sound is coming from and maybe some other sound off in the distance, maybe traffic off in the distance somewhere tells you*.” (OM6)

Insight #10. Familiarity as well as dissimilarity of sounds in a soundscape help an individual to switch their hearing focus.

Participants mentioned that “*sound localization*” is part of the concepts covered during training, and is a fundamental concept that “*can be taught or is a learning curve*”. However,

there are variations among students' efficiency in localizing sound. This could be because of students' hearing impairments, when present, that causes "*bilateral imbalance in their hearing.*" (OM3) Participants indicated that static sounds can be used as landmarks or reference points. This indicates that sound localization, while being a fundamental human feature, can be "*highly dependent on a person's ability to discern an angle of sound.*" Whether a sound is static or moving, also influences how much an individual can sample and associate meaning: "*[...] when you have a static sound you can use that specific sound for orientation purposes, right? Say that sound's been occurring at that location for the last several minutes, so why don't we use that as a point of reference as opposed to a moving sound?*" (OM1)

Prior work shows that sonification of chart axes adds context to audio charts [70]. Since static sounds are useful as references, accessible design could consider metronomes or always-present sounds to convey chart boundaries, legends, or even scales of the axes.

Insight #11. Estimating positions of and distances between sound sources varies greatly between individuals based on hearing and spatial awareness, with static sounds being most helpful.

For sighted individuals viewing a chart, their eyes move rapidly to perform actions similar to auditory actions such as filtering, scanning, differentiating, etc. But with hearing supporting lower information bandwidth, careful accessibility design may be needed to translate charts showing a large amount of data.

3.3.2 Interacting with Space as a Blind Individual

Overall, participants indicated that the white cane helped in interacting with the environment as an “extension of their body” and acts like an “antenna.” Participants noted that canes with a metal tip encourages the use of “*auditory information*” (OM4), whereas folding canes tend to use a plastic tip that does not provide the same auditory feedback (OM4). The cane helps produce a crisp sound that bounces off objects around the students. The echo that is produced conveys different aspects of the environment such as distance from buildings, number of objects, and wide versus narrow spaces. The duration of the echo also conveys meaning to the students. OM8 explains echolocation as follow: “*So an example is when they’re in a parking lot looking for a building, I would have them tap at various parts of the ground in front of them, they might tap at nine o’clock first, then 12 o’clock and three o’clock, based on the time it takes for the echo to come back to them, then that will tell them whether there is a building in that particular direction or not. [...] If the building is within 15, 20, 25 feet away from them where the echo would return, then they’ll quickly hear echo back, and the length of the echo varies depending on how far the object is.*”

Insight #12. Blind individuals often use *echolocation* to understand space around them.

In general, participants mentioned that their students visualize objects and space using their own body as reference. For example, participants described the positions and direction of objects using terms such as “eye-level”, “front”, “back”, “left side”, “right side” and “above.” This indicates that, considering 3D space, perspective appears to be from the point-of-view of the individual’s body or as extension of the body in the form of the white cane. All participants

mentioned the use of “cardinal directions” by their students during travel. Many participants also described the use of the sun’s position by perceiving the direction of heat to gain an understanding of both time of the day as well as understanding the cardinal direction they were traveling.

Insight #13. Blind individuals often interact with sound from a perspective that is relative to different parts of their body.

Our finding on egocentric sound perception suggests that future work on accessibility could explore egocentric perspectives for both sound and touch-based solutions. While this has been explored in pie chart sonification with sighted individuals [68], our findings highlight the value in exploration with Blind individuals.

3.3.3 Effectiveness, Information Access, and Usage

The findings above draw primarily from discussions about the idea of transferring sound and touch perception skills acquired from O&M training towards accessible sensemaking and charts. Participants were divided on using sound alone, and many participants recommended the use of both tactile and sound-based representations. Participants noted that many students are familiar with using “tactile maps” to understand spatial layouts as compared to sound. Some of these participants opined that *“touch and sight are more comparable than sound and sight”* (OM2), and also believed that *“touch is (was) probably a quicker avenue to the brain”* (OM3).

Insight #14. Tactile representation allow haptic feedback, which is more comparable to vision than sound, and can help people to gain an overview of the canvas.

While tactile representations were preferred owing to familiarity, the idea of audio charts

could succeed with enough training: *“Or for those who become Blind, some of them already have that experience through their visual sense. It’s just a matter of getting them to calibrate it to their other senses. And that’s also quite doable. We know that the brain is plastic. So over a period of time, if given the correct education, the brain can rewire itself to accept auditory, tactile, and proprioceptive input and spatial input.”* (OM7)

Insight #15. Sound representations can be made to work with sufficient training and calibration of sound perception.

Participants provided positive feedback about the idea of audio charts, and also provided specific feedback to make sound perception easier for Blind individuals. OM8 recommended that “audio descriptions” are the best way to provide spatial awareness by giving an overview of the canvas. OM5 also recommended using speech to convey specific information such as numbers because from their past experience, audio charts that use non-speech sounds are limited by the inaccuracy of mapping sounds to numbers: *“It’s not that they couldn’t give me comparative information, in other words this sound is lower than this other sound, but that they couldn’t give me the specific information, if that makes sense.”*

Insight #16. Non-speech sounds are more suitable for comparison while speech is preferred for conveying specific quantities.

Overall, participants recommended pursuing the idea of *sensory integration* as *“haptics could enhance that whole sound interpretation”*. A major reason for preference of tactile charts stemmed from prior experiences. OM8 explained that their institution uses an *“embosser like a Braille printer”* to explain scatterplots as *“there is nothing in a screen reader that can read those*

(chart) types of data, unless there's a description of it."

Insight #17. A combination of both sound and touch—*sensory integration*—best supports real-world analytical tasks.

Participants recommended using haptic feedback in addition to audio descriptions: *"something that they (students) can feel underneath their fingertips as well, something that they can explore tactically, i.e., using touch."* Haptic feedback was also described to be useful as interaction feedback; OM6 explained with an example of traversing a bell curve: *"If you have a chart displaying a bell curve, having maybe vibration or something that indicates to the person that they are following that curve with their hand so that they feel the actual curve, in addition to whatever information you might be able to provide, might be helpful in being able to use that chart effectively."* Our findings on the need and effectiveness of using multimodal solutions are in line with prior work in the sonification and accessibility disciplines.

Participants mentioned that students perceive charts or visualizations, especially maps, as a 2D construct. Many individuals may have seen charts before becoming Blind, or have "felt" charts in the form of tactile representations. Many participants indicated that students might know the concepts of "Axes", "Labels", and "Marks," and may also be aware of specific visualizations such as bar charts, line charts, and pie charts. However, participants also recommended a phases of understanding *"how well that (Blind individual) person's geometric concepts are"* (OM6), and that designers and researchers make an attempt to *"absolutely have to have the person understand what a chart is... they have to feel it, because otherwise it makes no sense."* (OM5)

Insight #18. Many Blind individuals are familiar with charts and its elements as 2D constructs, but accessible visualization design should still strive to explain chart elements.

When asked to describe the information that may be important to convey, participants highlighted the need to convey *“individual layers of information and the person can go through one layer at a time or they could overlay different layers of information, so that they can be in control of what they’re trying to understand.”* (OM6). OM8 discussed how the complexity of the chart, stemming from the amount of data could lead to information overload, while also indicating limitations of tactile representations: *“I think it’s a huge step forward in terms of accessibility, because with a scatterplot, there could be an infinite amount of dots on a page that indicates data. And again, with technology there’s no way to access that information. And even with Braille, right now they have Braille paper that have an XY grid on it, and you can physically feel where the dots are on the XY grid. But the problem is, if there are five things on the scatterplot, you can easily fill all five dots, and get that data from there. But if it goes any higher than that, if there’s things that start coming together, the more information that is on there, the more inaccessible it becomes.”*

Insight #19. Sensory and information overload is a major usability challenge when using non-visual senses to understand charts.

All participants recommended that, regardless of sound or haptic representations, solutions try to reduce the learning curve for individuals, by incorporating prior chart knowledge. Finally, participants mentioned that accessible design should also focus on creating and retaining a shared understanding of charts between sighted individuals and Blind individuals, as this be-

comes important: *“especially in a work environment, but also probably in a school environment. It’s the ability to communicate the understanding of the chart, [...] , because what we’ve got to do is communicate that chart, not some kind of a different chart, because it’s that chart that the sighted world is going to use. And in most of the companies that I’ve ever worked in, in my life, I was the only Blind person there, so what was useful to me, if it wasn’t useful to other people on my team, or in the company, then it wasn’t going to be useful. In other words, we live in a sighted world, and if we live in a sighted world then we have to figure out how am I going to communicate the information I have to other sighted people in a way that makes sense to them, and if you say, ‘well, that seems unfair that you should have to do that’—too bad.”* (OM5)

Insight #20. Solutions towards accessible visualization should not introduce new barriers for collaboration between sighted and Blind individuals.

3.3.4 Towards Accessible Charts: Needs and Challenges

O&M students tend to have varying levels of visual and other abilities while partaking in the training. For example, students may have some amount of residual but depleting vision, whereas some have no residual vision at all. Additionally, some students may have congenital blindness (from a young age) or may have become Blind at a later stage in their lives. Finally, students may also have other disabilities, such as hearing and/or cognitive impairments along with vision loss. Our participants stressed that each individual, while all have some amount of vision loss, have varying abilities. In the case of students with hearing loss, participants did encourage the use of residual vision (if available), but *“tweak the training to encourage them to use their vision in a*

realistic way [...] but as far as just aligning properly and possibly seeing the color of the light, if they can see that.” (OM2)

Insight #21. Individuals have varying levels of visual acuity, familiarity with charts, and other disabilities that require personalized designs for accessible visualizations.

All of the participants mentioned the use of “sleep shades” to occlude any residual vision of their students to ensure that they do not resort to using their weaker sense to travel. The use of sleep shades is central to the framework of Structured Discovery Cane Travel, and participants indicated that relying less on vision during the training helps optimize the use of residual vision after training. OM3 explains:

“From a practical point of view, it doesn’t make sense to start with the weakest sense. We know people will use their vision, and [there is] nothing wrong with that. But the idea is to develop mastery through the other senses, and then when vision is introduced after the training [...] In my opinion, by developing those alternative skills, using non-visual skills and techniques, actually helps optimize the use of vision.”

Insight #22. O&M trainers prioritize using only non-visual sense during training to avoid students using their weakest sense (residual vision) in sensemaking.

The primary goal for a student or client partaking in O&M training is to rely less on the visual sense while navigating the physical space around them. In addition to cane travel, participants mentioned that their students are taught to rely less if not eliminate their dependency on the visual sense to orient and navigate the environment. Instead, participants mentioned that students predominantly were taught to rely on their sense of sound and touch to navigate the

physical space around them. While cane travel was the primary outcome of the training process, participants also indicated that the emphasis on learning to “completely use non-visual skills” (OM1) in tasks such as “decision-making,” “route planning,” and “route navigation.”

Insight #23. O&M training familiarizes students with other analytical abilities such as planning, decision making, and navigation which indicates the importance of training and usability for accessible visualization systems.

Many participants explained about the importance of assessing different aspects about their students such as the level of vision and hearing, the amount of nervousness, and their travel routes and destinations, with the aim of building more confidence and effective decision-making and problem solving skills. This is especially important when students practice outside of the training classes without the instructors. In such circumstances, students need to be comfortable and confident in applying skills learned during training. OM5 summarizes these needs: *“So, initially, it’s a great deal of finding out what people do [...] Probably getting a real understanding of the student initially is really important to me, because I want to make sure that whatever I’m teaching them is something that, A) they’re going to be able to understand, and B) that they’re going to use it.”*

Insight #24. O&M trainers measure success not only by assessing navigation tasks, but also by assessing confidence levels and levels of comfort in relying on non-visual senses.

All our participants emphasized that instructors generally are aware of the differences in abilities, needs, and prior knowledge of their students; requiring them to “minimize prescriptive learning” (OM1). Instead, participants mentioned that O&M training is more of an “experiential

and incremental learning” experience. The process involves many “repetitions” which aids the students in “calibrating” their senses, and potentially updating their *sensory memory*. OM3 describes the role of “Socratic questioning” in a typical lesson: *For example, in a typical lesson, I don’t provide a lot of answers. If a student says, ‘‘am I going the right way?’’, we use Socratic questioning, meaning we ask them, ‘‘well, tell me about what you are sensing to whether you think you’re going the right way.’’ And we’ll help them through that, but help them think through the process in both multi-sensory, but probably more important developing self confidence through that problem solving strategy.’’*

Insight #25. Individuals undergoing O&M training calibrate their non-visual senses through incremental learning and practice.

Our insights from this section strongly indicate the need for accessibility solutions to define success in terms of task completion, confidence in accurately perceiving charts and data with low uncertainty. Prior sonification and accessibility work acknowledges the importance of training [44]. Our findings additionally highlight other aspects such as including calibration and assessing confidence during the learning. This becomes especially important as the bandwidth of the sound and touch senses are lower compared to vision.

Participants emphasized the need for their students to perceive and gauge the physical properties of objects in both indoor and outdoor environments. For example, during outdoor navigation, objects such as “buildings,” “people,” “vehicles,” and “parking lots” were described to be essential features of mental maps. In indoor navigation, objects such as “chairs,” “walls,” “doors,” and “electronic appliances” were important references. Each of these objects could be “static” or “moving objects”, had a set of physical properties such as “shape,” “size,” “texture,” “height,”

and “position.” In addition to the aforementioned properties, each of these objects could also have characteristic sounds and tactile properties that provided students with the ability to orient themselves, and construct mental maps of the space around them. Other spatial concepts include “intersections,” which indicated a sense of visualizing “perpendicular” streets or hallways. Students also actively perceived “distances” using units such as “city blocks” and “steps.”

Insight #26. Awareness and building of concepts related to indoor and outdoor navigation are crucial to perceiving and interacting with physical space using non-visual senses.

3.4 Discussion

Our aim was to make inroads towards supporting the millions of Blind and visually impaired users for whom data exploration, especially large-scale data exploration, remains inaccessible. Data visualization and visual analysis, with its principles, techniques, and tools, continue to introduce barriers for the Blind community. Here we describe design implications that we believe will guide visualization designers, analysts, data scientists, programmers, and researchers alike towards accessible visualization and visual analysis.

Overall, the findings validate previous research [7, 8] that sound and touch play a very important role in perceiving spatial layouts. Additionally, the findings also confirm that a combination of senses are used to perceive the environment, and familiarity of tactile charts could indicate that haptic feedback and tactile information may be necessary to effectively use sound-based representations. Many of our findings converge around the importance of interaction with non-visual environmental cues. While building accessible solutions, perhaps there are two levels of interaction using non-visual senses that need to be supported—interaction with non-visual

representations, and interaction with the data itself. Visual interactions in visualization and visual analysis have been extensively studied in the visualization community [109], and for accessible solutions the focus on interactions is more important.

3.4.1 Design Considerations for Accessible Visualization

Our most fundamental finding is that it makes sense to use visualization as an intermediary for sonification. In other words, instead of sonifying the data directly, the visualization can serve as an inspiration for how to spatialize the data in the sonified representation. Our findings indicate that Blind individuals tend to already be aware of the visual structures used in common charts from lived experience, even if they were born Blind. Rather than entirely discarding existing visual structure in favor of new structures based on alternate senses, we recommend focusing on better translation of visual structures such as marks and encoding. This means that the term “accessible visualization” is not a misnomer. The approach can also facilitate collaboration and communication between sighted and Blind individuals in data analysis. The importance of such visual semantics for Blind and low-vision individuals has also been confirmed in other work [110].

D1. Retain visual structures used in common charts, such as bar charts, pie charts, scatterplots, and line charts, for other media.

Our participants could only speculate about how sound and touch could be used in data analysis and translation of visual representations. However, the findings provide a detailed overview of how sound is mapped to different spatial and geometric properties such as size, shape, position, and distance. In visualization, these spatial or geometric properties are consid-

ered “visual variables” and are used to construct and classify visualizations [111].

Another design guideline is to consider using a combination of sound—both speech and non-speech—and touch modalities to complement visualizations. There is limited research on using sound and touch together in visualization, but designers and researchers can review a rich body of research in accessibility and HCI to identify how to build interactions using a combination of sensory modalities [8, 112]. Future work should explore how to effectively map visual variables to appropriate *audio* [43] and *haptic variables*.

D2. Use a combination of sound—speech and non-speech—and touch modalities to translate visual and interactive representations.

To a large extent, sighted individuals can gain a complete overview of the chart canvas simply by looking at the canvas. However, the sequential nature of sound and need for sampling in audio-based sensemaking indicates that gaining an overview of data from a soundscape is harder without active interactions with sound. If charts are translated to audio, interactions may only be with a subset of the visualization at any given time, and Blind users may not gain an overview instantaneously.

D3. Supporting interaction is more important for non-visual sensemaking than visual sensemaking.

D4. Clearly distinguish interface-related modal feedback from data-related modal feedback.

In O&M training, “concept building” and calibration of non-visual senses is central to the process of learning to perceive the environment using sound and touch. The findings also indi-

cate that Blind individuals are not a homogeneous group, and have different levels of perceptive abilities. While sound and touch as modalities of feedback are perceivable by Blind individuals, we believe that prescriptive mapping data quantities or chart elements to audio and touch modalities will not work for Blind individuals. We recommend that systems translating visual elements to other modalities include a training module, and settings to adjust levels of audio or haptic dimensions.

D5. Allow customization and calibration of modal encoding to effectively support accessible graphical perception.

During O&M training, Blind individuals perceive audio and haptic feedback knowing that they are in a 3D space. In addition to passively absorbing modal feedback, these individuals use human echolocation techniques to actively interact with their space. When designing audio and touch interactions for accessible 2D charts, their position relative to the visualization planes and layers needs to be clearly understood. Stereo sound [76] has a clear mapping to a 2D canvas, but perceiving height remains difficult owing to limitations of the human ear. Using spatial audio, in the form of binaural audio [113] or ambisonics [106] provides an encoding space for a 3D dimension, but the user needs to be aware of the orientation of the chart canvas.

D6. When using sound, clearly convey mapping between spatial dimension (2D or 3D) to the soundscape.

Research also demonstrates that using haptic and audio feedback allows Blind and visually impaired individuals to effectively understand geometric and spatial concepts such as circuit diagrams [114].

D7. When possible, use tactile representations and haptic feedback to provide chart overviews.

Improving chart decoding [5], exploring natural language generation to create audio descriptions [115], and using natural language interfaces [116] could also significantly improve the accessibility of visualization systems.

D8. Consider using automation and natural language to generate and convey insights.

We found that Blind individuals’ analytical goals are no different from sighted individuals. One of the main challenges described by the participants pertained to cognitive overload from excess information being “visualized” in charts. Some participants described a layered approach to conveying information to overcome this challenge. This is similar to the paradigm of Shneiderman’s Visualization Mantra [22]: *Overview First, Zoom and Filter, and Details on Demand*. In the sound domain, prior work discusses Audio Information Seeking Principles [76], which are again related to understanding and serving different levels of user intent. For example, just like for a visualization, overview is going to be important also in a sonification. Additionally, it is important to understand the role of sound and touch in different levels of visualization tasks [23]. Finally, our experts recommended that knowing the current position on the chart being explored is very important for individuals as they “zoom” in and out of the translated charts.

D9. Avoid sensory overload by using interactions to view layers of information—both raw data and sensory.

To improve usability and perception, principles such as *ability-based design* [117] can be adapted while building tools for chart accessibility. Accuracy of data and insights are important

aspects of accessibility. Our participants also echoed concerns about the unfamiliarity of audio-based charts, and recommended that we design solutions that are “easy to learn” and support “all” data needs.

D10. Clearly define and evaluate usability, and support various levels of analytical tasks.

Finally, incorporating sociotechnical considerations into the research process will help overcome issues related to technology costs, simplistic solutions, and inaccurate assumptions [2]. In particular, consider involving people with disabilities in your visualization work—as we did in this study—to better position it with regards to accessibility [118–120]. The intention is to avoid poorly researched, poorly documented, and poorly maintained artifacts that may lead to unrealistic, unsustainable, and impractical solutions for our users.

D11. Consider sociotechnical factors to build sustainable, holistic, and cost-effective solutions.

3.4.2 Example: Accessible Bar and Pie charts

Our goal is to provide a design framework to guide researchers in the visualization community to design accessible charts and visualization tools. Here we demonstrate how our framework of design guidelines and insights can be applied to bar charts and pie charts. We do so by adopting the notion of *auditory sweeps* [76]: a spatial traversal of a visual representation indicating the order the visual data will be sonified. For example, a horizontally-aligned bar chart—one where the bars are arranged on a common horizontal axis—typically uses a horizontal auditory sweep: values for each are sonified in the order left to right. Analogously, a more complex 2D represen-

tation such as a geographic map or a scatterplot could use different sweeps, such as zig-zagging, up-to-down, left-to-right, etc. Auditory sweeps have also been adapted for web charts, such as in Highcharts [121], and more recently for touchscreens, such as iOS audio charts [122]. Below, we demonstrate how one can use our design principles in conjunction with past sonification literature to pie charts and bar charts.

Bar and pie charts can be decomposed into building blocks such as the drawing plane, reference axes, and the visual marks representing quantity [105, 111]: position for bar charts, and angle for a pie chart. To be able to create a sonified representation of these 2D charts, we thus need to be able to represent the space, axes, and marks using sound and touch.

Overview. Overview is a central task in data visualization [22]. To support this task in sonification, we use auditory sweeps that present data by “sweeping” over the visual space: from left to right for a barchart, and in a circular motion from 12 o’clock for a piechart. We thus retain the visual construct of the original visualization (D1).

Marks and Channels. Our insights can also be used to map visual channels to sound dimensions. For example, timbre can be mapped to different colors [49]. While perception varies across Blind individuals, pitch is often used to recognize and distinguish objects from other sounds (Insight 5). Static sound helps estimate relative position (Insight 11) between sound sources and spatial audio provides references with respect to the user’s body (Insight 13). Furthermore, the dissimilarity of sounds, especially non-verbal ones, helps them switch focus across sounds (Insights 10 and 16). These insights may be used to convey individual marks by separating them in space.

The above example is not a comprehensive solution, but only a design sketch. For existing

examples of sonification, please see HighCharts [121] or iOS audio charts [122]. However, for many existing sonification tools in the marketplace, it is unclear whether Blind individuals were involved in the design and development process. We recommend that future work in this space actively involve Blind individuals, ideally as design partners [10].

3.5 Conclusion

Our findings are based on a limited sample of 10 Blind O&M instructors. However, we assume that the expertise in training multiple Blind individuals validates and adds weight to the opinions of the participants. Additionally, the feedback from the visualization brainstorming portion may not capture the opinions of students as participants mainly conveyed their own perspectives. Finally, Blind individuals who do not have O&M learning experience, or those who do not experience the *SDCT* model of teaching, may have different opinions and perceptive abilities when considering sound and touch. To avoid a technology-centered approach, we engaged the Blind community in our work by interviewing and discussing chart accessibility with 10 Blind O&M experts. We found that touch modalities are more comparable to vision, and Blind individuals are more familiar with tactile charts. We also found that complementing visualizations using a combination of touch and sound can lead to more holistic solutions. Finally, we identify key insights and discuss accessible visualization design considerations to guide technologists and designers interested in developing solutions for Blind users. In chapter 5, we utilize our design guidelines and insights in creating multimodal interactions with a 2D scatterplot.

Chapter 4: Understanding the Visualization and Analytics Needs of Blind and Low-Vision Professionals

4.1 Introduction

As the field of visualization and data science continues to expand, it is becoming increasingly inclusive of Blind individuals [2,20,54,85,99,123,124]. Despite these advancements, there remains a profound lack of understanding regarding the specific data analysis needs of Blind and low vision (BLV) professionals. Existing data analysis tools are designed for sighted users, which marginalizes Blind professionals by not accommodating their unique interaction paradigms. This not only restricts access to the field but also curtails the potential contributions of BLV professionals within the broader information landscape. But to know how to mitigate the shortfall in the first place, we will need to know the specific needs of BLV professionals for data analysis in situations where they differ from sighted users. To address this significant knowledge gap, we designed a two-step online survey aimed at understanding the data analysis practices of BLV information professionals. We uncover the specific challenges and strategies employed by BLV professionals in navigating the data-driven aspects of their careers. Accessibility challenges were prevalent, with heavy reliance on assistive technologies like screen readers. Collaboration with sighted colleagues was often necessary for creating and interpreting visual data, highlighting the

need for inherently accessible data visualization tools. To support BLV professionals, we must innovate and develop “born accessible” [125] tools to ensure full inclusivity and independence in data science.

4.2 Survey Methodology and Findings

We designed an online survey instrument to collect data about the analysis and visualization practices of BLV professionals. To ground our research in real-world experiences, we consulted a panel of four Blind professionals with advanced degrees who regularly conduct data analysis. They advised us to explore the broader conceptual knowledge of data analysis and understand personal accessibility workarounds and challenges. Our panel explained that BLV students can stay in K-12 until age 22, potentially entering the workforce later than their sighted peers. We developed a survey to explore the challenges, workarounds, and experiences of data analysis among BLV individuals, making adjustments based on our panel’s recommendations to ensure inclusivity. We developed survey questions focusing on demographics, assistive technology, and data analysis tools; making adjustments based on our panel’s recommendations to ensure inclusivity. Given the broad scope of data analysis and visualization, we included statistical, evidence, qualitative, geographic, marking, and free-form analysis types (as recommended by our panel).

We screened participants based on these criteria: *(1) adults 21+, (2) some degree of blindness, (3) currently employed, and (4) professional experience in data analysis.* We sent survey invitations via listservs for Blind professionals (e.g., National Federation of the Blind) and AccessComputing. The survey was hosted on Qualtrics and underwent accessibility checks with a screen reader.

Our panel recommended that we broadly understand the types of data analyses performed by BLV individuals, and also the varying levels of disability. In our work, we adopt a social model of disability [126], and wanted our participants to self-report their lived-experiences and identities as analysts (as recommended by our panel). Through our screening questions (see supplementary material), we were able to collect data on a broad list of data analysis types (e.g., text analysis) and workflows; allowing us to screen our participants for the longer survey.

We received 2,000 responses within 48 hours, likely boosted by a social media post (“freegift-card”) that we were not involved with, leading to many fraudulent entries. To address this, we revised the protocol, added open-ended screening questions, and warned about fraud consequences. After consulting our Institutional Review Board, we increased outreach through local NFB chapters, excluded multiple submissions from single IPs, and filtered out inconsistent responses. Two researchers reviewed open-ended responses and invited 47 participants to the main survey, eliminating fraudulent and outlier responses to yield 28 valid responses. Given the potential for fraudulent responses, we took a very conservative and careful approach. Screened participants received a \$10 gift card for completing the main survey. We used descriptive methods for fixed-response data and deductive thematic analysis for open-ended responses, starting with initial codes and adding emergent codes.

Our participants self-identified themselves with diverse degrees of visual impairment: 8 were legally Blind, 7 visually impaired, 5 with low-vision, 3 with light perception only, and 5 with no light perception. Eight had congenital vision loss, 6 began losing vision between 6 months to 10 years, and 16 experienced vision loss after the age of 10. Perceptions of impairment vary among BLV individuals, as Massof notes [127], are often influenced by whether individuals identify with having low-vision or blindness, affecting their use of assistive technologies and handling

of daily challenges. Our survey offered varied response options to accommodate such personal blindness perspectives. As described by our Blind collaborator: legal blindness definitions can vary across countries; and from an individual's perspective, a person who is legally Blind may or may not have light perception. Some individuals with some light perception, or other visual impairments may choose to identify as Blind or Low-vision. For the sake of data analysis, we have combined the categories of 'no light perception', 'legally Blind', and 'Blind' into 'Blind'; and combined 'light perception', 'visually impaired', and 'low-vision' into 'Low-vision'. This resulted in our data having responses from **13 Blind**, and **15 Low-vision** individuals (indicated by SurveyID-B/SurveyID-LV in our quotes).

All participants had at least a high school diploma, with 18 holding bachelor's degrees, 6 master's degrees, and 2 doctorates. Professionally, they worked as data or business analysts, and in roles like operations manager, accessibility consultant, and research staff; indicating broad engagement with data analysis and visualization. Most participants had at least 2 years of programming experience, with 15 having 5-10 years, and at least 10 had experience in web, mobile, desktop development, or data science.

4.2.1 Data Analysis Goals, Types, and Tools

Open-ended survey responses indicate that individuals conduct a variety of analyses, ranging from descriptive to predictive, and their data analysis goals include steps like data cleaning, data manipulation through querying, and analysis using both visualization and non-visual statistical methods. Participants worked on tasks such as data collection through surveys or focus groups, identifying trends, patterns, and other statistical relationships, and were often responsible

for database management, from simple spreadsheet maintenance to manipulating and querying data, as well as visualizing data. Tool use was widespread and diverse, commonly involving spreadsheet/tabular data analysis using Excel, Python, R, SAS, and other tools depending on the analysis task. *S10-B*, a JAWS screen-reader user, used SAS for analysis, along with Excel for data manipulation: *“I actually use SAS for all ‘real’ statistical analysis, but find that it often displays/reads better with Jaws in Excel, so I often copy from SAS to Excel. I also use Excel/CSV for organizing, cleaning and organizing data prior to importing into SAS.”*

Most participants used assistive technology like screen readers and magnification to access data and charts, listing devices such as screen readers, tactile graphics, audio graphs, magnifiers, and Braille keyboards. They also benefited from predictive text (*S28-B*) and screen sharing with sighted colleagues (*S3-B*), using Zoom features for both data visualizations and tabular views like tables and spreadsheets. The use of screen readers for visualizations suggests access to alt-text, captions, or advanced screen reader features such as auto-captioning or OCR (e.g., JAWS). Oftentimes managing data and analyzing data involves collaboration with other individuals. *S6-B* described the various actors involved as follows: *“Currently I determine the type of information collected and then I analyze it from a team of outreach consultants that work with local school districts, cooperative regions, parents, etc., concerning the services we provide.”*

4.2.2 Collaboration Practices

Consistent with findings from prior work [20], most participants collaborate with sighted individuals as part of their analysis workflow, though the goals varied—sometimes after completing their tasks independently, sometimes during the analysis process. Collaboration was not

always for accessibility purposes, as S6-B noted: “*Yes, but not for accessibility, more interpretation of results.*” Sighted colleagues often helped with visual tasks such as creating charts and providing feedback, acting as visualization authors by taking summarized data and creating visual presentations (S12-B). Participants appreciated feedback on visual aesthetics to ensure reports were (S1-B; *no light perception*) “*formatted in a visual, pleasing manner.*”. This quote from S8-LV illustrates how the participants may work with colleagues, but take ownership of an analytical task: “*Typically my analysis is independent. I will often send graphs or summaries to sighted individuals, but that is not really part of my workflow. I like to get feedback from them on how the graph looks aesthetically and if anything needs to be improved.*”.

While collaboration was viewed positively, participants also expressed a desire for independence, with (S9-LV) stating, “*sometimes I feel like [an] annoyance for needing help and would like to be independent.*” Accessibility issues in the analytical tools used by BLV users often required assistance from sighted colleagues, which would not have been necessary otherwise. S10-B explained how layout and visual aesthetics that sighted individuals rely on could introduce accessibility issues during non-visual access: “*I find that sighted people using Excel like to leave blank columns or rows for better visual layout, which sucks using JAWS and can mess up data analysis. So I am constantly cautioning against merged cells or blank rows or columns. Also, I have discovered that with text entries, JAWS may read the entire contents of a cell but visually much is cut off, so this causes confusion between sighted and Blind persons.*”

4.2.3 Authoring Data Visualizations

Participants' goals for creating data visualizations focused on clear and effective communication, improved data accessibility, and elements like labels, color use, and visual structure complexity. They aimed to present data in an understandable format for colleagues and clients, including BLV users; preferred tools integrated with assistive technology; used Tableau, Power BI, and Excel; and consulted sighted colleagues for assistance. Data communication goals help with choosing relevant chart types: (S11-B; legally Blind) *"All depends on the data and the story you are trying to tell with that data when it comes to choosing the various chart types. Building test charts with a subset of data to experiment is helpful."* Choice of charts are governed by the data, and visualization goals: (S5-LV) *"There is not one or two types of data visualization that are more helpful to me than others. In general, common bar charts, pie charts, and line charts were most popular. Visualizations are hard to create when tools are inaccessible, or when data is complex (S19-B; legally Blind): "The more complex a visualization is, the more difficult it can be for people with low vision to understand. For example, when I was working on a project to visualize data from different sensors, I used only one type of chart, the bar chart, and kept the number of bars in each chart to around four or five. This made it easier for me to see how much each sensor was contributing to the total amount of data being collected."* Visualizations that offer a clear linear path of data, or comprehensive overviews were preferred. S1-B mentioned the difficulty in being confident about colleagues' visualization work, especially without being able to independently verify the representation: *"I would say the greatest challenge is not being 100% confident in the ability of my colleagues to render the information visually. I couldn't double check on my own."*

4.2.4 Accessible Visualization Practices and Challenges

BLV individuals developed various strategies to access data visualizations, often relying on existing technologies or human assistance, and employing alternative, more accessible means such as tactile representations, alt-text, or other sensory methods. *S1-B* mentioned, “*asking questions, using AI, and finding alternative means of representing the data [in tactile form] worked well.*” Some individuals manually adjust data presentations to better suit their needs, including enlarging images or altering colors and fonts to enhance readability. “*I’ve copied many graphs into PowerPoint and enlarged them to fill a slide,*” *S7-B; legally Blind* explained. Tools that adjust the display settings like magnification, contrast, and color settings are crucial for those with low vision: (*S5-LV*) “*screen enlargement, contrast tools, magnifiers have been helpful.*” Accessible color palettes and comprehensive text descriptions aid those with color blindness or low vision: (*S11-B; legally Blind*) “*General design principles make a big difference. Keeping in mind color palettes that are usable by individuals with color blindness and designing dashboards with good alternative text to be used by screen readers.*” Some participants revert to purely statistical data analysis techniques, or other non-visual methods to extract necessary information: (*S15-LV*) “*When data visualization is not accessible, I will try to use other data analysis methods, such as statistical analysis, data mining, etc.*” Though not always effective, *sonification*, which converts data points into sound, can be beneficial for understanding simpler data relationships: (*S8-LV*) “*I tried sonification, but that did not work for me. The sound of the data was not interpretable to me, except with very simple linear relationships.*”

BLV users have personal preferences for alternate sensory modalities: “*I prefer them to be some sort of a tactile representation, but if I have to hear the audio, I prefer them to be different*

sounds to represent different lines on the chart.”(S5-LV). Preparing and transforming data into a format that can be visualized was challenging: (S21-LV) “When creating data visualizations, I faced two main challenges. First, I had to figure out how to get the data into a format that could be visualized. This meant ingesting large amounts of raw data and then transforming it into something usable for analysis. Second, I had to create a visual representation that made sense and was easily understood by others.” Perceiving and interpreting the overview of a chart was challenging: (S8-LV) “The largest challenge is getting a view of the entire graph at once (i.e., to understand the relationships between data points). I took a statistics class that required interpreting whether certain assumptions held based on the shape of the graph, and this was very challenging. This is where I learned the method of using a preview image.”

4.3 Discussion and Conclusion

Our study findings add to the growing literature [128–130] on the lived data visualization experiences of BLV individuals. Our data, from both Blind (legally Blind; no light perception; Blind), and low-vision (visually impaired; low-vision; light perception) demonstrates ways in which a person’s abilities, impairments, and personal experiences influences the preferred workarounds such as magnification, screen-readers, multimodal approaches, and dependency on colleagues, to accessibility challenges at different stages of data analysis (data wrangling, analysis, and presentation). We find that Blind individuals needed to create visual data representations (visualizations and reports) for the sake of their sighted colleagues. While magnification and collaboration were most observed accessibility solutions for Low-Vision individuals, a few participants (e.g., S8-LV) also tried multimodal approaches such as sonification. Considering the

breadth of challenges for individuals the spectrum of blindness, we believe that finding solutions for specific data analysis tasks, making data science education accessible [131], and focusing future work on data science and analytical tasks in collaborative professional settings can lead to more “born accessible” technology.

BLV professionals face pervasive accessibility challenges in data science due to the lack of implementation of accessibility guidelines (e.g., WCAG 2.2) in tooling solutions such as notebooks [132]. We found ambivalent views on multimodal accessibility options like sonification; while also finding the utility of traditional textual and tactile forms [128]. Learning to use alternate forms can be challenging, but their potential ought not to be disregarded prematurely. Combining modalities such as sound, touch, and speech to carry larger information bandwidths [133] can be advantageous. Future work must continue to explore efficient alternatives to textual representations; particularly as many BLV professionals may not have experienced optimally designed sonification systems, which could offer a more intuitive understanding of data when well-executed [89, 99, 134].

As recommended by Potluri et al. [132] and as seen in our data, there is a need to adapt data artifacts such as charts, reports, and data-rich notebooks to work with assistive technology such as screen-readers and magnifiers. We recommend finding solutions in which data artifacts can be easily translated to be equal and accessible non-visual data representations [129]. Such methods can ensure that current data-rich environments can be accessed through individual or combined multimodal approaches such as sonification, refreshable Braille displays, refreshable tactile displays (e.g., Graphiti and Monarch).

Our findings suggest an immediate need to create systems that enable BLV individuals, whether they are programmers or GUI users, to author visualizations independently [135]. By

developing tools that are inherently accessible (“born accessible” [125]), we can shift the narrative from dependency to autonomy, allowing collaboration with sighted colleagues to stem from a desire for enhanced productivity [136] rather than a necessity due to inaccessible practices. We wish to conclude by discussing our future research direction: we want to conduct contextual inquiries with our survey participants to gather nuanced insights into the daily challenges and successes. Furthermore, we also intend to contribute to the effort for more inclusive visualization authoring for BLV workers.

Chapter 5: Design space for Crossmodal Sensory Substitution

5.1 Introduction

The sense of touch is critical for most blind individuals. Bereft of full use of their vision, blind people often use their hands to explore unfamiliar objects or their white cane to learn about the world surrounding them. Building on this idea, *data physicalization* [14] creates tangible representations of data to enable a blind person to feel rather than see the physical shape of a bar chart [15], 3D landscape [16], or node-link graphs [17]. However, data physicalizations that are cheap and accessible, such as thermoform paper and 3D printing, are static and require significant time to produce. More advanced data physicalization techniques that enable interactive feedback—such as shape-changing displays [18], haptic touch displays [19], and refreshable Braille displays—rely on specialized technology that is expensive and therefore not readily available to an often underemployed blind audience with limited purchasing power. Furthermore, the accessibility field is rife with “silver bullet” technologies that have been abandoned by over-optimistic inventors [2], making investing in experimental devices both costly and risky. Additionally, collaboration between sighted and blind individuals in data-rich social contexts such as work and school might still be challenging due to technology that places sighted and blind individuals in two different silos. While these sophisticated technologies may make data accessible for blind individuals, adoption at scale is not guaranteed because of the aforementioned

limitations.

What is readily available, however, are touchscreen devices. Modern smartphones have had a near-revolutionary impact on blind individuals, putting screen readers into virtually everyone’s pocket [20]. While still costly, smartphones have significant utility for both personal and professional use and thus enjoys widespread adoption—more than 46% [21]—among blind people, and the number is likely higher for gainfully employed knowledge workers. What if we could design a method for sensing complex datasets on smartphones and tablets using the same touch-based exploration that blind people routinely use with physical objects but without requiring specialized haptic technology?

In this chapter, we propose to achieve this by producing audio rather than haptic output in response to touch exploration. This approach is based on *sensory substitution* [6, 25], a common technique from assistive technologies where stimulus for one sensory system is replaced with stimulus for another, such as a screen reader verbalizing written text on a screen with synthesized speech. Our use of sensory substitution is crossmodal, a special case of *multimodal substitution* [26, 27] utilizing multiple sensory channels, because the approach explicitly “crosses” touch input with sound output. The experience of crossmodal substitution is similar to *synesthesia*—a perceptual phenomenon in which stimulation of one sense leads to involuntary experiences in a second sensory system. In our approach we cross the sense of touch with sound, an approach similar to producing sound when seeing colors [137, 138]. To explore and validate this idea, we propose TACTUALPLOT, a crossmodal substitution technique for scatterplots that enables a person to “touch data” spatialized in two dimensions on a smartphone touch screen, similar to a visual 2D scatterplot. With TactualPlot, a blind user can use their fingertips to explore the shape of the data, receiving a dynamically changing audio tone in response that conveys the density un-

der the user’s touch. Unlike many other accessible data representations, TactualPlot was designed for scalability, with thousands of data points in mind.

We designed TactualPlot in a user-centered manner by engaging our collaborator and co-author, who is blind, in a series of formative design sessions. Our observations yielded several design revisions, including the need for multiple touch interaction and axis manipulation. Our participatory design sessions helped us understand that it is important to develop a touch-based, non-visual graphical perception technique that could be generalized beyond scatterplots. We then conducted an in-depth expert review with two blind professionals to assess the utility of TactualPlot, and—by extension—the validity of the crossmodal substitution concept. During the hour-long sessions, our experts used TactualPlot to explore data and answer questions about their findings.

The main contributions of this work include: (i) the design and implementation of the TactualPlot prototype for exploring scatterplots using sensory substitution where tactile feedback is sonified; (ii) results from an in-depth and longitudinal formative design process involving our blind collaborator and coauthor; and (iii) findings from an expert review involving two blind professionals using TactualPlot for multidimensional data.

5.2 Design Space: Crossmodal Substitution

Sensory substitution is the practice of replacing one sensory system for another when producing output for some perceptual task [6,25]. It is a common approach for assistive technologies because it enables replacing a sensory system inaccessible to a person with disabilities with a sensory system that remains accessible. For example, a screen reader uses sensory substitution to

replace text on a screen—which requires vision to perceive—with synthesized speech—which uses hearing. This allows a Blind person to read digital documents, web pages, and articles.

We propose the notion of *simultaneous crossmodal sensory substitution* (SCSS), or just *crossmodal substitution*: replacing in real-time the output for one sensory system that is produced by the user interacting with the world with output using another sensory system. A specialized form of *multimodal sensory substitution* [26, 27], which uses multiple sensory channels for feedback, crossmodal substitution only makes sense in a digital space where the normally rich physical interactions of the real world do not hold. For example, manipulating a 3D graphical object using a standard mouse typically yields none of the touch, feel, and heft of manipulating an artifact in the real world. However, visual feedback will still yield a facsimile of the sensory output inherent with handling such a physical object; it may move, rotate, and even have inertia similar to the real object.

Our notion of crossmodal substitution is essentially a specialization of *direct manipulation* [139], and is clearly a fundamental (and unremarkable) aspect of graphical user interfaces. However, it has an important additional affordance when applied to assistive technologies for people with disabilities: it can be used to separate the means of manipulating the world (or the digital system) from the sensory output normally produced by this interaction. More specifically, it could be used to, for example, let a deaf person tap a sound source in a video—such as a car, person, or airplane—and receive a textual description of the nature of the sound, or to let a Blind person tap a web page to get an audio representation of the selected content (which is the general idea explored in this chapter). Another use may be to couple an eye tracker with a screen reader, producing a system that automatically verbalizes whatever text the user’s eyes alight on. We specifically focus on the idea of letting users interact with a touch screen containing spatialized

data to produce a sonification and verbalization of the data. However, as indicated above, we think there is much additional potential for expansion to the TactualPlot technique.

5.3 The TactualPlot Technique

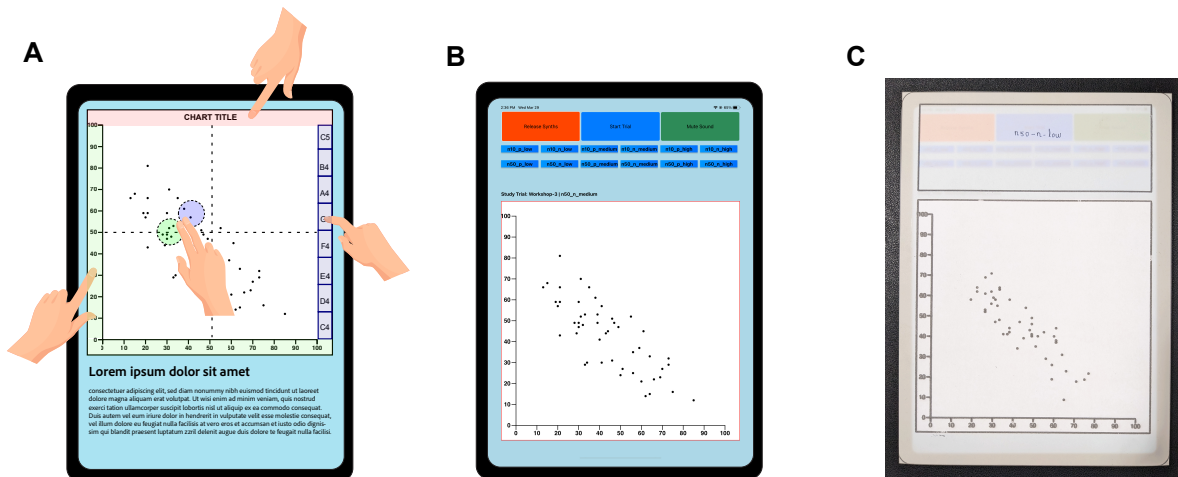


Figure 5.1: **Designing the TactualPlot technique.** (A) Illustration of the TactualPlot technique with its continuous and discrete touch actions and regions. (B) Our implementation of the technique that was evaluated in formative design session 3 and design review sessions. (C) Tactile graphics aligned to scale, and overlaid on an Apple iPad to collect touch information.

TACTUALPLOT (figure 5.1.) is a crossmodal substitution technique for exploring multidimensional data using touch input to produce sound output. The technique spatializes the data by projecting data items to the physical space defined by the extents of the touch screen, similar to a 2D scatterplot for visual representations. Users can then explore these spatialized points by touching them on the screen, similar to how you can explore a rough 3D surface using your fingers. However, instead of providing haptic feedback through your fingertips—which is obviously impossible for standard touch displays—the feedback is crossmodally redirected to sound: the data is sonified using a continuous audio tone. The audio playback is derived from sampling the spatialized data points under the user’s touch and modulating the pitch according to the data

density. In this way, TactualPlot can interactively sonify hundreds of data points even on a small touch surface and give a Blind user an understanding of the data distribution through progressive exploration.

In this section, we describe the basic principles behind TactualPlot’s spatial mapping and interaction models. We also describe various interaction methods for touching data as well as the edge of the screen, and the resulting verbalizations and sonifications for representing data. Please note that we did not implement and assess all the features described in this section during our formative design sessions. We recommend carefully implementing these features as the interplay of sound, touch, and data abstraction can be cognitively taxing for our users. The features we have implemented are marked with a solid circle: ●.

5.3.1 Spatial Mapping

Effective data representations for Blind users are often based on spatializing—rather than visualizing—data [54]. TactualPlot maps data to space using a direct projection from a data dimension to a geometric dimension. The technique maps data to the horizontal (x) and vertical (y) axes; in other words, it is a 2D spatial representation, similar to a visual scatterplot. Most commonly, the projection from data space to visual space is linear, although logarithmic mappings can be useful.

The TactualPlot spatial mapping is designed to consume the full screen of the device, i.e. its entire length and width. This gives a Blind user a direct mapping from the physical display itself—as well as from proprioceptive feedback from their own body—to the symbolic data dimensions in the dataset being represented.

Note that while TactualPlot shares many similarities with a 2D scatterplot, the marks sonified using the technique can really only convey two scalar data dimensions (the two Cartesian axes) and one categorical data dimension (the data item class). Scatterplots, on the other hand, can use the color, shape, and size of marks to convey additional data dimensions.

5.3.2 Interaction Model

TactualPlot's interactions are designed according to a fundamental rule: *discrete* actions, such as tapping or double-tapping the screen, yield *discrete* feedback (verbalized information), whereas *continuous* actions, such as dragging and pinching on the display, yield *continuous* feedback (continuous audio sonifying the underlying data). In practice, this means that tapping the left margin of the screen will cause TactualPlot to read the name of the data dimension mapped to the vertical axis as well as its current minimum and maximum values, whereas dragging your finger along the axis will read out its current axis values. We discuss these interactions below.

The TactualPlot direct spatial mapping to a physical device facilitates perceiving physical space as data space. This allows, for example, a Blind user to slide their finger from left to right and understand that the price of the houses they encounter on the display is increasing.

5.3.3 Continuously Touching Data

Reading data off a TactualPlot display is achieved by touching the display, which will aggregate the data points contained within the *sampling area* centered on the user's finger and translate the points into audio feedback. Using a circular sampling area [140] rather than a point makes it easier for the user to find all of the data on the plot.

The sampling area can be either set to a specific size (roughly corresponding to the physical size of a typical fingertip) or a size controlled by the user. Another approach is to use a dynamic size for the sampling area that changes based on the movement speed of the user’s finger: the faster the finger moves, the larger the sampling area. This can improve the likelihood of sampling all the points on the chart canvas. This enables fast and ballistic movements to form a rough overview, e.g. quickly scribbling with your finger across the display, followed by a slower and more deliberate tracing of the data to get the details.

Every time the user’s touch moves on the display, points that fall within the sampling area are re-aggregated. If the points are of different classes, such as a dataset of real estate containing both condominiums, single-family houses, and farms, they can be partitioned into separate groups. The number of points in each group is then normalized globally for the entire chart and the calculated for the current density.

5.3.4 Data Sonification

Data in a sampling area being sonified using TactualPlot is conveyed using pitch to represent data density; the higher the density, the higher the pitch ●. Pitch rather than volume has been shown in past work on sonification to be the optimal channel to convey quantitative values [20].

In keeping with the continuous nature of the drag interaction, the sound generated in TactualPlot is also continuous. As recommended [134], we wanted a pleasant sound and we implemented a flute like sound—“*okay, now that sounds like a flute.*” (R1 in our design review). The tone persists as long as the user’s finger is touching the display, and it modulates smoothly in

pitch as the user moves their finger and the data density under the sampling area changes.

If the underlying dataset has multiple classes, such as different types of real estate, different voices (such as instruments) can be played simultaneously. Again, to maintain consistency with the continuous interaction, individual tones must not be segmented or split. In other words, this requires polyphonic sound generation where multiple tones are played at the same time. Another approach is to use natural sounds that have been shown to blend well together [95].

Finally, TactualPlot can use ●spatial sound output—stereo or full 3D binaural audio—to redundantly encode the position of the touch point on the physical device. Alternatively, different stereo channels can be used to divide multiple data classes; for example, playing the current density of condos in one ear, and the density of single-family houses in another. However, Blind users commonly use only one headphone while interacting with a mobile device [20], especially in situations where they need to listen to conversations in their surroundings, so techniques that require both ears are not always practical.

- *Drag - Sonify Sampled Data:* The basic interaction of TactualPlot; the data in the sampling region under the user's fingertips is sampled and the density conveyed using pitch.
- *Tap - Drill Down:* Retrieve a list of the data values in the sampling region under the user's fingertip (see Section 5.3.6).
- *Two Finger Tap/Pinch - Zoom:* Change the zoom level or centerpoint of the viewport (see Section 5.3.6).

5.3.5 Edge Interactions

The edges of the TactualPlot display are significant and interactions are different from when interacting with the main area of the display. Typically you would define the 10% of the outer parts of the display as the edge. We define four different edge regions with specific affordances:

○ **Top edge - Title:** Interactions for the entire chart.

○ *Tap - Chart Title:* The title of the chart is verbalized.

○ *Swipe - close chart:* The TactualPlot display is closed down, yielding a verbal status message.

● **Left edge - Vertical axis:** Interacting with the y axis.

○ *Double Tap - Axis title:* Vertical axis title is verbalized.

● *Drag - Axis ticks:* Tick marks are indicated using an earcon.

● *Tap - Axis ticks:* Tick mark value is verbalized.

● **Bottom edge - Horizontal axis:** Interacting with the x axis.

○ *Double Tap - Axis title:* Horizontal axis title is verbalized.

● *Drag - Axis ticks:* Tick marks are indicated using an earcon.

● *Tap - Axis ticks:* Tick mark value is verbalized.

● **Right edge - Legend:** Interacting with audio legends.

- *Tap - Data density legend:* The audio class tone of the sonification is played and their corresponding point values are verbalized. In our prototype, tapping directly on the points conveys pitch mappings to the point density.

Overall, all state changes in the TactualPlot interface are accompanied with a text-to-speech status message giving the user verbal feedback for their interaction.

5.3.6 Zooming and Details-on-Demand

In addition to continuously touching the data, the main touch surface (and not the edge) of the display supports several additional interactions:

- **Pinching (two fingers):** Users can zoom into a region of the data display by pinching, thereby changing the data extents on the vertical and horizontal axes. Discrete zoom values in multiples of magnification are verbalized as the display is zoomed in and out. The display cannot be zoomed out past $1x$ magnification, where all of the data is contained within the viewport. Leaving the display untouched for some time (30 to 60 seconds) will revert the magnification back to $1x$, which is also announced verbally.
- **Tapping (one finger):** Users can drill down into the data to get details-on-demand by tapping on a region. The data density inside the sampling area around that touch point will be verbalized. If there is none, a brief sound or no sound can play. If there is more than a predefined number of points (5 or more), the summary statistics of the points can be verbalized.
- **Zoom level (discrete):** Double tapping on the screen can be used to convey spatial information (geometric zoom), or the designer can choose to enable zooming in the data.

5.3.7 Beyond Scatterplots

The TactualPlot technique was designed specifically to be an interactive sonification of 2D scatterplots, and uses many of the same metaphors and interactions as a visual scatterplot would. However, these principles could no doubt also be applied to other types of visualizations to yield comparable interactive sonifications. We propose to expand TactualPlot to bar charts, pie charts, and line charts in chapter 6.

5.4 Formative Design Assessment: TactualPlot

TactualPlot was improved using a user-centered, participatory approach. We derived the original design (Section 5.3) through in-depth discussions in our research team, where one of our collaborators is a Blind individual with long experience in assistive technologies and human-computer interaction.

Tactile graphics are often used by teachers of students with visual impairments (TVSI) to teach graphical perception in educational contexts. Blind individuals have varying levels of expertise in perceiving representations such as Braille and tactile graphics. Nevertheless, tactile representations are ideal for conveying spatial awareness, especially since multiple fingers can provide parallel channels for tactile information. Therefore, we decided to base our TactualPlot technique on tactile chart exploration with a crossmodal representation using sound.

5.4.1 Design Probes

To help inform our design process, we built two design probes [141, 142] as low-fidelity prototypes: (1) tactile graphics implemented using swell touch paper, and (2) a prototype web-

based app running on smartphones and tablets. Our goal was to let design lessons and findings for the tactile graphics scatterplots inform the design of the mobile application.

Tactile graphics. The tactile graphs were implemented in consultation with our university’s assistive technology lab. We performed two iterations of the scatterplot design; the first session enabled us to fixate on printing parameters such as dot sizes, aspect ratio, and data density, whereas the second yielded graphics suitable for both this formative design as well as the subsequent design sessions and user study (Section 5.5). We describe each session and its outcomes below.

We used swell touch paper made by American Thermoform in standard U.S. Letter size (8.5 × 11 inch; 215.9 mm × 279.4 mm). Scatterplots were printed using a standard laser printer and then “fused” using an American Thermoform Swell Form Machine, which causes ink to swell. It is possible to achieve different heights for the graphical elements by varying the (1) saturation of the ink, and (2) the temperature setting during the fusing process. In our study, we use a single height across the entire tactile graphic. We chose the point diameter in the tactile graphics and the digital TactualPlot system to the base dot size of the North American Braille—1.44 mm; 0.057 inches. This may help retain familiarity among Braille literate Blind users, and the size is proven to be easily perceivable to touch.

TactualPlot implementation. We implemented TactualPlot as a web-based application for mobile platforms (smartphones and tablets) using basic HTML, CSS, and JavaScript technologies as well as Apache Cordova.¹ Our implementation generates sound using ToneJS,² a JavaScript

¹<https://cordova.apache.org/>

²<https://tonejs.github.io/>

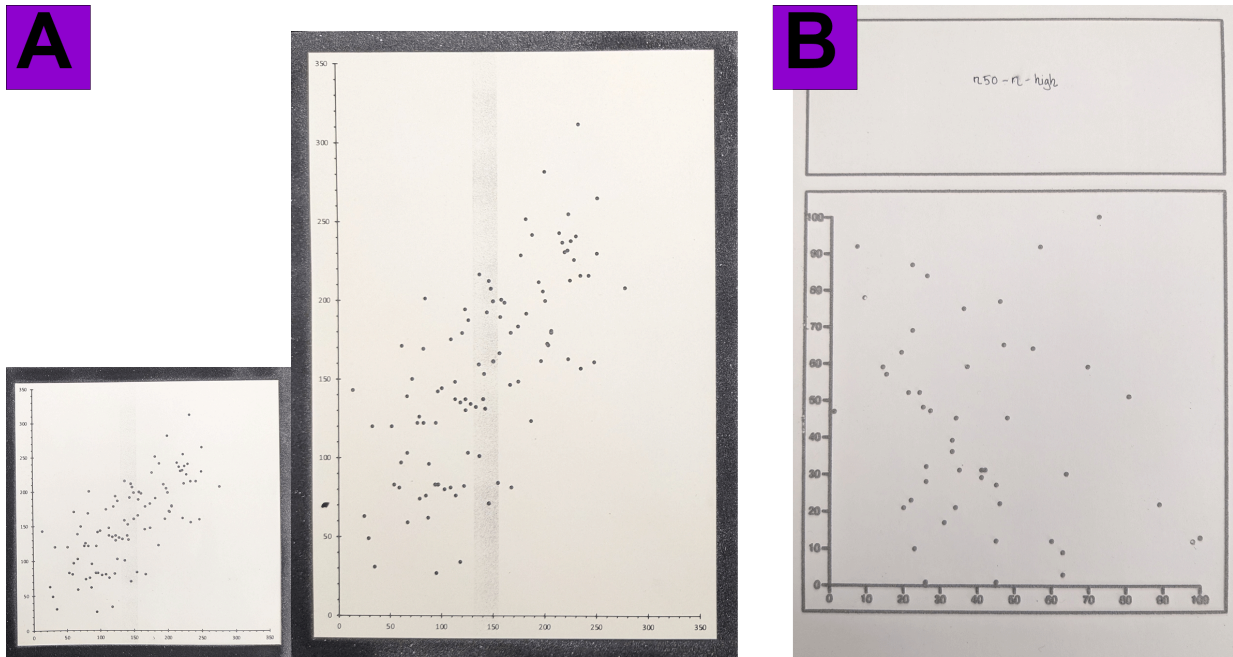


Figure 5.2: **Tactile graphics.** Scatterplots implemented using American Thermoform swell touch paper to match the dimension of the D3.js visualization in the TactualPlot system.

toolkit based on the Web Audio W3C API.³ Finally, touch interaction is detected and handled using the Touch Web API that can handle multi-touch interactions.⁴

5.4.2 Participatory Design Sessions

We followed an iterative design process to design our TactualPlot interaction technique for touchscreen chart interaction. We conducted three participatory design sessions [143] over three weeks, which helped guide our design decisions. The first two sessions lasted 2 hours each, and the final session was 3 hours. The goal was to understand how Blind individuals might want to interact with a crossmodal substitution device where tactile input results in auditory output.

Our collaborator is Blind, Braille-literate (both reading and writing), and has had recent exposure to tactile graphics and screen readers.

³<https://www.w3.org/TR/webaudio/>

⁴<https://www.w3.org/TR/touch-events/>

5.4.3 Dataset and Tasks

We generated 12 datasets to be used in our design sessions and external design reviews. We modeled the data as follows:

- **Data Scatter:** The Pearson's correlation coefficient that varies the strength of the linear relationship between the two variables. We chose three levels for this factor:
 - **Low:** $\rho \in [0.0, 0.30]$
 - **Medium:** $\rho \in (0.3, 0.7]$
 - **High:** $\rho \in (0.7, 1.0]$
- **Data Volume:** The complexity of the dataset is expressed in the number of items being represented in the scatterplots. We chose two levels for this factor:
 - **Small:** 10 items
 - **Medium:** 50 items
- **Polarity of the linear relationship:** This indicates if the linear relationship is positive or negative.

We settled on these values through pilot printing to ensure that we were able to create high-quality tactile points without occlusion. We used the equation: $y = mx + c$, where $1 \leq x \leq n$ and $n \in \{10, 50\}$ and $m \in \{-1, 1, 2, -2\}$, and $c \in \{0, 10, 50\}$. Using a negative m value allowed use to generate negative trends in the scatterplot. To introduce a scatter, we added $noise(\epsilon)$ to both x and y values generated by the linear equation, where $\epsilon \sim \mathcal{N}(\mu, \sigma^2)$. While changing the slope allows us to control the angle of the trend with reference to the x-axis, we could translate

and scatter the points by changing the following values: μ_x , μ_y , σ_x , and σ_y in addition to m and c . We have included our final data specifications and the corresponding (x, y) datasets in the supplementary material. We adapted 3 tasks spanning the 3 categories as described by Sarikaya and Gleicher [144]. We describe the question structure for each of the task types in Table 5.1.

TASK CATEGORY	TASK TYPE	QUESTION STRUCTURE
Object-centric	Locating (L)	Identify range on Y -axis with maximum value for range between X_1 X_2 on X -axis.
Browsing	Explore trend (T)	As X values increase from left to right, are Y values increasing, decreasing, or random?
Aggregate-level	Numerosity (N)	How many points exist in a specific quadrant: top-left; top-right; bottom-left; or bottom-right?

Table 5.1: **Task types.** List of task types and corresponding question structures for our user study. Each trial corresponded to a given task sub-type.

5.4.4 Apparatus

We asked our design partner to use both paper-based tactile graphics generated using swell touch paper as well as our prototype implementation of TactualPlot running as a native app using Apache Cordova.

We ran the TactualPlot prototype on an Apple iPad Pro 128 GB with an 11-inch (diagonal) Liquid Retina display (a Liquid Crystal Display, LCD); the actual screen dimensions were 247.6 mm \times 178.5 mm. During the test, we ran the native app in full-screen mode and disabled all notifications.

For both tactile graphs and TactualPlot, we used a square display space measuring approximately 153 \times 153 mm. For the tactile graphic, we simply cut each scatterplot to size. For the TactualPlot prototype, we masked the remaining part of the iPad display surface with acrylic

plastic cut to size using a laser cutter to prevent accidental touches outside of the scatterplot area. In fact, we placed the iPad underneath the scatterplot even for the tactile graphics condition so that we could track the participant's touch interaction with the tactile graphic as well.

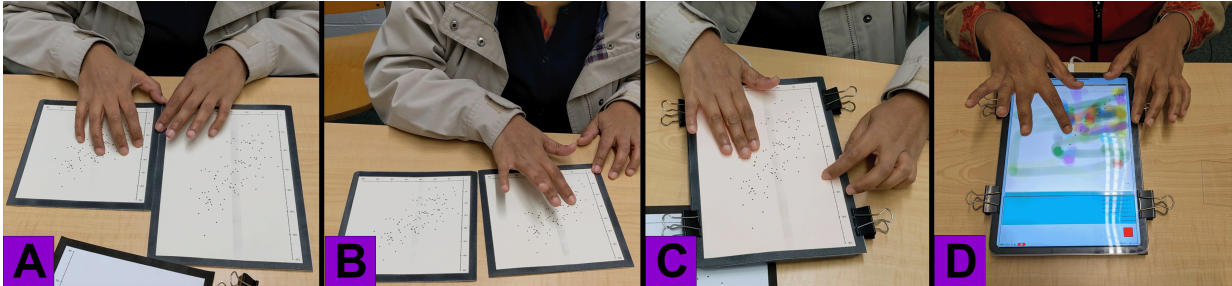


Figure 5.3: **Design Sessions 1 and 2.** Our Blind collaborator interacting with a low-fidelity tactile graphic using both hands and multiple fingers.

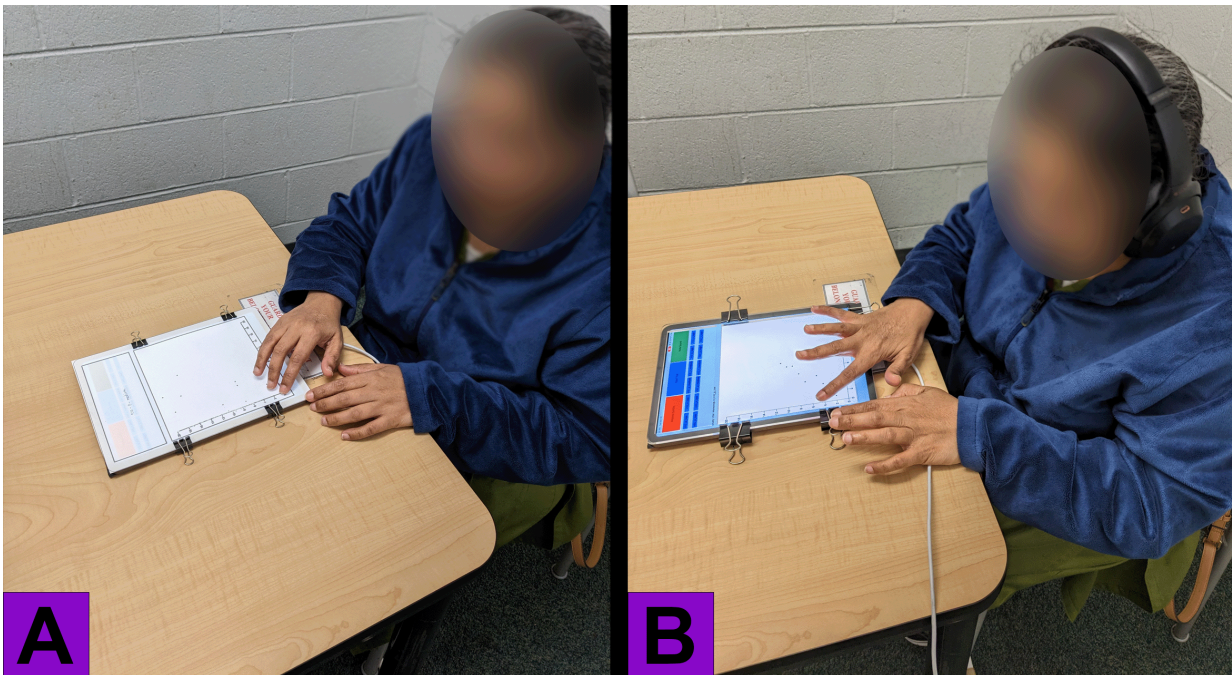


Figure 5.4: **Design Session 3.** Our Blind collaborator interacting with the final version of our TactualPlot system.

5.4.5 Design Session 1

Our goal for the first design session was to understand how chart characteristics such as axis lengths, orientation, data volume would influence data perception. We printed four tactile scatterplots, where $N \in \{50, 100\}$ with 2 plots each of uniform axis and non-uniform axis lengths. As seen in Figure 5.2, we asked our collaborator to identify if the two different datasets were same when printed with uniform vs. non-uniform axis lengths. Just like for visual perception, axis lengths did skew perception. With 100 items and uniform axes, our collaborator sometimes could not tell duplicates apart, based on the exploration route. Overall, we decided use uniform axes to reduce cognitive load.

We had originally designed TactualPlot to support only one-finger interaction. However, it quickly became apparent during the session that our Blind collaborator was using not just two hands to interact with the prototypes, but also multiple fingers (Figure 5.2). They would hold the graphic with one hand, which they reported as a form of physical “anchor” for the other hand. The participant would then use two or even three fingertips of the other hand to slide along the surface of the graphic to sense the embossed data points. For our touch prototype, such multi-touch interaction was not implemented at the time of testing, and thus did not yield the expected behavior.

This finding also caused us to prioritize such multiple sampling areas rather than speed-dependent dynamic size for a single sampling area. Lastly, we built a test bed to capture touch logs of the exploration route by placing and fastening the tactile graphics to the iPad screen using binder clips. Despite the layer of swell touch paper with raised dots and axes, the iPad touchscreen was able to detect the touches. This motivated us to explore hybrid scatterplots for

future versions—a combination of tick mark sonification to indicate that a tick is being touched, and tapping the tick marks to verbalize the tick values.

5.4.6 Design Session 2

In response to findings from the previous design session, we added multi-touch interaction to the TactualPlot technique so that a user can use several fingertips to spawn multiple sample regions for sensing a larger area on the display. We added brown noise to sonify empty regions by playing a low pitch “buzzing” sound. We experimented with sound envelopes by varying the Attack, Decay, Sustain, and Release (ADSR) values to yield a subjectively pleasing sound for point density.

Our goal was to elicit user exploration strategies [145] given a particular data task. For this session, we used the TactualPlot apparatus (frame **D** in Figure 5.3), and datasets where $N \in \{10, 50, 100\}$. We first focused on exploring trends (T) in the data using our system. We provided (1) an explanation of the sonification design, (2) verbal description of a linear trend and how that might appear spatially—e.g., “for a positive trend, imagine that a line is drawn at 45 or 60 degrees with reference to the horizontal axis, and if points are scattered closed to the line, there is a high correlation between x and y ”, and (3) a recommendation to start with one finger exploration and transition to multiple fingers.

We recorded the iPad screen and implemented a finger trail visualizer that allowed us to study the exploration route for the trends analysis task. Each color represents a a touch using a new finger—a ‘new’ finger could be the same human finger, i.e., sequential touches with the same index finger is mapped to two different colors. In total, we cycled through 10 different

colors to handle 10 concurrent touches (iPad supports 10 touches). Axis, origin, and point density verbalization had not yet been implemented for Session 2.

We include sample exploration strategies to demonstrate the various touch paths that may be possible. In Figure 5.5, we can see that at the beginning, our collaborator started at the origin and moved horizontally, and moved from the bottom of the canvas to the top. And towards the end of the trial, our participant had sampled all 10 points, but two parts of the canvas remained unexplored (indicated by lack of color). In Figure 5.6, our collaborator followed a similar trajectory as the previous example, but instead of one finger, they moved two fingers concurrently across the canvas. In this example, all the points were sampled at least once, and only a very small portion of the screen remained unexplored.

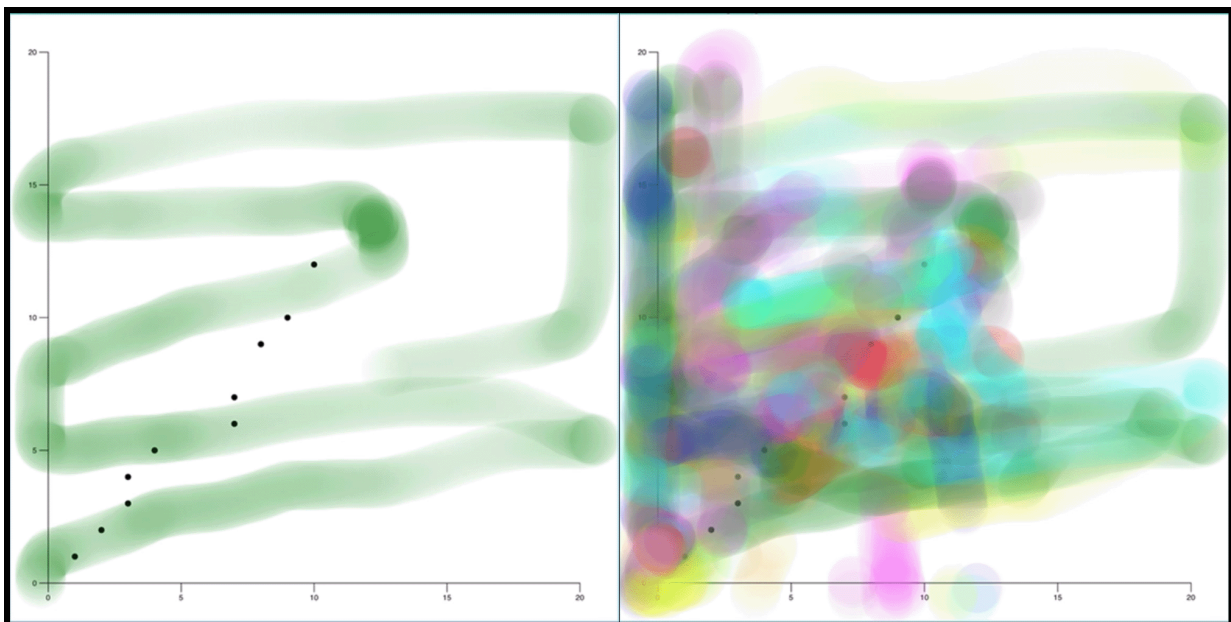


Figure 5.5: **Lateral scanning.** *Left:* Initial one finger exploration that starts at the origin, and moves laterally across the screen. *Right:* Final touch trail at the end of the trial.

In Figure 5.7, our collaborator placed two fingers at the origin and moved them upwards and then towards the right. After nearing the right extremity of the canvas, our collaborator

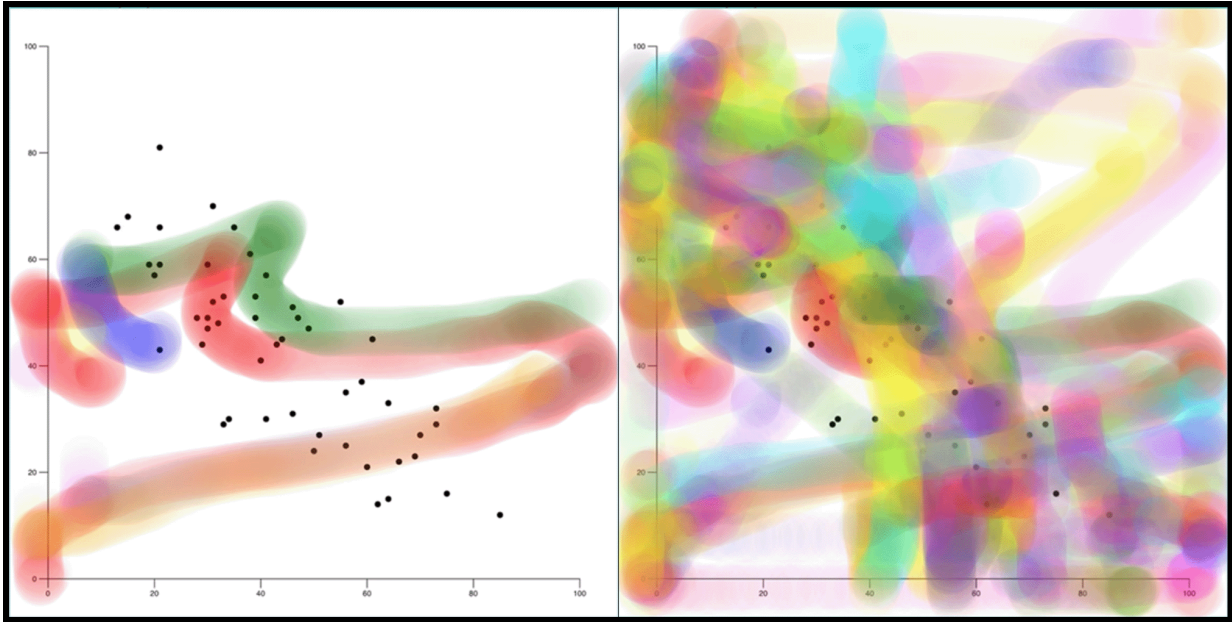


Figure 5.6: **Two-finger lateral scanning.** *Left:* Exploration started with two fingers being placed on the origin *Right:* Final touch trail where all the data points have been sampled.

reestablished contact with the screen at the origin and proceeded to move higher the second time. As seen in the right frame, all 50 points were sampled, but portions of the chart are still unexplored. We considered varying the lens size according to the panning speed, but decided against it. With a fixed lens size, our participant could detect variations in pitch, but could not accurately map the point density value to a particular pitch value.

5.4.7 Design Session 3

We incorporated the feedback from Session 2, and implemented new verbalization features to help better understand “how many points are under your finger” by allowing the user to tap on a particular location to verbalize the point density—“1 dot” or “5 dots.” Additionally, we included a “clicking” earcon if the user touched a tick mark while panning. We included another discrete touch sound, i.e., a one finger tap on the tick mark would verbalize the tick mark values.

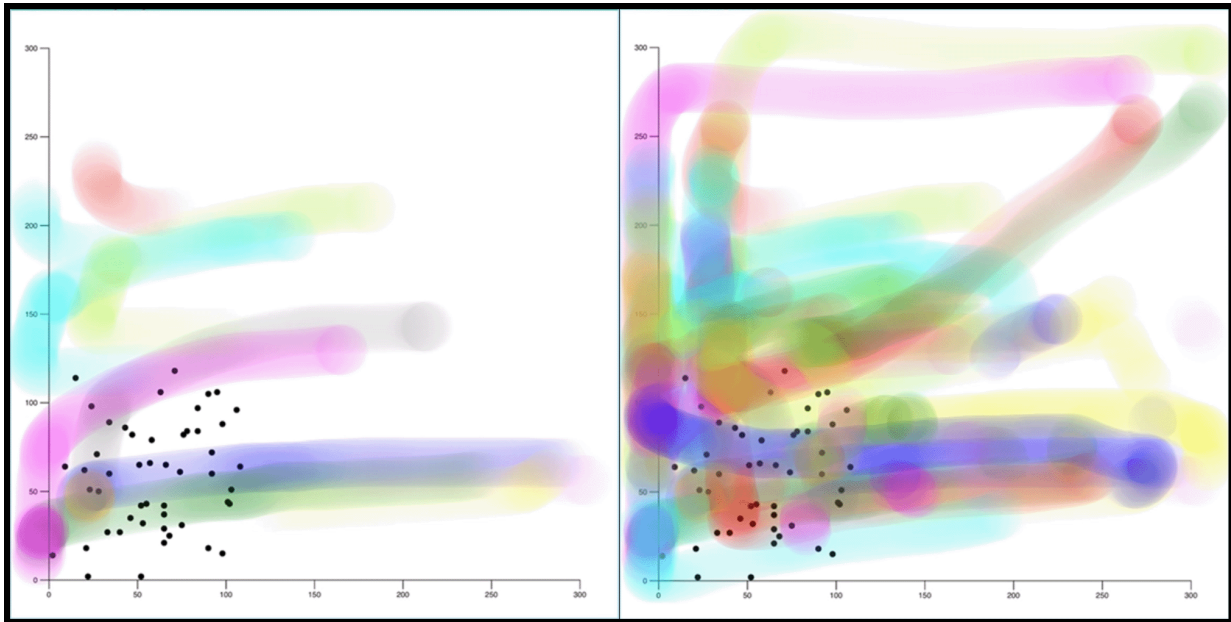


Figure 5.7: **Two-finger vertical scanning.** *Left:* Exploration started with two fingers being placed on the origin and moved vertically and then towards the right. *Right:* All the data points have been sampled, and 3 unexplored regions.

For example, “X-axis: 12” or “Y-axis: 10.” Our collaborator found the “buzzing” brown noise overwhelming after a while, so we decided to play no sound while continuous dragging on empty space, and instead chose to verbalize “0 dots” on tapping an empty region. We added stereo panning to provide better information of screen location, and played a “click” when the user crossed the mid point of the chart canvas.

Method. For Design Session 3, we wanted to understand if there were any differences in user exploration strategies or perception between TactualPlot and tactile graphics. For a more detailed assessment than the previous two design sessions, we conducted a 3-hour workshop. In addition to the trend task, we asked our collaborator to attempt the Numerosity Task (see Table 5.1). We collected touch logs, qualitative feedback, and task responses. Our collaborator completed the Numerosity tasks using tactile graphics first (see Figure 5.4A) and then used the TactualPlot

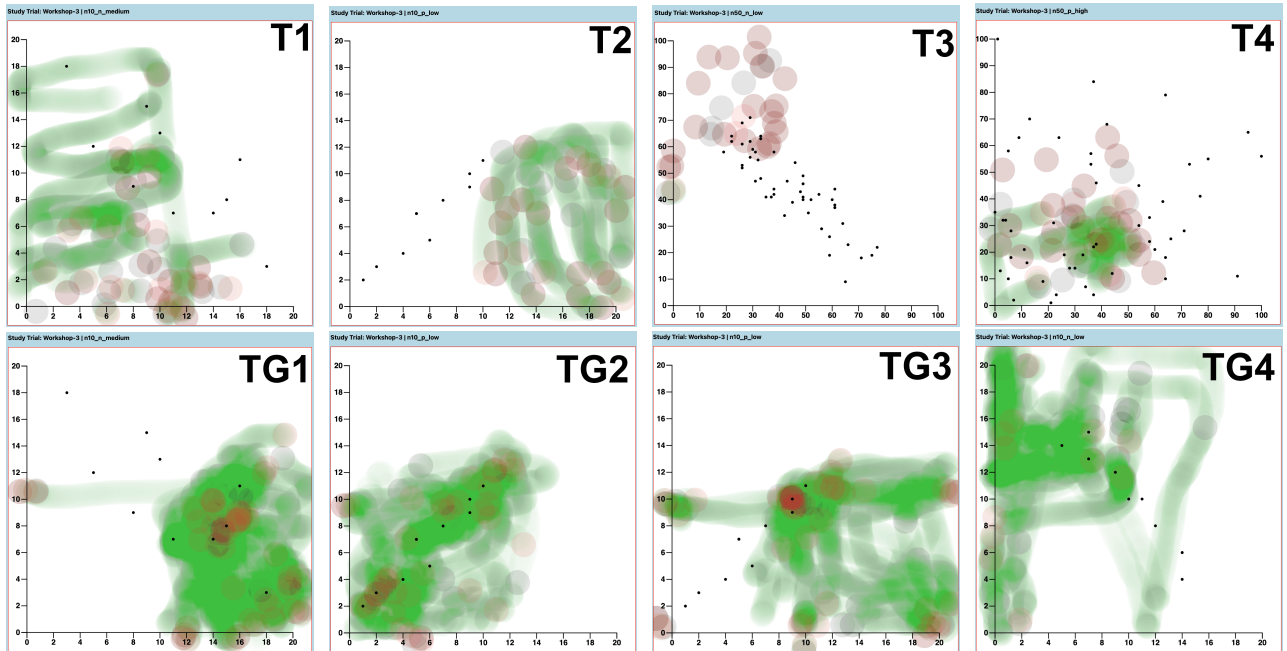


Figure 5.8: **Comparison of touch behavior.** Touch interaction logs for TactualPlot and tactile graphics (TG).

apparatus (Figure 5.4B).

To complete the Numerosity task, our user would have to understand the spatial distribution of the data in addition to perceiving their own fingers' location on screen, and potentially use the axes interactions. To compare both techniques (TactualPlot and tactile graphics) and have time for qualitative feedback, we selected 4 datasets per technique for the numerosity task.

Results. Our collaborator was able to successfully complete all 8 tasks using both tactile graphics and TactualPlot. We report the results in Table 5.2. We extracted and visualized the touch logs for these tasks in Figure 5.8. Figure 5.8 indicates the final state of the system at the end of a trial. We encoded taps (discrete interactions) using a red circle, and continuous dragging in green. A higher opacity of color indicates that a particular region has been sampled more using continuous or discrete interactions. In all 8 trials, the estimated Numerosity value in a particular quadrant was approximately close to the actual value. From the touch logs, we observed that using both

Table 5.2: **Performance comparison.** Comparing Tactile Graphics and TactualPlot for the Numerosity (N) task.

ID	DATA VOLUME	DATA SCATTER	POLARITY	QUADRANT	ESTIMATED VALUE	ACTUAL VALUE
<i>Tactile Graphics</i>						
- TG1	10	Medium	N	Bottom-Right	4	5
- TG2	10	Low	P	Bottom-Left	6	9
- TG3	10	Low	P	Top-Right	0	0
- TG4	10	High	N	Top-Left	4	5
<i>TactualPlot</i>						
- T1	10	Medium	N	Bottom-Left	0	0
- T2	10	Low	P	Bottom-Right	1	1
- T3	50	Low	N	Top-Left	20	17
- T4	50	High	P	Bottom-Left	15	24

techniques, our collaborator was able to restrict finger movement to the quadrant under consideration. Additionally, we observed both from the touch log and qualitative feedback that the sound design for the axes was effective in helping understand finger location. We can observe rough perpendicular finger trails leading to and from the axes, followed or preceded by a discrete tap to hear the tick value. During the session, the researcher observed the interaction style change for the numerosity task; which is reflected in Figure 5.8.

Observations and Qualitative Feedback. Our collaborator switched from continuous dragging to discrete taps to understand point density because of accidental touches. We removed the “buzzing” sound after the second design session and replaced that with a tap to verbalize “0 dots” for the third session. Continuous dragging, especially using multiple fingers would often trigger unintended verbalization of the point densities.

The haptic feedback from the tactile dots made it easy to count during continuous dragging, whereas in the TactualPlot system, dragging did not provide exact density estimates: “no, tactile

graphics, I could feel the dots. You know, so that was not my problem, counting them; figuring out—okay, this is, this is the trend, whatever. The audio was a little bit, means, I was not 100% sure. But, it was when you said you know, roughly how many and I said okay, so I counted...one place there's seven, one place was three, then there was two...five...four. That's how I estimated the number."

When asked if the interface should convey the presence of non-sampled data points our collaborators indicated that when analyzing non-synthetic data, users might better understand what they might have missed:

"Oh, you don't need to tell me if I'm looking at real data. Yeah, I'm trying to figure it out, you know, if I pan it like left and right and whatever...If it has given me the music then I will be able to figure it out that way. Okay, because the points [with] the music in it, it's getting closer and closer."

5.5 Design Review

Our goal with TactualPlot is to provide a hybrid representation combining tactile input with sonified output, thereby addressing challenges with both. While we do not anticipate that the approach will be a perfect replacement for a fully dynamic tactile display, we want to provide an acceptable substitute using current touchscreen devices.

To validate the approach, we conducted an expert design review [146] with two Blind individuals with domain expertise in statistics and Braille. Our research study was approved both by our university's IRB (ethical review board) as well as the Research Advisory Council of the National Federation of the Blind (NFB) in Baltimore, MD, USA.

5.5.1 Participants

We recruited two participants for our expert design review (2 female) through a local NFB chapter. Demographic details of the reviewers are available in Table 5.3. Both reviewers were Blind screenreader users, and reviewer R1 was also hard of hearing with a Cochlear implant. R1 uses an omni-directional microphone to amplify the sound of the hearing aids. During our session, we connected our system to a Bluetooth speaker and placed it next to her microphone. R1 was recruited for her knowledge of statistics, and R2 for her expertise as a Braille proofreader. The study was conducted in-person because of the need for specialized equipment. To promote participation for people with limited mobility, all sessions were conducted at a public library close to the reviewers’ own homes. Reviewers were compensated with a gift card worth \$50 for their time and effort.

Table 5.3: **Expert review participants.** Demographics and experience of the participants.

ID	Age	Gender	Education	Recruitment criteria
R1	59	Female	Master’s degree	Statistics knowledge
R2	60	Female	Bachelor’s degree	Braille expertise

5.5.2 Method and Insights

Tutorial. We introduced our “touching data” presenting tactile graphics and TactualPlot together to allow the reviewers to compare and contrast both approaches. From our formative design sessions, we learned that connecting and abstracting spatial information to scatterplot tasks requires understanding of the visual structure. The researcher explained the concepts of “positive and negative trends”, “scatter”, and how to perceive a trend with an understanding of

point density.

Free Exploration. After receiving confirmation that they had a basic understanding of the sound mapping and interactions, we asked our reviewers to attempt trend (t) tasks (Table 5.1). Reviewers were asked to freely explore 4 datasets with a low scatter level and both polarities.

We asked our reviewers to think-aloud so that the researcher could provide assistance when needed. They could use the equivalent tactile graphic as their “help” system, if needed. At the end of the exploration, the researcher conducted a design debrief to understand how to improve the usability of the TactualPlot technique before .

Results. Both our reviewers able to use the features of the system to locate the data points, and perceive some of the semantics of the scatterplot such as angles from the reference axes, clustering and spread along a linear line: (R1) *“Ah, yes. So once you find the one dot, you try to basically hold...You have one hand...hold the dot, and nd then go over to the Y-axis and then one down to the X-axis. Just as, as you normally would, with a protractor back, back in the day.”*. With more time spent on free exploration, R1 started abstracting the spatial and sound information towards identifying the data trend: *“It [pitch]] doesn’t seem to be going up as fast, and it [pitch] starts out lower. The sound is not as as high. At least to me, to me. So, I don’t think it seems. And because it sounds lower, I think that the that the plot is more spread out.”*.

R2 highlighted the trade offs between tactile plots and TactualPlot and believed that she prefers tactile plots because she is more attuned to “reading quickly” with multiple fingers. R2 pointed out the difficulty in understanding which finger was producing the sound when too many fingers produced the sound.

Both reviewers said that they needed more time get used to the idea of crossmodal substitution: *“So, but I think intuitively, it, it has a lot of sense. If, you know, you can just, you know, I think, get used to some, some of maybe the technical things, like I, I’m, you know, I didn’t get a computer until I was like, in my 30s. So, some of it, it may be just more like technical.”*

5.6 Discussion

Our longitudinal participatory design method allowed us to make better design decisions towards discovering the strengths and limitations of crossmodal substitutions. Secondly, our comparison to tactile graphics provided an opportunity to better understand touch-bases data exploration strategies which are crucial in helping with graphical perception in touchscreens [145].

5.6.1 Improving crossmodal sensory substitution

Below, we describe the challenges that our participants faced while using our technique and discuss solutions that can be introduced to improve touchscreen data accessibility.

Continuously touching data could be better for understanding trends, but for certain tasks where accuracy of the touch location matters, we noticed accidental touches that could add complexity to interpreting the data. Discrete actions on the other hand are slower but provide more control. Accidental touches can be a problem in sonified scatter plots, as they can lead to unintended disruptions during data exploration. Additionally, discrete interactions could be leveraged towards providing more granularity [1] by allowing the user to drill-down into the data. Introducing a grid structure [12] and other scaffolds such as rulers can help users understand the spatial relationships between data points more easily. Guiding sounds can be played to ensure that users

confidently sample all the data points necessary to complete a data task [147].

Tactile graphics can provide better parallel access to data, allowing Blind users to explore the plot more efficiently. As we observed during our assessments, careful sound design is needed to ensure that users are not overwhelmed by sound and speech. Designing pleasant and engaging soundscapes can help improve the user experience.

Voice interactions and question-answering [148] can be a useful addition to our technique; allowing users to interact with the plot using spoken commands or queries for data related tasks while relying on touch to perceive the chart structure. For large-scale data sets, it may be useful to provide aggregate functions, such as summary statistics or clustering, to help users identify patterns and trends in the data. In addition to providing more information, listening to summary statistics may also improve confidence during data exploration.

5.7 Conclusion

We have presented TactualPlot, a multitouch-actuated scatterplot display for Blind users that yields data density sonified using pitch. This crossing from one sense—touch—to another—sound—is an example of cross-modal sensory substitution, a concept that we also coin in this chapter. We describe the in-depth design process and qualitative validation that we conducted for TactualPlot. Together with our Blind collaborator, we have described the long and winding journey in designing a novel form of assistive technology for data visualization. Exploration using tactile graphics made our participants more confident in their answers when compared to TactualPlot. However, this is not surprising; paper-based tactile graphics are essentially best in class for perceiving spatial data representations, and they have an important limitation: they are

not dynamic. For comparison, we ended up spending approximately \$30 (\$1.50 per sheet) in total on the swell touch paper used in this study, and printing a single sheet was both cumbersome and inconvenient.

Once refreshable tactile displays such as the RTD are widely available, the need for software-only tools such as TactualPlot might diminish. However, that day is still in the future, and even when it comes, their cost will likely supersede existing smartphone devices. While we are confident in the state of TactualPlot, we also feel that the technique would benefit from a wider and more quantitative evaluation involving a diverse set of participants. In chapter 6, we present a study that will allowed us to (1) extend the scope of TactualPlot beyond scatter plots to include bar charts, pie charts, and line charts (2) evaluate the TactualPlot technique quantitatively with a diverse set of Blind individuals, and (3) compare TactualPlot with an RTD—the Monarch, and an audio-only screen reader system that provides hierarchical textual descriptions.

Chapter 6: Sound, Touch, or the full Monty: a comparison study of multimodal accessibility

6.1 Introduction

Information professionals who are blind or have low vision (BLV) face significant challenges in accessing and interpreting data, an essential aspect of many data-rich disciplines [54]. Screen readers have traditionally been the primary tool for navigating digital content by verbalizing text into sound to convey information [20]. However, recent advancements have introduced tactile devices such as the Monarch by HumanWare [28], which offer an alternative by providing haptic feedback (touch) to represent data. In addition, hybrid approaches, such as TactualPlot [99], combine both sound and touch to enhance data accessibility. Understanding when and how to deploy these different modalities—sound, touch, or a combination—remains a crucial yet underexplored area in ensuring equitable access to data for BLV professionals.

To address this gap, we conducted an empirical study that compares the efficacy of these modalities—sound, touch, and their combination—in real-world settings. Our study was designed in the tradition of cognitive psychology but adapted to the field, engaging blind professionals in their actual work environments. Given the sensitive nature of working with a protected population, our study involved traveling to participants' locations to conduct qualitative inter-

views and observational assessments. This approach provided a nuanced understanding of how BLV professionals interact with data using different modalities and offered insights into their cognitive processes and preferences.

Our study involved three specific tasks with varying levels of complexity: single-item data reading, two-item comparison, and multi-item distribution characterization. Participants used three distinct devices across these tasks: the Monarch tactile display, the Olli data table screen reader [1, 12], and the TactualPlot method that generates sonification of the user’s touch interaction on a capacitive touch display [99]. To ensure a comprehensive analysis, we included four types of data visualizations: scatterplots, line graphs, bar charts, and pie charts. Incidentally, this required enriching the TactualPlot technique to support these additional chart types beyond scatterplots.

This work makes several key contributions: (1) empirical findings from our user study, which highlight the strengths and limitations of each modality across different tasks; (2) qualitative insights from blind participants, offering valuable perspectives on the use of sound versus touch in data interpretation; (3) enhancements to the TactualPlot technique, extending its capabilities to support a broader range of data visualizations; and (4) findings from a co-design session with a blind participant to understand the challenges of visual analytics tasks when using novel refreshable tactile displays.

6.2 Design Space: Multimodal Assistive Technologies for Representing Data

Multimodal assistive technologies are emerging as powerful tools for representing complex information. By leveraging multiple sensory channels, these approaches aim to create more

inclusive and effective data experiences. This section explores the design space of multimodal assistive technologies, with a focus on their application in representing data for people who are blind or have low vision (BLV).

6.2.1 Definition: Multimodal Data Access

Multimodal data access refers to the use of two or more sensory *modes* (or sensory channels) to represent and interact with data. In this context, modalities are different types of sensory input or output that can be used to convey information. The key principle of multimodal data access is that these modes should support and complement each other, providing a richer and more accessible experience for users. An example of multimodal access is the use of touch for spatial interaction with information presented in the form of audio—this principle is used in systems such as TactualPlot [99] and ChartA11y [100]

The combination of multiple modalities allows for:

1. **Redundancy:** presenting the same information through different channels;
2. **Complementarity:** using different modalities to present different aspects of the data; and
3. **Enhanced understanding:** leveraging the strengths of each modality to improve overall comprehension.

While various sensory modalities can be employed in data representation, we focus primarily on those most relevant to individuals who are blind or have low vision (BLV). For BLV individuals, the main modalities that can be utilized include

- **Sound (Auditory):** Utilizing audio cues and speech to represent data. – *examples:* sonification, text-to-speech (TTS), earcons (audio icons).
- **Touch (Haptic/Tactile):** Using physical sensations to convey information. – *Examples:* Braille, tactile graphics, vibration patterns.
- **Vision (for individuals with low vision):** Enhancing visual elements for easier perception – *Examples:* High-contrast displays, magnification, color-coding

While less common, other sensory modalities can also be explored for data representation:

- **Smell (Olfactory):** Using scents to convey information or enhance other modalities. – *Potential applications:* Associating scents with data categories or intensity levels [41, 101].
- **Taste (Gustatory):** Employing taste sensations to represent data. – *Potential applications:* Using different flavors or intensities to represent data points.

We primarily explore the combination of touch and sound as complementary modalities for data access. Combining modalities allows designers and programmers to convey more data and information to translate a visual chart into a more accessible representation. Novel multi-line refreshable braille displays such as the Monarch [28] and the Graphiti [149] provide access to pin-based haptic feedback while also having hardware features capable of providing audio and verbal feedback. Such tactile displays offer a unique design challenge for data visualization accessibility: visualization designers can make their charts accessible using touch, while also utilizing the audio and speech rendering capabilities of these devices. However, these RTDs are very expensive, and cheaper touchscreen displays such as the iPad, Android tablets, and smartphones can also be used to provide audio output, and parallel access to chart elements

through *direct touch interactions*. Rich screen reader chart descriptions are also used as an *audio only* way of interacting with charts that are otherwise inaccessible to the visual sense for blind individuals. Our goal was to perform a qualitative and task-based *comparison of audio only, touch only, and a combination of audio and touch accessibility systems*, to isolate and better understand the benefits and challenges of a particular sensory modality. We derived insights that can help future visualization designers adapt their visualization to a combination of sensory modalities.

Table 6.1: **Comparison of Different Chart Characteristics and Interaction Modes**

	Standard Charts	Olli	TactualPlot	Monarch
Chart Characteristics	Vision	Audio	Audio	Touch
Data Characteristics	Vision	Audio	Audio	Touch
Chart Interaction	Vision	Keyboard	Touch	Touch

We designed pie charts, bar charts, line charts and scatterplots using Vega-lite [150] for our study and adapted them to work with *Olli* and the *Monarch* display. We implemented D3.js charts and extended the design space for *TactualPlot* to work with the aforementioned chart types used in our comparative study. The *Olli* system generates a hierarchical set of textual data descriptions that users can navigate through a standard keyboard and *listen* to using their screen reader. *TactualPlot* is a multimodal system in which users can directly *touch* chart elements such as data encodings (visual elements such as shapes, labels, titles, and axes) and *listen* to the relevant sonification and verbalization. And finally, the *Monarch* is a system in which users rely solely on their sense of *touch* to both interact and feel the chart elements. Our choices allowed us to isolate and map design challenges for systems that use single sensory modalities (*touch, sound*) and multimodal interaction (*sound plus touch*). In the next three sections, we describe the interaction techniques used by our participants to complete visualization tasks on each device.

6.2.2 TactualPlot: A Crossmodal Data Access Technique

TactualPlot is an innovative crossmodal technique that combines touch input with auditory output to represent visual data [99]. The core concept of TactualPlot is as follows:

1. **Input:** Users explore a spatial representation on a touchscreen using their fingers;
2. **Processing:** The system tracks the user’s touch input and correlates it with the underlying data that has been spatially laid out on the screen; and
3. **Output:** Data touched by the user’s fingertips is sonified in real-time, providing auditory feedback based on the user’s exploration.

This technique allows BLV users to “feel” the structure of a visual representation while simultaneously hearing the data values through sound. The original TactualPlot focused on scatterplots, enabling users to explore data points in a two-dimensional space.

6.2.2.1 Design Principles for TactualPlot

TactualPlot was originally designed to work with scatterplots. We retained the original design principles, and added our own design goals to ensure that our study participants can easily learn and use the sonification-based system. To that end, we employ the following design principles:

- **Sampling area size:** Provide users the sensation of “touching” chart elements by fixing the sampling area to a circular lens that is roughly the size of the user’s fingertip.

- **Employ audio representation:** Integrate auditory feedback to the elements of the chart, ensuring that the underlying data or structure is discernible through sound and the spatial layout being discernible through tactile feedback.
- **Minimize target hunting:** Reduce cognitive and physical effort in locating and interacting with small or sparse elements. Avoid leaving large empty regions that force users to search extensively for interactive features.
- **Leverage the entire display:** Utilize the full available screen space to provide a consistent reference frame. By allowing interaction across the entire display, users can better orient themselves and understand spatial relationships.
- **Allow interaction with single or multiple data series:** Present data in manageable segments that allow users to focus on one series at a time or allow comparison among multiple data series. Restricting the display to a single series minimizes complexity and fosters clarity, making interpretation simpler. However, comparison between multiple data series, for example, in a line chart, enables users to perform higher-level data comparison tasks.
- **Use differentiable and pleasant audio scales:** TactualPlot represents the density of data within the sampling area using pitch: higher densities produce higher pitches. To align with the continuous drag interaction, the system continuously modulates a pleasant tone [99] in real time as the user's finger moves. Through piloting, we created 5 distinctly yet pleasant instrument scales where the pitch can be modulated to sonify quantitative values. For multiple data classes, TactualPlot employs polyphonic sound (e.g., different instrument voices) so each class is heard simultaneously without breaking the continuous audio stream.

- **Highlight empty space and chart element boundaries:** Clearly indicate the absence of data in the sampling area and trigger sounds or vibrations when chart boundaries or chart elements are touched. This allows users to better understand the spatial or “visual” position of the chart elements such as lines, points, bars, and slices. Using sounds to signify chart boundaries and axis tick marks provides better positional awareness to users with respect to the entire chart view—zoomed or otherwise.
- **Enable On-demand labels:** Allow users to retrieve labels or descriptions through simple, direct interactions such as tapping. This approach facilitates focused exploration and reduces audio clutter when labels are not needed immediately.

6.2.2.2 Sound design and mapping

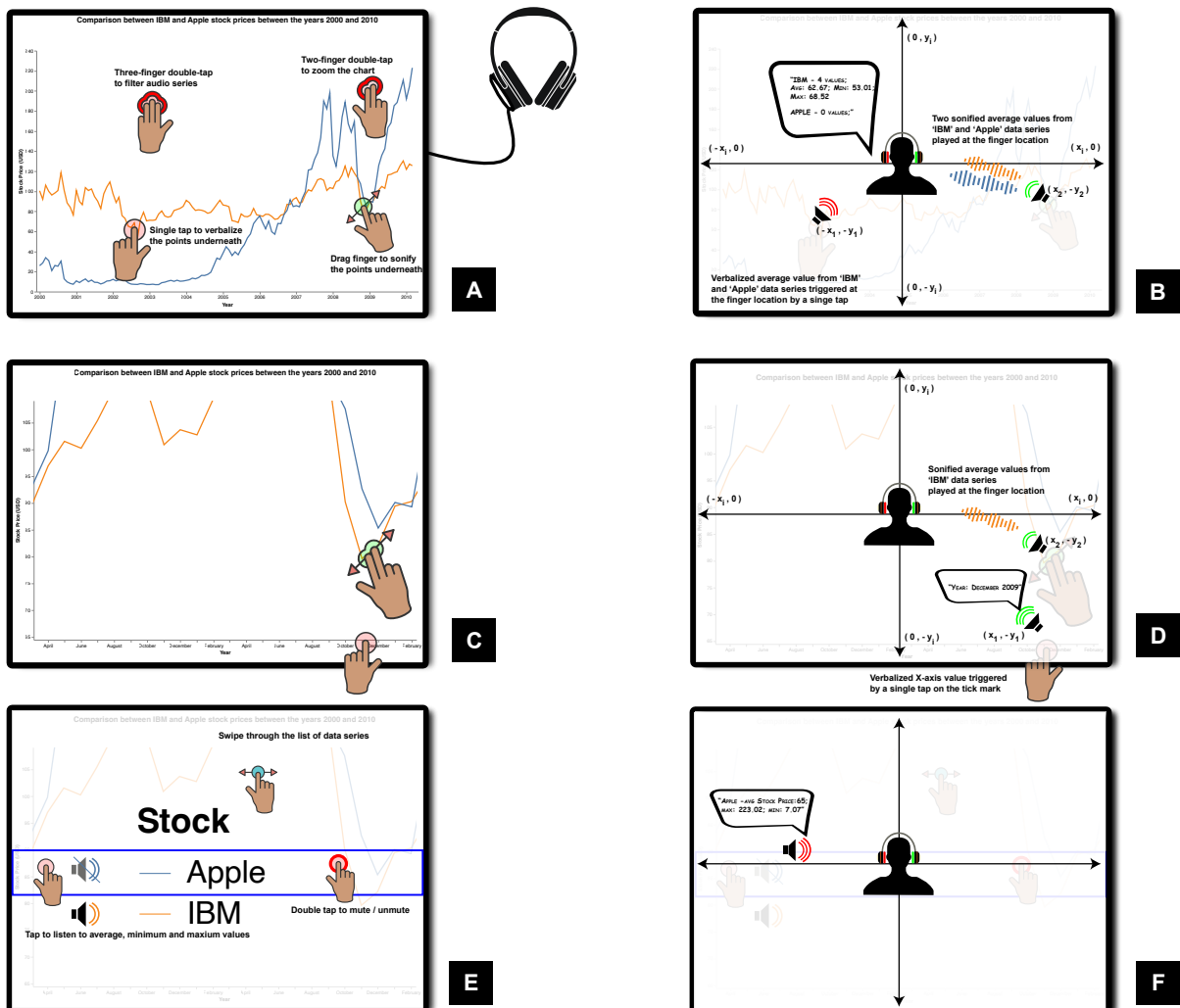


Figure 6.1: **TactualPlot interactions.** An overview of the TactualPlot system’s interactive techniques for line charts. Panels (A–F) illustrate key gestures such as dragging to continuously sonify data, tapping to trigger verbalization of data values, and multi-finger actions for filtering and zooming. These interactions enable blind users to explore and interpret visual data through a combination of touch and auditory feedback.

For TactualPlot, we use a discrete audio space based on MIDI notes that starts from MIDI note 21 (which is **A0** in the musical scale) and goes up to a maximum of 120 (which is **C9** in the musical scale). This ensures exactly 100 distinct audible steps, spanning A0 to C9. We choose

a discrete audio space because we do not encode sound directly from the data domain to the sound domain. Instead, the values from the visual scales or the axis scales to our discrete sound domain. Users can compare the pitches between two different notes to distinguish them while dragging their fingers across the display. While dragging, the users touch the chart elements, and the corresponding tone is played, and is sustained for 1.5 seconds before being muted. If the user comes into contact with another sonified element before the 3 seconds are completed, a new audio note corresponding to the new value is played. Encountering empty space produces a muffled noise to indicate the absence of sonified chart elements under their finger. Users are not required to identify the musical notes to complete visualization tasks. To retrieve the absolute data value, they can tap on an element to have the system verbalize it. Using a combination of panning and tapping, users can make sense of the underlying chart. For all chart types, we use the same audio scale. However, the mapping between the visual elements and the audio notes changes based on chart type. For every relevant item (e.g., tick marks, bar segment, pie slice, point density, point on a line) in the chart domain, we apply a linear interpolation function to find the corresponding MIDI value. Given a value x from 0 to some positive maximum x_{\max} , we wish to map every data value $x \in [0, x_{\max}]$ to one of the 100 integer MIDI notes $\{21, 22, \dots, 120\}$. The mapping is defined by:

$$\text{noteIndex}(x) = \left\lfloor \frac{x}{x_{\max}} \times 99 \right\rfloor, \quad \text{MIDI}(x) = 21 + \text{noteIndex}(x).$$

Here, $\lfloor \cdot \rfloor$ denotes the floor function. For any $x \leq 0$, no note is played (treated as **silence**). When $x > 0$, the function linearly interpolates x to a discrete note index in $[0, 99]$, then shifts it by 21 to cover the MIDI note range from 21 (for very small x) to 120 (for $x = x_{\max}$). Once a user touches

a chart element, the corresponding $MIDI(x)$ value is sonified.

For different classes of sounds, we change tone parameters in ToneJS,¹ a JavaScript toolkit based on the Web Audio W3C API.²; rendering a MIDI note’s pitch value as an audibly different tone. This allows us to sonify a quantitative value from different data series as categorically different sound notes. This allows us to create “*audio instruments*” that can be assigned to different data series, and thereby adapt charts that have nominal variables encoded using color or shape.

While we utilized multi-finger touch interactions across the system, we restricted our audio-sampling lenses to two fingers. In other words, users can continuously touch and drag two fingers around the display to trigger the non-speech sounds that are mapped to the data values and chart elements. Two-finger sampling still enables our users to hear sound from two different regions of the chart and make comparisons. We believe that such comparisons allow users to better trace chart elements in a step-by-step manner—i.e., users can use a combination of tapping for verbalizing and dragging to find their way around a chart.

We adopt the axis and title sonification schemes from TactualPlot [99] in our implementation. For charts that have multiple categories such as line charts, scatter plots, and stacked bar charts, users can filter the audio stream for each category by using the audio legend panel. Users can perform a *three finger double tap* to open and close the *audio legend panel*. In this panel, users can swipe through a list of audio streams and choose to mute a particular category by *double tapping* a category. For example, while exploring a line chart with 3 data series, a pairwise comparison is possible by only selecting two of the three data series. As users drag their fingers

¹<https://tonejs.github.io/>

²<https://www.w3.org/TR/webaudio/>

across the screen, we provide stereo panning of the audio stream to convey the horizontal and vertical touch positions of each sampling lens—also the same as the touch location of the user’s finger(s). This is made possible using the *Panner3D* node of ToneJS. We initialize the Z-axis as 0 to restrict audio to a two-dimensional space.

6.2.2.3 Adapting TactualPlot for different charts

Here, we discuss our specific interactive sonification approach for the four chart types used in our study:

Pie charts: a circular statistical chart that is used to convey numerical proportions (e.g., the market share of different smartphone manufacturers) by dividing a circle into *segments or slices* - each slice representing a single data point.

- *Spatial layout:* The visual space is split into circle segments or “slices”, one per data point, originating from the center of the space. Each circle segment has an arc proportional to its data point value in relation to the other data values. The order of the circle segments follow the order of data points in the dataset.
- *Chart interaction and sonification:* The proportion of the currently selected data item—normalized against the full 100% of the entire pie chart—is sonified as pitch. The TactualPlot pie chart does not have an outer perimeter; it fills the entire available visual display space. This eliminates the need for the user to “hit” the circular shape; they can instead drag their fingers along the perimeter of the touchscreen. The proportion of the currently selected data item—normalized against the full 100% of the entire pie chart—is sonified

as pitch. Tapping on a circle segmented representing a data item will verbalize the textual label for the item. Dragging a finger across a pie slice boundary triggers a drum beat to indicate crossing between slices.

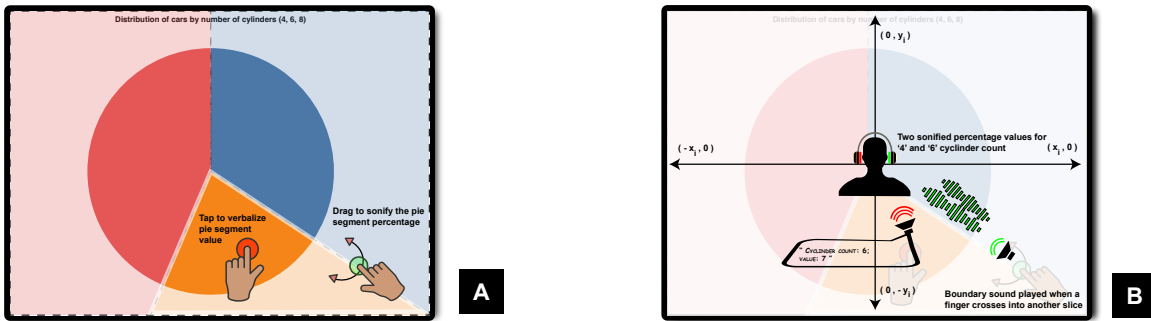


Figure 6.2: **TactualPlot—Pie Charts.** Users can drag their finger along pie segments to sonify proportional values and tapping actions that verbalize labels, with auditory cues (earcons) signaling transitions between slices for improved spatial awareness.

Bar and stacked bar charts: a statistical graphic using rectangular bars of varying lengths to show comparisons among categories.

- *Spatial layout:* The visual space is split into bar segments, one per data point, originating from horizontal axis. The height of each bar corresponds to the quantitative values of the data points. In the case of a stacked bar chart, the bar segments of each data series are stacked on top of one another for each data point in the dataset. The order of the bar segments follow the order of data points in the dataset. Users can continuously drag up to two fingers to sonify or verbalize the bars and the axes.
- *Chart interaction and sonification:* The proportion of the currently selected bar—normalized against the full 100% of the entire bar height—is sonified as pitch. Therefore, a percentage value for each bar segment is calculated with the total height possible being equal to the

maximum value shown on a given axis. This percentage value is then mapped to a MIDI note to indicate size of a bar segment as an audio note. Normalizing the value allows bar charts with different scales to sound similar. For example, two bar charts with a y-axis range—[0, 7.5] and range—[0, 80] can be mapped to notes that sound similar. Tapping on a bar segment verbalizes the corresponding value of the bar in the data domain. For a stacked bar chart, users can similarly drag their fingers across the chart to touch a bar segment of a particular category. On being touched, the MIDI note corresponding to the audio instrument mapped to that particular category of the bar segment is played.

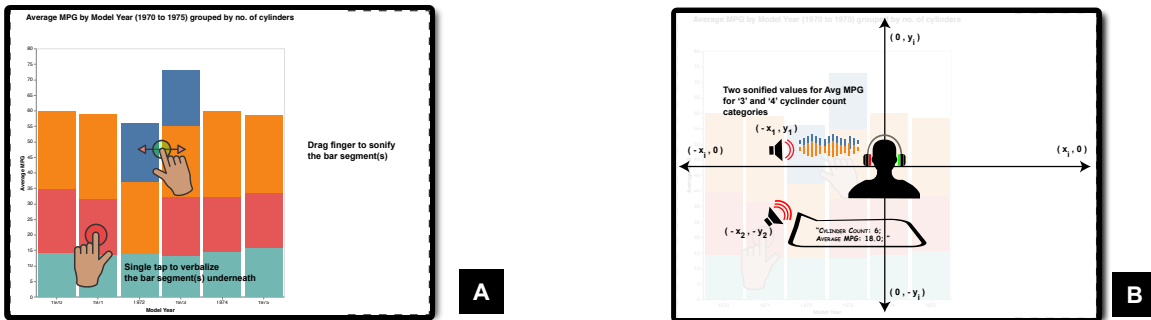


Figure 6.3: **TactualPlot—Bar Charts.** Users can drag across bar segments to receive sonified representations of quantitative values—where pitch maps to bar height; and tap to obtain precise numerical feedback.

Single and multi-series line charts: a statistical graphic that displays continuous information as a series of points connected by lines (such as the Google stock market value over time).

- *Spatial layout:* A data point's x and y values are plotted against the x -axis (*horizontal*) and y -axis (*vertical*) respectively. For example, a line chart showing monthly Apple stock price values between the years 2000 and 2010. Users can place their fingers on the chart, and listen to the sonified vertical (y) values of points under their finger. First, we count the number of points within the sampling area, and then calculate an average value. This

aggregated value serves as an indicator of the average vertical position (y-value) of the data in that region of the chart. For a multi-line chart, one average per data series is calculated when a sampling area contains points from multiple data series.

- *Chart interaction and sonification:* On touching a line segment, the average y-value of the points under a sampling lens—normalized against the full 100% of y-axis—is sonified as pitch. This average value is then mapped to a MIDI note to indicate height of the line segment as an audio note. If more than one line segment is under the sampling area, the average value from each series that is touched is sonified using the *audio instrument* corresponding to each data series. Every note is played in unison, and the tone of the note allows users to differentiate between the data series. Tapping on a line segment verbalizes: 1) the number of values in the sampling area, and 2) the *extrema*—maximum value and minimum value. For a multi-line chart, the verbalization is repeated for every point on the line segment from each data series.
- *Zooming:* a zoomed view of a particular sampling area can be rendered by choosing an area of interest using one finger, and then performing a *two-finger double tap* with the other hand. This modifies the chart view by changing the extents of the x-axis and the y-axis to the data ranges from the area of interest. In the refreshed view, we also include one step on either side of the sampling area's data range. The zoomed view follows the same sonification structure as the non-zoomed view. This is done to ensure that leave a trail of data from the original non-zoomed view. If the display is untouched for 30 seconds, we reset the zoom level. Users can verbalize the current zoom level in the chart by performing a two-finger tap anywhere on the display. For our study, only one level of zoom is enabled

for the sake of simplicity, and visualization tasks can be accurately completed with one additional level of zoom.

Single and multi-class scatterplots: a type of statistical graphic that displays data as a collection of points. Each point's position on the x-axis and y-axis indicates values for two quantitative variables. Multi-series scatterplots use different colors or symbols to distinguish among multiple categories or data series.

- *Spatial layout:* A data point's x and y values are plotted against the x -axis (*horizontal*) and y -axis (*vertical*) respectively. For example, a scatter plot that compares petal lengths (quantitative) and petal widths (quantitative) of iris flowers across 3 different flower species (nominal). Users can place their fingers on the chart, and listen to the sonified density of points under their finger. We count the number of points that are within the circular sampling areas under the users' finger(s). For a multi-class scatterplots, the count of values for each class of points that are within the sampling area is calculated.
- *Chart interaction and sonification:* On touching a chart region, the total count of the points under the sampling lens (finger) is sonified as pitch by mapping the point density to the corresponding MIDI note. The (x, y) positions of the points are also mapped to 2D positions in the auditory space using the spatial audio rendering capability of Tone.JS—as users move horizontally and vertically, the sound location changes with every move of the finger. If more than one class of points lie under the sampling area, point density from each data series or class is sonified using the *audio instrument* corresponding to the data series. Every note is played in unison, and the tone of the note allows users to differentiate between the data series. Tapping on a region verbalizes: 1) the number of points in the

sampling area, and the *extrema*—maximum value and minimum value. For a multi-class scatterplot, the verbalization is repeated for each data series.

- *Zooming*: the zoom technique is similar to that of line charts. In the refreshed view for scatterplots, we only include the sampling area's data range.

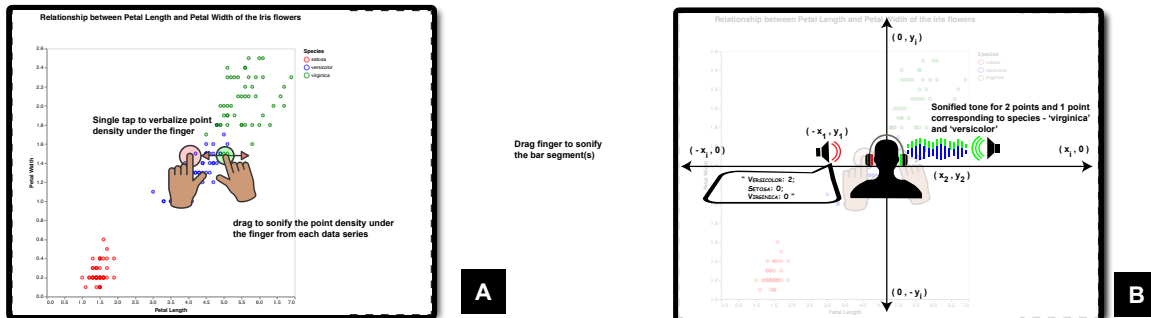


Figure 6.4: **TactualPlot—Scatterplots.** Continuous finger dragging triggers real-time auditory feedback based on point density and distribution, while tapping provides verbal summaries of the data within a given region, facilitating multi-series comparisons.

6.2.3 Olli: screen reader accessibility solution that uses audio only

Olli is an open-source framework that makes data visualizations accessible to blind and low-vision (BLV) users through structured text descriptions and interactive navigation [12]. Olli parses common chart specifications (e.g., from libraries such as D3, Chart.js, or Vega-lite) for metadata underlying a visualization. This includes details such as chart type, scales, axes, and individual data points. Having gained access to the semantically rich representation of the visualization, Olli generates textual descriptions that communicate both high-level insights (e.g., overall trends or comparisons) and low-level details (e.g., exact data values) in a textual format. This text is then rendered as a hierarchical tree of textual descriptions or text nodes which are nested at 4 or 5 different levels. While Olli primarily focuses on generating textual descriptions

of static charts, it also supports interactions akin to “drilling down” for more information or comparing multiple views.

The steps for generating accessible output in Olli are:

1. **Specification Parsing:** Olli takes a chart specification (e.g., a JSON file describing a bar chart) and reads information about the data fields, encoding channels, and visual mappings.
2. **Semantic Extraction:** Next, Olli interprets the chart’s structure (axes, labels, legends) and extracts the main data elements (bars, lines, points) along with their relationships (e.g., groupings, stacks, or comparisons).
3. **Text Generation:** The system uses pre-defined templates or rules to transform these extracted elements into meaningful text. This can include brief summaries (e.g., “This bar chart compares quarterly revenues for 4 products”) and specific details (e.g., “The tallest bar represents Product C with \$3.2 million in revenue”).
4. **Interactive Exploration:** Through screen readers, keyboard navigation, or other assistive interfaces, users can navigate the described chart. They can query specific segments, drill down into the data, or request summaries, allowing for dynamic data exploration without relying on sight.

6.2.3.1 Encodings

The hierarchical structure of the system is driven by the underlying encodings of the visualization. Because of this direct mapping, each hierarchy follows the visual format of the original chart or graph.

- **Top-Level Summary (L1):** This root node notifies the user that a hierarchical representation is available and provides a concise overview of the visualization (e.g., the chart type and data domain). If the visualization contains multiple chart facets (multi-series line charts), each facet (line) is nested as a separate node in the level below the summary level.
- **Encodings (L2):** The next level contains individual nodes for each axis or legend from the original visualization.
- **Intervals or Categories (L3):** Each axis or legend node expands into child nodes that represent discrete intervals (e.g., ranges along a numeric axis) or categories (e.g., distinct labels in a legend).
- **Data points (L4):** The last level of detail is a table listing all individual data points in the selected interval or category.

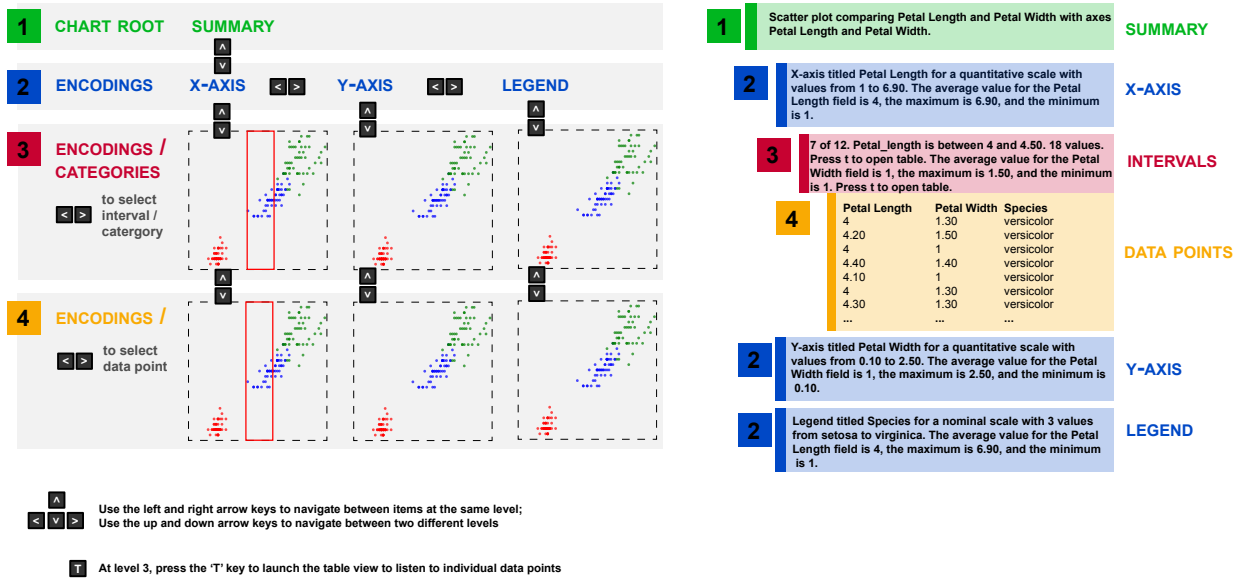


Figure 6.5: **Olli interactions.** This figure has been adapted from Zong et al. [1] A chart is broken down into levels—from an overall summary to axis encodings, categorical intervals, and individual data points; enabling structured, audio-guided exploration.

6.2.3.2 Interaction

Users explore and refine their understanding of the data hierarchy through a set of keyboard controls, making the system navigable for blind or low-vision (BLV) users. The text is then read aloud by the native screen reader. By pressing the **arrow keys**, they can move between levels and sibling nodes:

- **Down Arrow:** Moves down one level in the hierarchy, revealing a finer granularity of information (e.g., from the X-axis node to specific intervals along that axis).
- **Up Arrow:** Moves up one level, returning to a higher-level view of the data.
- **Left/Right Arrows:** Switch between sibling nodes at the same level of detail (e.g., moving

from one interval or category to the next).

- **Table View - T:** the final level or the data table for an interval along an axis or category in a legend can be opened by pressing the “**T**” key when the focus is on an interval level node (L3).

For instance, imagine a scatterplot comparing penguin body mass (Y-axis) against flipper length (X-axis). Starting at the top-level summary, the user learns that they are examining data about penguins. Pressing the Down Arrow moves into the axis-level nodes, landing first on the X-axis (flipper length). A second press goes deeper, revealing intervals of flipper length divided into 10-millimeter ranges (e.g., 170–180 mm, 180–190 mm, etc.). The user can then press Right to scan through these ranges. If they discover an interval with an interesting distribution (e.g., a large number of points), they can press Down again to open a table listing each data point, including details such as species or precise measurements. This step-by-step approach—moving from broad summaries to precise details—echoes the “overview first, details on demand” model. It leverages both hierarchical encoding (for structured exploration) and straightforward keyboard interactions (for intuitive navigation), ensuring that users can efficiently understand and analyze the data without relying on traditional visual cues.

6.2.3.3 Adapting Olli for different charts

The Olli library supports the generation of multi-level textual descriptions for various chart types, including stacked bar charts, multi-series line charts and scatterplots. We created charts using Vega-Lite and provided the chart specifications to Olli.

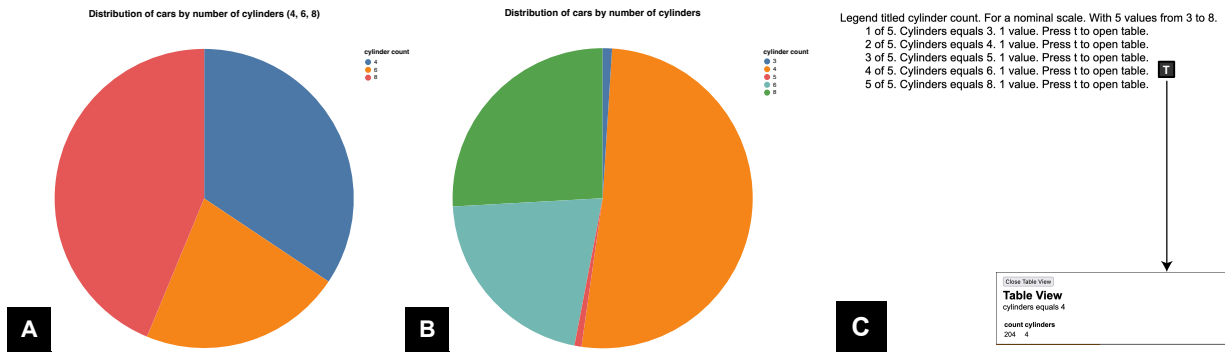


Figure 6.6: **Olli—Pie Charts.** Panels (A–C) show the progression from a top-level summary to detailed descriptions of individual pie slices, supporting an screen reader exploration of categorical proportions.

For *pie charts*, olli generates a high-level summary (level-1), and items for each slice of the pie segment (see Figure 6.6.).

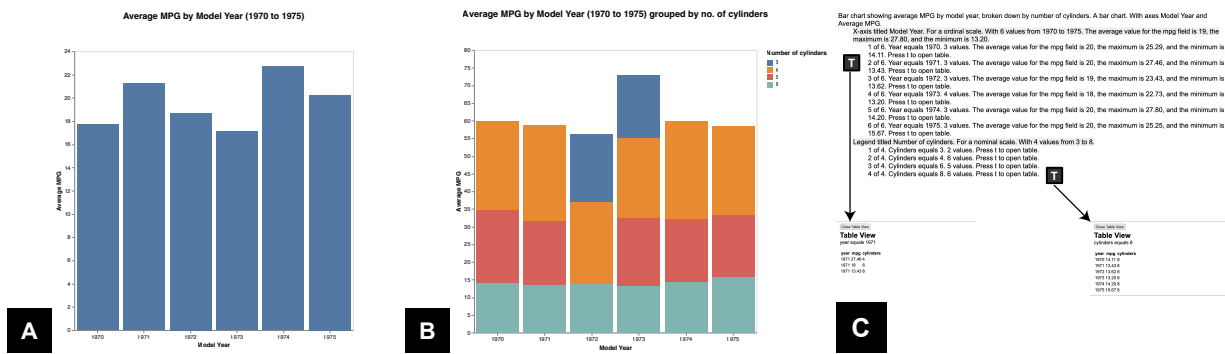


Figure 6.7: **Olli—Bar charts.** Panels (A–C) illustrate a hierarchical approach—from chart summary to axis intervals and detailed data points—facilitating navigation through both simple and stacked bar charts using auditory feedback.

For *bar charts*, olli generates a high-level summary—level-1, and items for the X-axis—level-2, followed by items for X-axis intervals—level-3, and users can use the table view by pressing the ‘T’ key while on an interval item to access individual data points—level-4. For stacked bar charts, there is also a legend item at level-2 (see Figure 6.7.).

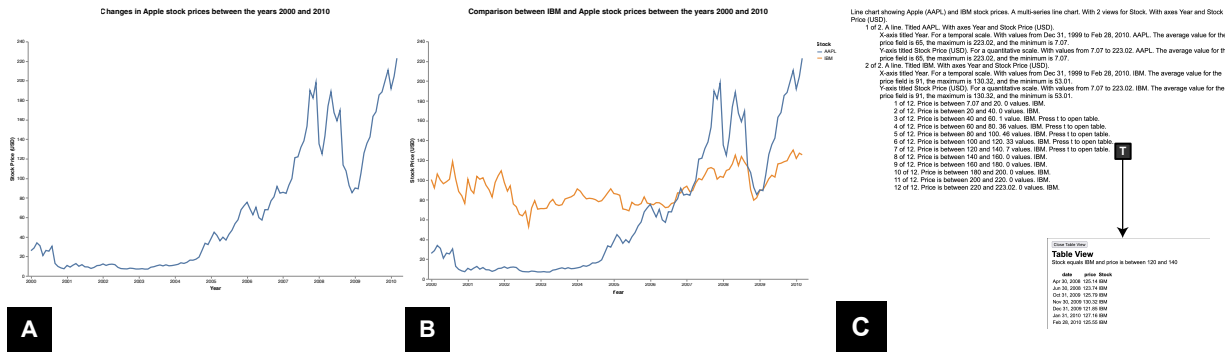


Figure 6.8: **Olli—line charts.** Panels (A–C) detail the breakdown from a high-level summary to specific X and Y-axis intervals, allowing users to drill down into trends and compare multiple data series.

For line charts, olli generates a high-level summary—level-1, and items for each line or data-series—level-2, followed by items for X-axis and Y-axis intervals—level-3. At level-4 are items for intervals for the axes nested under level-3. And users can use the table view by pressing the ‘T’ key while on an interval item to access individual data points—level-5 (see Figure 6.8).

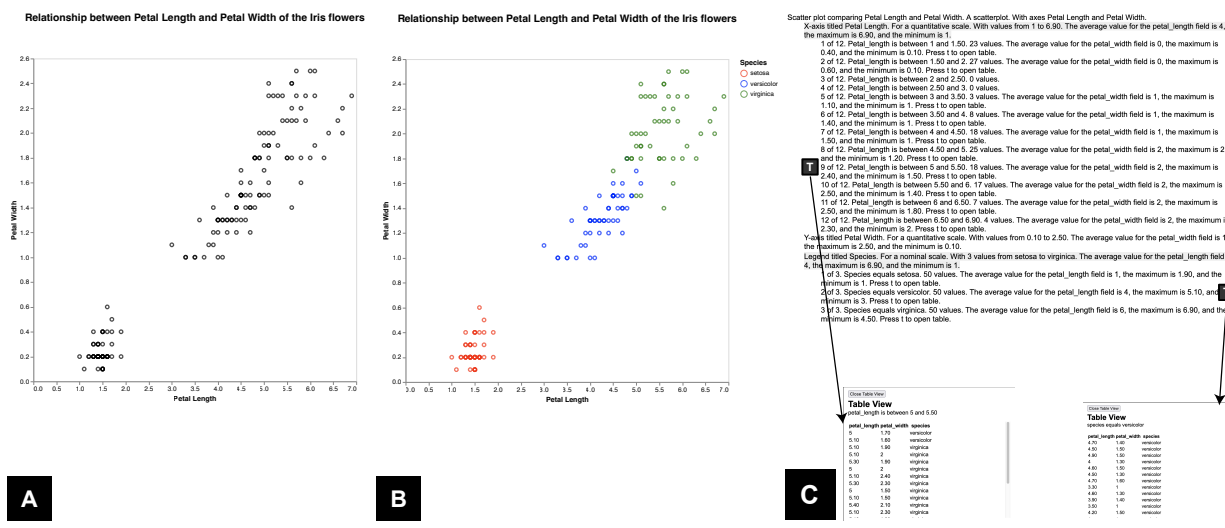


Figure 6.9: **Olli—Scatterplots.** Panels (A–C) guide the user from an overall chart summary to detailed intervals that capture the distribution and density of data points across different categories.

For scatterplots, olli generates a high-level summary—level-1, and by items for X-axis and Y-axis intervals—level-2. At level-3 are items for intervals for the axes nested under level-2. And

users can use the table view by pressing the ‘T’ key while on an interval item to access individual data points—level-4 (see Figure 6.8.). For a scatter plot with multiple categories, a legend item is added at level 2. Nested under the legend are items for each category of the nominal variable being visualized.

6.2.4 Monarch: multi-line refreshable braille display that uses touch only

Monarch is a RTD designed to provide tactile access to both text and graphics for blind or low-vision users. Figure 6.10 shows an annotated schematic of the device.

6.2.4.1 Device layout and interaction

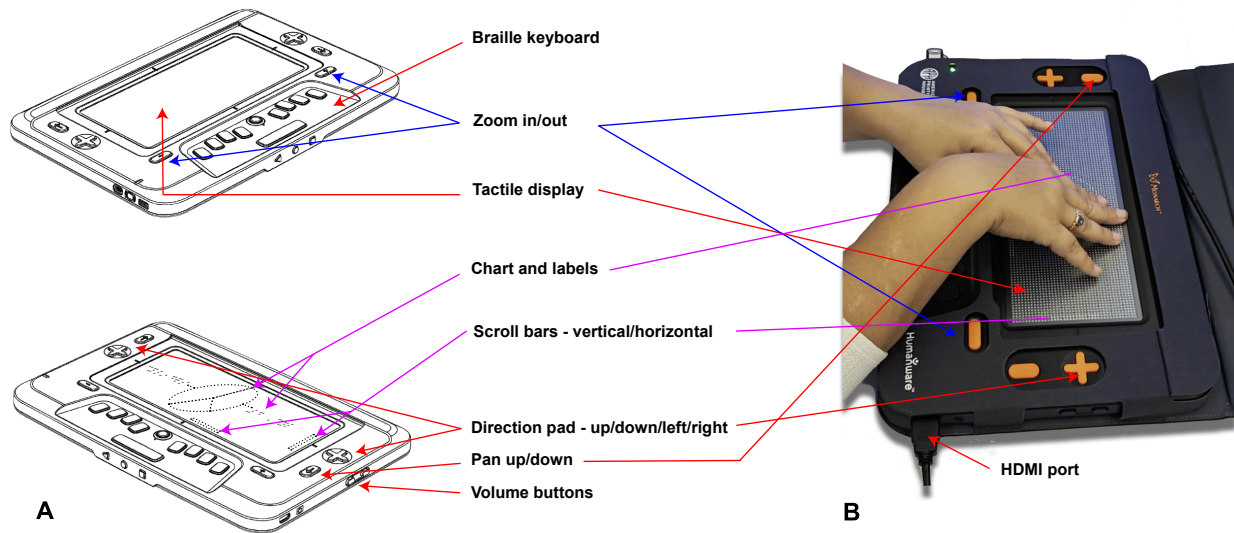


Figure 6.10: **Monarch Interactions.** Panels (A–B) highlight key features such as the Braille keyboard, tactile display, and navigation buttons that enable blind users to access both static text and graphical content through touch.

When placed on a flat surface, the Monarch tablet is oriented such that the *Braille keyboard* is closest to the user (front edge). On the left edge, from front to back, users will find a USB-A port, the square-shaped Power button, and a USB-C port (for charging or data transfer). On the

right edge, the device provides an HDMI port, a 3.5 mm audio jack, and volume keys. The *tactile display* occupies the central region, with 10 lines of 32 Braille characters each. Monarch’s tactile display is made up of an array of pins forming multiple lines (up to 10 lines; 32 Braille cells per line), enabling dynamic refresh of Braille text or tactile graphics. The pin dimensions are 96 x 40 (W X H). Each cell is composed of 8 pins (dots 1–6, plus dots 7–8). A dedicated orange *Refresh button* near the Braille keys can refresh the pin array in a case of pin actuation errors. The device supports *zoom in/out* buttons that adjust the spacing and number of Braille lines displayed. This zooming allowed our participants to zoom into the chart, if needed, while performing the tasks. Two *D-Pads* (directional pads—one on each side of the tactile display) for panning the view after zooming in. There are *Pan Up* and *Pan Down* physical buttons for panning large documents or multi-page text content. Along the front edge, users have a conventional 6-dot Braille input layout plus dot 7 (Backspace), dot 8 (Enter), and a Space bar.

6.2.4.2 Designing charts for Monarch

The Monarch device runs the Android operating system, and comes pre-installed with apps to view documents, a mobile browser, and access to tactile graphics through an app called *Tactile Viewer*. We designed charts to work with the Tactile Viewer application as the mobile browser was only able to render text from websites, and not images or SVG charts. Tactile viewer uses a *thresholding* approach to segment an image into the foreground and background. We created charts using the Vega-Lite library and exported the charts as PDFs to be rendered on the Monarch device. Tactile Viewer applies the thresholding technique and then scales the image to be viewable on the tactile display. Through piloting, we identified a web-chart resolution that would

be appropriately rendered on the pin display. The application did not support a focus zoom, where users could point to a section of the chart to zoom into. However, users can zoom into the current view and use the d-pad to pan the zoomed view. This meant that users would lose the reference axes while viewing a region far away from the x-axis and y-axis. With these constraints in mind, we designed simple grayscale charts with minimum clutter. Although the device supports interactions through buttons and the tactile display, the charts we designed were “static visualizations”.

Every chart included a title, x and y-axis (when applicable), axes labels, tick marks, and tick mark labels. While creating the charts, we converted labels and titles to ASCII Braille characters using a simple character mapping function. We adjusted the font size to ensure that the braille text is readable after zooming in. For charts that had multiple data series being visualized, we also included a legend with a title, and labels for each category. Overall, we only used borders for the chart elements, and did not fill the elements such as bars, pie slices, and scatter plot symbols. We piloted the designs within the research team (one author is blind), and decided to use the space within to include annotations or other labels. For visual charts, annotations and labels are laid out at various angles (for example, a y-axis label could be printed vertically). However, considering the nature of braille, we had to ensure that labels were horizontally rendered (see Figure 6.10). To estimate the sizes and data values of the chart elements, users would have to use the tick mark labels on the axes.

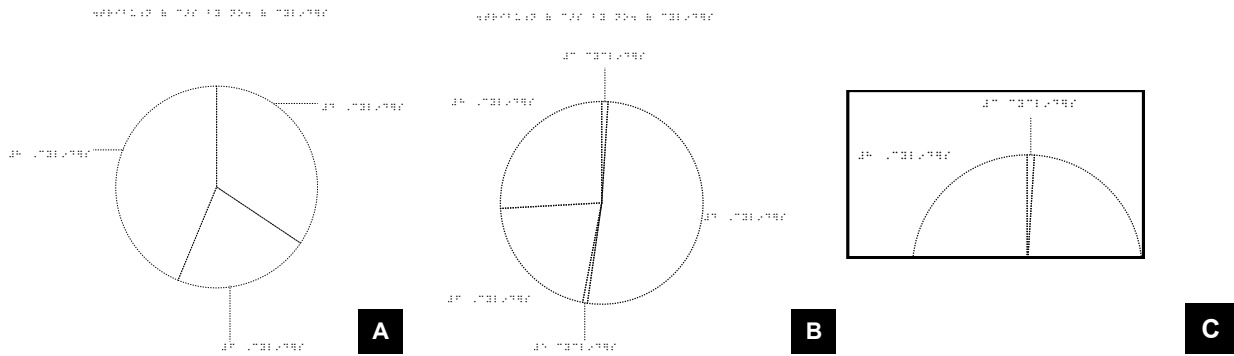


Figure 6.11: **Monarch—Pie Charts.** Panels (A-C) show a pie chart adapted for the Monarch device, where each segment is annotated with an external Braille label connected by a guiding line.

For *pie charts*, we included labels for each pie segment outside the pie. When pie segments were smaller, we included a line to connect the label to the pie segment (see Figure 6.11).

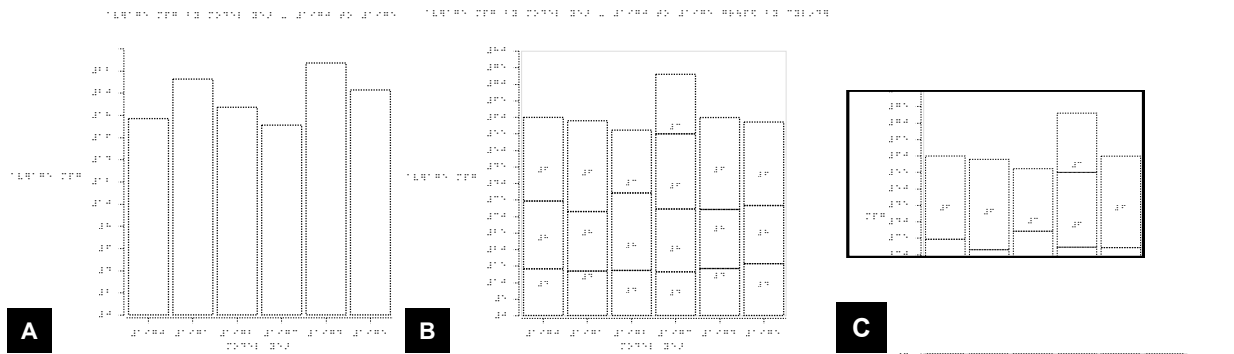


Figure 6.12: **Monarch—Bar Charts.** Panels (A-C) show a simple and stacked bar chart. The tick marks and in-cell labels allow users to identify quantitative differences and categorical groupings through tactile exploration.

For *bar charts*, each bar segment was assigned a tick mark and labeled. In the case of stacked bar charts (see Figure 6.12.B), the category of a bar segment is included as a label inside every bar segment corresponding to that particular data series.

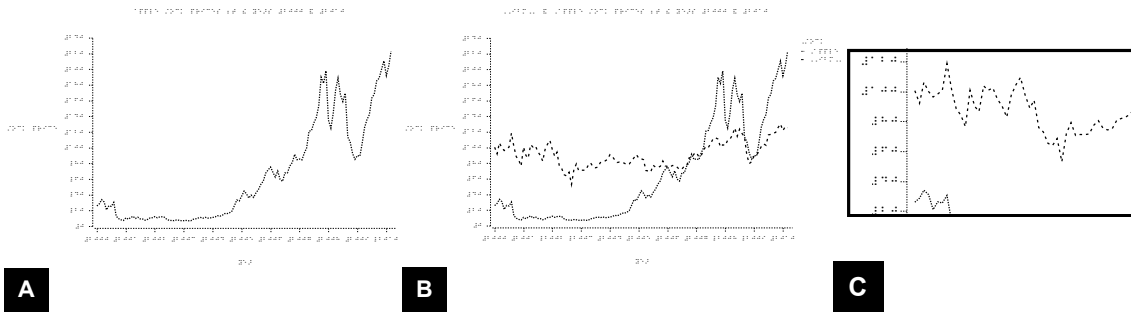


Figure 6.13: **Monarch—Line Charts.** Panels (A–C) show a single and multi-series line charts created for the Monarch. Panel B shows that for multi-series line charts the design embeds different line types (dashed vs. dots) for each data series.

For *line charts*, we used different line stroke patterns to encode the categorical values. We ensured that each pattern was perceptually differentiable to the sense of touch through internal piloting. In the case of multi-series line charts (see Figure 6.13.B), the category of a series is included as a label inside every bar segment corresponding to that particular data series. We chose not to annotate the points on the line because of clutter; especially in multi-series line charts.

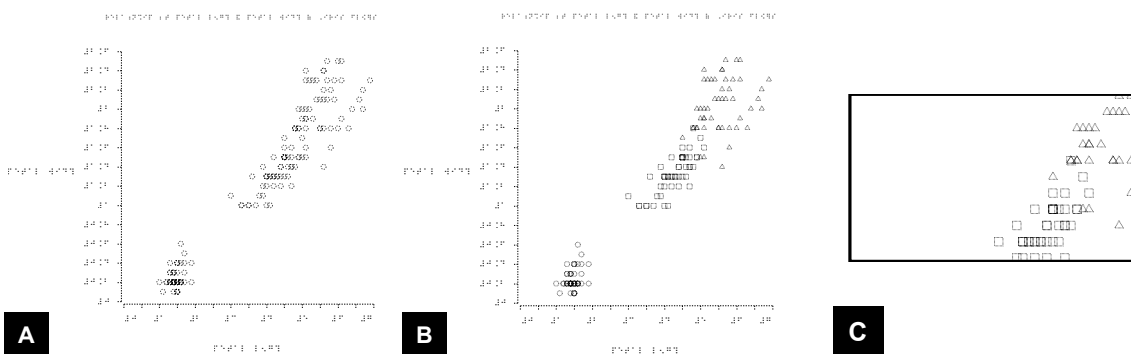


Figure 6.14: **Monarch—Scatterplots.** Panels (A–C) show the tactile rendering of scatter plots where different shapes (such as circles, squares, and triangles) encode categorical values.

For *scatter plots*, we used different shapes (circle, square, and triangle) to encode the categorical values. Based on the data distribution, there is a possibility of occlusion (see Figure 6.14.B), and despite zooming, the positions of the points remain the same, and the zooming

algorithm of Tactile Viewer simply magnifies the size, and does not introduce spacing to make points more perceivable while zooming. This is a limitation of our implementation, and we ensured that the tasks used in our comparison study did not require such granular zooming.

6.3 User Study

In this section, we describe a comparison study to understand the tradeoffs and strengths of each data accessibility approach.

6.3.1 Overview

Our goal was to explore how Blind and low-vision (BLV) professionals interact with different data representations using various devices, focusing on the efficacy and user experience of each method. In order to better design multimodal experiences, we compared inclusive data visualization access through 1) screen-reader access to chart descriptions, 2) interactive sonification, and 3) tactile representations on a refreshable braille display. Participants were expected to complete data visualization tasks by exploring bar charts, pie charts, line charts, and scatter plots. Each chart was adapted for three systems: 1) Olli [12] for screen reader access 2) TactualPlot [20] for sonification, and 3) Monarch [28] for tactile representation, and completed 3 tasks per chart type ($n = 4$). The study was approved by the National Federation of the Blind (NFB) in Baltimore and our university's Institutional Review Board (IRB).

6.3.2 Participants

We recruited participants through NFB’s mailing lists, and snowball sampling. Our inclusion criteria was that participants had to: *be Blind or have low vision, have experience with data analysis, and live in the U.S.* As part of the consent and scheduling process, participants filled an online survey through which we collected demographic information, information on their blindness, assistive technology usage, experience with data visualization, and familiarity with non-visual analysis techniques (sonification and tactile graphics).

6.3.2.1 Demographics and background

Ten Blind adults (n = 10) were recruited after our screening and consent process. Table 6.2. outlines key demographics and background information for each participant. Our participants were between the ages of 18 and 60, with the average age being Seven participants identified as female, two as male, and one chose not to specify their gender. Majority of our participants reported being ‘totally Blind’ (n = 7), and three participants reported that they were ‘legally Blind’. Most of our participants (n = 7) were Blind since birth; two reported onset between 0-5 years of age, and one experienced onset between 13-18 years. All participants had at least a high school diploma: five had completed master’s degrees, three completed bachelor’s degrees, and two had completed high school. Six participants reported that they can read braille fluently; and four can read with some difficulty. Eight participants reported that they can write braille fluently; and two can write with some difficulty. A summary of the participant demographics can be found in Table 6.2.

Table 6.2: **Participant demographics.**

ID	Age	Gender	Blindness	Onset	Braille Reading	Braille Writing	Education
P1	49	F	Totally blind	From birth	Some diff.	Fluently	Master's
P2	41	F	Legally blind	13-18 yrs	Some diff.	Fluently	Master's
P3	36	F	Legally blind	From birth	Some diff.	Some diff.	Master's
P4	37	N/A	Totally blind	From birth	Fluently	Fluently	Master's
P5	39	M	Totally blind	From birth	Fluently	Fluently	High school
P6	59	F	Totally blind	From birth	Some diff.	Some diff.	Master's
P7	60	F	Totally blind	0-5 yrs	Fluently	Fluently	Bachelor's
P8	18	M	Totally blind	From birth	Fluently	Fluently	High school
P9	35	F	Totally blind	0-5 yrs	Fluently	Fluently	Bachelor's
P10	28	F	Legally blind	From birth	Fluently	Fluently	Bachelor's

6.3.2.2 Technology usage

All of our participants used screen readers daily. Similarly, all participants reported using desktop/laptop computers and smartphones; with four participants additionally using a Tablet/iPad. All of our participants reported having used Microsoft Windows; five participants also used Apple MacOS; and one participant was familiar with Linux. In terms of smartphone operating systems, all participants were familiar with Apple iOS; and two participants were familiar with Android. Among the ten participants, data analysis experience ranged from “Little to no experience” (n=1) to “Moderate experience, such as advanced coursework, or occasionally using charts and statistics for work” (n=2), with the remaining seven reporting “Some experience, such as an introductory course in school, but no advanced training”. Comfort with bar and pie charts was most commonly “Somewhat comfortable” (n=7) though a few reported “Very comfortable” (n=2) or “Not very comfortable” (n=1). Line and scatterplot familiarity followed a similar pattern, and one participant indicated “Very comfortable” with scatterplots while another indicated “Not at all comfortable”. Most participants were at least “Somewhat comfortable” (n=5) with tactile

graphics, while exposure to sonification tended to be “Not very comfortable” (n=5) or “Somewhat comfortable” (n=3); with two “Not at all comfortable”. Comfort level with screen reader access to charts was split among “Somewhat comfortable” (n=5), “Not very comfortable” (n=2), and “Very comfortable” (n=3). Overall, these responses showcase a range of comfort and experience levels across different chart types and sensory modalities. A summary of the participants’ technology usage and data analysis experience can be found in table 6.3.

Table 6.3: Technology and data analysis experience.

ID	Data Analysis	Bar Charts	Pie Charts	Line Charts	Scatter Charts	Tactile Graphics	Sonification (Familiar)	Screen Reader
	(Exp.)	(Comfort)	(Comfort)	(Comfort)	(Comfort)	(Familiar)		(Familiar)
P1	Some	Somew.	Somew.	Very	Somew.	Very	Not Very	Very
P2	Some	Somew.	Somew.	Not Very	Not Very	Somew.	Not at all	Not Very
P3	Some	Somew.	Somew.	Somew.	Somew.	Somew.	Not Very	Somew.
P4	Some	Very	Very	Very	Somew.	Very	Not at all	Somew.
P5	Some	Somew.	Somew.	Not Very	Not Very	Somew.	Not Very	Very
P6	Some	Not Very	Not Very	Not Very	Not at all	Somew.	Somew.	Somew.
P7	Little	Somew.	Somew.	Somew.	Somew.	Not Very	Not Very	Not Very
P8	Moderate	Very	Very	Somew.	Somew.	Very	Somew.	Very
P9	Moderate	Somew.	Somew.	Somew.	Somew.	Somew.	Somew.	Somew.
P10	Some	Somew.	Somew.	Somew.	Very	Very	Not Very	Somew.

6.3.3 Apparatus

Our study used three different approaches to data accessibility, each representing a different modality or combination of modalities for presenting data to BLV users. These approaches were chosen to cover a range of current and emerging technologies in the field of accessible data visualization.

1. **TactualPlot**: installed on an Apple iPad (latest generation), providing a hybrid audio-tactile interface for data exploration.

2. **Monarch device:** a HumanWare tactile tablet featuring a 96x40 (WxH) retractable and refreshable pin grid to generate tactile experiences.
3. **Screen reader:** participants used screen reader software in conjunction with the Olli navigator for accessing textual chart descriptions.

6.3.4 Dataset, charts and tasks

We utilized basic multidimensional statistics datasets commonly provided in R, matching each dataset to a specific representation:

- `mtcars` dataset (fuel consumption and automobile design) - pie charts, bar charts and scatterplots;
- `auto-mpg` dataset (fuel efficiency data) - pie and bar charts;
- `stocks` dataset (monthly stock price of companies between years 2000 and 2010) - line charts; and
- `iris` dataset (Measurements of iris flowers) - scatterplots.

In total we created 24 charts, with 6 charts per visual representation so that every participant does not encounter the same chart while using all three devices. To introduce some complexity in the charts, we created two levels of difficulty—**CD01**, and **CD02**. For pie charts, difficulty was based on number of pie segments. For bar charts, CD01 did not have a nominal variable visualized, CD02 was a stacked bar chart (includes nominal variable). For line charts, CD01 include only data from one series, and CD02 included a multi-series line chart with data from two series. For scatterplots, CD01 included a relationship between two quantitative variables,

and CD02 included a nominal variable where the chart included a third encoding to group data by categories. Participants completed three types of tasks for each chart, introduced through the concept of “cardinality” (one item, two items, all items):

T1 **Single-Point Identification** (cardinality: one item): Identify specific data points (e.g., “What was the average MPG of 3 cylinder cars”);

T2 **Pairwise Comparison** (cardinality: two items): Compare two data points or categories (e.g., “Which has a higher MPG: 3-cylinder or 4-cylinder cars?”); and

T3 **Trend Analysis** (cardinality: all items): Describe overall trends or patterns in the data (e.g., “What is the relationship between petal length and petal length”)

6.3.5 Experimental Factors

Our study considered the following factors:

- **Device (DT):** Olli (**OLL**), TactualPlot (**TAP**), and Monarch tactile graphics (**MON**)
- **Visual Representation (VR):** pie charts (**PIE**), bar charts(**BAR**), line charts (**LINE**), and scatterplots (**SCATTER**)
- **Task Type (TT):** single-point identification (**SP**), pairwise comparison (**PC**), trend analysis (**TA**)

6.3.6 Experimental Design

Considering the experimental factors, participants attempted 36 tasks (3 x 4 x 3). We chose an experimental design within subjects where all participants experienced all conditions

during the study. The order of presentation of the devices (DT) was counterbalanced using a Latin square design. We did not include chart difficulty as an experimental factor to restrict the number of tasks in the experiment, and to reduce fatigue during the study session. However, we ensured that the participants performed 18 tasks on each CD01 and CD02 charts on the three devices.

6.3.7 Procedure

After obtaining informed consent online, we administered a demographic survey to gather background information on each participant's visual impairment, professional experience, and familiarity with assistive technologies. On the scheduled date, we met participants in a laboratory space in our university or in their personal space of choosing to ensure comfort and familiarity with the environment. We gave participants an introduction to the session, and explained the study procedure. Participants received a 10-minute hands-on training on each device and data representation method before performing tasks. While we dedicated 10-minutes for the training, training times often varied between participants, with a maximum of 17 minutes. Participants typically learned to use Olli and the Monarch faster than TactualPlot. This training phase was designed to ensure that all participants had a baseline understanding of how to interact with each device and interpret the different data representations. Following the training, we conducted timed and recorded trials for each of the 36 task combinations. Participants were encouraged to think aloud during the trials, providing verbal insights into their thought processes and any challenges they encountered. Considering the novelty of some of some of these devices, participants could also ask the researcher for help if they were stuck during a task. Tasks were read out loud to

the participant, and we informed participants about the 4-minute time limit for a task. To reduce study demands, the researcher recorded task times, and also selected the task answer after receiving verbal confirmation from the participant. Completion times were measured with the start time being the moment after the task was read-out loud to the participant, and the stop time was when a task option was chosen. We restricted the task time to ensure that participants attempted all the tasks on all three devices. Upon completion of all trials, we conducted a semi-structured interview with each participant. Participants also filled the NASA Task Load Index (TLX) workload questionnaire to collect subjective ratings for each of the devices. These interviews allowed us to gather qualitative feedback on the participants' experiences with each device and representation, their preferences, and any suggestions for improvement. The average duration of the study session was 3 hours and 18 minutes (breaks were offered to prevent fatigue).

6.3.8 Data Metrics and Analysis

We collected the following data for analysis:

- **Accuracy:** correctness of responses for each task.
- **Task completion time:** measured for all trials across all devices.
- **Qualitative feedback:** gathered through post-task interviews and think-aloud protocols during the trials.

Our analysis involved both quantitative and qualitative methods:

- **Quantitative analysis:** Analysis of effect sizes and 95% confidence intervals to compare task completion times and accuracy across devices, representations, and task types.

- **Qualitative analysis:** Thematic analysis of interview transcripts and think-aloud data to identify recurring themes, preferences, and challenges associated with each approach.

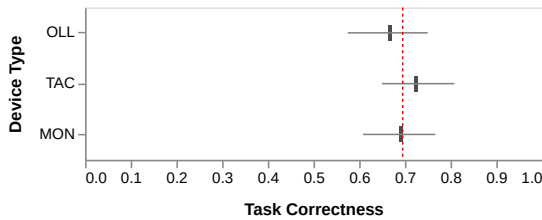
This mixed-methods analysis helped provide a comprehensive understanding of the strengths and limitations of each data accessibility technique in the context of BLV individuals' real-world data exploration needs.

6.4 Results

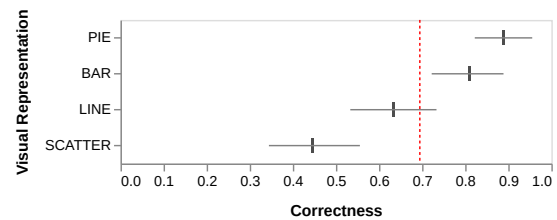
In this section, we present results from our analysis of 360 tasks from $n=10$ participants. The tasks were distributed as follows for each condition: DT—120 per device type; VR—90 per visual representation; TT—120 per task type. We analyzed all our data using estimation methods to derive 95% confidence intervals (CIs). We employed non-parametric bootstrapping [151] with $R = 1,000$ iterations— to follow current best practices for fair statistics in the field of HCI [152]. The goal of our analysis was to explore challenges with performing analysis tasks (TT) on each device (DT), and to understand what kind of challenges different chart types (VR) pose while using a particular device. We measured accuracy (task correctness) and task completion times. Since we used a think-aloud protocol, the completion time measure includes time spent on performing a task as well as any time taken for any communication between the researcher and participant. However, we note that completion time can be a good indicator for how difficult or easy a task was to perform. Additionally, we report subjective NASA TLX ratings, and include a thematic analysis [153] of the post-task completion interview, and participants' thoughts while performing the tasks.

6.4.1 Task Correctness

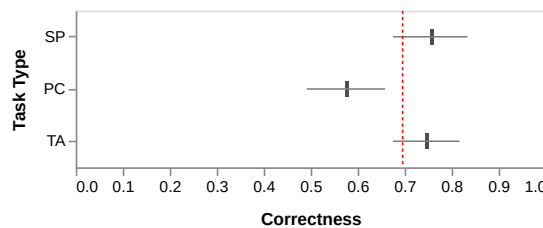
Our analysis results show that participants completed 250 (out of 360) tasks correctly with an accuracy of 69.4%. First, we compared task correctness between devices, and observed that the accuracy with: Olli (OLL) was 69.2%; TactualPlot (TAC) was 72.5%; and the Monarch (MON) was 66.7%. Participants had accurately completed 80/120 tasks with Olli; 87/120 tasks with TactualPlot; and 83/120 tasks with the Monarch. Thus, TactualPlot resulted in a better accuracy than Olli and the Monarch. However the error bars (see Figure 6.15a.) for all three devices have a large overlap and do not have too much of a separation despite the mean values being apart.



(a) Comparing task correctness between device type (DT) levels (error bars represent 95% confidence intervals).



(b) Comparing task correctness between visual representation (VR) levels (error bars represent 95% confidence intervals).



(c) Comparing task correctness between task type (TT) levels (error bars represent 95% confidence intervals).

Figure 6.15: **Analysis of correctness (accuracy) across the experimental factors.** Results from an analysis of 95% CIs after bootstrapping (R = 1000).

We compared task correctness between different visual representations (VR), and observed

a clear separation between the means. The accuracy for: pie charts was 88.9%; followed by 81.1% for bar charts; 63.3% with line charts; and only 44.4% for scatterplots. Participants had accurately completed 80/90 tasks with pie charts; 73/90 tasks with bar charts; 57/90 tasks with line charts; and 40/90 tasks with the scatterplots. We can clearly notice a separation between the means of each visual representation (see Figure 6.15b.) and the overlap between the error bars of each VR is very minimal. This shows that participants found certain chart types easier than the others.

We compared task correctness between task types (TT), and observed that the accuracy with: single-point identification (SP) was 75.8%; pairwise comparison (PC) was 57.5%; and trend analysis (TA) was 75%. Participants had accurately completed 91/120 single-point tasks; 69/120 pairwise comparison tasks; and 90/120 trend analysis tasks. Thus, pairwise comparison tasks, which involved comparing two different data values by navigating, and locating the right chart element (TP and MON) or textual description (OLL) were harder than single-point identification and trend analysis. In Figure 6.15c., we can see that the means of task types TA and SP are higher than the overall average (red line); with the mean value and error bars of PC tasks clearly separated from both the overall average and the other task types.

Table 6.4: **Comparison of mean task correctness for a combination of Device Types (DT) across Visual Representations (VR) and Task Types (TT).** Task correctness values are reported as percentages, and we also show the no. of correct tasks for each condition.

(a) Visual Representation (VR) x Device Type (DT).

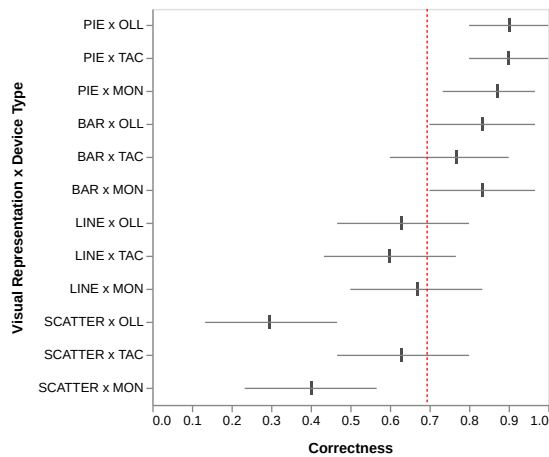
	Pie	Bar	Line	Scatter
Olli	90.0% 27/30	83.3% 25/30	63.3% 19/30	30.0% 9/30
TactualPlot	90.0% 27/30	76.66% 23/30	60.0% 18/30	63.3% 19/30
Monarch	86.6% 26/30	83.3% 25/30	66.6% 20/30	40.0% 12/30

(b) Task Type (TT) x Device Type (DT).

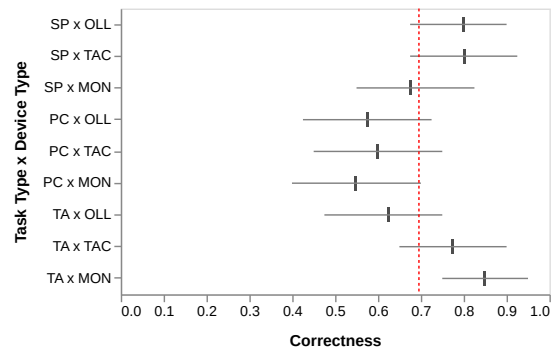
	Single point	Pairwise	Trend
Olli	80.0% 32/40	57.5% 23/40	62.5% 25/40
TactualPlot	80.0% 32/40	60.0% 24/40	77.5% 31/40
Monarch	67.5% 27/40	55.0% 22/40	85.0% 34/40

Next, we wanted to further explore and understand the relationship between device type (DT) and visual representation (VR); especially considering scatter plots and line charts had lower task correctness. The mean task correctness for each combination of factors are shown in Table 6.4. Figure 6.16a demonstrates the trend in our data, where scatterplots and line charts had lower task completeness, compared to bar charts and pie charts; with pie charts being the most accurate across all device types. The error bars for bar and pie charts overlap indicating that both visual representations were similar in task correctness; with bar charts on Tactualplot showing the least accuracy. With scatterplots, TactualPlot showed more task correctness compared to

Olli and the Monarch; and the error bars of TactualPlot and Olli do not overlap. Olli and the Monarch showed higher task correctness as compared to TactualPlot for bar charts and line charts; However, the error bars (CIs) in Figure 6.16a overlap when comparing all three devices for pie, bar, and line charts.



(a) Comparing mean task correctness between visual representation type (VR) x device type (DT) (error bars represent 95% confidence intervals).



(b) Comparing mean task correctness between task type (TT) x device type (DT) levels (error bars represent 95% confidence intervals).

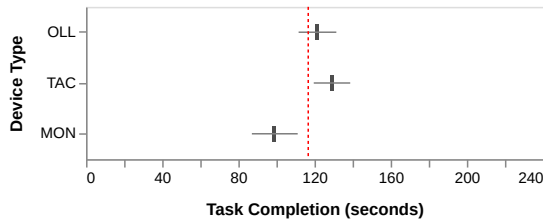
Figure 6.16: **Analysis of correctness (accuracy) across a combination of experimental factors.** Results from an analysis of 95% CIs after bootstrapping (R = 1000).

Finally, we compared task correctness for a combination of task type (TT) and device type (DT). The mean task correctness for each combination of factors are shown in Table 6.4. Figure 6.16b displays these means along with 95% confidence intervals generated from bootstrapping. For PC tasks, we note that the confidence intervals largely overlap across devices—indicating comparable performance. For the TA condition, non-overlapping error bars between Monarch and Olli, suggesting that there was a large difference in task correctness.

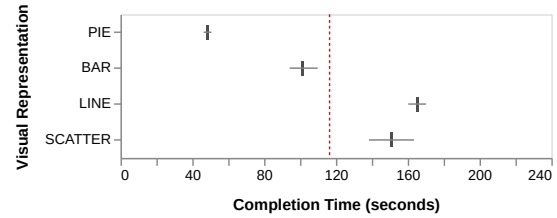
6.4.2 Task Completion Time

We performed a similar analysis of task completion times using the bootstrapping technique. The mean task completion time was 116.6 seconds ($SD = 60.7$ s). A comparison of the means of correct (94.5 s) and incorrect (166.8 s) tasks indicated that participants spent more time on incorrect tasks. We note that the increased time could also be impacted by the time spent by the participant on thinking out loud (some individuals expressed more thoughts than others) and discussing the task with the researcher. We compared task completion time between devices, and observed that the completion: Olli (OLL) was 121.4 s; TactualPlot (TAC) was 129.3 s; and the Monarch (MON) was 98.9 s. The error bars (see Figure 6.17a.) for the mean completion times for Olli and TactualPlot show that participants spent more than the average task completion time (116.6 s—indicated by the red line) on Olli and TactualPlot tasks. Figure 6.17a. also shows that the error bars for the Monarch do not overlap with those of the other two device types (OLL and TAC).

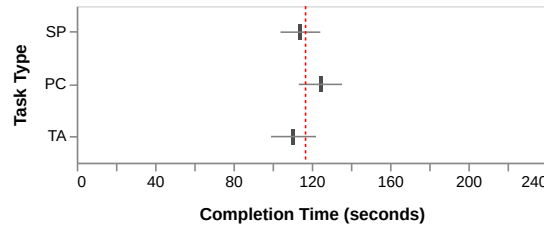
Next, we compared completion times between different visual representations (VR), and observed a clear separation between the means. The completion time (lowest to highest) for: pie charts was 48.4 s; followed by 101.6 s for bar charts; 150.9 s for scatterplots; and the highest values was 165.3 s for line charts. We can clearly notice a separation between the means of each visual representation (see Figure 6.17b.) and there is no overlap between the error bars of each VR. This shows that participants spent more than average time with line charts and scatter plots, as compared to pie and bar charts.



(a) Comparing mean task completion time between device type (DT) levels (error bars represent 95% confidence intervals).



(b) Comparing mean task completion time between visual representation (VR) levels (error bars represent 95% confidence intervals).



(c) Comparing task completion time between task type (TT) levels (error bars represent 95% confidence intervals).

Figure 6.17: **Analysis of mean task completion time across the experimental factors.** Results from an analysis of 95% CIs after bootstrapping (R = 1000)

We compared mean completion times between task types (TT), and observed that the time for: single-point identification (SP) was 114.4 s; pairwise comparison (PC) was 124.7 s; and trend analysis (TA) was 110.7 s. This indicates that participants spent the least time on trend analysis tasks, followed by single-point identification, and most time on pairwise comparison tasks. In Figure 6.17c., we can see that the means of task types TA and SP are lower than the overall average (red line). And, the mean completion time for PC tasks was the highest.

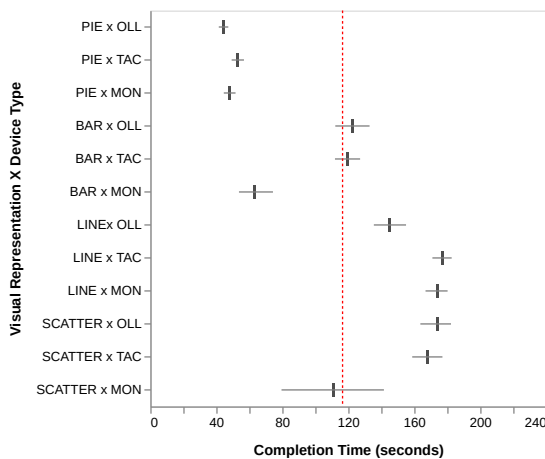
Table 6.5: Comparison of mean completion times for a combination of Device Types (DT) across Visual Representations (VR) and Task Types (TT). The completion time is measured in seconds (s).

(a) Visual Representation (VR) x Device Type (DT).

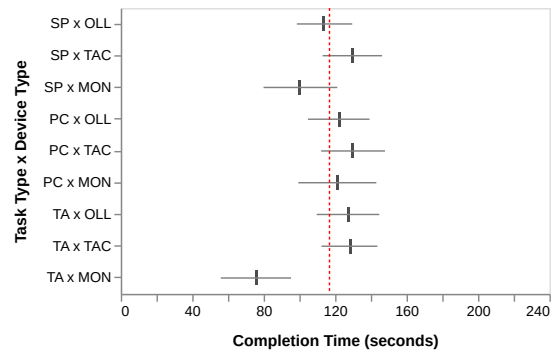
	Pie	Bar	Line	Scatter
Olli	44.2	122.4	145.2	173.8
TactualPlot	53.0	119.3	176.8	168.2
Monarch	48.1	63.0	173.9	110.9

(b) Task Type (TT) x Device Type (DT).

	Single point	Pairwise	Trend
Olli	113.6	123.3	127.4
TactualPlot	129.5	129.6	128.9
Monarch	99.9	121.3	75.8



(a) Comparing mean task completion time between visual representation type (VR) x device type (DT) (error bars represent 95% confidence intervals).



(b) Comparing mean task completion time between task type (TT) x device type (DT) levels (error bars represent 95% confidence intervals).

Figure 6.18: Analysis of mean task completion times. Comparison across a combination of experimental factors—results from an analysis of 95% CIs after bootstrapping (R = 1000)

Next, we wanted to further explore and understand the relationship between device type (DT) and visual representation (VR). The mean completion times for each combination of factors are shown in Table 6.5a. Figure 6.16a indicates small error bars (95% CIs) for each condition

except for scatterplots on the Monarch. Pie charts showed the lowest mean completion times on all three devices, followed by bar charts on the Monarch. Scatterplots on the Monarch also had a mean completion less than the study mean (red line). We suspect this was because participants struggled with scatterplots on the Monarch considering the occlusion that required multiple levels of zooming and panning; with participants often feeling lost. Some of our participants gave up and chose the “unsure of the answer” option to complete the task (incorrectly). For line charts, the mean completion time for Olli was lower than TactualPlot and the Monarch—both of which had similar mean completion times.

Lastly, we compared mean completion times for a combination of task type (TT) and device type (DT). The mean completion times for each combination of factors are shown in Table 6.5b. We note that the Monarch had the lowest mean task completion time among all the three task types; followed by Olli, and the highest was TactualPlot. Single point tasks (129.5 s) on TactualPlot had higher mean completion time than every combination of task type and devices except for pairwise tasks on the TactualPlot (129.6 s). The error bars (see Figure 6.18b.) after bootstrapping do overlap for many of our conditions; but trend analysis tasks on the Monarch shows a clear separation between all the conditions, except single point tasks on the Monarch.

6.4.3 Subjective Ratings: NASA TLX

Figure 6.19., shows the mean NASA TLX subscale scores (0–20) reported by our participants for each device type. We assessed the devices across six dimensions: *Mental Demand*, *Physical Demand*, *Temporal Demand*, *Performance*, *Effort*, and *Frustration*. In every dimension, a lower score indicates a better rating.

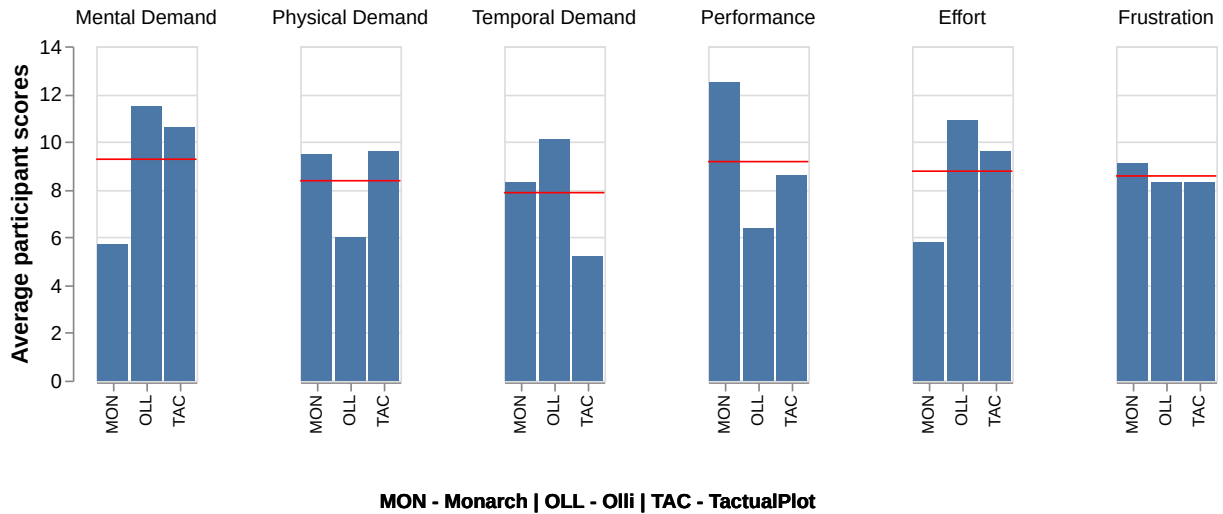


Figure 6.19: **NASA TLX Ratings.** Comparison of mental demand, physical demand, temporal demand, performance, effort, and frustration on a 20-point scale between the three device types. A lower score indicates a better rating.

- **Mental Demand.** Participants rated Olli (OLL) the highest (11.5) on mental workload, whereas TactualPlot (TAC) tended to be lower (10.6). Mental Demand rating for Monarch (MON) was the lowest (5.7).
- **Physical Demand.** MON (9.5) and TAC (9.6) both received moderate physical demand scores. OLL had the lowest rating (6.0) for physical demand, possibly due to minimal physical interaction beyond keyboard or gesture navigation.
- **Temporal Demand.** Participants using OLL felt slightly time intensive (10.1). MON ratings (8.3) indicated that participants felt less time than OLL while performing tasks. TAC ratings (5.2) indicated lowest temporal demand.
- **Performance.** OLL was rated at 6.4, TAC was rated at 8.6, and MON scored 12.5. This suggests that participants felt they performed best with OLL, moderately with TAC, and least effectively with MON.

- **Effort.** OLL’s rating was 10.9, TAC was 9.6, and MON only 5.8. Participants perceived MON as requiring the least effort, with TAC in the middle, and OLL demanding the most effort.
- **Frustration.** Both OLL and TAC received a rating of 8.3; while MON scored slightly higher at 9.1. These results indicate that participants experienced similar levels of frustration with OLL and TAC, but slightly more frustration with MON.

6.4.4 Qualitative Findings

We present results from a thematic analysis [153] of 10 participants’ interview and other study responses. Participants explored bar charts, pie charts, line charts, and scatter plots, performing tasks like identifying largest slices, spotting trends, or comparing data points. We highlight major themes, challenges, and benefits of each modality.

6.4.4.1 Initial Learning Curve and Familiarity

Participants who had significant practice with tactile media (e.g., embossed Braille) adapted faster to the Monarch, while those accustomed to screen readers found Olli more familiar: *“I already had experience with tactile, so there’s less of a learning curve than a purely verbal system.”* (P5). Others (P2, P3) reported inconsistent exposure to tactile in past schooling, which led to early hesitation but quick adaptation: *“I’ve used charts before but not often. After a few minutes of feeling the pins on Monarch, it made sense.”* (P3). Despite initial confusion, most participants mentioned a turning point where the interface “clicked”: *“When the beep in TactualPlot got higher for bigger values, that’s when it all made sense. I was like, ‘Oh, that’s*

the pattern!'.’” (P2). Similarly, users initially had to get accustomed to the features of the Tactile Viewer application: *“I struggled with the scroll bars on Monarch at first, but once I zoomed in properly, it was straightforward.”* (P1).

6.4.4.2 Spatial Overview vs. Precise Detail

Many participants praised Monarch for broad overviews: *“I can run my fingers along the bars and see which one is tallest, without reading five lines of text.”* (P1). However, dense or closely spaced data (e.g., scatter plots) could become a “blur of pins” if there was no filtering or zoom: *“When there’s a big cluster of data, it’s all lumps. I’d need more zoom or maybe fewer points at once.”* (P3). Participants used Olli to verify exact numeric values, though some worried about verbosity: *“If it’s 53 vs. 54, I’d rely on Olli’s text. But it can get overwhelming when it rattles off 10 lines in a row.”* (P4). They liked hierarchical breakdowns but wanted quick summaries, and had personal preferences on what information receives priority: *“Just give me the min and max upfront, so I don’t arrow through everything to find it.”* (P8) TactualPlot helped participants “feel” a chart while hearing real-time sonification: *“I love hearing a beep go higher with a taller bar, then tapping for the exact label. It’s a great combo.”* (P2) Yet interpreting pitch differences posed challenges for some: *“I’m not musically trained, so if the pitch difference is small, I can’t tell if it’s a bit bigger or a lot bigger.”* (P1)

6.4.4.3 Chart-Specific Observations

Bar chart visual structures were familiar to some of the participants, and having this prior knowledge helped users to adapt to various device types: *“If it’s a stacked or grouped bar chart, I*

can still figure out each segment, or just arrow through the categories.” (P8). P2 emphasized how past experience provided ease of access: *“Bars are very direct in tactile or audio. I recognized them from past math classes, so it felt natural.”* Pie charts made it easy to spot the largest or smallest slice: *“I can immediately tell if something’s half the circle, but guessing it’s 20% or 25% is trickier without labels.”* (P10). Line charts effectively showed peaks or dips: *“I can trace with my finger. It’s super obvious where it spikes around 2007, then dips slightly after.”* (P6). However, multiple lines overlapping each other confused participants without a way to isolate lines or reduce clutter with TactualPlot. Participants often struggled with locating previously explored areas during comparison tasks. Scatter plots presented the greatest challenge, especially with overlapping points: *“When points bunch together, I’d need more zoom or a filter, or it’s just lumps of pins or lumps of beeps.”* (P9) Scatter plots consistently posed challenges. P1 explains: *“Scatter. Scatter plots have been hard for me to understand because there’s so much going on in so many different areas.”* This difficulty was largely attributed to overlapping data points and the lack of distinct tactile cues (Monarch). Similarly, shape encoding or polyphonic audio (for multiple categories) demanded a lot of attention from the participants.

6.4.4.4 Sonification Challenges & Opportunities

Below are key challenges and benefits specific to TactualPlot’s audio and touch design. We fold in additional quotes that highlight pitch perception, multi-category audio, and the need for text confirmations. P4 discusses how it was important to be able to differentiate pitches for overview tasks: *“I’m okay with moderate pitch intervals, but if it’s too subtle, I miss it. A bigger jump is easier to detect.”* Participants noted that accidental touches could obfuscate trends in

the chart while tracing the display by touching: *“If I accidentally touch two data points, I get two beeps simultaneously. Then it’s a bit confusing.”* (P10). Participants also indicated that unexpected sounds can be overwhelming: *“More than two categories can create chords. That’s neat but also overwhelming if I’m not expecting it.”* (P3) We note that having an understanding of the dataset or distributions can assist in audio-tactile exploration. Participants emphasized the need for verbal confirmation to interpret the pitch values, and how TactualPlot’s tapping feature can help with validating data values: *“Even if the beep helps me see it’s bigger, I’d still tap for the label. I want to know if it’s 53 or 62 exactly.”* (P2). We observed that the spatial audio rendering became harder to interpret when there were multiple musical tones playing for each category. P6 explains: *“But I do worry about ear fatigue after too many pitch streams in a row. We might need breaks or varied sounds.”*.

6.4.4.5 Implications for multimodal accessibility

For Olli, participants appreciated the depth of data-related information that users had access to, but for a better experience, they emphasized the need to customize verbosity of the text: *“I like Olli’s exact values, but I’d prefer a short summary. I don’t need to hear all intervals unless I want them.”* (P9). The Monarch provided participants with a quick understanding of the overview of a chart. However, participants explained that displaying a large number of data points at the same time made them zoom and pan extensively; with overlapping pins causing confusion: *“It’s so satisfying to feel the chart’s shape directly. But if there’s a lot of points, I’d like a smaller view or smaller region.”* (P3) Participants who were familiar with printed tactile graphics, explained that having the ability to render pins at different heights could be helpful; especially considering

the need for grid lines to assist with exploration: “*So the traditional way, you make the axis at 100% dot height, you make the line at 100% dot height, and you make the grid lines at 50% dot height. But this [Monarch] doesn’t offer that capability.*” We find that a combination of direct touch and sonification fosters immediate feedback—good for scanning. However, audio clutter with overlapping pitches, and subtle audio-intervals require user training. Additionally, we also note that our participants were least familiar with sonification(see table 6.3). For both the Monarch and TactualPlot, participants emphasized that clear and effecient labeling was crucial to improving multimodal accessibility. For example, P4 explained how more labels could have helped with line charts on the Monarch: “*I would have liked to have the prices [stock] in Braille somewhere.*” This was echoed by other participants as well, especially when considering charts that were not used in the study such as maps which “lose a lot of information” (P6) without labels. Overall, no single modality solved all the user needs; participants saw them as complementary, wishing for a hybrid system that combines tactile for overview, audio for quick magnitude cues, and text for precise numbers.

6.5 Discussion

This study provides insights into the efficacy of different modalities for data accessibility—sound (Olli), touch (Monarch), and combined sound and touch (TactualPlot)—for blind individuals. Our within-subjects methodology (section 6.3.), where ten blind participants with diverse backgrounds and technology usage (section 4.2) completed a range of data analysis tasks across four common visualization types (pie, bar, line, and scatter charts). This allowed for a direct comparison of their strengths and weaknesses so that future tools that have both audio-tactile

capabilities such as the Monarch can combine modalities effectively.

6.5.1 Sound, touch, or the Full Monty?

The findings on task correctness reveal that TactualPlot generally led to better accuracy, although with overlapping confidence intervals across devices overall. However, a clear trend emerged based on visualization type, with pie and bar charts exhibiting higher accuracy across all devices compared to line and scatterplots. This aligns with observations from related work suggesting that certain visual structures might translate more readily to non-visual modalities than others. For instance, the inherent part-to-whole relationship in pie charts and the discrete comparisons in bar charts may be more easily conveyed through sound or touch than the continuous and often overlapping data in line and scatterplots. The analysis of task completion time indicated that the Monarch generally had the lowest completion times, compared to Olli and TactualPlot. This suggests that for certain tasks and visualizations, direct tactile exploration might offer a more efficient means of accessing information for BLV users familiar with tactile media. However, the higher completion times for scatterplots on the Monarch, potentially due to occlusion and navigation challenges, highlight the importance of considering the interaction design and the complexity of the data being represented in tactile formats. The longer completion times for TactualPlot and Olli underscores the cognitive load and potential difficulties associated with interpreting data through non-tactile modalities. The subjective NASA TLX ratings provided further insights into the user experience. Olli was rated highest in mental demand, while the Monarch received the lowest rating in this dimension. This could reflect the cognitive effort required to process sequential auditory information compared to the spatial overview afforded

by touch. However, the slightly higher frustration score for the Monarch might be linked to the aforementioned challenges with complex visualizations and occlusion (for example, scatterplots that visualized multiple shape).

Olli (screen reader) leverages existing familiarity with auditory interfaces for many BLV users and excels at delivering precise, albeit sequential, data. However, its limitations in conveying spatial relationships and the potential for information overload are significant HCI challenges. The Monarch offers the potential for direct spatial comprehension but requires careful design to avoid clutter and to provide effective navigation and labeling, especially for complex datasets. The need for consistent tactile encoding, as highlighted in the co-design study is crucial for effective interaction. TactualPlot (audio-tactile) attempts to bridge the gap by offering real-time multimodal feedback, potentially enhancing both spatial awareness and value perception. However, the effectiveness of sonification is dependent on learnability and the design of intuitive sound mappings, and the combination with touch needs to be carefully orchestrated to avoid sensory overload or conflicting cues. The study also corroborates the long-standing recognition of screen readers [13] as essential tools for accessible data visualization, while also empirically demonstrating their limitations with complex charts that visualize a large amount of data (e.g., scatterplots and scatterplot matrices).

6.5.2 Towards multimodal chart accessibility

Our study contributes to the growing body of research exploring the potential of tactile displays and sonification as complementary or alternative approaches. The findings particularly highlight the complexities of designing accessible visualizations for modalities beyond vision,

emphasizing the need for user-centered design approaches, and the consideration of individual user preferences and prior experiences. The performance variations across visualization types and tasks underscore that a one-size-fits-all solution is unlikely, and future research should focus on developing adaptive and multimodal systems that can tailor the presentation modality to the specific chart representation, visualization tasks, and analytical goals of blind individuals. More complex charts such as UpSet plots [154] may also consider tactile and audio representations for future accessibility implementations. Systems such as TADA [155], ChartA11y [100], and TactualPlot [99], can further extend their design space to support more complex charts on devices such as the Monarch and Graphiti. The availability of the tactile modality will help with better tracing of trends and overviews. Brushing across modalities is might lower the cognitive demand on the user. However, sufficient training and practice is required to become familiar with the different modalities used for specific visualization tasks in a multimodal system. Combining hierarchical description of text along in the form on audio narratives [57, 156]; and personalizing options to control verbosity and configure other statistics [157] that may help further personalize the experience for blind individuals.

As stated by our participants, their experience with sonification was minimal, with more comfort and familiarity with tactile graphics. Recent audio-tactile design studies [100, 155] shows the usefulness of touch-based interactions and audio representation for common charts such as— bar charts, pie charts, line charts, scatterplots, and graph visualization such as node-link diagrams [155]. Scatterplots are 2D visualizations that can often include a third visual variable to encode multiple data series values. These audio-tactile systems use touch interactions to gain spatial awareness and tactile feedback, with non-speech audio used (sonified tones with pitch variation) being mapped to data or chart elements. Recent theoretical work on audio-visual ana-

lytics characterizes audio having a temporal component [158]. But, combining audio and touch interactions enables parallel access to audio, which can be triggered when elements are touched by multiple fingers. This reduces the need for sequential sonification or verbalization, thereby reducing the cognitive and temporal demand to remember the audio sequences. When designed effectively, parallel playing tones can help users compare the individual data values in a region (for example, a bar’s height being mapped to a pitch value) or the aggregated values (point density in scatterplots or hues in a heatmap).

The MAIDR system [133] utilizes: 1) a sequence of audio tones (repetition) to convey box plot features such as whiskers and outlier values, and 2) uses point-density for regions in a heatmap. Similarly, Chartreader and ChartA11y use non-speech tones to represent point densities for scatterplots. Stereo-audio panning is often used to encode positional values; and in TactualPlot spatial audio is used to vary the sound source location using the panner3D node. In our study, we did not specifically evaluate the effectiveness of spatial audio. Considering the increasing use of sonification for accessibility, we believe that further research is needed to establish validated audio scales (akin to Colorbrewer [159] for colors) so that standards can be established for accessible solutions that use non-speech audio. Sequential sonification and verbalization of charts is supported by existing sonification tools such as Highcharts [160] and sonification grammars such as Erie [161]. Both these solutions offers default audio scales, but do not support 2D or 3D spatial audio. Spatial audio and audio scales are important to sonify multi-dimensional visualizations; especially those that map data to visualize visual variables such as color and texture. For example, our implementation of TactualPlot only handles 100 unique tones based on musical scales—we adopt musical scales with a range that spans a full-sized piano to ensure that each tone can be differentiable when played in sequence.

To help easily create tactile graphics from visual charts, Pineros et. al [162] extended the vega-lite visualization library by implementing features that can encode textures and braille labeling automatically. However, our study shows that Braille labels often take up large amounts of space on RTDs such as the Monarch and Graphiti. These devices, unlike printed tactile graphics, are refreshable, and can support chart interactions such as zooming, panning; and direct manipulation of chart elements. We suggest using spatial audio to help with tracing tasks [163] for better audio-tactile interactions. Additionally, we recommend that speech interaction [89] be combined with non-speech audio and tactile representation to assist in visualization tasks—especially to save time and improve direct access to data values. We believe further research is needed to design accessible charts for this unique multimodal device—especially to make the grid view of pins responsive to user interactions. To the best of our knowledge, research to understand accessibility of RTDs [149] has explored combining tactile exploration with speech-input; with blind individuals taking on the role as consumers of charts and not the authors. Thus, to better understand how blind users create tactile charts for the Monarch, we conducted a co-design study with a blind participant.

6.6 Co-designing tactile graphics

Although our large study provided quantitative and qualitative insights into the performance of sound, touch, and multimodal interactions, it also prompted further research questions on how such systems could be used as part of a user’s data analysis workflow [164]. For instance, how can blind users author charts for devices with multimodal capabilities such as the Monarch. Prior work has explored authoring sonification and structured navigation [135] using a screen

reader. Refreshable Tactile displays are novel systems that help blind people consume visuals in a tactile manner. While multimodal data exploration on RTDs has been recently explored [149], there is limited work on authoring visualizations [102] for these devices.

We conducted a 3-hour co-design session with a blind individual where a researcher and the participant co-created and explored charts created using Python and rendered on the Monarch. Our goal was to understand how novel refreshable braille displays are used by blind individuals as part of their data analysis process. For this study, we adopted the pair analytics method [165] to drive the analysis and chart creation process. In this method, a subject matter expert (SME)—the participant, collaborates with a visual analysis expert (VAE)—a researcher to analyze data. The role of the participant as the SME was to drive the analysis by working with the VAE whose role it was to assist the SME with inputs on the visual analysis process. The VAE only provided expertise on refining the charts, and did not drive the analysis goals of the participant. This method allowed us to understand the challenges and opportunities that the blind participant faces while creating charts for the Monarch.

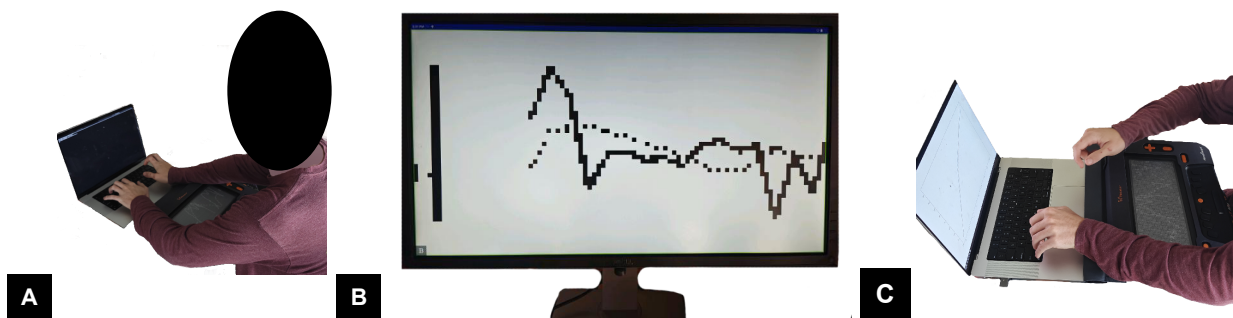


Figure 6.20: **Co-design study setup.** Panel A and C illustrate the participant’s workstation where charts are iteratively created using a personal laptop and the Monarch. Panel B displays the tactile chart in a visual form in an external monitor connected to the Monarch.

6.6.1 Methodology

Here, we describe the procedure used to conduct the design session.

6.6.1.1 Recruitment

Our study participant—D1 (P8) was recruited for the design session after indicating an interest in creating charts using his own dataset. D1 was interested in learning about stock market investments, and wanted to understand how to use the Monarch to visualize a stream of stock market data to learn how to make investment decisions. The demographic and analysis experience of our participant can be found in Table 6.2 and Table 6.3.

6.6.1.2 Apparatus

The Monarch was used as the main visual analytical tool and the participant was responsible for controlling the device. We did not enforce any constraints on the chart creation process—the participant was free to use a dataset, and visualization tool of their choice. The participant used a personal laptop to create and iterate the charts to be viewed on the Monarch’s Tactile Viewer application. Our participant chose to use `Matplotlib` (Python visualization) for chart creation. A monitor was connected to the Monarch to ensure that the researcher view the charts that were being rendered on the Monarch (see Figure 6.20.).

6.6.1.3 Procedure

Our design session consisted of 4 stages after we scheduled the participant session. We received consent from the participant through an online consent form (approved by our IRB), and

offered a compensation of \$250 for the 3-hour session.

Pre-study stage and datasets. Our participant (D1) curated data based on Tesla (TSLA) stock prices. The participant (SME) created two data files for the session and emailed the data to the researcher (VAE) ahead of time. The first data file contained 286 items where each item contained the stock's 'high', 'low', 'volume', and 'WMA' (weighted moving average). The second data file contained 4224 items where each item contained the stock's 'open', 'high', 'low', 'close', and 'volume'. The participant mentioned having an interest in exploring candlestick charts. So, we created a sample candlestick chart using a different dataset as a reference for the participant.

Establishing session goals. On the day of the session, we completed the study setup at the participant's home, and received consent for recording the session. The Monarch device was placed next to D1's personal laptop (see Figure 6.20.) so that the participant could quickly iterate on the chart design using Python, and upload every iteration to the Monarch. Since D1 had already participated in our comparative study, he was comfortable with using the Monarch. Although interested, the participant mentioned having very little to no experience with exploring candlestick charts beyond understanding the concept of the chart. While we provided a sample candlestick chart, we did not mandate the participant to create a candlestick chart; and D1 could create any chart type. We wanted to understand the entire data exploration process as opposed to only limiting the session to creating only a particular chart type.

Pair analytics. We explained the roles of each member of the analytics dyad (VAE and SME), and emphasized to the participant that the researcher will only provide support and feedback on the chart iteration, and guidance on design changes to make the session charts useful. We ensured that the researcher would not provide insights on the data, and explained to D1 that

he would have to come up with analysis questions to drive chart exploration. For example, it was up to the participant to: choose variables that need to be visualized, choose any chart types beyond the candlestick chart, and explore the charts and derive insights. The participant spent approximately 2 hours of the 3-hour session designing and iterating on the charts. The researcher provided syntax hints for Matplotlib to help the participant iterate on the chart designs. After every design iteration of the chart encoding, such as adding grids, changing thickness, filtering data, we loaded the chart on the Monarch for the participant's review. We provided breaks when needed, and concluded the pair analytics stage of the session after the participant was happy with his progress. In total, D1 spent 1 hour and 52 minutes iterating on the chart design and exploring the datasets.

Design debrief. After the pair analytics stage, we conducted a design debrief (semi-structured interview) and asked questions about the challenges faced with exploration using the Monarch.

Throughout the session, we collected audio records, photos, and chart images for every design iteration, and qualitatively analyzed the data.

6.6.2 Findings

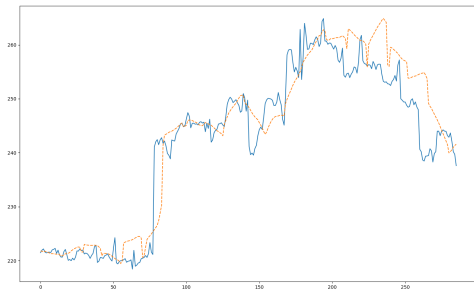
In this section, we present the key findings from the co-design session, structured around the design decisions during the iterative design session, and the themes identified through qualitative thematic analysis. Our analysis reveals insights into the participant's chart design and data exploration strategies, and usability of tactile displays.

6.6.2.1 Chart Iterations

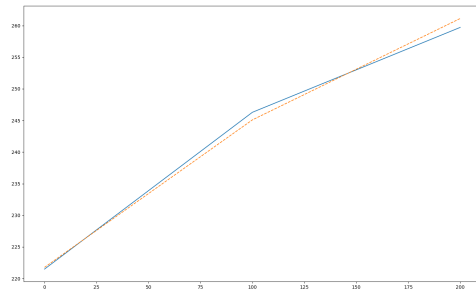
While viewing the tactile candlestick chart for the first time, the participant discussed the visual encoding and structures with the researcher to better understand how to interpret the candles (“popsicles”). This quote shows the initial reaction from the participant:

“Oh, boy. See, I’ve...I’ve never felt this is a really good way to show this, because I’ve never felt a candlestick chart in real life. I don’t even know what they look like. I know the idea, but I have no clue what they look like. So this is really good and like this is, I don’t know what it looks like visually, but it feels like a mess...Yeah, um, let’s increase let’s zoom in, I guess. Let’s increase detail. Hold on, let me...tell me if this is, you know, the wrong way to say it, but like the way I envision a candle, I think of a cylinder in the middle, or a rectangle in the middle, and then out of the top and the bottom of that rectangle are sticks that come up and down. So those Yes, so the cylinder goes, or the rectangle ocean, the high to the low, and then the stick goes from the open to the or, sorry, the the the cylinder. The way I would describe it is, imagine a popsicle stick, yes. A popsicle stick can go up and down, right, yes. And the middle, the size of the Popsicle. Popsicle is open to close. And high low the stick is, yeah, how low is the stick?”

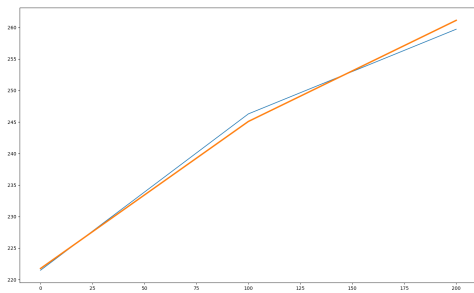
The participant preferred to use a line chart to start the data exploration. Line charts were a more familiar representation for the participant because of prior experience with analyzing stock data using tables, and having used a Braille embossed line chart. Overall, D1 performed seven different iterations (see Figure 6.21) of line charts during the study. We describe the iterations (I1–I7) below:



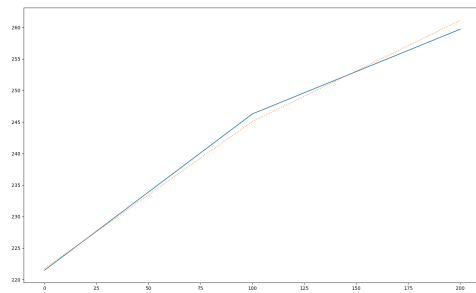
(a) I1



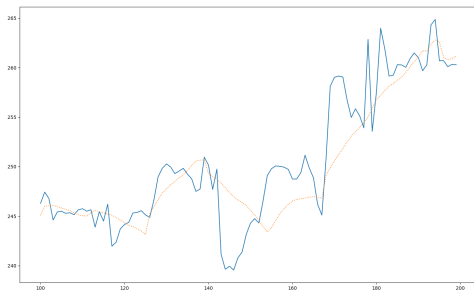
(b) I2



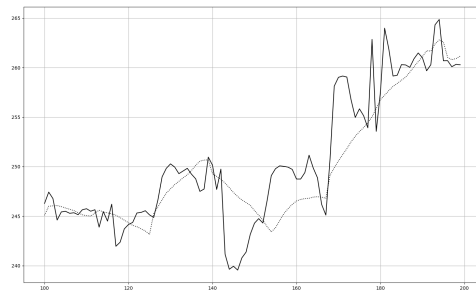
(c) I3



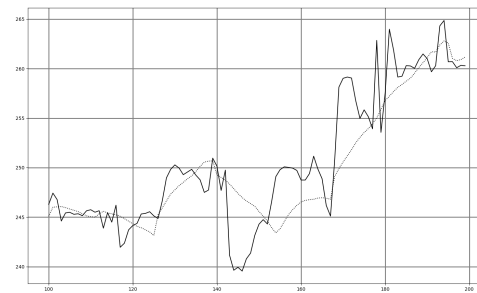
(d) I4



(e) I5



(f) I6



(g) I7

Figure 6.21: Sequence of design iterations.

- **I1:** The participant wanted to compare the High values and the weighted moving average values. To gain an overview, all the items were visualized using a solid blue line for high values, and a dashed orange line for WMA. The participant initially struggled to find patterns because of issues with chart resolution as the default Matplotlib chart resolution did not match the resolution of the Monarch.
- **I2:** Rather than spending time trying to resize the chart using trial and error, the participant instead chose a filtering approach to find a larger trend in the data. D1 only visualized three items—the first item, the 100th item, and the 200th item. The goal was to understand how moving averages varied with the high values in the trading date. D1 faced the same issue as in I1, where the resolution of the chart did not appropriately fit the entire view of the Monarch. Considering the data distribution, the two overlapping lines made it difficult to perceive each data series individually.
- **I3:** Next, D1 tried to make the lines more perceivable by using line thickness to encode the two data series. While the Monarch rendered the two lines to be noticeably different, D1 remarked that it was still difficult to understand regions where the lines overlapped.
- **I4:** D1 felt that the spacing between the dashed lines, in conjunction with the data distribution sometimes made both the solid and dashed lines “feel” the same. So, D1 used a dotted line instead of the dashed line to represent WMA. At this stage, D1 was satisfied with the idea of having to differentiate a solid blue line and a dotted orange line.
- **I5:** Next, the participant employed the encoding scheme from I4 to all of the data, and generated a variation of the chart from I1; but with only the first 200 items.

- **I6:** At this stage, D1 was curious if the contrast in the images could influence the thresholding-based rendering approach of the *Tactile Viewer* app. Additionally, D1 added grid lines to better understand the values of the peaks and dips. However, after multiple levels of zoom, D1 was uncertain if he was touching a grid line or the data series.
- **I7:** For the last iteration, D1 increased the thickness of the grid lines to make them noticeably different.

After the last iteration, D1 mentioned gaining a better understanding of the data. However, these insights were not gained from just one of the versions; rather each iteration built up the insights gained. This quote illustrates the advantage of an iterative design process for Blind individuals: *“Like, this is all good information. And I really think what we what we have determined, and, you know, correct me if I’m wrong—but, what I think we need is an interface that all of this that we just did...most of the graphs, I can think of, at least four graphs that we’ve created today that could be useful all in the same workflow, right? Like the first graph with no grid lines to determine the trends, right? And then, and then another graph where, maybe, you know, like the first graph was just that, that just the first 100 data points where it was very easy to see...And then the the third thing would be the, I guess, the idea that you know, you can see all of the data points. And then the fourth thing would be like, add grid lines. So that way you can, you know, know exactly where you are on the thing. Once you once you already know, like, what you’re feeling, then it might be easier to have the grid lines. So all four of those graphs would be great...Obviously, more useful would be if we could figure out how to throw the graphics directly up here with an application, because then the graphs could be up, you know, could be here in, like a live preview. And I think that would more allow for Blind people to create the graphs.”*

6.6.2.2 Chart Design Decisions

The participant's approach to chart design was highly iterative, involving multiple refinements to improve the legibility and interpretability of stock market trends. A key observation was the participant's emphasis on aligning the chart with the grid structure of the Monarch, which aided in understanding spatial relationships in the data: *"It's very helpful that I'm looking at this graphic on a pinned display that's in a grid, because this graph is obviously designed on a grid, and so it makes it a lot easier and more intuitive to understand that I'm looking at it on a grid."* However, despite the benefits of a structured tactile layout, the participant struggled with certain visual encodings, particularly dashed lines. The participant found the tactile representation of dashed lines misleading, as the spacing between dashes was inconsistent and could be mistaken for rendering artifacts rather than intentional design choices: *"Like, you can tell it's dashed, don't get me wrong, right? But it's so infrequently dashed that it's almost like it's just artifacts that the display is not doing it correctly."* This finding suggests that current tactile design conventions may need to be reevaluated, particularly in how line styles are encoded for pin-based displays.

6.6.2.3 Challenges with Tactile Viewer

Throughout the session, the participant encountered several usability challenges related to rendering stock market visualizations on the Monarch. One major issue was the difficulty in distinguishing overlapping data series, particularly with multiple zoom levels: *"All the way zoomed out, definitely one. Okay, let's try one level zoom... The tick marks actually, on the x-axis, went away. But I'm not sure if that's because there's no room for them."* . The participant initially struggled to perceive whether there were one or two distinct lines, an issue exacerbated

by the Monarch's display resolution, and the data density and distribution. Additionally, zooming and panning operations were described "arbitrary" and "unpredictable", leading to difficulties in maintaining context while navigating the chart: *"I had to be pretty zoomed in, and then I lost the context. You know what I mean?"*. This suggests a need for more intuitive zooming and navigation controls. The participant proposed adding "adaptive zooming", where contextual grid lines and axis references are preserved across zoom levels, to prevent disorientation when focusing on finer details. While the structured layout of the device was an asset for understanding slopes and relationships, the limited resolution and unpredictable rendering of certain elements reduced confidence in decision-making: *"Literally, it becomes one line. They physically cross over each other, and then up here at the top, you can very much see that it's dotted."* This issue became more pronounced when attempting to determine precise crossover points in stock data, which are critical for making trading decisions. The participant emphasized that grid lines and axis labels should persist across all zoom levels, preventing loss of reference points. Additionally, the participant recognized the trade-offs between resolution and accessibility, noting that higher resolution displays (similar to printed tactile graphics), or more granular control over tactile rendering would significantly enhance usability: *"If we had that granular control, when we zoom in and out, and we knew exactly where we were, it would be so much better."*

6.6.2.4 Data Exploration Strategies

The participant engaged in self-driven data exploration, leveraging the tactile charts to extract meaningful stock market trends. One key approach was iteratively adjusting zoom levels to verify perceived trends, particularly in identifying when stock prices represented by the lines

crossed: *“Now that I am zoomed in, I’m up in the part of the line where I start to see this weighted moving average really drop below the line, and that’s when I know, okay, this is definitely an uptrend.”*. The participant suggested experimenting with alternative encoding, such as replacing dashed lines with discrete points to perceive initial trends rather than focusing on creating the ideal chart: *“Instead of drawing a line for the weighted moving average, could we put a point at each x value? Just put a point that is the y value. So almost like making a scatter plot out of WMA values.”*. This highlights a potential design opportunity to provide multiple encoding options within tactile stock charts, allowing users to select representations that best suit their perception and analytical needs. By maintaining the participant’s role as the primary analyst, the study avoided introducing bias from the researcher’s visual perception. The participant reflected on how access to real-time, dynamically updating charts could enhance independent stock analysis: *“If I want to trade stocks, it would be so useful to be able to connect with the Yahoo Finance API, pull down this stuff, apply the settings I configured, and then show them on the display.”*. This underscores the need for accessibility tools to move beyond static representations, and adapt to support a diverse set of data exploration strategies.

6.6.2.5 Reflections on the design process and future improvements

The session provided the participant with a novel way to engage with stock market data, which differed significantly from previous experiences relying on tables or textual representations. The ability to feel stock trends in real-time enhanced comprehension and intuition: *“I’ve heard all of that stuff, but it’s like, you just, it changes your perception when you actually get to feel it for real.”*. Reflecting on future improvements, the participant discussed the need for a

dedicated tactile charting tool that simplifies the process of generating and iterating on financial visualizations: “*We could write some type of interface where you configure all this stuff, throw in a CSV file, and then it makes PNGs that you could put on a thumb drive. That could be really useful.*”.

6.7 Design Guidelines for Authoring Accessible Multimodal Visualizations

Our findings show the importance of automation and accessibility in visual data analysis, suggesting future research should focus on streamlining chart creation while preserving the user’s control over data interpretation. Recent work by Potluri et al. [166] shows the critical need for Blind individuals to be empowered as expert users, while also highlighting the need for development tools (such as accessibility “linting” in Python notebooks) to assist sighted and Blind individuals during data exploration. Studies also show that chart libraries need to be made accessible [134], and an adaptive approach of sonification and textual description solutions is an effective way to also support the authoring - such as tactile Vega-lite [162]. When considering sonification-based accessibility, we argue for immediate need for better theoretical frameworks [158] and standards—for example, a pitch-mapping is a common sonification technique, but for users to authors multimodal charts, we need to develop more validated audio-visual and audio-tactile scales. We believe these efforts can help design audio tones and systems that can minimize audio fatigue, and sound more pleasant and user-friendly [134]. Most importantly, Blind individuals will have more flexibility with audio-encoding for both chart consumption and authoring in multimodal authoring systems such as Umwelt [135] and MAIDR [133]. The co-design session revealed that while a user can identify trends and adapt chart design strategies,

technical limitations, such as rendering inconsistencies and unpredictable zooming on RTDs, can hinder efficiency and limit confidence. Future work should explore improving tactile encoding methods, enhancing navigation controls, and developing interactive stock visualization tools tailored for Blind individuals that can be integrated into their current data analysis workflow.

The study highlights the strengths and limitations of different modalities for data access by Blind and low-vision (BLV) users, which has direct implications for adhering to WCAG principles on both desktop and touch interfaces. Additionally, existing auditing methods such as Chartability [56], which also adopts WCAG principles for creating accessible data visualization, can be extended to multimodal contexts. Below we illustrate the implications of our study findings on some of the existing WCAG 2.1 [167] guidelines. We discuss how WCAG 2.1 [167] success criteria (SC) can be addressed by multimodal charts:

6.7.1 Perceivable

- **Text Alternatives (SC 1.1):** The success of Olli demonstrates the importance of providing structured text alternatives for data visualizations. This directly aligns with WCAG SC 1.1. However, the study also points out that verbosity and the need for quick summaries are important considerations for usability. WCAG guidelines should emphasize not just the presence of text alternatives, but also their conciseness and adaptability to user needs.
- **Alternatives for Time-based Media (SC 1.2):** While not directly addressing time-based media, the study's exploration of sonification in TactualPlot can be seen as an auditory alternative for visual data. WCAG SC 1.2 principles could be extended to consider the design of effective non-visual (auditory or tactile) representations for dynamic or complex

data that is often presented visually over time.

- **Adaptable (SC 1.3):** The study reveals that different visualizations and tasks are better suited to different modalities. This shows the importance of making data presentations adaptable to various sensory outputs (speech, touch, and audio). WCAG SC 1.3 should encourage the provision of data in multiple formats or through interfaces that allow users to choose their preferred modality. The challenges with zoom and context loss on the Monarch also highlight the need for adaptable content that remains understandable at different magnification levels.
- **Distinguishable (SC 1.4):** In the context of tactile displays, ensuring clear and distinguishable tactile patterns and labels (as emphasized by participants) is a tactile equivalent of WCAG SC 1.4. The difficulties with distinguishing dashed lines on the Monarch point to the need for careful consideration of tactile contrast and distinctness.

6.7.2 Operable

- **Keyboard Accessible (SC 2.1):** Olli relies on keyboard navigation for exploring the hierarchical textual descriptions. This is a direct application of WCAG SC 2.1. The study highlights the effectiveness of this approach for detailed data exploration.
- **Enough Time (SC 2.2):** The study imposed time limits on tasks, indicating the practical considerations of data exploration. WCAG SC 2.2 emphasizes providing users with enough time to read and use content. For non-visual modalities, this might translate to ensuring screen reader users have sufficient time to process information, and limiting searching and navigation time on audio-tactile systems.

- **Seizures and Physical Reactions (SC 2.3):** Our study findings may not apply to seizures and other physical reactions.
- **Navigable (SC 2.4):** Olli’s hierarchical structure provides a form of navigation through the data. For tactile interfaces like the Monarch, the challenges with panning and zooming indicate that intuitive and consistent navigation mechanisms are crucial for operability. The “adaptive zooming” proposed by a participant suggests a need for navigation that maintains context. For touch-based sonification in TactualPlot, the risk of accidental touches highlights a potential barrier to smooth operation could be addressed through principles of discrete and structured division of the touch area. Existing toolkits such as Data Navigator [168] can help designers create structured navigation schemes across modalities.

6.7.3 Understandable

- **Readable, Understandable, Predictable (SC 3.1 and SC 3.2):** Olli’s structured text aims for readability and understandability. However, the study’s findings on the need for customizable verbosity imply that “understandable” can be user-dependent. The consistency of sound mapping in TactualPlot (using the same audio scale across chart types) contributes to predictability (WCAG SC 3.2). The challenges some users faced in interpreting pitch differences indicate a potential barrier to understandability.
- **Input Assistance (SC 3.3):** While we did not directly explore input assistance in our study, we believe that interaction features such as the directional lock mechanisms and dynamic sampling sizes in ChartA11y [100] can help Blind individuals gain more spatial awareness and better understanding of the current view in relation to a previous view. Such input and

navigation assistance is essential, especially with large data volumes, interactive charts, and complex charts.

6.7.4 Robust

- **Compatible with Assistive Technologies (SC 4.1):** Our study revolves around the use of assistive technologies like screen readers (with Olli) and tactile displays (Monarch), as well as a novel audio-tactile technique (TactualPlot). The findings directly inform the compatibility and effectiveness of these technologies for multimodal access to data visualizations. Finally, robust systems and chart libraries should strive to help Blind individuals both create, explore, and communicate data visualizations. While not directly designed for accessibility, Large Language Model (LLM)-powered tools such as Pluto [169] offers bi-directional chart and summary editing. Such tools can help Blind individuals by generating textual summaries to gain an overview of current data transformations, chart view, and data values. Chen et al. [162] recommend designing tactile-first data visualizations to counter empty space in tactile visualizations. However, considering the robustness aspect of accessibility, care should be taken to not completely change the visual structure of commonly used charts to facilitate better collaboration between sighted and Blind individuals.

This study provides empirical evidence that can inform and strengthen WCAG 2.1 guidelines related to non-visual data accessibility. It emphasizes the need to move beyond basic text alternatives to consider multimodal approaches, the importance of user-centered design, and the specific challenges and opportunities presented by different assistive technologies and interaction paradigms on both desktop and touch platforms. Future updates to WCAG guidelines for

Blind and low-vision individuals could benefit from incorporating more specific guidance on designing accessible sonifications, tactile graphics, and multimodal interfaces for data visualization. In summary, authoring for RTDs and multimodal accessibility requires a multi-faceted approach encompassing: accessible authoring tools, standardized multimodal scales, improved tactile rendering and navigation, and combinations of audio, touch, and speech to empower Blind individuals in the creation and exploration of data visualizations.

6.8 Limitations and Conclusion

While our study provides valuable insights into the efficacy of sound, touch, and combined modalities for data accessibility, we acknowledge the limitations in our study. The study involved ten Blind adults with diverse backgrounds and technology usage. While this allowed for within-subject comparisons, the sample size might limit the generalizability of the quantitative findings to the broader population of Blind individuals. Additionally, the tasks were performed within a controlled study environment, although efforts were made to conduct sessions in participants' preferred spaces. The 10-minute training provided on each device, and method may have been sufficient for a baseline understanding, but more extensive training can potentially impact task performance and user preferences. We also note that the implementation of TactualPlot was limited to 100 unique tones based on musical scales, which might not be sufficient for all complex datasets. Future work can explore how to expand the sonification design space; and can consider layering the audio—with audio mapping to overviews, and textual descriptions to read data values at deeper zoom levels when fewer points are available to sample. The charts designed for the Monarch were static visualizations due to limitations with the Tactile Viewer application, poten-

tially not fully leveraging the interactive capabilities of the device. The co-design session, while insightful, involved only one participant, limiting the breadth of understanding regarding tactile chart creation by BLV individuals; especially considering the variability in Blind individuals' technical expertise and experience with data analysis.

In conclusion, this comparative study contributes to the growing body of research on data accessibility for Blind individuals by empirically evaluating the strengths and weaknesses of screen readers, tactile displays, and audio-tactile approaches. Our findings show that TactualPlot generally led to better accuracy, while the Monarch often resulted in lower completion times, suggesting a trade-off between these modalities depending on the task and visualization type. The study shows that pie and bar charts were generally more accessible across all devices compared to line charts and scatterplots. Qualitative feedback highlighted the importance of prior experience and learning curves associated with each modality, as well as user preferences for specific features like hierarchical textual descriptions in Olli, and the direct manipulation of chart elements in TactualPlot. The co-design session provided valuable insights into the challenges and opportunities of using refreshable braille displays for creating tactile graphics, emphasizing the need for improved tactile encoding, navigation controls, and integration with existing workflows. Our research emphasizes the need for user-centered design approaches in developing accessible visualizations and highlights the potential of multimodal systems that can adapt to different data characteristics, tasks, and individual user needs. Future work should focus on developing standardized multimodal scales, enhancing tactile rendering and navigation, and exploring combinations of audio, touch, and speech to empower Blind individuals in both the consumption and creation of data visualizations. Finally, we discuss the direct implications of our findings for strengthening accessibility guidelines (WCAG) for data visualization.

Chapter 7: Conclusion and Future work

This dissertation has addresses the critical need for accessible data visualization solutions that empower blind and low-vision (BLV) individuals to engage with data effectively. Traditional visual representations create barriers, and this research explored the design of multimodal touchscreen interactions leveraging audio and haptic feedback on commercial touchscreen devices, which are increasingly being adopted by blind individuals. The central question driving my work was whether a method could be designed for sensing complex datasets on these devices using touch-based exploration, similar to the way blind individuals interact with physical objects but without requiring specialized haptic technology. To answer this overarching question, this dissertation adopted a mixed-methods approach that involved interviews; a survey; a design study to design multimodal (sound and touch) touchscreen chart representations and interactions for scatterplots; and finally I compare audio, touch, and audio-touch with the goal of deriving a multimodal design space.

7.1 Key Findings and Contributions

Here, I summarize the contributions of this dissertation.

7.1.1 Understanding sensory substitution and data analysis practices of blind individuals

The interview study with ten blind Orientation and Mobility (O&M) experts provided valuable insights into how blind individuals perceive spatial layouts using sound and touch. These experts highlighted the use of sound and touch towards non-visual sensemaking of spatial concepts. The study explored how to translate a visualization's visual semantics into non-visual modalities based on how blind individuals perceive visual semantics of space. The findings indicated that blind individuals learn to use sound and touch to perceive and navigate physical space. I find that data accessibility should consider translating charts for different modalities, as opposed to inventing new multimodal representation of the data for blind and low-vision users. This ensures that sighted and blind individuals can collaborate effectively on the same visual representation. A survey of blind and low-vision professionals highlights the importance of considering existing analysis experience, personal preferences and analysis workflows, and the collaborative nature of professional jobs while designing accessibility solutions.

7.1.2 TactualPlot: Crossmodal Sensory Substitution

I implemented the TactualPlot system to explore the idea of crossmodal sensory substitution (CMSS), substituting touch input with sound output. TactualPlot was informed by formative design sessions with a blind collaborator who interacted with printed tactile scatterplots during the design session to help create an audio-tactile design space for touchscreens. These sessions highlighted the need to support multi-finger interactions, build scaffolds to help abstract perceiv-

able system output to data tasks, and allow personalizable sound design. Through an in-depth expert review with two blind professionals, I assessed the utility of TactualPlot.

7.1.3 Comparative Study of Modalities

I conducted an experiment that compared the efficacy of sound (Olli), touch (Monarch RTD), and the combination of sound and touch (TactualPlot) across different chart types (scatterplot, line graph, bar chart, and pie chart) and tasks. The results indicated that TactualPlot generally led to better accuracy. The Monarch often resulted in lower completion times. Qualitative insights from blind participants offered perspectives on the use of sound versus touch in data interpretation.

7.1.4 Co-designing Tactile Graphics

I conducted a co-design session with a blind participant using the Monarch refreshable Braille display explored the challenges of visual analytics tasks when using novel refreshable tactile displays. This helped understand the challenges and opportunities that the blind participant faces while creating charts for the Monarch. The findings from this co-design session and the aforementioned comparison study indicated the need for standards, and multimodal support for accessible data visualization and data analysis tools.

7.1.5 Design Guidelines for Accessible Multimodal Visualizations

First, I derive design eleven guidelines for employing sensory substitution for chart accessibility. Next, the design of TactualPlot for scatterplots helped better understand the multimodal

design space. Based on the study findings, the dissertation discusses accessible visualization design considerations to guide technologists, researchers, and chart designers. These considerations include retaining visual structures of common charts, using a combination of sound and touch, supporting different levels of visualization tasks, and considering sociotechnical factors. Next, I conducted a comparison study of different modalities, and a co-design session to explore chart authoring for novel RTDs. The results from both these studies; reflections on my own design workflow, as a sighted person; and related work on multimodal accessibility underscores the critical need for standards, multimodal chart artifacts such as validated audio scales, and automated responsiveness to various novel RTDs. Finally, I discuss the implications of my findings on established Web Content Accessibility Guidelines (WCAG 2.1).

7.2 Future Work

Exploring effective spatial audio for TactualPlot: In the future, I would like to improve the TactualPlot technique and system by expanding the sound and verbalization design to support multidimensional data, uncommon and complex chart types such as Treemaps, Candlecharts. I believe that longitudinal design studies to conduct participatory design sessions with blind users and audio designers to qualitatively assess the expanded sound design and audio information seeking interface actions. This can help design audio scales for a combined visualization-sonification data representations. Future work can also explore the use of ADSR sound envelopes, and audio filters for audio waves (sine, cosine, saw-tooth, etc.) and testing with headphones capable of personalized spatial audio, such as Apple AirPods Max, to improve sound localization and enhance user experience is also a direction for future work. Audio libraries such as ToneJS

and Erie [161] make it feasible to computationally design audio tones, but there is limited research on audio perception, especially with spatial audio, related to audio-visual tasks with blind individuals.

Developing multimodal authoring tools: There is a recognized need to create systems that enable BLV individuals to author visualizations independently. Exploring accessible "linting" in Python notebooks [166] to assist sighted and blind individuals during data exploration is also relevant. Making chart libraries accessible and developing an adaptive approach of sonification and textual description solutions to support authoring, such as tactile Vega-Lite, are important future steps.

This dissertation contributes to a deeper understanding of how multimodal interactions on touchscreen devices can provide accessible data visualization for blind and visually impaired individuals. By investigating sensory substitution, developing and evaluating the TactualPlot system, comparing different sensory modalities, and exploring tactile chart creation, this research offers valuable insights and design considerations for creating more multimodal data experiences. Ultimately, this work aims to lower accessibility barriers, empower BLV individuals to actively engage with data, and foster collaboration in an increasingly data-centric world.

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