Slide-Tone and Tilt-Tone: 1-DOF Haptic Techniques for Conveying Shape Characteristics of Graphs to Blind Users

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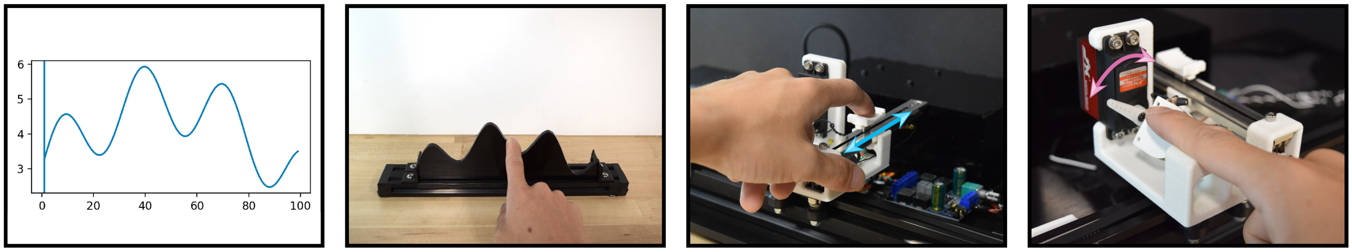

(a) Visual Graph (b) Laser-cut Profile (c) Slide-tone (d) Tilt-tone

Figure 1: Informed by formative workshops that explored how haptic cues for fingerpad position and inclination support shape perception of data graphs (a-b), we introduce two refreshable, 1-DOF audio-haptic interfaces for data exploration. Slide-tone (c) relies on finger position with sonification, and Tilt-tone (d) relies on fingerpad contact inclination with sonification to provide shape feedback to users.

ABSTRACT

We increasingly rely on up-to-date, data-driven graphs to understand our environments and make informed decisions. However, many of the methods blind and visually impaired users (BVI) rely on to access data-driven information do not convey important shape-characteristics of graphs, are not refreshable, or are prohibitively expensive. To address these limitations, we introduce two refreshable, 1-DOF audio-haptic interfaces based on haptic cues fundamental to object shape perception. Slide-tone uses finger position with sonification, and Tilt-tone uses fingerpad contact inclination with sonification to provide shape feedback to users. Through formative design workshops (n = 3) and controlled evaluations (n = 8), we found that BVI participants appreciated the additional shape information, versatility, and reinforced understanding these interfaces provide; and that task accuracy was comparable to using interactive tactile graphics or sonification alone. Our research offers insight into the benefits, limitations, and considerations for adopting these haptic cues into a data visualization context.

CCS CONCEPTS

• **Human-centered computing** → **Accessibility systems and tools**; **Visualization systems and tools**; **Haptic devices**.

KEYWORDS

haptic data visualization, accessibility, accessible data visualization

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1 INTRODUCTION

The rapid growth of computing resources and data during the digital age has changed the way we consume information. Line graphs are one type of data visualization that is increasingly used across a variety of applications, ranging from personal health and finance to climate trends and social issues [8, 11, 43, 64]. Users can quickly gauge a variety of information from a line's shape: how a variable changes over time, acceleration and deceleration, proportions

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of time above or below a threshold, inflection points in curves, magnitudes and locations of extrema, unusual patterns, and more. However, such data visualizations, which are critical for processing and building intuition of data-driven information, [30], are largely inaccessible to people who are Blind and Visually Impaired (BVI) [27, 39].

Tactile graphics are often used to provide access to this information for BVI users. However, because their production requires significant time, design expertise, and specialized equipment to produce [38], they are rarely used for the many data-driven applications that require up-to-date information [41]. Recent studies show that data-driven information, particularly trend-type information, are still largely inaccessible to people who are blind and visually impaired (BVI) despite widespread need for access [76].

Alternatively, sonified representations of data graphics only require the audio capabilities ubiquitous to common computing devices and are much easier to make widely available. Sonification schemes that provide a direct translation of a data waveform to the audible domain [24] have recently gained traction for use in practice [1, 2, 4, 5] and have been shown to be effective for a variety of data-visualization tasks [95, 102]. Drawbacks to these approaches are that they require additional layers of cognitive mediation that may demand greater attention and do not directly specify spatial relationships [38]. How effective different types of shape parameters can be simultaneously conveyed through sonification remains an open question. In a data visualization context, prior work has found that unfamiliar users are sometimes not confident in their interpretations of sonified graphs [76].

We believe that there is a need and opportunity for a device to enable low-cost haptic interactions to augment sonification and provide more comprehensive and robust means to consume data. Prior work has shown that haptic feedback can improve task performance, reduce workload, and improve recall when used in conjunction with sonification [44, 95]. However, these studies investigate simple bar graphs and rectangular maps, in which understandings of shape features such as slope and curvature are less important. Other studies have looked towards both kinesthetic and cutaneous-based devices to provide more refreshable and interactive access [29, 31, 69, 77, 83, 90, 97]. However, the cost of kinesthetic devices makes them prohibitively expensive for widespread use, while cutaneous-based devices typically lack explicit guidance cues, which may require users to exert significant mental effort to build a global overview [67].

To provide a refreshable, low-complexity method for conveying the many important shape-characteristics of line graphs in a data visualization context, we looked towards haptic perception literature. When a finger traverses along a curved surface, the position of the finger follows the position (0th order) of the contact surface, and the angle of contact between the surface and the finger (which we will call finger contact inclination) follows the orientation (1st order) of the contact surface, which changes as a function of the surface profile. Prior work has found finger position and finger contact inclination to be important cues that are natural to object shape perception, and have investigated the importance of these cues for curvature perception and shape discrimination [26, 58, 91]. In this work, we investigate how these haptic cues are used by BVI persons to support shape understanding and what interactions are important to consider for data exploration.

We begin our investigation by conducting a series of design workshops with blind users (n=3) to better understand how to support finger position (0th order information) and finger contact inclination cues (1st order information) in a data visualization context. We found that compared to tactile graphics, laser-cut cutouts, which users perceive using both cues, felt more salient, were easier to trace, and conveyed sharp corners and high-density features more effectively. When using these cues in a data visualization context, participants recommended a series of touch-based and speech-based interaction techniques, which include providing a verbal gist of the context and enabling on-command speech output of specific values.

Based on these findings, we introduce two interactive multimodal prototypes to investigate the use of fingerpad position and inclination cues for exploring line graphs. The first system, Slide-tone, uses a combination of sonification and finger position cues provided through a motorized slider to convey and reinforce the y-value progression of a line-graph trend. The second system, Tilt-tone, uses the same sonification scheme to convey the value-progression, and fingerpad contact inclination cues to convey the slope-progression of the line graph. An evaluation comparing both systems found that participants appreciated the additional shape information, versatility, and reinforced understanding these simple haptic cues provide; and that accuracy of four data tasks was comparable to using interactive tactile graphics or sonification alone.

Our paper contributes:

1. The design and evaluation of two audio-haptic systems that provide haptic shape, sonification, and speech output for accomplishing data visualization tasks.
2. Types of shape-based data visualization features participants were able to identify using the different data exploration methods.
3. Insights into participants' strategies and experiences forming mental models and retrieving information across the different audio-haptic schemes.
4. Generalized design considerations and recommendations for multimodal and digital data interfaces.

2 RELATED WORK

2.1 The Data Accessibility Gap

Making informed decisions using data is a critical skill for both personal and professional matters [38]. Gorlewicz et al. characterize the lack of access to graphical material as *"one of the biggest challenges to the independence and productivity"* of BVI people, having *"detrimental effects on the educational, vocational, and social prospects for this demographic"* [38]. Recent studies highlight some of the gaps that persist in making data accessible to BVI screen reader users [41, 74, 76]. Sharif et al. found that BVI screen reader users, when interacting with digital data visualizations, spend significantly more time and are less accurate extracting information compared to their sighted peers [74]. Data visualizations available on the web either encourage presentation of a textual alternative (alt text) or a tabular representation [74]. Textual representations offer a more subjective lens and do not provide direct access to the data [76]. Tabular representations, on the other hand, impose high cognitive load [47, 80] and lack support for gaining a holistic understanding of the data [74, 76]. Siu et al. also report on factors that affect users' confidence, including users not being able to make their own interpretation or not receiving access in a timely manner [76]. There is a need for accessible data systems that support timely and independent access and enable users to draw their own interpretations from the data to make informed decisions.

2.2 Multimodal Data Exploration Systems

Multimodal interfaces including both audio and haptic affordances have the potential to be more effective for a larger number of users [33, 48]. We review several systems that leverage multimodal feedback to improve access to data for BVI users.

The use of non-speech cues, such as in sonification, has been used to effectively complement access to data through commonly-available tabular representations [71, 80]. Sonification can be effective at providing a quick auditory overview of large amounts of data [88]. Recently we have seen a number of these technologies used in practice to support access to real world data charts for education and personal matters [1–3]. Auditory displays can deliver a high level of detail, but with multiple mapping possibilities and few standards in place [73], users are generally not confident in their interpretation [76], and "good strategies" for formiing accurate interpretation need to be learned [40, 102]. However, a considerable advantage of auditory displays is that information can be easily supported across common audio-enabled devices.

Compared to auditory representations, touch-based solutions are considered the most suitable for BVI users to access highly spatial and graphical information such as data charts [67]. Traditional approaches to producing tactile material (e.g. raised line drawings, embossed reliefs) can be slow and costly as they often require specialized equipment and expert designers [38]. More critically, they often result in hard copy graphics, which offer limited updatability and reduced information density to avoid tactile clutter [38, 67]. Several studies have investigated audio-augmented tactile graphics that offer some limited interactions and help reduce tactile clutter [12, 32, 57].

Interactive haptic systems can offer up-to-date access and more interactions for exploring data (See Holloway et al. [20] for a recent review). Prior work has shown that haptic feedback can improve task performance, reduce workload, and improve recall when used in conjunction with sonification [44, 94]. Yu et al. investigated the use of a kinesthetic force-feedback device and sonification for exploring bar charts [94]. They found that audio was useful for getting a gist of the data while the haptic feedback was useful for navigation/localization, comparing/confirming relative sizes of bars, and reducing ambiguity in the audio representation [94].

Other haptic systems have investigated cutaneous-based devices. Earlier studies have explored mounting tactile displays onto a computer-mouse form factor to communicate shape, and found the feedback to be too limited in size and resolution to be effective [89, 92]. More recent studies have shown that vibrotactile feedback on touchscreens can communicate simple graphs [34] and graphical components [37] successfully to blind users. However, cutaneous-based shape exploration typically relies on sequential exploration [52, 96] without guidance cues that involves significant mental effort to build a global overview [67, 96].

These prior studies investigated simple data charts (e.g. bar charts), in which understandings of shape features such as slope and curvature are less important. Moreover, the cost and complexity of these haptic devices make them prohibitively expensive for everyday use. In this work, we investigate low cost and low complexity haptic devices that complement sonification methods. We focus on supporting multimodal interactions for data exploration of line graphs based on complex real-world datasets.

2.3 Haptic Shape Perception

The exploratory procedures (EPs) supported by a given medium can impact the efficiency of shape recognition [45, 51, 75]. When certain EPs are restricted, shape recognition performance can decrease [52]. A study comparing embossings versus cutouts of tactile graphics found that displaying the information as cutouts allowed users to better acquire global shape information [45]. The increase in performance is attributed to cutouts allowing users to leverage enclosure EPs as opposed to strictly contour following EPs with embossings [45, 52]. Prior studies assessing haptic performance tasks with BVI users have shown that the use of multiple hands and fingers, which allows more diverse EPs, offer a significant advantage [61].

Prior work has also investigated important characteristics for haptic shape perception, including: the role of passive vs. active exploration [26], the contribution of finger position (0th order information), and finger contact inclination (1st order information) [58, 91]. Dostmohammad et al. conducted a study to understand the effects of these characteristics on curvature discrimination (concave vs. convex). The study found that actively exploring the surface provides a significant advantage on curvature discrimination compared to passive exploration of the same stimuli [26]. Wijntes et. al. found that the trajectory of the contact region on the fingered is a sufficient cue for discrimination [91]. In a slightly different task, Kuchenbecker et al. found that displaying contact location significantly improves user's ability to follow a contour [49]. Dostmohammad et al. also found that multiple contacts has a small but significant advantage [26].

Several systems have applied these concepts to support active shape perception using lower degree-of-freedom haptic devices [59, 68, 70]. Memeo et al. designed a haptic mouse capable of rendering surface elevation (0th order) and slope (1st order). A study comparing 0th and 1st order cues found that there is less variance in discrimination when 1st order cues are provided, but providing additional 0th order cues alongside 1st order cues reduces mental load [59]. These studies have involved simple curvature discrimination tasks with sighted users. Other works with BVI users have explored haptic shape perception in combination with auditory modalities for other application contexts, which include teaching shape trajectories [22, 62] and editing audio waveforms [82]. In this work, we aim to extend the applicability of these concepts to support haptic shape perception of complex real-world data contours, which may involve different strategies from low-level curvature perception or shape recognition.

3 FORMATIVE WORKSHOPS

Engaging visually impaired users through user-centered design activities with physical mockups can be a powerful tool both for understanding the specific abilities of users and for informing design [82]. We organized formative 90-minute IRB-approved workshops with three participants to 1) better understand the use of 0th order finger position and 1st order contact inclination cues for feature identification and discrimination and 2) co-design ways to support important data-visualization interactions using physicalizations that provide these cues. Workshops were semi-structured to focus discussion on the study objectives while encouraging open dialogue, ideation, and reflection on perceptual and data experiences. A smartphone mounted to a gooseneck stand recorded videos of conversations and participants' interactions throughout the workshops. Below is a summary of workshop activities; the full protocol is included in the supplementary materials.

Due to the COVID-19 pandemic, separate workshops were held for each individual in accordance with Stanford University and government health and safety guidelines. On a 5-point Likert scale (1 to 5 with 5 indicating highest), participants' self reported extremely high levels of familiarity with braille (5), varying familiarity with tactile graphics (2 to 4), sonification (2 to 3); and varying levels of comfort with data manipulation (2 to 5). Each participant received a 50 USD Amazon gift card as compensation for their time. Appendix Table A contains a breakdown of demographics by participant.

3.1 Workshop Activities

3.1.1 Understanding Shape Perception of Line Graphs. In the first activity, we presented a series of 2.5-dimensional laser-cut cutouts to understand how participants might use 0th order finger position and 1st order inclination cues to explore and perceive different features. The goal of using generic, low-fidelity mockups was to promote conversation around these haptic cues without biasing discussion to a particular type of device or actuation scheme. Participants could perceive both cues by running their hands over a half-inch edge that outlined the shape of the graph, which was vertically mounted to be perpendicular to the plane of the table (Figure 2a). As a secondary objective, because tactile graphics convey line graphs in the tabletop plane while 1st order inclination cues are better suited to convey graphical information in the perpendicular plane, we wanted to also understand whether the orientation of the physicalizations made a difference in feature perception and user strategy.

Each cutout outlined the shape of a graph trend, and was designed to highlight different facets of shape perception that may be relevant for data-driven information, which include curvature discrimination, identification of sharp corner features, feature height comparisons, and general trend perception with low and high frequency features. We provided tactile graphics analogues of the cutouts showing the same trends as a reference and for comparison. The tactile graphics were constructed in accordance with the Braille Authority of North America (BANA) guidelines [65]; the graphics used thick bold lines to render trends and thinner dotted lines to convey gridlines (Figure 2b).

For each shape outline, we provided the tactile graphic and cutouts separately, and asked participants to describe the overall shape, features that stood out, and any challenges using a think-aloud protocol [84]. While participants explored the cutout, we made note of participants' hand movements, comments describing the general shape of the graph (increases, decreases, curvature, sharp features, relative heights of features), discrepancies between verbal descriptions and feature shape, and recurrent themes in conversations. After exploring the set of three shape outlines, we discussed with participants their general impressions of the tactile graphics and cutouts, as well as the strategies they used to perceive features.

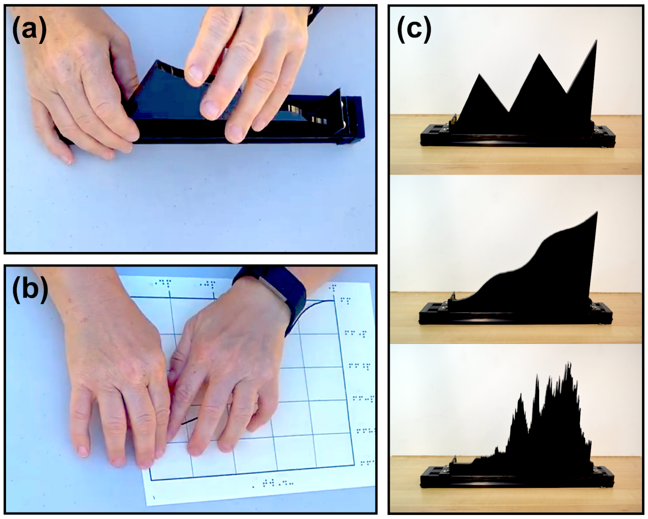

Figure 2: In the formative workshops, participants explored line graphs presented through a) static cutouts and b) a standard tactile graphic. c) Participants explored a variety of datasets emphasizing different shape-features. Our observations highlight some of the potential benefits of cutouts in guiding exploration and making some shape features more perceivable.

3.1.2 Investigating Multimodal Interaction for Data Exploration. In the second activity, we used a different series of laser-cut cutouts to explore how participants might use the cutouts in a data-visualization context. These cutouts were constructed from real stock market and COVID-19 data. We first provided participants with contextual information about the plot, which consisted of what it represents, the x-value range, and the y-value range. Participants were then instructed to freely explore the plot and comment on features that stand out. We then brainstormed interaction techniques with participants as if the cutout was a "smart" interface that could sense their voice and hands, change shape, and vocalize information. To ground these interaction techniques, we provided several data visualization tasks, such as identifying extrema, retrieving values, estimating averages, and understanding ranges. When possible, we also encouraged participants to further explore several interaction ideas using Wizard-of-Oz techniques [23]. For example, if participants wanted to explore the use of haptic gestures to retrieve specific types of information, we articulated the requested information upon seeing the gesture, acting as gesture-sensing and speech output augmentations to the cutout.

3.2 Workshop Results

3.2.1 Shape Perception and Exploration. Our early observations point to several potential advantages and trade-offs that the cutout provided compared to the tactile graphic for shape discrimination. First, we observed that while both representations provide 0th order finger position cues, several participants (P1, P2) thought that the cutout provided a more *"realistic"*, *"dramatic"*, and *"distinct"* representation of the graph shape. As P1 slid their finger back and forth on the cutout, they described that *"the cutout felt more realistic in the way it dipped. You could clearly feel it"*. These observations suggest that 1st order finger contact inclination cues may contribute to a more distinct impression of shape. This impression may be due to the fact that BVI people have far more experience haptically exploring 3D physical objects through activities in their daily living as opposed to tactile graphics, which are not common in daily life. Researchers have hypothesized that this discrepancy may explain preferences and performance gains for 3D printed maps over tactile graphic maps [42].

Second, participants traced along the shape features of the cutout more easily than the tactile graphic. With the tactile graphic, participants (P1, P2) had difficulty following along curves that had sharp corners and regions with high line density, misinterpreting sharp corners as discontinuities and regions with high line density as multiple data series. These were features where directional cues for determining subsequent hand movements were more difficult to discern. In contrast, participants were able to more easily trace the cutout edge with their finger and accurately describe the overall shape of the graph. As participants navigated horizontally across the cutout edge, the impenetrable boundary effectively acted as a physical guide that directed finger exploration along the shape of the curve. These observations show how physical movement constraints could serve as guides to help facilitate better understanding of complex curves, such as those with sharp and high density features.

Third, we observed that all participants were able to accurately articulate features and overall shapes— including rises, falls, curvature, sharp points, and relative heights— simply by sliding one or two fingers over the top ridge of the cutouts from left to right. In contrast, participants often needed to devote a two-handed contour-following strategy to trace along more complicated features on the tactile graphic, in which one finger searches for new regions of the curve while another finger provides an anchor for the leading finger to move back to. These observations suggest that users may be able to quickly explore graph shapes through sequential, single-finger approaches when receiving finger position and contact inclination cues.

Fourth, all participants were generally receptive to vertically orientated physicalizations of graphical shape features. P1 said that the vertical orientation provided *"a better understanding of height"*. However, they expressed concern about the ergonomics and comfort of keeping their hands elevated or bending their wrist to perceive the top edge of the cutout for long-term exploration. P1 also appreciated how they could *"actually measure the height, can physically measure it"* by anchoring one finger at the base and their index finger at the top.

3.2.2 Interactions for Data Exploration. Participants suggested several interactions to support data exploration with the cutouts. Participants emphasized hypothetical techniques using both touch and speech output if the cutout were to become a "smart" data visualization interface. *"As you touch a spot, [it] would be helpful to get the date and the stock value...Maybe when you slide, it could tell you the minimum or maximum value of the range (P2)"*. With sound, P1 described, *"you could do so much. You could give people a lot of information"*. They continued to explain that they *"like the audio part of it, like the idea of the sounds, not just by voice...Something that really connects you to what people could be studying"*. Speech cues could be used to provide information on labels [18] while non-speech cues, such as sonification, could be effective in providing a global understanding of the graph [28, 102].

All participants recommended that regardless of the interface, contextual information should be provided prior to exploration. The context should include the title, axes, units, range; and ideally some method to provide a global picture of the graph. Prior work with digital interfaces found that similar contextual information was important prior to exploration [10, 102]. Before being provided the data context, P2 had trouble distinguishing data features on the tactile graphic. After being provided the context, they described: *"Once I knew what it is, then I could say I understand, but it took that context…I think for these graphics, I think its very important to have contextual information"*.

Participants also recommended having a method to retrieve specific aspects of the data-driven information on demand. We used Wizard-of-Oz techniques to test different retrieval interactions that provided access to the data through hypothetical speech output. P1 incrementally retrieved values at points of interest and remarked that they *"can really picture [the graph] with the values"*, furthering the idea that having data-information can aid spatial understanding. After prototyping several retrieval schemes with different data visualization tasks, P2 preferred separate commands for retrieving x and y values and *"getting the value when I want to. You just don't want to get overloaded with audio information"*. P2 and P3 recommended using the speech interface to determine additional pieces of information as well. These suggestions included methods to determine the maxima and minima, to retrieve averages, and to highlight particular areas of the graph.

P1 cautions that speech output should work synchronously, and could not replace understandings gained through touch. *"In teaching, if someone can feel a structure, they get a better idea visualizing it in their head. For example, with biology, it can show me the shape of a kidney. If someone tried to describe the shape to me, I couldn't understand it as well as me actually feeling it"*.

4 1-DOF HAPTIC INTERFACES FOR DATA EXPLORATION

We were encouraged from observations of workshop participants that finger position and contact inclination cues could effectively convey shape characteristics, even through single-finger approaches. To investigate the contributions of these cues further and integrate data interactions suggested from the workshop, we introduce two interfaces for multimodal data exploration: Slide-tone and Tilt-tone.

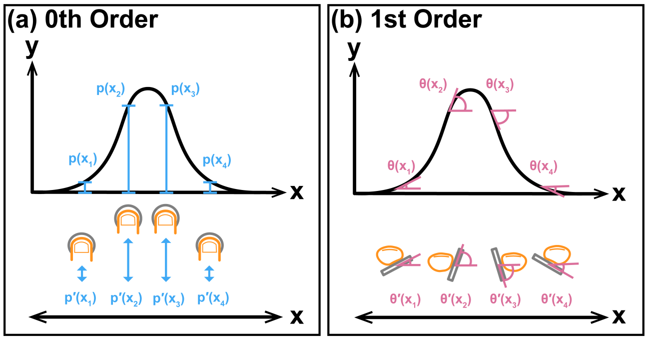

Figure 3: In Slide-tone (a), a platform conveys 0th order position cues by moving the user's finger position ($p'(x)$) corresponding to the trend's height ($p(x)$) across different x-positions. In Tilt-tone (b), a platform provides 1st order inclination cues by tilting so that the contact surface angle ($\theta'(x)$) corresponds to the angle the trend's local tangent makes with the x-axis ($\theta(x)$) across different x-positions.

4.1 System Overview

In line with recommendations provided by Zhao et. al. for auditory data exploration [103], Slide-tone and Tilt-tone provide a set of interactions that support the following actions: *gist*, *navigate*, and *details-on-demand* [103]. Users can listen to an audified *gist* that conveys important data visualization context, such as the title, axes labels, units, and ranges. Users *navigate* the graph by actively moving a sliding platform with their exploration hand. The horizontal position of the platform corresponds to the user's position along the x-axis. Users can also press separate buttons to listen to specific x and y values *on-demand*, as recommended by workshop participants.

Additionally, in Slide-tone, we emulate the 0th order positional feedback users would have access to if tracing their finger along a physical edge in the shape of the graph's trend. As the user moves their hand horizontally to traverse across the x-axis, a translating platform guides their index finger's position ($p'(x)$) back and forth along a trajectory that maps linearly to the trend's height ($p(x)$) (Figure 3a). Based on ergonomic considerations from the workshop, the sliding motion is oriented along the plane of the table to more comfortably support exploration.

In Tilt-tone, we emulate the 1st order contact surface angle the user's index finger would make if placed on a physical edge that is in the shape of the graph's trend. As the user moves their hand horizontally to traverse across the x-axis, a tilting platform adjusts inclination ($\theta'(x)$) to correspond with the angle that the trend's local tangent makes with the x-axis ($\theta(x)$) (Figure 3b).

In-line with our goal of exploring low cost and multimodal data visualization exploration methods, we also provided interactive sonification driven by horizontal sliding movement to both systems. Given that 1st order finger contact inclination cues do not directly provide access to y-values, sonification helped fill this data-access gap of the Tilt-tone system.

4.2 Interface Implementation

Figure 4a shows the tabletop prototyping platform used by both systems. The platform consists of a gantry plate that slides along a horizontal rail which enables $20cm$ of exploration space. A belt attached to the platform drives a rotary encoder to measure the platform's horizontal position. Two sets of value-retrieval buttons sit on both sides of the rail to accommodate both left and right-handed operation. Pressing the top and bottom buttons of each set provides the user with speech output of x and y data values associated with the horizontal position of the plate along the rail respectively. The speech output is provided through macOS' (version 10.15.5) native text-to-speech capabilities.

Mounted to the right side of the gantry platform and perpendicular to the x-axis rail is a motorized fader (RSA0N11M9A04) with a 3-D printed finger platform (Figure 4b), which we call the motorized slider. In Slide-tone, as a user moves the gantry plate along the x-axis, the user's index finger is guided back and forth along the motorized slider to provide 0th order finger position cues of corresponding y-value. We drew inspiration from Tanaka et. al., who used a similar scheme to provide kinesthetic renderings of audio waveforms for audio editing [82].

Figure 4b shows a close-up of the sliding mechanism, and Figure 4d shows how the finger platform moves to convey a trendline. A PD controller keeps the finger platform at the desired position corresponding to the graph. Operating at $9V$, the motorized slider system supplies $2N$ of force under stalled conditions, and has a $0.34s$ 10%-to-90%rise time under no-load conditions. The system provides $6.6cm$ of finger-movement range for the study.

Mounted to the left side of the gantry platform is a 3-D printed finger platform mounted onto a servo motor (JX-PDI-6802MG). In Tilt-tone, as a user moves the gantry plate along the x-axis, the finger platform tilts to provide 1st order inclination cues to the user's finger corresponding to the trend's local tangent. Figure 4c shows a close-up of the tilt mechanism, and Figure 4e shows how the finger platform moves to convey a trendline. Operating at $4.8V$, the servo has a specified stall torque of $6.8kg/cm$ and an operating speed of $0.07s/60deg$.

A Python library was written to compute sonified tones, target positions for the motorized slider in Slide-tone, and target tilt angles for the servo motor in Tilt-tone, based on an imported time-series dataset. For Slide-tone, linear changes in the y-value are mapped to linear changes in the motorized slider position and logarithmic changes in the sonified frequency, based on recommended sonification guidelines [19]. A low-pass filter with a cutoff frequency of 1kHz was applied to improve the perceived smoothness of the slider's motion. For Tilt-tone, the same sonification mapping was used as in Slide-tone. However, to reduce high-frequency masking of broader low-frequency trends and to improve the perceived smoothness of the system's motion, a low-pass filter attenuates the haptic rendering of features smaller than 5% of the graph following guidance from pilot participants. The inclination was then computed based on tangents of the graph, with the maximum absolute angle normalized to a 60-degree tilt of the platform. Slider positions and tilt angles are serially communicated to a Teensy 3.2 microcontroller that controls the haptic hardware. The microcontroller

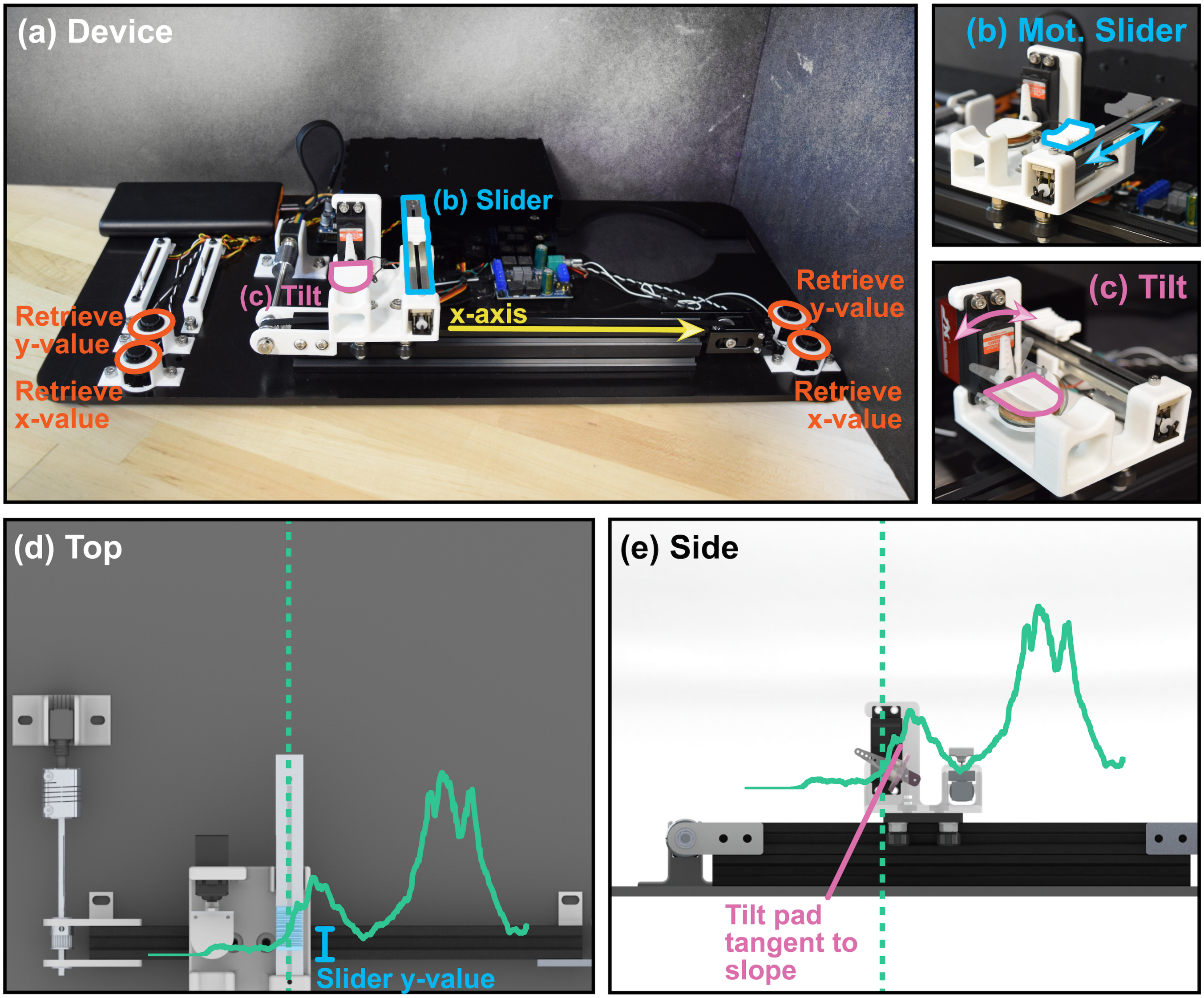

Figure 4: Users slide a platform along a rail to actively explore line graphs (a). In Slide-tone, a sliding platform (b) provides position feedback of the trend's height (d) to the user's finger. In Tilt-tone, a tilting platform (c) provides inclination feedback of the trend's local tangent (e) to the user's finger. Both systems provide sonification and x-value, and y-value retrieval through speech output.

communicates the platform position with 0.2*mm* precision back to the Python script.

5 PROTOTYPE EVALUATION

We conducted an IRB-approved controlled study to evaluate user performance and experience using Slide-tone and Tilt-tone benchmarked against sonification and tactile graphics. In these studies, participants completed a set of data visualization tasks using the four different modal schemes in a within-subject experimental design. User performance was measured through task completion accuracy and time. User experience was investigated using both qualitative and quantitative metrics. To provide a more holistic perspective on the use of these schemes in a data visualization context [50], we collected subjective ratings of performance, mental effort, and frustration; task-completion strategies; think-aloud transcripts; and post-experiment interview responses. Additionally, participants were asked to explore, describe, and optionally sketch data trends prior to completing the tasks to assess the types of features participants could identify using each modal scheme. The full protocol is included in the supplementary materials.

5.1 Participants

We recruited 8 different participants than from the formative workshops through local San Francisco Bay Area community organizations. The study took roughly 90-minutes to complete. Four participants self-identified as totally blind and four self-identified as very low vision. Two participants lost their sight after the age of 40, while others had consistent levels of vision from a very young age (<3 yrs old). On a 5-point Likert scale (1 to 5 with 5 indicating highest), participants' self reported varying levels of familiarity with braille (1 to 5), tactile graphics (1 to 5), and sonification (1 to 4); and varying levels of comfort with data manipulation (2 to 5). All participants indicated having primarily interacted with data graphs either haptically (P1, P2), or auditorily (P3-P8), such as through the use of a screen reader. Each participant received a 50 USD Amazon gift card as compensation for their time. Appendix Table A contains a breakdown of demographics by participant.

5.2 Materials & Methods

5.2.1 Conditions. The study had four conditions: 1) *Interactive Tactile Graphic*, 2) *Sonification Only*, 3) *Slide-tone*, and 4) *Tilt-tone*.

In the *Interactive Tactile Graphic* condition, participants explored data through an embossed line graph (A4 sheet of paper) that was overlaid on a touchscreen device (Microsoft Surface Book 3). The tactile graphics used for this condition were constructed similar to the workshop graphics. To keep the availability of information consistent across conditions, we added two embossed touch-buttons located on the bottom-left corner of the screen that allowed participants to retrieve specific x and y-coordinate values based on the location of an exploration finger on the graphic. We also provided touch interactions that spoke the contents of braille labels through text-to-speech for non-Braille readers.

In the *Sonification Only* condition, participants heard a sonified tone corresponding to the position of the platform as they actively moved the platform along the x-axis rail. Participants also had the option to retrieve specific x and y-coordinate values using the buttons (Figure 4a).

In the *Slide-tone* condition, participants had access to all the interactions available in the *Sonification Only* condition in addition to the 0th order position cues provided by the motorized slider (Figure 4b).

In the *Tilt-tone* condition, participants had access to all the interactions available in the *Sonification Only* condition in addition to 1st order inclination cues provided by the tilt platform (Figure 4c).

5.2.2 Dataset. To assess the ecological validity of the data exploration systems, we use real-world datasets that were relatively complex (Figure 5). The datasets depicted the progressions of daily new COVID infections over the State of Nevada [60], the price of General Motors stock [93], Google searches for the term "unemployment" [36], and a sample bank account checking balance. All of the datasets contained several global inflection points as well as local high-frequency information at different regions. Figure 5 shows the tactile graphic versions of the datasets used in the study.

5.2.3 Data Visualization Tasks. For each condition, we asked participants to complete a set of four data visualization tasks based on fundamental data literacy questions proposed by Boy et. al. [16]. These tasks were chosen to be broadly familiar to participants, general for a variety of visualizations and use cases, and require spatial intelligence and mental projections rather than mental math [16]. The ordering of the tasks was the same for each condition. The first task (maximum localization) asked participants to identify the x-location of the maximum, and required participants to successfully identify the peak to complete the task. The second task (value comparison) asked participants to compare between y-values of two x-values, and could be aided through a general understanding of the curve shape. The third task (value retrieval) asked participants to retrieve the y-value at a specific x-value, and did not require an understanding of the shape information. The fourth task (mean estimation) asked participants to estimate the average, which like the second task, could be aided through a general understanding of curve shape.

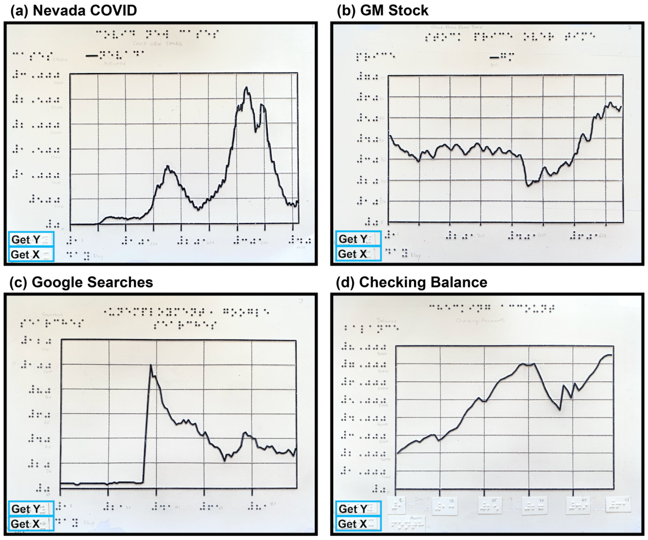
(a) Nevada COVID
(b) GM Stock
(c) Google Searches
(d) Checking Balance

Figure 5: Four datasets were used in the evaluation (a-d). Images show the tactile graphic representation.

5.2.4 Study Setup. Participants interacted with the study interfaces on one side of a table. On the other side of the table, we as study facilitators controlled a pre-prepared Python script to progress through the study protocol, dataset-condition pairings, and tasks. The script also allowed us to record and log task completion times. A smartphone mounted to a gooseneck stand recorded videos of participants' interactions and conversations for the entire study length.

Participants wore Audio-Technica ATH-M50X over-the-ear headphones connected by auxiliary cable to receive audio and speech cues. We were able to monitor the audio volume and quality with a separate pair of headphones connected by a two-way splitter.

Due to the COVID-19 pandemic, we took additional health and safety precautions in accordance with health and safety guidelines, which include masking, social distancing, providing disposable earmuffs, and additional sanitization and disinfection. To reduce transmission risks to participants, studies were either conducted in pre-approved and health-compliant spaces, or in secluded outdoor locations at or near participants' residences. For outdoor locations, we provided tables and chairs for the study. Locations were selected to be convenient for participants and minimize potential external distractions.

5.3 Study Procedure

After filling out a consent form and demographics questionnaire, we guided participants through a 30-minute training exercise to familiarize participants with the different conditions. Participants explored a series of simple line graphs with each of the four conditions, starting with the *Interactive Tactile Graphic*. We asked participants to describe the trend to confirm their understanding with each condition. Participants were also introduced to the concepts of finger location and contact inclination cues using a cutout similar to ones used in the design workshops. Value retrieval buttons and interactive features available in each condition were introduced at the end of the training session.

In each study condition, participants were assigned to explore one of the four data visualization graphs. A Latin squares design was used to counterbalance graph assignment and condition ordering. At the beginning of each condition, participants were first asked to take five minutes to explore and describe, with optional sketches on a tactile drawing pad, the overall trend in as much detail as they could without retrieving any specific values. Participants were then asked to complete four data visualization tasks for each study condition. We delivered the tasks verbally, instructed participants not to explore the graph until questions were finished being asked, and prompted participants to verbally articulate their final answer after arriving on one. We used a keystroke command to flag on the study script when the question was finished being asked and when an answer had been verbally articulated. Participants were also prompted to provide approximate answers as quickly as they could. Because the time and effort associated with narrowing in on exact values could be sensitive to spatial resolution differences between the touchscreen and the other interfaces, we encouraged approximate answers to better capture the perceptual and cognitive differences between the conditions. At the end of each condition, we asked participants to rate on a 7-point Likert scale their perceived performance, mental effort, and level of frustration in completing the tasks. Participants repeated this process for each of the four conditions.

Aside from when completing the data visualization tasks, participants were asked to employ a think-aloud protocol. We encouraged participants to describe the strategies they used in each condition. At the end of the study, we asked participants what they liked and found challenging in each condition, and for any open-ended feedback on the different data-exploration methods. The questions were meant to elicit summary comparisons between the conditions and capture any additional considerations that would not be captured through the study tasks alone.

5.4 Study Measures and Analysis

We gathered a variety of quantitative and qualitative data to form a more holistic understanding of the modal cues explored in the study. For quantitative data, which include task accuracy, time, and subjective ratings, we used a model comparison approach to make statistical comparisons. Qualitative data, such as identified graphical features, user strategies, think-aloud transcripts, and interview responses were captured through audio-video recordings and cross-referenced with key quotes we took note of during the study. We then de-identified, transcribed, and segregated the data into individual excerpts based on similarity; inductively coded the excerpts; and reported them quantitatively (as with graphic features and user strategies), or as broader themes that were constructed through a reflexive thematic analysis (as with think-aloud transcripts and interview responses).

5.4.1 Feature identification based on Trend Descriptions.

We analyzed transcripts of participants' descriptors of graph trends to understand the types of information participants could gain through the different study conditions. Because several participants had difficulty drawing or chose not to draw, we based our analysis on the provided descriptions alone in a protocol similar to that used by Carswell et. al., which coded and counted participants' descriptions of graphs by feature types [21]. Three members of the researcher team developed independent codebooks to categorize different visualization features from a subset of user descriptions, then jointly discussed and defined a final set of codes (Appendix Table B). We then classified all remaining trend descriptions accordingly. All feature types identified in the final codebook were relevant in all datasets.

5.4.2 Task Accuracy, Time, and Subjective Ratings.

We wanted to understand how the conditions compare for completing low-level data visualization tasks. Because we were more interested in overall condition effects, we chose to accommodate precision variations in the datasets and value retrieval methods by considering the maximum localization and value retrieval tasks correct if they fell within 10% of the data range, and the mean estimation tasks correct if they fell within 20% of the data range. Value comparison tasks were considered to be correct through the correct indication of whether one value was greater than or less than the other. In the *Interactive Tactile Graphic* condition, because the overlaid tactile graphic reduced the touch sensitivity of the touch screen, users sometimes needed to press on labels several times to activate value retrieval functionality. Times of repeated presses were subtracted from recorded task times in that condition.

A model comparison approach was used to test for the effects of condition and interaction effects between condition and task type on task performance [14, 15]. We fit a mixed effects logistic regression to predict task correctness and a linear mixed effects model with a Gaussian distribution to predict task completion time. We included condition, task, dataset, and two-way interactions between condition and task type as fixed effects; and a random intercept for each participant. Likelihood ratio tests compared a complex model to a reduced model with and without the effects of interest to determine the significance of those effects. A similar model comparison approach was used to determine the effect of condition on subjective ratings participants provided about perceived performance, mental effort, and frustration. For those results, the maximal model consisted of condition and dataset as fixed effects and a random intercept for each participant. Tukey correction was used used when making pairwise post-hoc comparisons.

5.4.3 Cross-Modal Strategies. To gain insight into how cross-modal strategies may have affected task accuracy and time, three members of the research team independently reviewed video footage of the study and provided a summary of the strategies participants used to complete each task. We first summarized a subset of the videos and then jointly discussed important strategies to observe. These included navigation trajectory, value retrievals, and when applicable, the use of multi-hand strategies and whether participants had their hands on or off the interface or the embossed line. We then summarized the remaining task videos.

Individual task strategies were grouped by similarity within each task under each condition. We formed sub-themes based on these groupings and used these sub-themes to construct overarching summaries of the strategies used in each condition. To ensure credibility and exploration of various aspects of the data, repeated discussions and debriefings were conducted among members of the research team.

5.4.4 Think-aloud Transcripts and Interview Responses. To gain insight into the broader practical considerations and participant preferences, we employed a reflexive thematic analysis [17] on think-aloud transcripts and interview responses to identify important overarching themes to consider when using these multimodal systems. We first decomposed verbatim transcriptions into individual excerpts. Data excerpts were then grouped by similarity and assigned summary statements using inductive and latent approaches. We formed sub-themes based on these summary assignments, which were then summarized into main themes that make up the individual sections of the qualitative results (Section 5.5.5). Repeated discussions and debriefings were conducted among members of the research team at each step of the process to ensure credibility and promote exploratory breadth.

5.5 Results

5.5.1 Features Identified Across Conditions. Figure 6 shows the number of features mentioned by participants in each condition. At least one participant made an observation for every feature we coded, suggesting that the identification of each feature was theoretically possible in all the conditions.

Several features were mentioned by a similar number of participants across conditions. Almost all participants (≥7/8) commented on the slope direction with each modality using phrases such as *"rising"*, *"falling"*, *"going up"*, etc. However, a low number of participants (2/8) made observations comparing the slope of one region of the graph to that of another in the four conditions. Half of participants made comparisons between the relative heights of features at different points of the plot (4/8), and a slightly higher number of participants used shape metaphors (5/8), such as *"s shaped"*, *"w shaped"*, *"wavy"*, *"bump"* to describe trends. The number of participants mentioning high-frequency variations varied slightly, though all the conditions fell between 3 and 5 participant mentions.

More participants commented on the curvature characteristics of the graph in the *Interactive Tactile Graphic* (5/8) and *Tilt-tone* (4/8) conditions than in the *Slide-tone* (2/8) and *Sonification Only* (1/8) conditions. Feature heights or y-positions were mentioned by more participants in the *Slide-tone* condition (6/8) than in the other conditions (3/8). Finally, more participants made comments on the location or length of features through *Interactive Tactile Graphic* (8/8) and *Slide-tone* conditions (8/8) than through *Sonification Only* (5/8) and *Tilt-tone* (4/8) through phrases such as *"in the beginning..."*, or *"for a while..."*, or *"...until the end"*.

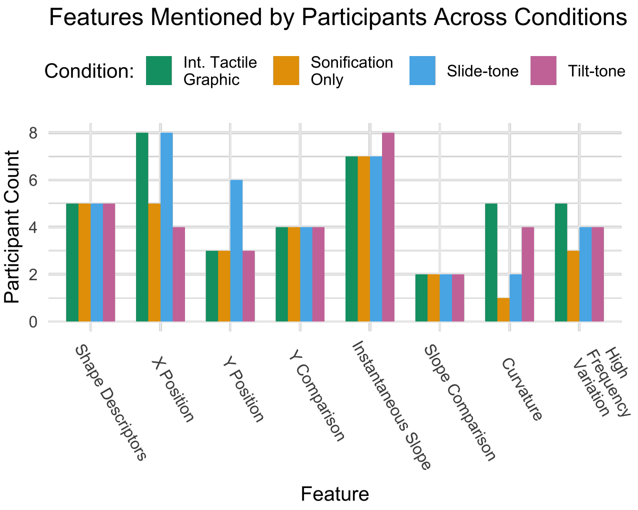

Figure 6: Coding of descriptions shows different features that participants identified in each condition.

5.5.2 Task Accuracy and Time. Figure 8 shows the number of correct responses for each task across modality. Condition did not have a significant effect on task accuracy ($\chi^2(3) = 0.80, P < .85$). A high number of participants (between 6/8 to 8/8) answered the maximum, comparison, and value retrieval tasks correctly for all tasks and conditions. Most incorrect answers either swapped x and y values, identified a local maxima as the global maxima, or did not provide precise enough values. The mean estimation task was relatively difficult for all participants, as only 1-3 participants answered the question correctly for each condition.

Condition had a significant effect on task time ($\chi^2(3) = 9.26, P = .03$) (Figure. 7). Post-hoc pairwise comparisons show a significant difference in task time ($t.ratio(11) = 2.91, P = .02$) in the *Tilt-tone* condition ($\bar{x} = 33, SE = 4.95$) compared to the *Interactive Tactile Graphic* condition ($\bar{x} = 50, SE = 2.85$). While not statistically significant, average task time using the *Interactive Tactile Graphic* was also highest out of all conditions for all but the maximum retrieval task.

As an additional check for study validity, particularly as we used four different real-world datasets across different applications for our evaluation, we ran additional likelihood ratio tests to assess the effect of dataset on task accuracy ($\chi^2(6) = 6.32, P = .39$) and time ($\chi^2(6) = 4.38, P = .63$). When controlling for condition and task as fixed effects and participant as a random effect, we found that dataset was not a statistically significant predictor.

5.5.3 Task Strategies. While task accuracy was similar across conditions, participants used several strategies that were grounded in their modes of exploration. With maximum localization tasks, all participants used the available audio or haptic feedback to first

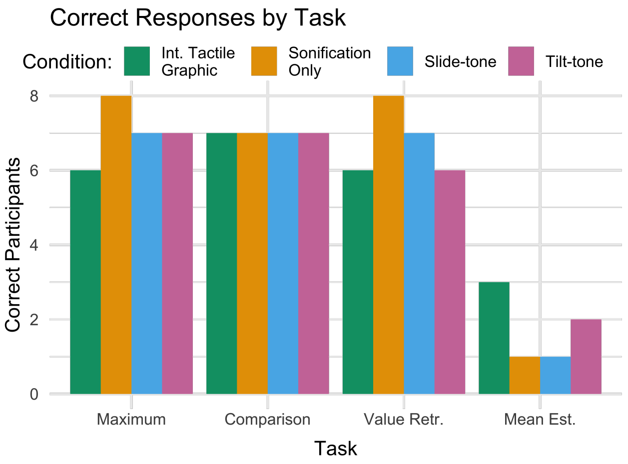

Figure 7: The number of correct responses for each of the data tasks. Higher is better performance. Accuracy was not significantly different across conditions.

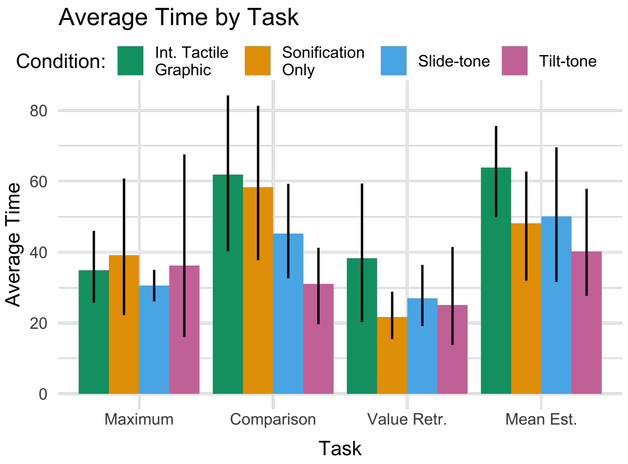

Figure 8: The average task time for each of the data tasks. Lower is better performance. Participants were significantly faster at completing tasks in the *Tilt-tone* condition than in the *Interactive Tactile Graphic* condition.

locate a perceived maxima before retrieving any values. One participant (P1) lifted their finger off of the fingerpad and relied on sonification alone in the *Slide-tone* condition.

With comparison tasks, a few participants in each of the conditions did not need to retrieve y-values, and relied on a combination of haptic and audio cues to make relative height judgments (P1-P4, P8). For example, P7 augmented Slide-tone with non-exploration fingers as markers on the motorized slider (0th order cues). These markers allowed them to easily gauge if and when another value exceeded a "marked" y-value. Two participants (P1, P6) using the interactive tactile graphic anchored one hand on the first value, navigated to the second value with their other hand, and used the relationship between both to compare between values. For most participants in most conditions, however, comparisons were accomplished by navigating to both x-positions to retrieve and compare their respective y-values.

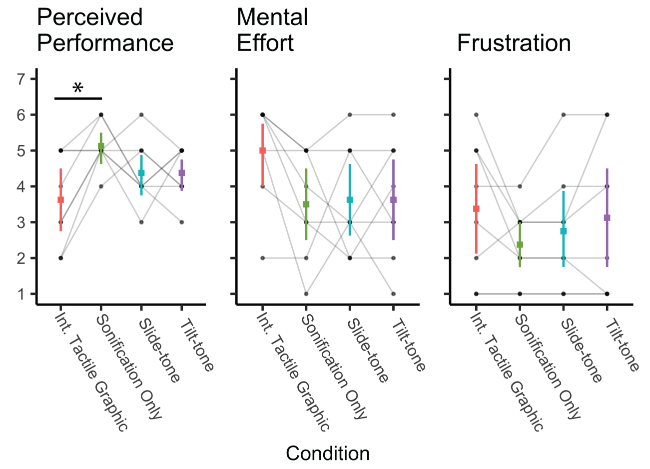

Figure 9: In each condition, participants reported their perceived performance, mental effort, and frustration. Participants' perceived performance was significantly higher in the *Sonification Only* condition than the *Interactive Tactile Graphic* condition. Post-hoc tests did not reveal any other significant pairwise contrasts.

The strategies participants used for the value retrieval task was mostly independent of the individual affordances available in each condition. All participants iteratively retrieved x-values until reaching the location of interest, and then retrieved the y-value to obtain the solution.

For mean estimation tasks, 2-3 participants sampled values along prominent features as they traversed along the x-axis to mentally form weighted estimates of the mean, 2-5 others in each condition mentally averaged values retrieved at evenly spaced intervals along the x-axis, and several participants simply averaged between the highest and lowest values within each condition.

5.5.4 Subjective Assessment. Figure 9 shows the mean and 95% bootstrapped confidence interval for the subjective ratings participants provided about perceived performance, mental effort, and frustration on a 7-point Likert scale from 1 (extremely low) to 7 (extremely high). Condition had a significant effect on perceived performance ($\chi^2(3) = 10.22$, $P = .02$) and mental effort ($\chi^2(3) = 8.77$, $P = .03$), but not frustration ($\chi^2(3) = 4.32$, $P = 0.23$) when controlling for dataset as a fixed effect and participant as a random effect. Post-hoc tests showed *Sonification Only* ($\bar{x} = 5.13$, $SE = 0.23$) and *Interactive Tactile Graphic* ($\bar{x} = 3.63$, $SE = 0.46$) conditions to be significantly different ($t.ratio(18) = 3.07$, $P = .03$) for perceived performance. Dataset was not a statistically significant predictor of perceived performance ($\chi^2(3) = 0.35$, $P = .95$), mental effort ($\chi^2(3) = 4.28$, $P = .23$), and frustration ($\chi^2(3) = 1.83$, $P = .61$) when controlling for condition as a fixed effect and participant as a random effect.

5.5.5 Qualitative Results. Accuracy and task completion time measures only capture one aspect of data visualization [63]. Qualitative transcripts gathered from think-aloud protocols and interviews captured more information about user experiences and preferences when using the modal cues in a data context.

Sonification provides quick overviews and is efficient for data visualization tasks, but is less effective for conveying important shape characteristics such as curvature.

In this study, several participants indicated that sonification was actually easier (P1), clearer (P3), and quicker (P1, P3, P7) than tactile graphics for exploring the real-world datasets used for the study. P1 indicated a preference for sonification to *"get a quick overview"*, while P7 would use it to crunch data as *"fast as I could"*. Participants thought several data features were easy to understand through sonification alone, including relative heights (P1, P7), extreme features (P7, P8), and whether the slope was moving up or down (P2, P8).

However, some participants (P1, P2, P7) thought that understanding other features, such as the magnitude of slope and curvature, were much more difficult to do using sonification. When exploring a training curve that contained peaks of varying sizes, P2 said *"I can sense the steepness but I can't sense how steepness varies across the different peaks as clearly"*. For an exponentially rising curve, P1 described that they were not able to *"detect [the increasing slope] so well with just the audio, because [it] does not tell me the slope at any point"*.

0th order finger location cues provide a versatile, more absolute method for understanding shape in data-visualization contexts.

Two participants (P7, P8) felt that the 0th order finger location cues perceived through the motorized slider provided the most versatile method for understanding a variety of shape features in a data visualization context. While P7 indicated a preference towards sonification for quick data manipulation, they described how *"if I only had one out of sound, tilt, and slider, I would go with the slider… I could tell [acceleration of changes] right away, as well as max min, and on average if its going up and down, and use that as a vehicle for identifying averaging"*.

The same two participants (P7, P8) articulated that the motorized slider provides an effective way to understand both absolute slope and curvature, features that several participants (P1, P2, P7) indicated were challenging to perceive using sonification. *"The slope of each side of the peak or valley is better communicated because the tactile feedback is moving much quicker when the slope is steeper and not as quickly when the slope is not (P8)"*. In addition to providing a better sense of slope, half of the participants (P1, P4, P7, P8) also articulated that the motorized slider felt more absolute. For P4, exploring with a *"finger is more concrete"* and for P7, the physical motion *"was much more effective in helping [them] draw a picture of the graph in mind"*.

The main drawbacks participants described of Slide-tone were related to movement speed of the motorized slider. P1 felt that quick jumps, as a result of features in the data, could be disorienting. P7 had to slow down exploration to understand the shape, and as a result, thought that exploring with *"the slider is not as fast as sound"*. Participants also had differing impressions on the direction of motion of the slider. P6 appreciated the back and forth movement of the slider because they were *"familiar with interpreting graphics seeing them on a table"*. Yet, for P3, the back and forth motion was kind of *"disorienting"*.

1st order inclination cues provide a realistic impression of bumps, shapes, and curves; but are easy to misinterpret in a data visualization context.

Upon first impression, five participants (P1-P3, P5, P6) felt that the 1st order cues perceived through the tilt platform provided a realistic and compelling method for conveying shape features. *"It creates the slides and dips as you go along, it seems a bit real when you're sliding it (P2)"*. Like with Slide-tone, several participants felt Tilt-tone (P1, P5, P6, P8) more effectively conveyed curvature than sonification alone.

Participants, however, indicated several key limitations for using tilt to understand shape. First, as described by P5, relying on tilt was *"a little more difficult to tell the exactness of the y-value."* When using 1st order inclination cues, users would need to integrate their haptic perception of slope over time to understand the y-value of a curve. Second, the finger platform used to provide inclination cues was easy to misinterpret. While participants accurately used the tilt platform to identify curvature in the training exercise, half of the participants (P1, P6-P8) indicated initial confusion about whether they should pay attention to the angle, the left edge, or the right edge of the finger platform. P7 described this well when they said *"if left to my own in a room, I would go back and forth between is it a slope indicator or is the leading edge of the [platform] telling me the absolute value of the graph"*. For participants (P1, P7) that focused their attention on the height of the left or right edge, they often felt that the tilt platform moved ahead of the sonification, or that the haptic cues did not match the sonification. An example of this was when an upward-curving trend caused the right edge of the platform to rise, but the y-value pitch remained low. For those participants (P6, P7), confusion reduced over time as they gained familiarity with the system. P6 asked to perceive the tilt along with the slider to better understand the differences between how they conveyed shape. Afterwards, they said *"I felt more familiar with the movement of the back and forth (the motorized slider), but once you get used to the tilt, it's pretty similar and useful too"*.

Multimodality is generally preferred over single modality exploration because it is perceived to reinforce understanding, improve versatility, and enhance overall experience.

The majority of participants felt that having haptic feedback is better than perceiving audio alone. Four participants (P3, P6-P8) in the *Slide-tone* condition and four participants (P3, P4, P7, P8) from the *Tilt-tone* condition expressed that sonification and their respective haptic cues helped reinforce their interpretation and understanding of aspects within the graph. *"It's confirming. The tactile portion confirms what I'm hearing...if you were not sure about what you were hearing, you have the choice to put your finger on it (P8)"*. For P6, who had tried but did not understand sonification years ago, the haptic reinforcement was described to have helped them understand sonification better. *"I tried [the] audio graph, it didn't really make sense to me. When I combined it with the haptic, it really made sense. I could [now] do audio only, but I would still like that haptic to confirm what I hear and what I feel (P6)"*.

Most participants (P4-P8) also appreciated the versatility that the different sensory methods provided for completing a variety of data-visualization tasks. As P7 explained, *"I would refer to these* *as a quiver of tools, and which tool I pull out of the quiver depends on the task at hand....If what I want to know, is where on the chart is the greatest rate of increase or decrease, I'm going to feel for the slope change, and I could analyze that with the slider, but the [tilt] is going to give it to me almost immediately because it's actually representing the slope. If what I would like to do is identify relative changes, the slider is a good augmentative tool to the audio because I can with my finger identify parts of the slider keeping my thumb fixed at the bottom, I can feel it move it with another finger".*

The presence of multimodal cues accommodates the diversity of different preferences and strategies participants had for answering the data visualization tasks. Two participants (P2, P5) indicated that they focused on the audio for completing the benchmark tasks, but relied more on the haptic cues for understanding the general trends. Two participants (P4, P8) indicated preference for haptic exploration in general, while one (P2) had a preference for sound alone. Between the slider (0th order cues) and the tilt platform (1st order cues), half the participants (P5 - P8) felt that the slider provided a better way to explore data, as it felt more intuitive and complete, while one (P3) preferred the tilt platform (1st order cues) because the tilting motion felt more intuitive than the back and forth motion.

Overall, five participants (P4-P8) felt that simultaneous perception of haptic cues with sonification enhanced the overall data exploration experience, both through reinforcing the same information and by providing complementary information. Four participants (P3, P6-P8) appreciated how the slider and sonified tone moved together. *"The sound changed and because the slider changed, so I was able to tell the difference a little more. Both working together helped (P5)"*. For the tilt condition, three participants (P3, P5, P6) thought the information provided haptically and auditorily provided a more holistic understanding of shape. *"Well when I was moving without platform, I was hearing up and downs, but I couldn't relate what is what, the high pitch and low pitch, now I can feel when its in a valley, then on high point it is higher, I can follow how much it changes (P6)"*.

Additional digital interface considerations: navigation sensitivity, constraints as guidance

Participants provided additional feedback that could inform the development of digital interfaces for data visualization. While participants (P1, P6, P7) appreciated the high information density enabled by the prototypes, several expressed that finding specific x-values was a time consuming and tedious process. We observed that participants had to continuously reposition along the x-axis to retrieve specific values. Participants recommended several interactions to reduce navigation effort, such as being able to adjust the x-axis navigation density (P7), being able to zoom and pan to regions of interest (P7), or receiving feedback each time a specified threshold had been crossed (P6, P7). For the latter idea, P7 described how *"If I know I'm 5 away from my target date, and I could just go 1-2-3-4-5 [clicks] and have great confidence instead of just guessing"*.

In the *Interactive Tactile Graphic* condition, three participants (P3, P7, P8) indicated that following along the trendline requires significant concentration, and half of the study participants (P3, P5, P7, P8) described having trouble following along the thicker trendline, especially in the presence of the thinner gridlines. *"Distinguishing between the thinner lines inside the graph to show the levels on the axis and the actual graph itself, for me sometimes it's hard to tell depending on the graph where you are (P8)"*. The interface used for the other three conditions constrains users to a single-DOF exploration on places of interest, removing the effort and concentration needed to trace along the graph. *"[The interface] is easy to follow, I don't have the risk of losing the graphic line (P7)"*.

6 DISCUSSION

The quantitative results showed similar task accuracy across study conditions, as well as slower response time and lower perceived performance in the *Interactive Tactile Graphic* condition than in the *Sonification Only* and *Tilt-tone* conditions respectively. As with several prior studies comparing between different modalities [13, 66], the qualitative results captured additional information about the different experiences that the haptic cues provided to participants. We address both to provide a holistic discussion of the use of these modal schemes in a multimodal data context.

6.1 Supporting Data Visualization Tasks

We did not detect any significant accuracy differences between the multimodal and *Sonification Only* conditions compared to the *Interactive Tactile Graphic* condition, despite participants working with relatively complex ecologically situated graphs having received minimal training ($<$ 10 minutes) with each study condition. Because the *Slide-tone* and *Tilt-tone* conditions at baseline contain all the features of the *Sonification Only* condition, these results suggest that task accuracy with our implementation of the *Sonification Only* condition, even without the haptic cues, performs comparably well. We attribute the relatively quick and effective adoption of the *Sonification Only* condition to several factors.

First, participants relied heavily on speech output of values across all conditions, which is typically the most common method blind people negotiate information with computers, even if it may not be the most efficient strategy [95]. Second, to interact with the sonified data, participants actively and kinesthetically navigated along the structure of the line graph, which is often the most suitable way for blind people to explore spatial relationships [6, 7, 55]. While a prior study found that people appreciated the exploration autonomy of tactile graphics over passive listening of sonified data [85], our participants tended to prefer sonification with the ability to actively navigate. Additionally, Yu et. al. found that with an audio-haptic implementation that uses both tonal and speech output, participants relied on haptics primarily for navigation and performed data visualization tasks more accurately than using tactile graphics [95]. For our tasks, we found accuracy to be similar between the multimodal and tactile graphic condition. Third, our interface constrained navigation along the x-axis dimension and provided access to only values that are a part of the line series compared to the tactile graphic, which requires users to understand the entire planar layout to find and effectively navigate the data. This may explain how contrary to Yu et al's observations that task completion and mental demand using their multimodal interface, which relied on planar exploration, took significantly longer than tactile graphics [95]; our interface did not demand greater cognitive load and time.

Effective independent use of tactile graphics is difficult without adequate training [72, 99, 100]. The lack of familiarity many participants had with tactile data graphics contributed to the slower response time and lower perceived performance in the *Interactive Tactile Graphic* condition, which we found to be statistically significant when compared to the *Tilt-tone* and *Sonification Only* conditions respectively. We found these challenges to be indicative of a broader tension between flexible exploration, as provided by the tactile graphic, and constrained guidance, as provided by the prototype interface. With the *Interactive Tactile Graphics* condition, familiar participants (P1, P6) used labels to quickly find regions of interest, leveraged multi-hand techniques to facilitate comparisons to other points and regions, and navigated across gridlines to determine all locations where the trendline crosses a threshold to quickly and effectively complete the tasks. However, most participants found tracing the line and coordinating tracing with value retrieval to be challenging (P3-P5, P7, P8). Several participants (P3-P5, P7) did not trace along the raised line to complete at least one of the tasks, but instead, relied completely on the value-retrieval buttons as they moved one finger across the x-axis at the bottom of the graph. By not using the trendline, these participants effectively used the interactive tactile graphic as a look-up table that they kinesthetically navigated. As all participants were able to use the interface of the three other conditions after the brief training session, we see the use of active but constrained navigation along the trend as a way to balance approachability to beginners with flexibility for accomplishing data visualization tasks. More functionality can then be layered to support additional strategies for experienced users.

One key question we wanted to address was whether the 0th order position and 1st order inclination cues worked well in a multimodal context, especially since prior work has shown that haptic feedback can improve accuracy and time for certain data visualization tasks [95]. However, our results show that the addition of 1-DOF haptic cues do not significantly improve or detract much from participants' accuracy or time retrieving task-relevant information for the tasks we chose; suggesting that the combination of sonification, speech output of values, and active navigation used in the *Sonification Only*, *Slide-tone*, and *Tilt-tone* conditions were mostly sufficient for the first three tasks where exact answers could be retrieved. All participants expressed that the mean estimation task was much more difficult. While gestalt overviews provided by multi-hand exploration strategies enabled by the *Interactive Tactile Graphics* condition may help with mean estimation tasks, we did not find differences in that condition to be statistically significant in this particular study.

Despite the haptic cues not significantly affecting task accuracy and time compared to the *Sonification Only* condition, participants almost always placed their fingers on the haptic cues when they were available, and made comments about how those cues contributed to their understanding and completion of tasks, which we elaborate on in the next section.

6.2 Modal Cues for Understanding Features

All participants expressed ways in which the addition of haptic cues influenced or augmented their understanding of the graphs, despite the haptic cues not significantly affecting the quantitative performance metrics. Transcripts from the think-aloud protocol and post-task interviews highlight differences in how the modal schemes support participants' understanding of the line graphs and completion of data visualization tasks.

Primarily, sonification, 0th order positional cues, and 1st order inclination cues seemed to provide both complementary and redundant sets of information about the graph, which is a function of both the information they are mapped to as well as differences in human perception. Both sonification and 0th order haptic positional cues map directly to the 0th order y-value information of the data, meaning the modal cues need to be differentiated to identify the slope, and differentiated again to identify the curvature. However, participants described having a better understanding of both absolute y-values (P1, P4, P7) and curvature (P7, P8) through the 0th order cue provided by the motorized slider than through sonification. Comparisons in the number of mentions of y-position and curvature between the *Sonification Only* and *Slide-tone* conditions in Section 5.5.1 seem to reflect participant comments. Perceptual differences through how these features are interpreted may offer insight as to why.

Understanding the absolute height of a trend through sonification requires participants to compare the pitch of the data value to the pitch interval of the entire data range. Zarate et. al. found that comparing pitch intervals is difficult for people without sufficient training [98]. In contrast, using the separation between two fingers is quite suitable for estimating length [25, 46, 61]. Participants using Slide-tone placed one or several fingers anchored to the base of the motorized slider while another finger moved in proportion to the data's y-value height. This continuous use of finger-separation to estimate length (which is proportional to y-value height) may contribute to a better understanding of y-value height.

Curvature perception using sonification also requires users to identify changes in the rate of tone change (i.e. the second derivative) as they actively explore the plot. Interval discrimination at moving base-tones is known to be particularly difficult for non-musicians [98]. While a prior study in haptic curvature discrimination reported lower performance when using 0th order haptic cues compared to 1st order haptic cues [91], the size of curved features conveyed by Slide-tone in our study exceeds the minimum curvature discrimination thresholds of 0th order cues [91], which may contribute to participants' (P7, P8) impression of curvature through the motorized slider. How much curvature should be conveyed in a data visualization context is still an open question to be explored.

The 1st order inclination cue in Tilt-tone is different from sonification and 0th order position cues in that it maps to the 1st order slope information rather than to the 0th order y-value information of the data. Participants would need to integrate as they explored to keep track of the 0th order height information, and differentiate to keep track of the 2nd order curvature information. Participants described understanding absolute height through the tilt platform, which requires keeping track of the integration of inclination cues, to be difficult (P5) or impossible (P7). For perceiving instantaneous slope and how slope changes over time, however, transcripts (P1, P5, P6, P8) and feature mentions suggest that the 1st order cues conveyed by the tilt platform are well-suited. With Tilt-tone, the steepness is directly reflected in the inclination angle of the fingerpad, and any change in inclination would signify a curvature change.

We observed several additional considerations for using 1st order inclination cues in the data visualization context beyond feature perception. Several participants indicated an additional feeling of realism (P1-P3, P5, P6), possibly due to the role of these cues in everyday object perception. However, Memeo et. al. found that 1st order inclination cues perform worse than 0th order finger position cues when discriminating between shapes of similar sizes [58].

We also observed confusion caused by ambiguity from multiple haptic cues. While our intent was for participants to make 1st-order associations between the inclination of the finger platform and the slope of the graph, half of the participants (P1, P6-8) attempted to make 0th order associations of the left or right edge of the platform to the y-value instead, which do not accurately reflect the data. We believe that additional research needs to be done before making judgements on whether to recommend the use of these cues in this data visualization context, such as investigating the combination of 0th and 1st order haptic cues together— in which case the left and right edge may more accurately reflect the data.

6.3 Multimodal Integration

Multimodality is often the recommended solution to complement advantages and compensate for shortcomings of individual modalities [34, 66, 95], reinforce users' understandings from a single modality [56], and accommodate diverse modal preferences, such as between speech and audio [56, 66], touch and keyboard [7], and haptic and audio [78]. In the context of prior studies, our *Sonification Only* condition can be considered multimodal in that it incorporates sonification, active kinesthetic navigation, and speech output. Participants on average using the *Sonification Only* condition interface performed data visualization tasks with comparable accuracy, time, and better perceived performance to tactile graphics. The additional perception of 0th order position cues or 1st order inclination cues, while not significantly affecting task accuracy or time, was preferred by 6 of 8 participants (P3-P8) because they were reported to reinforce understanding (P3, P4, P6-P8) and improve versatility (P4-P8). Five participants (P4-P8) felt that simultaneous perception of the cues enhanced the data experience. Even if participants chose to perceive or focus on one of the cues, the availability of multiple cues may better accommodate the diverse strategies that different people use to answer data visualization tasks.

Our observations reinforce prior findings and demonstrate that individual modalities should be chosen to ideally span the complete set of information users might be interested in while strengthen users' understanding for overlapping information across modalities. With Slide-tone, participants described that 0th order position cues provided by the motorized slider better communicate absolute y-values (P1, P4, P7, P8) and curvature (P7, P8) while sonification provides a quicker way (P1, P3, P7) to interact with the data and identify extreme points (P7, P8), an example of the modalities potentially providing complimentary information. Participants also indicate that both sonification and the motorized slider reinforce how y-values are increasing or decreasing (P4, P5), an example of the modalities potentially strengthening users' understanding. However for Tilt-tone, while several participants (P3, P4, P7, P8) described that information provided by tilt and sonification compliments, conflicting 0th order information provided by sonification and inadvertently caused by the rise and fall of the tilt platform edges produced confusion (P1, P7, P8) which can undermine understanding.

It is also possible that that different time responses of the modal cues may also undermine understanding. Sonification communicates the plot near-instantaneously while mechanical latency and filtering of the haptic systems introduces additional lag in the haptic cue renderings and may have contributed to why several participants (P1, P3, P7) felt that sonification seemed *"quicker"* for completing the data visualization tasks. Yet, most participants described using the haptic cues to enhance the sonification and reinforce understanding (P3-P8), despite the audio reacting quicker than the haptics. It is in cases when the haptics reacted before sound, such as when the left or right edge of the finger platform in Tilt-tone quickly moved, when participants felt and commented on discrepancy between the cues. These results may suggest an asymmetric user tolerance threshold for sensitivity differences between audio and haptics, perhaps owing to differences between perceptual sensitivities to slight movements and vibrations than to slight deviations in pitch relative to their relative perceptual ranges— though additional research is needed to investigate this.

This work highlights how the modal cues do not necessarily need to be mechanically complicated and expensive to augment and improve users' experience with and understanding of data-driven information. We believe there are opportunities to more systematically investigate the psychophysical limits of different modal cues and mappings under a 0th order, 1st order, and 2nd order data visualization framework to form a more granular understanding of how information is complemented and reinforced through modal integration. Continued work to formalize and synthesize the capabilities and limitations of different modal cues can help inform multimodal combinations that more effectively layer the information the cues convey.

7 LIMITATIONS & FUTURE WORK

Data visualization tasks: We chose tasks that were generally used for a variety of visualizations, are broadly familiar, and focused on perceptual intelligence and mental projections [16]. While we observed that Slide-tone, Tilt-tone, and our implementation of sonification performed well for these rudimentary tasks, they were not optimal for teasing apart task performance differences between the conditions. Higher difficulty tasks such as feature and slope estimation, while more context specific, might better differentiate performance across the conditions. Tasks requiring comparisons across different datasets are also important to consider in future studies.

Evaluation Methods: Benchmark tasks and usability tests is a subset of many potential evaluation methods that provide different perspectives on the utility of data visualization access methods [50]. Future work could investigate the higher-level insights that people may gain through these methods using open-ended insight-based methodologies [63]. Additional interaction techniques commonly used in a data visualization context, including those recommended by study participants (such as pan and zoom) could be explored to facilitate these broader insights.

Participants' verbal descriptions of trends in Section 5.5.1 captured several types of features participants attended to and the language they used to describe these features. Because we used real-world datasets in which the prevalence of these features vary drastically, these results are not directly indicative of feature interpretability through the different modal schemes. For follow-up studies, the codebook of features identified from this study can be used to craft balanced sample datasets. Asking participants to describe trends based on these new datasets could provide more definitive and statistical assessments of feature interpretability within different modal schemes.

Sonification: This work explores one implementation of line-graph sonification that is most commonly explored in research and used in practice, in which y-values are mapped to tonal frequency. Prior work has also explored alternative mapping schemas, such as using curvature [9], differing polarities [87], or varying tempo, duration, volume, and timbre [54, 86], which would likely yield different results. Exploring how these different mappings might provide complementary information in multimodal contexts may be another area to further investigate.

Single Point-of-View Exploration: Our 1-DOF interfaces only provides a single point-of-view. Prior work suggests that multi-finger strategies are much more effective for several tasks [61]. In our formative work, we saw some indication of this. Participants had preference for cutouts that allowed whole hand interaction, allowing users to quickly and simultaneously gain a gestalt overview of shape features. Similarly, in the controlled study, several participants (P7, P8) appreciated the quick overview that multi-finger strategies using the cutout provided in the training session. As P7 described, "*[My] ability to grasp the totality of the data with this tactile representation, its almost instantaneous…I can instantly identify the highest point, I can instantly identify the lower point, I can simultaneously analyze the whole data at the same time*". Supporting these interactions in a data visualization context and at low cost is an important avenue for additional research.

System Hardware: There were inherent limitations in the specific hardware prototypes for practical use, such as actuator response time and hardware size. The haptic cues provided by the prototype platform could also be reduced to a mouse-sized form factor such as the one developed by Memeo et. al. [59], or be incorporated into a mobile haptic ecosystem similar to ones explored in shiftIO [81]. A higher-power actuator and more sophisticated control techniques could improve the perceived stiffness and response time of the system.

Participant Demographics: Prior experiences, level of vision, and age range of this group of participants may have also influenced study results. Participants on average reported high self-ratings on data manipulation familiarity, which may have contributed to high overall accuracy for the first three tasks. Additionally, two participants (P7, P8) who had interacted with graphs visually before losing their sight may have had additional experience with spatial data relationships given the broader availability of data graphics through visual means.

Participants self-reported similar familiarity with tactile graphics ($\bar{x}$ = 3.4) as with sonification ($\bar{x}$ = 3.0) on a 5-point Likert scale (1 to 5 with 5 indicating highest). Particularly with tactile graphics, we observed that unfamiliar participants had much more difficulty completing the data visualization tasks. For this reason, we suspect that accuracy, time, and qualitative results in the *Interactive Tactile Graphics* condition were much more sensitive to prior familiarity.

Haptic acuity [35, 79] and auditory perception [101] are known to decline with age, and all of our participants were over the age of 40. However, some evidence suggests that for groups of people who rely on their sense of touch and sound, tactile acuity and pitch discrimination does not decline with age, at least not to the same extent [53, 101].

The participants in this study had very low to no vision, while visual conditions and functional abilities fall along a broad continuum [34]. As all participants primarily interact with data graphics non-visually in their prior use, our results reflect contributions from the explored audio and haptic cues alone. The visual presentation of line graphs on the graphic and associated with the study interfaces could have played a role in task strategies and affected quantitative results had users who visually consumed graphics participated.

Because we advertised this study as an investigation of data visualization exploration methods, many study participants had domain-specific interest in data accessibility. P6, who frequently reviewed tactile graphics for teaching math, indicated that *"I mean I really, I was amazed, it was really cool...I'd love to show the kids (P6)"*, while P1 mentioned that the tilt platform (1st order cues) *"could be a great tool for teaching some tangent in calculus (P1)."* Investigating the role of these haptic cues in teaching data visualization concepts could be an interesting avenue of further research.

8 CONCLUSION

Providing easy and up-to-date access to data visualization is important in this increasingly digital age. As one participant described, *"there are so many graphs we explored about stocks, COVID, bank, we really need access to stuff like this (P4)"*. Our motivation was to investigate how simple, 1-DOF haptic cues used for shape perception can augment people's interactions with data trends and the information they gain through digital interfaces. While task accuracy and time was comparable across multimodal and sonification-only conditions, we found that participants generally appreciated the additional shape information, versatility, and reinforced understanding these interfaces provide. Our results suggest that even providing simple haptic feedback, especially in multimodal schemes, can improve people's experiences interacting with ecologically valid datasets through factors beyond benchmark evaluations. Improving our understanding of these factors, especially in-the-wild is an important next step towards reducing the access gap.

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REFERENCES

[1] [n. d.]. Apple Accessibility API. https://developer.apple.com/documentation/accessibility/audio_graphs. (Last accessed: August 24, 2021).

[2] [n. d.]. Desmos Graphing Calculator. https://www.desmos.com/calculator. (Last accessed: August 24, 2021).

[3] [n. d.]. Microsoft Soundscape. https://www.microsoft.com/en-us/research/product/soundscape/. (Last accessed: August 24, 2021).

[4] [n. d.]. SAS Graphics Accelerator. https://support.sas.com/software/products/graphics-accelerator/. (Last accessed: August 24, 2021).

[5] 2020. Accessible COVID-19 Pandemic Data. https://covid.ski.org/. (Last accessed: August 27, 2020).

[6] Amandine Afonso, Alan Blum, Christian Jacquemin, Michel Denis, and Brian FG Katz. 2005. A study of spatial cognition in an immersive virtual audio environment: Comparing blind and blindfolded individuals. Georgia Institute of Technology.

[7] Dragan Ahmetovic, Cristian Bernareggi, João Guerreiro, Sergio Mascetti, and Anna Capietto. 2019. Audiofunctions. web: Multimodal exploration of mathematical function graphs. In *Proceedings of the 16th International Web for All Conference*. 1–10.

[8] Jordan Allen et al. 2020. *Coronavirus in the U.S.: Latest Map and Case Count.* https://www.nytimes.com/interactive/2020/us/coronavirus-us-cases.html

[9] Miguel A Alonso-Arevalo, Simon Shelley, Dik Hermes, Jacqueline Hollowood, Michael Pettitt, Sarah Sharples, and Armin Kohlrausch. 2012. Curve shape and curvature perception through interactive sonification. *ACM Transactions on Applied Perception (TAP)* 9, 4 (2012), 1–19.

[10] James L Alty and Dimitrios Rigas. 2005. Exploring the use of structured musical stimuli to communicate simple diagrams: the role of context. *International journal of human-computer studies* 62, 1 (2005), 21–40.

[11] Apple. [n. d.]. *Health.* https://www.apple.com/ios/health/

[12] Catherine M Baker, Lauren R Milne, Jeffrey Scofield, Cynthia L Bennett, and Richard E Ladner. 2014. Tactile graphics with a voice: using QR codes to access text in tactile graphics. In *Proceedings of the 16th international ACM SIGACCESS conference on Computers & accessibility*. 75–82.

[13] Sandra Bardot, Sawyer Rempel, Bradley Rey, Ali Neshati, Yumiko Sakamoto, Carlo Menon, and Pourang Irani. 2020. Eyes-free graph legibility: using skin-dragging to provide a tactile graph visualization on the arm. In *Proceedings of the 11th Augmented Human International Conference*. 1–8.

[14] Dale J Barr. 2013. Random effects structure for testing interactions in linear mixed-effects models. *Frontiers in psychology* 4 (2013), 328.

[15] Douglas Bates, Reinhold Kliegl, Shravan Vasishth, and Harald Baayen. 2015. Parsimonious mixed models. *arXiv preprint arXiv:1506.04967* (2015).

[16] Jeremy Boy, Ronald A Rensink, Enrico Bertini, and Jean-Daniel Fekete. 2014. A principled way of assessing visualization literacy. *IEEE transactions on visualization and computer graphics* 20, 12 (2014), 1963–1972.

[17] Virginia Braun and Victoria Clarke. 2006. Using thematic analysis in psychology. *Qualitative research in psychology* 3, 2 (2006), 77–101.

[18] Anke M Brock, Philippe Truillet, Bernard Oriola, Delphine Picard, and Christophe Jouffrais. 2015. Interactivity improves usability of geographic maps for visually impaired people. *Human–Computer Interaction* 30, 2 (2015), 156–194.

[19] Lorna M Brown, Stephen A Brewster, SA Ramloll, R Burton, and Beate Riedel. 2003. Design guidelines for audio presentation of graphs and tables. International Conference on Auditory Display.

[20] Matthew Butler, Leona M Holloway, Samuel Reinders, Cagatay Goncu, and Kim Marriott. 2021. Technology Developments in Touch-Based Accessible Graphics: A Systematic Review of Research 2010-2020. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems*. 1–15.

[21] C Melody Carswell, Cathy Emery, and Andrea M Lonon. 1993. Stimulus complexity and information integration in the spontaneous interpretations of line graphs. *Applied Cognitive Psychology* 7, 4 (1993), 341–357.

[22] Andrew Crossan and Stephen Brewster. 2008. Multimodal trajectory playback for teaching shape information and trajectories to visually impaired computer users. *ACM Transactions on Accessible Computing (TACCESS)* 1, 2 (2008), 1–34.

[23] Nils Dahlbäck, Arne Jönsson, and Lars Ahrenberg. 1993. Wizard of Oz studies—why and how. *Knowledge-Based Systems* 6, 4 (1993), 258–266.

[24] Roger T Dean and Roger T Dean. 2009. *The Oxford handbook of computer music*. OUP USA.

[25] Alfred G Dietze. 1961. Kinaesthetic discrimination: The difference limen for finger span. *The Journal of Psychology* 51, 1 (1961), 165–168.

[26] Hanifa Dostmohamed and Vincent Hayward. 2005. Trajectory of contact region on the fingerpad gives the illusion of haptic shape. *Experimental Brain Research* 164, 3 (2005), 387–394.

[27] Melanie Ehrenkranz. 2020. Vital Coronavirus Information Is Failing the Blind and Visually Impaired. Retrieved January 14, 2021 from https://www.vice.com/en_us/article/4ag9wb/vital-coronavirus-information-is-failing-the-blind-and-visually-impaired

[28] John H Flowers and Terry A Hauer. 1995. Musical versus visual graphs: Cross-modal equivalence in perception of time series data. *Human factors* 37, 3 (1995), 553–569.

[29] American Printing House for the Blind. 2021. *American Printing House for the Blind and Orbit Research Announce the World's First Affordable Refreshable Tactile Graphics Display.* https://sites.aph.org/pr/aph-and-orbit-research-announce-the-worlds-first-affordable-refreshable-tactile-graphics-display/

[30] Peter Fox and James Hendler. 2011. Changing the equation on scientific data visualization. *Science* 331, 6018 (2011), 705–708.

[31] Jason P Fritz and Kenneth E Barner. 1999. Design of a haptic data visualization system for people with visual impairments. *IEEE Transactions on rehabilitation engineering* 7, 3 (1999), 372–384.

[32] Giovanni Fusco and Valerie S Morash. 2015. The tactile graphics helper: providing audio clarification for tactile graphics using machine vision. In *Proceedings of the 17th International ACM SIGACCESS Conference on Computers & Accessibility*. 97–106.

[33] John Gardner. 2014. Can mainstream graphics be accessible? *Information Technology and Disabilities* 14, 1 (2014).

[34] Nicholas A Giudice, Hari Prasath Palani, Eric Brenner, and Kevin M Kramer. 2012. Learning non-visual graphical information using a touch-based vibro-audio interface. In *Proceedings of the 14th international ACM SIGACCESS conference on Computers and accessibility*. 103–110.

[35] Daniel Goldreich and Ingrid M Kanics. 2006. Performance of blind and sighted humans on a tactile grating detection task. *Perception & Psychophysics* 68, 8 (2006), 1363–1371.

[36] Google. 2021. *Google Trends.* http://trends.google.com/trends

[37] Jenna L Gorlewicz, Jessica Burgner, Thomas J Withrow, and Robert J Webster III. 2014. Initial experiences using vibratory touchscreens to display graphical math concepts to students with visual impairments. *Journal of Special Education Technology* 29, 2 (2014), 17–25.

[38] Jenna L Gorlewicz, Jennifer L Tennison, Hari P Palani, and Nicholas A Giudice. 2018. The graphical access challenge for people with visual impairments: Positions and pathways forward. In *Interactive Multimedia-Multimedia Production and Digital Storytelling*. IntechOpen.

[39] Jenna L Gorlewicz, Jennifer L Tennison, P Merlin Uesbeck, Margaret E Richard, Hari P Palani, Andreas Stefik, Derrick W Smith, and Nicholas A Giudice. 2020. Design guidelines and recommendations for multimodal, touchscreen-based graphics. *ACM Transactions on Accessible Computing (TACCESS)* 13, 3 (2020), 1–30.

[40] Thomas Hermann. 2002. *Sonification for exploratory data analysis*. Ph. D. Dissertation. Bielefeld University.

[41] Leona Holloway, Matthew Butler, Samuel Reinders, and Kim Marriott. 2020. Non-visual access to graphical information on COVID-19. In *The 22nd International ACM SIGACCESS Conference on Computers and Accessibility*. 1–3.

[42] Leona Holloway, Kim Marriott, and Matthew Butler. 2018. Accessible maps for the blind: Comparing 3D printed models with tactile graphics. In *Proceedings of the 2018 chi conference on human factors in computing systems*. 1–13.

[43] Intuit. [n. d.]. *Mint.* https://mint.intuit.com/

[44] Wooseob Jeong and Myke Gluck. 2002. Multimodal bivariate thematic maps: Auditory and haptic display. *Proceedings of the American Society for Information Science and Technology* 39, 1 (2002), 279–283.

[45] Amy Kalia, Rose Hopkins, David Jin, Lindsay Yazzolino, Svena Verma, Lotfi Merabet, Flip Phillips, and Pawan Sinha. 2014. Perception of tactile graphics: Embossings versus cutouts. *Multisensory research* 27, 2 (2014), 111–125.

[46] Astrid ML Kappers and Wouter M Bergmann Tiest. 2013. Haptic perception. *Wiley Interdisciplinary Reviews: Cognitive Science* 4, 4 (2013), 357–374.

[47] Johan Kildal and Stephen A Brewster. 2006. Providing a size-independent overview of non-visual tables. In *12th International Conference on Auditory Display (ICAD2006)*. 8–15.

[48] NW Kim, SC Joyner, A Riegelhuth, and Y Kim. 2021. Accessible visualization: Design space, opportunities, and challenges. In *Computer Graphics Forum*, Vol. 40. Wiley Online Library, 173–188.

[49] Katherine J Kuchenbecker, William R Provancher, Günter Niemeyer, and Mark R Cutkosky. 2004. Haptic display of contact location. In *12th International Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems, 2004. HAPTICS'04. Proceedings.* IEEE, 40–47.

[50] Heidi Lam, Enrico Bertini, Petra Isenberg, Catherine Plaisant, and Sheelagh Carpendale. 2011. Empirical studies in information visualization: Seven scenarios. *IEEE transactions on visualization and computer graphics* 18, 9 (2011), 1520–1536.

[51] Rebecca Lawson and Sarah Bracken. 2011. Haptic object recognition: How important are depth cues and plane orientation? *Perception* 40, 5 (2011), 576–597.

[52] Susan J Lederman and Roberta L Klatzky. 1987. Hand movements: A window into haptic object recognition. *Cognitive psychology* 19, 3 (1987), 342–368.

[53] Gordon E Legge, Cindee Madison, Brenna N Vaughn, Allen MY Cheong, and Joseph C Miller. 2008. Retention of high tactile acuity throughout the life span in blindness. *Perception & psychophysics* 70, 8 (2008), 1471–1488.

[54] Suresh K Lodha, John Beahan, Travis Heppe, Abigail Joseph, and Brett Zane-Ulman. 1997. Muse: A musical data sonification toolkit. Georgia Institute of Technology.

[55] Jack M Loomis and Susan J Lederman. 1986. Tactual perception. *Handbook of perception and human performances* 2, 2 (1986), 2.

[56] Sergio Mascetti, Lorenzo Picinali, Andrea Gerino, Dragan Ahmetovic, and Cristian Bernareggi. 2016. Sonification of guidance data during road crossing for people with visual impairments or blindness. *International Journal of Human-Computer Studies* 85 (2016), 16–26.

[57] Giuseppe Melfi, Karin Müller, Thorsten Schwarz, Gerhard Jaworek, and Rainer Stiefelhagen. 2020. Understanding what you feel: A mobile audio-tactile system for graphics used at schools with students with visual impairment. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*. 1–12.

[58] Mariacarla Memeo and Luca Brayda. 2016. How geometrical descriptors help to build cognitive maps of solid geometry with a 3DOF tactile mouse. In *International Conference on Human Haptic Sensing and Touch Enabled Computer Applications*. Springer, 75–85.

[59] Mariacarla Memeo and Luca Brayda. 2016. Mind the bump: effect of geometrical descriptors on the perception of curved surfaces with a novel tactile mouse. In *International Conference on Human Haptic Sensing and Touch Enabled Computer Applications*. Springer, 438–448.

[60] Meg Miller. 2020. 2019 Novel Coronavirus COVID-19 (2019-nCoV) Data Repository: Johns Hopkins University Center for Systems Science and Engineering. *Bulletin-Association of Canadian Map Libraries and Archives (ACMLA)* 164 (2020), 47–51.

[61] Valerie S Morash, Allison E Connell Pensky, Steven TW Tseng, and Joshua A Miele. 2014. Effects of using multiple hands and fingers on haptic performance in individuals who are blind. *Perception* 43, 6 (2014), 569–588.

[62] Annika Muehlbradt, Madhur Atreya, Darren Guinness, and Shaun K Kane. 2018. Exploring the design of audio-kinetic graphics for education. In *Proceedings of the 20th ACM International Conference on Multimodal Interaction*. 455–463.

[63] Chris North. 2006. Toward measuring visualization insight. *IEEE computer graphics and applications* 26, 3 (2006), 6–9.

[64] Government of Canada. 2021. *5 data visualization 5.5 line chart*. https://www150.statcan.gc.ca/n1/edu/power-pouvoir/ch9/line-lineaire/5214824-eng.htm

[65] Braille Authority of North America. 2010. Guidelines and Standards for Tactile Graphics. http://www.brailleauthority.org/tg/

[66] Uran Oh, Shaun K Kane, and Leah Findlater. 2013. Follow that sound: using sonification and corrective verbal feedback to teach touchscreen gestures. In *Proceedings of the 15th International ACM SIGACCESS Conference on Computers and Accessibility*. 1–8.

[67] Sile O'Modhrain, Nicholas A Giudice, John A Gardner, and Gordon E Legge. 2015. Designing media for visually-impaired users of refreshable touch displays: Possibilities and pitfalls. *IEEE Transactions on Haptics* 8, 3 (2015), 248–257.

[68] Claudio Pacchierotti, Domenico Prattichizzo, and Katherine J Kuchenbecker. 2015. Displaying sensed tactile cues with a fingertip haptic device. *IEEE transactions on haptics* 8, 4 (2015), 384–396.

[69] Sabrina Paneels and Jonathan C Roberts. 2009. Review of designs for haptic data visualization. *IEEE Transactions on Haptics* 3, 2 (2009), 119–137.

[70] Duncan Raitt, Peter Fairhurst, Calum Michael, Zoltan Melkes, Yeongmi Kim, and Matthias Harders. 2019. OCTA Display: A Pin-Actuated Triangle-Surface Fingertip Shape Display–Design & Initial Tests. In *2019 IEEE World Haptics Conference (WHC)*. IEEE, 479–484.

[71] Rameshsharma Ramloll, Stephen Brewster, Wai Yu, and Beate Riedel. 2001. Using non-speech sounds to improve access to 2D tabular numerical information for visually impaired users. In *People and Computers XV—Interaction without Frontiers*. Springer, 515–529.

[72] L Penny Rosenblum, Li Cheng, and Carole R Beal. 2018. Teachers of students with visual impairments share experiences and advice for supporting students in understanding graphics. *Journal of visual impairment & blindness* 112, 5 (2018), 475–487.

[73] Nik Sawe, Chris Chafe, and Jeffrey Treviño. 2020. Using Data Sonification to Overcome Science Literacy, Numeracy, and Visualization Barriers in Science Communication. *Frontiers in Communication* 5 (2020), 46.

[74] Ather Sharif, Sanjana S Chintalapati, Jacob O Wobbrock, and Katharina Reinecke. 2021. Understanding Screen-Reader Users' Experiences with Online Data Visualizations. In *To Appear*.

[75] Yutaka Shimizu, Shinya Saida, and Hiroshi Shimura. 1993. Tactile pattern recognition by graphic display: Importance of 3-D information for haptic perception of familiar objects. *Perception & Psychophysics* 53, 1 (1993), 43–48.

[76] Alexa F Siu, Danyang Fan, Gene SH Kim, Hrishikesh V Rao, Xavier Vazquez, Sile O'Modhrain, and Sean Follmer. 2021. COVID-19 highlights the issues facing blind and visually impaired people in accessing data on the web. In *Proceedings of the 18th International Web for All Conference*. 1–15.

[77] Alexa F Siu, Son Kim, Joshua A Miele, and Sean Follmer. 2019. shapeCAD: An accessible 3D modelling workflow for the blind and visually-impaired via 2.5 D shape displays. In *The 21st International ACM SIGACCESS Conference on Computers and Accessibility*. 342–354.

[78] Lee Stearns, Ruofei Du, Uran Oh, Catherine Jou, Leah Findlater, David A Ross, and Jon E Froehlich. 2016. Evaluating haptic and auditory directional guidance to assist blind people in reading printed text using finger-mounted cameras. *ACM Transactions on Accessible Computing (TACCESS)* 9, 1 (2016), 1–38.

[79] Joseph C Stevens, Emerson Foulke, and Matthew Q Patterson. 1996. Tactile acuity, aging, and braille reading in long-term blindness. *Journal of experimental psychology: applied* 2, 2 (1996), 91.

[80] Tony Stockman, Christopher Frauenberger, and Greg Hind. 2005. Interactive sonification of spreadsheets. In *11th International Conference on Auditory Display (ICAD2006)*.

[81] Evan Strasnick, Jackie Yang, Kesler Tanner, Alex Olwal, and Sean Follmer. 2017. shiftio: Reconfigurable tactile elements for dynamic affordances and mobile interaction. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*. 5075–5086.

[82] Atau Tanaka and Adam Parkinson. 2016. Haptic wave: A cross-modal interface for visually impaired audio producers. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*. 2150–2161.

[83] Jennifer L Tennison and Jenna L Gorlewicz. 2016. Toward non-visual graphics representations on vibratory touchscreens: Shape exploration and identification. In *International Conference on Human Haptic Sensing and Touch Enabled Computer Applications*. Springer, 384–395.

[84] Maarten Van Someren, Yvonne F Barnard, and J Sandberg. 1994. The think aloud method: a practical approach to modelling cognitive. *London: AcademicPress* 11 (1994).

[85] Karen Vines, Chris Hughes, Laura Alexander, Carol Calvert, Chetz Colwell, Hilary Holmes, Claire Kotecki, Kaela Parks, and Victoria Pearson. 2019. Sonification of numerical data for education. *Open Learning: The Journal of Open, Distance and e-Learning* 34, 1 (2019), 19–39.

[86] Bruce N Walker. 2002. Magnitude estimation of conceptual data dimensions for use in sonification. *Journal of experimental psychology: Applied* 8, 4 (2002), 211.

[87] Bruce N Walker and Lisa M Mauney. 2010. Universal design of auditory graphs: a comparison of sonification mappings for visually impaired and sighted listeners. *ACM Transactions on Accessible Computing (TACCESS)* 2, 3 (2010), 1–16.

[88] Bruce N Walker and Michael A Nees. 2011. Theory of sonification. In *The Sonification Handbook*, Thomas Hermann, Andy Hunt, and John G Neuhoff (Eds.). Logos Verlag Berlin, Chapter 2, 9–39.

[89] Steven Wall and Stephen Brewster. 2006. Feeling what you hear: tactile feedback for navigation of audio graphs. In *Proceedings of the SIGCHI conference on Human Factors in computing systems*. 1123–1132.

[90] Steven A Wall and Stephen A Brewster. 2006. Tac-tiles: multimodal pie charts for visually impaired users. In *Proceedings of the 4th Nordic conference on Human-computer interaction: changing roles*. 9–18.

[91] Maarten WA Wijntjes, Akihiro Sato, Vincent Hayward, and Astrid ML Kappers. 2009. Local surface orientation dominates haptic curvature discrimination. *IEEE transactions on haptics* 2, 2 (2009), 94–102.

[92] Steven F Wiker, Gregg Vanderheiden, Seongil Lee, and Steven Arndt. 1991. Development of tactile mice for blind access to computers: importance of stimulation locus, object size, and vibrotactile display resolution. In *Proceedings of the Human Factors Society Annual Meeting*, Vol. 35. SAGE Publications Sage CA: Los Angeles, CA, 708–712.

[93] Yahoo. 2012. YAHOO! FINANCE.

[94] Wai Yu and Stephen Brewster. 2002. Comparing two haptic interfaces for multimodal graph rendering. In *Proceedings 10th Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems. HAPTICS 2002*. IEEE, 3–9.

[95] Wai Yu and Stephen Brewster. 2003. Evaluation of multimodal graphs for blind people. *Universal access in the information society* 2, 2 (2003), 105–124.

[96] Wai Yu, Ramesh Ramloll, and Stephen Brewster. 2000. Haptic graphs for blind computer users. In *International workshop on haptic human-computer interaction*. Springer, 41–51.

[97] Wai Yu, Rameshsharma Ramloll, Stephen Brewster, and Beate Ridel. 2001. Exploring computer-generated line graphs through virtual touch. In *Proceedings of the Sixth International Symposium on Signal Processing and its Applications (Cat. No. 01EX467)*, Vol. 1. IEEE, 72–75.

[98] Jean Mary Zarate, Caroline R Ritson, and David Poeppel. 2012. Pitch-interval discrimination and musical expertise: Is the semitone a perceptual boundary? *The Journal of the Acoustical Society of America* 132, 2 (2012), 984–993.

[99] Kim T Zebehazy and Adam P Wilton. 2014. Charting Success: The experience of teachers of students with visual impairments in promoting student use of graphics. *Journal of Visual Impairment & Blindness* 108, 4 (2014), 263–274.

[100] Kim T Zebehazy and Adam P Wilton. 2014. Quality, importance, and instruction: The perspectives of teachers of students with visual impairments on graphics use by students. *Journal of Visual Impairment & Blindness* 108, 1 (2014), 5–16.

[101] Benjamin Rich Zendel and Claude Alain. 2012. Musicians experience less age-related decline in central auditory processing. *Psychology and aging* 27, 2 (2012), 410.

[102] Haixia Zhao. 2006. *Interactive Sonification of Abstract Data-Framework, Design Space, Evaluation, and User Tool*. Ph. D. Dissertation. University of Maryland (College Park, Md.).

[103] Haixia Zhao, Catherine Plaisant, Ben Shneiderman, and Jonathan Lazar. 2008. Data sonification for users with visual impairment: a case study with georeferenced data. *ACM Transactions on Computer-Human Interaction (TOCHI)* 15, 1 (2008), 1–28.

A PARTICIPANT DEMOGRAPHICS

Table 1 shows participant demographics. Participants in the formative design workshops are labeled WS#. Participants in the evaluation are labeled P#.

Participant	Age Group	Profession	Level of Vision	Braille Familiarity	Tactile Graphics Familiarity	Sonification Familiarity	Data-Manipulation Comfort
WS1	40-59	Accessibility Specialist	No vision	Extremely	Moderately	Moderately	Extremely
WS2	60-79	Engineer	No vision	Extremely	Slightly	Slightly	Slightly
WS3	40-59	Consultant	No vision	Extremely	Very	Moderately	Very
P1	60-79	Accessibility Media Specialist	Legally blind	Extremely	Extremely	Very	Very
P2	40-59	Access Technology Specialist	Low vision	Not at all	Not at all	Not at all	Not at all
P3	40-59	Court Reporting Student	Low vision	Extremely	Moderately	Very	Very
P4	60-79	Retired Programmer	No vision	Extremely	Moderately	Moderately	Moderately
P5	40-59	Unemployed	Light perception	Very	Very	Slightly	Very
P6	40-59	Special Education Teacher	No vision	Extremely	Very	Slightly	Very
P7	60-79	Lawyer and CPA	No vision*	Not at all	Extremely	Very	Extremely
P8	40-59	Clinical Social Worker	No vision*	Not at all	Slightly	Very	Extremely

Table 1: Participant demographics. Participants in the formative design workshops are labeled WS#. Participants in the evaluation are labeled P#. The symbol * indicates loss of vision during adulthood

B EVALUATION CODEBOOK

Table 2 shows the codes used for classifying trend descriptions described in Section 5.4.1.

Code	Description	Examples
Shape Descriptors	Shape metaphors	"peak", "valley", "spike", "s-shaped "w-shaped"
X-Position	Length or position of feature along x-axis	"starts with", "for 1/3 of the graph", "in the end"
Y-Position	Height relative to graph range	"high", "low", "bottom", "top", "middle"
Y-Comparison	Height relative to other features or points	"higher than", "lower than", "greater than"
Instantaneous Slope	Slope at one point	"rising", "falling", "getting higher", "getting lower"
Slope Comparison	Slope relative to slopes at other points	"steeper than", "more gradual than"
Curvature	Changing progression of slope	"curving up", "curving down", "leveling off"
High Frequency Variation	Small features	"small bumps", "small oscillations", "small zigzags"

Table 2: Codes used for classifying trend descriptions described in Section 5.4.1