Using Tactile Charts to Support Comprehension and Learning of Complex Visualizations for Blind and Low Vision Individuals

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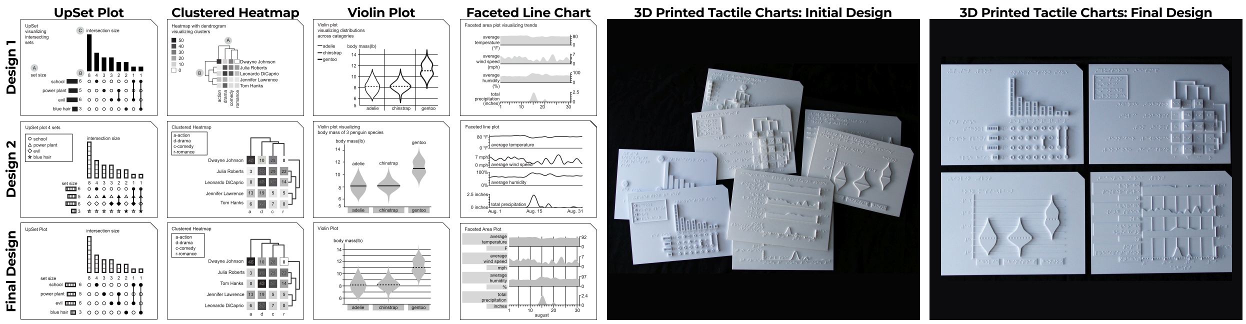

Fig. 1: Design iterations and final designs for tactile template charts for four visualization techniques: UpSet plots, clustered heatmaps, violin plots, and faceted line charts. Left: Sighted versions; larger in Appx. O and Appx. Q. Right: 3D-printed tactile charts, with final designs on the far right; larger in Appx. P and Appx. R. Models and additional materials are also available on `osf.io/9dwgq` and our accessible website: vdl.sci.utah.edu/tactile-charts/

Abstract—We investigate whether tactile charts support comprehension and learning of complex visualizations for Blind and Low Vision (BLV) individuals and contribute four tactile chart designs and an interview study. Visualizations are powerful tools for conveying data, yet BLV individuals typically can only rely on assistive technologies—primarily alternative texts—to access this information. Prior research shows the importance of mental models of chart types for interpreting these descriptions, yet BLV individuals have no means to build such a mental model based on images of visualizations. Tactile charts show promise to fill this gap in supporting the process of building mental models. Yet studies on tactile data representations mostly focus on simple chart types, and it is unclear whether they are also appropriate for more complex charts as would be found in scientific publications. Working with two BLV researchers, we designed 3D-printed tactile template charts with exploration instructions for four advanced chart types: UpSet plots, violin plots, clustered heatmaps, and faceted line charts. We then conducted an interview study with 12 BLV participants comparing whether using our tactile templates improves mental models and understanding of charts and whether this understanding translates to novel datasets experienced through alt texts. Thematic analysis shows that tactile models support chart type understanding and are the preferred learning method by BLV individuals. We also report participants' opinions on tactile chart design and their role in BLV education.

Index Terms—Accessibility, tactile representations

1 Introduction

Visualization is an important tool for communicating complex information in professional contexts, making visualization literacy essential across many careers. However, blind and low vision (BLV) individuals—as audiences of visualizations [43, 52, 74]—often face barriers to access them [13, 56, 58]. Most commonly, BLV individuals have to access the information contained in visualizations through alternative text (alt text), which provides descriptive text for the content of charts [43, 55]. Alt text, in principle, works well for simple charts, yet it can be difficult to both read and write when applied to complex visualizations [43]. The challenge is amplified when BLV individuals lack a corresponding mental model of these chart types, thus hindering them in effectively interpreting its alt text [44, 46, 47].

Tactile charts—charts that can be experienced by touch—are another modality that makes visualization accessible for BLV individuals. They are beneficial in helping users understand spatial relationships and data patterns [6, 58, 82, 85]. Prior work on tactile charts has focused on simple chart types and direct data representations rather than as educational tools (e. g., [13, 13, 24, 38, 45]). However, as data representations, compared to alt texts or other digital methods such as interactive data explorers [87], sonifications [39], tactile charts are slower and more costly to produce, and cannot be updated [11, 63]. While there are prototypes of refreshable tactile displays (e. g., [36, 68]), they are expensive, low resolution, and not widely available.

Considering the strengths and limitations of both tactile charts and alt texts, this work explores the use of tactile charts as tools for learning chart types rather than solely for data representation. We thus propose that tactile charts can function as "template charts" to support BLV individuals in developing mental models when learning about chart types. We adopt the concept of a mental model from cognitive psychology [42] to refer to the internal representation of a chart type's structure, aligning with related work in our field (e. g., [37, 44, 63, 85]). Once individuals form mental models of specific chart types, we hypothesize that they will be better equipped to interpret digital representations, such as alt texts, that utilize those chart types. We note that our approach is visual-first, i. e., only minimally adapts chart layouts to better suit tactile representation, as we aim to support BLV individuals when consuming extant visualizations and to facilitate collaboration between sighted and blind readers of visualizations. While tactile charts are widely used in BLV education [29, 73] and have been used to explain interactive systems [86], their application to teaching complex chart types remains unexplored. Given their infrequent need for updates,

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creating custom 3D-printed tactile charts is a practical approach for educational purposes.

To evaluate this hypothesis, we designed tactile template charts for four chart types: UpSet plots [53], clustered heatmaps [17], violin plots, and faceted line charts. We chose these charts because they are complex, yet commonly used, e. g., in scientific publications and professional contexts. Since our goal is to use tactile charts as a learning tool, we designed them with simple, familiar datasets to help people focus on the chart types rather than the content. We followed existing tactile chart design guidelines (e. g., [6, 35, 64, 70]) where available and sensible, yet we found that many guidelines do not capture essential aspects of the plots we intended to design.

To address gaps in existing guidelines, we leveraged our expertise in visualization and collaborated closely with our blind co-author, as well as consulted another BLV psychology researcher. Following an iterative design process, we initially created two design variations for each chart type, developed accompanying exploration instructions, and then refined these designs based on feedback from our BLV collaborators to one tactile model per chart type.

For logistical reasons (recruiting, distribution, length of interviews), we selected two of our four tactile charts—the clustered heatmap and the violin plot—to conduct an interview study with 12 BLV participants to evaluate their utility for learning transferable knowledge about the chart type. Participants first learned about the chart using either a tactile model paired with textual instructions, or just textual instructions. We then provided them with an unfamiliar alt-text of a dataset visualized with the chart type, and asked questions about the new dataset. We compared BLV participants' learning experiences, outcomes, and preferences between these two training modalities and elicited experiences and feedback on the tactile charts.

In summary, this work contributes: (1) The design of tactile template charts for four complex chart types with exploration instructions; (2) Results from an interview study with 12 BLV participants, showing that tactile charts with exploration instructions support comprehension and learning of complex visualizations and are a preferred learning method; (3) Insights into BLV individuals' learning strategies and experience with unfamiliar chart types, their perspectives on tactile chart design, and the potential of tactile charts in BLV education; and (4) Refined design recommendations for creating tactile charts for complex visualizations for learning purposes.

2 Related Work

In this section, we first discuss visualization accessibility, and then focus on chart type comprehension challenges and tactile charts.

2.1 Visualization Accessibility

In our increasingly data-driven society, visualizations are prevalent, both in a professional and personal context. However, because visualizations require the visual system for interpretation [12], they inherently bring challenges for BLV individuals. Despite these challenges, BLV individuals need to access to the rich information conveyed through visualizations and need to reason about data [58]. Unfortunately, they frequently encounter inaccessible visualizations across various contexts [55], which can create substantial difficulties in their daily lives [74] and limit access to employment opportunities in the knowledge economy. Ensuring information accessibility is therefore a matter of social justice. In recognition of this, researchers in the visualization community have increasingly called for greater attention to accessibility [13, 58] and provide evaluation guidelines [18, 56].

To improve visualization accessibility, researchers have explored various non-visual approaches to information representation [48], including speech [55, 59, 87], sonification (e. g., [15, 30, 39]), and haptic or tactile representations (e. g., [25, 32, 85]). Researchers also recommend for multi-modal approaches (e. g., [34, 57, 72, 77, 78]) to reduce the limitations of individual modalities and enhance data access and comprehension. These approaches, however, often come with higher economic and learning costs [13, 33, 45]. Other work has focused on methods, such as extracting original data from chart images [12], developing question-answering systems [47], interactive exploration systems [19, 87] or using LLM for low level visual analysis tasks [84]. These methods are helpful; however, to fully benefit from them, users need to understand the used chart types.

Among these alternative modalities, alternative text (also alt text or text descriptions) is the most common and practical, particularly in digital environments such as web pages [43, 49]. Alt text consists of textual descriptions of visual content that BLV individuals can access, e.g., through screen readers [43]. Researchers have studied the generation of alt text and evaluated its effectiveness (e. g., [4, 44, 55]). Recent efforts on developing text descriptions for complex charts [59, 75] are an attempt to remedy the dismal situation of accessibility of scientific articles and data resources [56]. Given the widespread use and practicality of alt text, we adopt it as a representative accessibility method in our evaluation study to assess the learning outcomes of BLV participants.

2.2 Chart Type Understanding

Understanding chart types is crucial for BLV individuals to access visualizations, as it might allow them to form a mental model for interpreting the data and the encoding mechanisms used in the visualization [44, 46]. Visualizations are often more than a raw representation of the data. A histogram, for example, communicates the distribution of a dataset. It hence makes sense to describe visualizations instead of describing the underlying data directly. Prior studies show that BLV individuals express a need for understanding chart types when using different assistive technologies. For example, Jung et al. [44] investigate how to better write alt text and recommend that alt text should first describe the chart type for uncommon charts. Kim et al. [47] explored the use of question-answering systems to help BLV individuals interpret visualizations and found that participants frequently asked about visualization layouts and tried to understand chart types.

BLV individuals are generally familiar with basic chart types (e. g., bar charts, pie charts, and line charts), however, they often struggled with more advanced chart types. Engel et al. [23, 24] find BLV individuals are less familiar with stacked bar charts, scatter plots and area charts. Wang et al. [79] report that BLV individuals are relatively unfamiliar with violin plots, and also unfamiliar with donut charts and area charts. These findings align with the fact that BLV individuals are typically exposed only to basic chart types in school [73]. In addition, most existing visualization accessibility technologies and research focus primarily on simple chart types [48, 83], while studies on accessible representations of more complex chart types remain underrepresented [83].

Therefore, to address the challenges of making complex visualization accessible [58], it is essential to study how to teach BLV individuals about advanced chart types—an area that remains largely unexplored. Kim et al. [46] investigate different strategies for explaining unfamiliar chart types to BLV individuals, including referencing familiar charts, using declarative versus procedural knowledge, and providing abstract versus concrete explanations. They also developed a prototype system for automatically generating explanations for 50 chart types. Similarly, Smits et al. [76] found using a gradual explanation method can help BLV individuals to comprehend unfamiliar genomics data Visualizations (sequence logos and Circos plots). These work both focus only on textual explanation; our work shares a similar goal but extends the scope by incorporating tactile charts and covering different chart types.

2.3 Tactile Charts

Tactile charts are a subset of tactile graphics and a form of data physicalization [40, 41]. In this work, we focus on their use for accessibility—enabling BLV individuals to access data representations through touch [24]. Prior research points out the benefits of tactile representations in supporting the comprehension of visualizations, particularly for obtaining an overview of charts [13, 20, 28, 29, 33] and conducting data analysis tasks [20, 45, 81, 85]. Moreover, studies identify tactile charts as a preferred method for BLV individuals to interpret and analyze data [20, 81]. In addition, blind participants have expressed a desire for tactile representations for understanding specific chart types, such as UpSet plots, when hearing alt texts [59].

Tactile charts can be static or refreshable. Static tactile charts are physical charts that are hard or impossible to change once produced.

The most common methods for creating these charts include embossing and the use of swell paper, which is cost-effective and efficient [69]. However, these techniques are limited in terms of embossed height and resolution. In contrast, 3D printing enables the production of more detailed and durable tactile charts [54]. Prior research has shown that BLV individuals tend to prefer 3D-printed tactile charts over embossed ones [20, 54]. Refreshable tactile displays, on the other hand, are dynamic devices that show tactile graphics on an updatable surface (e. g., [36, 68]). Although they offer the advantage of data flexibility, they are generally expensive and provide lower resolution compared to static alternatives. Given our aim of using tactile charts as an educational tool, affordability and resolution are key considerations. Since our charts serve as templates and do not need updates with new datasets, we focus on static tactile charts. Moreover, considering the complexity of the chart types explored in our study and our emphasis on small-scale production for learning, rather than rapid manufacturing for novel datasets, we use 3D printing to create charts.

The design of tactile charts influence their readability [25]. There exists established guidelines for tactile graphics (e. g., [6, 35, 64, 70]), and we can also find suggestions and recommendation articles online, such as from educational websites[1]. However, these resources are scattered, and most focus on tactile graphics in general. They offer broad design principles (e. g., ensuring clarity) and practical recommendations (e. g., on braille size, element dimensions, spacing for discriminability, and pattern filling). They also cover only basic chart types and provide limited guidance on chart-specific elements [25].

Beyond general guidelines, researchers have explored specific design considerations for tactile charts, including texture-based encoding [65, 80], grid lines [2, 5, 51], braille labels [66], and tactile line styles [10]. Some studies also propose additional design considerations based on user feedback and empirical evaluations [20, 23–25]. In our work, we incorporate relevant recommendations from these sources (discussed in detail in Sec. 3.2) and also supplement existing tactile chart design guidelines with insights gained from our design process.

To facilitate tactile chart creation, researchers explored different automated and semi-automated tactile chart creation approaches driven by images or data [11]. Image-driven systems [14, 60, 61] typically use image-processing techniques to convert charts from visual format into tactile formats. These systems have the risk of data loss for complex charts, since they rely on image input. In contrast, data-driven systems generate tactile charts directly from structured data inputs (e. g., [3, 21, 31, 82]). Chen et al. [11] introduced Tactile Vega-Lite and simplified the programmatic creation of accessible tactile charts. These data-driven tools, however, all focus only on basic chart types (i. e., bar charts, pie charts, line charts, and scatter plots). Since our study focuses on complex charts that they do not cover, we adopt a manual design process to ensure optimal tactile representation.

3 Template Chart Design

To effectively teach BLV users about different chart types, we need well-designed example tactile charts, which we describe in this section.

3.1 Chart Types and Datasets

We chose chart types that are common in scientific publications but that were not covered by previous tactile designs. We also chose charts that have different visual encodings to improve the generalizability of our approach. We ultimately selected four advanced chart types: UpSet plots, which are used to visualize set intersections, clustered heatmaps, which are used to visualize large numerical tables, violin plots, which are used to visualize (multiple) distributions, and faceted line charts, which are common e. g., in genome browsers.

To help people focus on understanding chart types we used real-world datasets on familiar topics to create the charts. We refined these datasets by selecting subsets and modifying data to balance the simplicity with sufficient data features for showing each chart type's unique characteristics. For example, to create a bi-modal distribution in the violin plot, we selectively removed entries from the original dataset. Appx. A provides details on the dataset selection and modifications.

3.2 Design Process and Design Variations

We began by generating charts with Python (see Appx. B), and "transcribed" these charts into 2D designs for tactile charts, carefully considered our design choices. Following existing tactile chart design guidelines (discussed in Sec. 2.3), we prioritized simplicity while ensured their meaningfulness for BLV readers. In addition, to facilitate communication between BLV and sighted individuals, we kept our design as similar as possible to the commonly used sighted version. For aspects not covered by extant design recommendations, we drew on our design expertise and feedback from two BLV collaborators. We also developed exploration instructions alongside the charts.

We followed an iterative design process. To explore different options for designs, we created two initial variations of each chart (see Fig. 1). We provide details on our design considerations regarding chart size, orientation cues, title and legend, spacing and styling of chart elements, and the use of raised labels in Appx. C.

To compare design variations, gather feedback, and refine our prototypes and instructions, we consulted our blind co-author and a second BLV researcher. We shipped our initial designs of four pairs of chart types to them and consulted them via videoconferencing. We asked them to explore the charts one by one and also review the accompanying instructions, while "thinking aloud" during the process. We then asked for their feedback on the design and instructions, and refined each chart into a third, final design. Fig. 1 shows the two initial versions and the final designs (more figures see Appx. O–R). Next we present our design variations and the rationale going into each design.

UpSet Plots. We experimented with two main aspects for UpSet plots: bar styles and direct labeling vs. legends. For bar styles, we compared solid bars (Design 1) to bars with "notches" (Design 2), as recommended by Schuffelen [70]. The idea of notches is to make the bar size "countable". We also tried different shapes for each set (circles, triangles, diamonds and stars, as shown in Design 2) and a legend, as opposed to direct labels and uniform shapes (Design 1). Our collaborators appreciated the countable bars, but preferred the direct labeling to support easier reading, resulting in the final design.

Clustered Heatmaps. For the heat map, we experimented with direct labeling vs. a legend for the bar heights (darkness), dendrogram placement, and vertical labels vs. abbreviations with a legend. Design 1 used smaller, unlabeled cells; readers inferred values based on cell height and by referring to a legend. The second design used larger squares with embedded Braille numbers, avoiding the need for a legend. Our collaborators again preferred direct labeling. For the dendrogram placement, Design 1 followed conventional layouts seen in sighted versions, positioning the dendrogram on the left and movie actor names on the right. Design 2 reversed this arrangement, with the names on the left and the dendrogram on the right. Feedback from our collaborators indicated that reading order is critical, especially as tactile perception lacks the ability to see an overview. Hence, our final design places the labels on the left. Finally, we again experimented with direct labeling vs legend, but this time for vertical labels below the heat map. It is generally recommended that Braille text should be written horizontally, and our collaborators agreed. Also, foregoing direct labels allowed us to print the heat map significantly larger, resulting in the only instance where our final design uses a legend instead of direct labeling.

Violin Plots. For violin plots, we explored filled shapes vs. outlines, the use of grids, stippled vs. solid median lines, whether to use raised labels, and again whether to use direct labeling vs. legends. Design 2 also used redundant labels (above and below the violin). Our collaborators preferred filled violins and the horizontal grid lines. For vertical distinction of the categories, they preferred the raised labels over the vertical grid lines. They found redundant labels unnecessary.

Faceted Line Charts. For faceted line charts, we explored the use of filled area charts vs. line charts, and the amount of ticks to use. The line charts require a lot of labels, communicating not only what a particular line encodes, but also the units and the scale. We didn't consider a legend, but instead attempted to place labels within the chart (Design

[1]Including accessiblegraphics.org, aph.org, brailleaustralia.org, pathstoliteracy.org, perkins.org, etc.

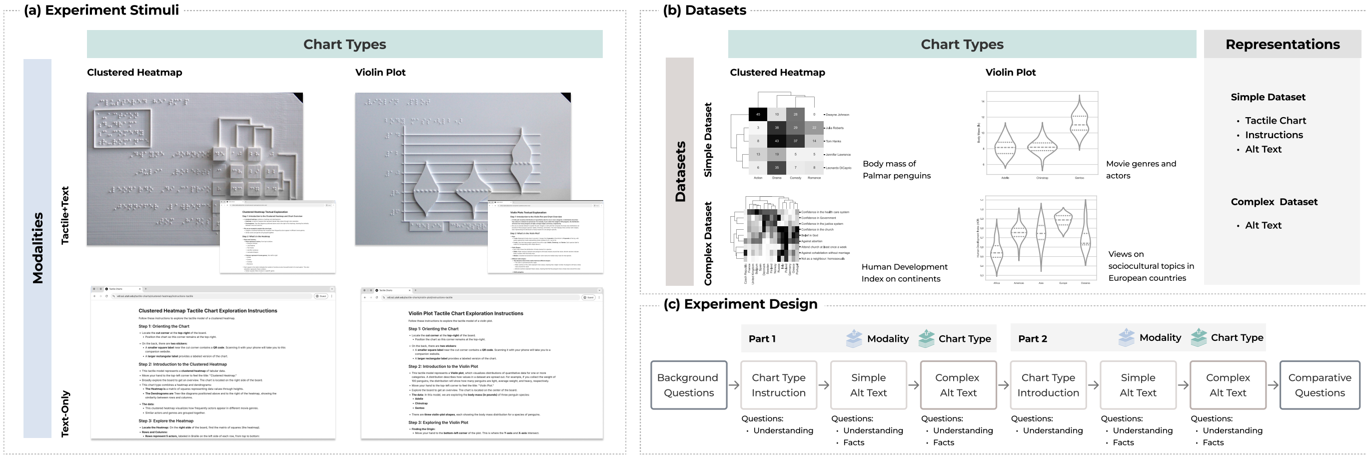

Fig. 2: Overview of the experiment. (a) Participants were assigned one combination of chart type (violin plot, clustered heatmap) and modality (tactile chart with instruction, textual introduction), for one part of the experiment, and the opposite combination for the other part. (b) We used four different datasets in the experiments. The simple datasets are shown in the tactile charts, described in the instructions and in the alt text. For the complex datasets, we provided only alt texts. (c) After background questions, the experiment was conducted in two parts, with different modality / chart type combinations. Each experiment part first introduced the chart type, then provided alt-text for the simple dataset and the complex dataset. These stages was accompanied by factual and understanding questions. The interview ended with comparative questions.

1). Our collaborators found this hard to read, as the lines interfered with the labels. Hence, our final design uses labels on the left, adopts the raised labels from the violin plot, and moves the axis and scales to the right. We again opted for a solid representation over the outline, and used horizontal but not vertical ticks. One collaborator also suggested reducing the density of tick marks on the Y-axis. Another suggested adding the name of the month to the X-axis to improve interpretability, and adding a vertical grid line for reference.

Adapting Visual Encodings for Tactile Perception. Our design is based on existing visualizations; however, we adapted them to support tactile reading. When a visual channel is spatial and thus compatible with touch (e. g., position), we preserved it. For purely visual channels, we identified alternative spatial attributes to replace them. For example, in heatmaps, we translated color intensity into height.

General Design Feedback. We tested raised labels (A, B, C) on one design of UpSet plot and clustered heatmap, and referenced them in the instructions. However, we removed them because a collaborator found them potentially confusing without the instructions. We experimented with long and short titles for each chart, and adopted a collaborator's suggestion to directly use chart type names as titles.

Regarding the Braille, participants noted that the placement of Braille labels was sometimes too close to raised chart elements, and thus hard to read. Although we initially followed spacing guidelines from existing tactile design literature, those guidelines might be developed primarily for embossed swell paper, which has limited height variation. In contrast, our 3D-printed charts include higher elements. As a result, we increased the distance between Braille labels and raised elements to improve tactile readability. Participants also reported that the Braille dots felt too sharp and might be too high. We experimented with dome-shaped Braille to reduce sharpness, but they did not print well, given the 3D printer's resolution. Ultimately, we retained the cylindrical dot shape but reduced the Braille height to 0.6mm (the minimum recommended value) to improve comfort.

3.3 Exploration Instructions

Our instructions use four steps: (1) orienting the chart, (2) an introduction to the chart type and the data shown in the chart, followed by (3) detailed exploration instructions for the chart. The exploration instructions consistently use spatial guidance (e. g., on the top left corner) and combine it with specific information about the data. The instructions conclude with a (4) brief recap, summarizing key points that are essential to remember. We elicited feedback from our blind collaborators on our initial instructions. Both experts appreciated the overall structure and clarity of our instructions, as well as the content used to explain each chart. One collaborator suggested that we should improve our spatial references. Based on this feedback, we revised the instructions for the updated chart designs. We provide instructions on how to explore the tactile models and hosted the instructions on an accessible website: vdl.sci.utah.edu/tactile-charts/. We also provide the initial and final versions of instructions in Appx. E and Appx. F.

3.4 3D Model Creation

3D printing was a suitable modality that could produce charts with the level of detail we wanted to include. Based on the 2D designs, we created digital 3D models (available in `osf.io/9dwgq` and on our companion website) and printed them. We provide details on the model creation procedure and the associated costs in Appx. D.

3.5 Chart Backside

We attached two stickers to the back: a small one that links to the exploration instructions, and a large one with a labeled version of the chart. The labeled version is intended to facilitate collaboration with sighted people, e. g., when sighted educators teach blind students, but also as a reference for those with residual vision.

4 Evaluation Study

Using our finalized tactile charts, we conducted an interview study with BLV individuals to evaluate their effectiveness. We pre-registered our study on OSF (`osf.io/uhq68`) and received IRB approval from the University of Utah (№ IRB_00180924).

Our goal of using tactile charts is not only to introduce BLV individuals to these chart types, but also to improve their comprehension when engaging with digital, easily generated representations (e. g., alt text) of arbitrary datasets presented using these chart types. Based on our goal and the benefits of tactile charts discussed in the Sec. 2, we developed the following research questions:[2]

RQ1: Does a tactile model help BLV individuals develop a better understanding of new advanced chart types compared to a textual explanation alone?

RQ2: Does a tactile model enhance BLV individuals' comprehension of alt-text for an advanced chart? Specifically, we expect tactile charts support high level comprehension but not memorizing individual facts.

RQ3: Do BLV individuals prefer learning new advanced chart types with a tactile model rather than textual explanations alone?

RQ4: Do BLV individuals believe that tactile models can teach them transferable knowledge about a chart type.

[2]Our preregistration also contains hypothesis statements associated with these research questions. However, we later realized that our predominantly qualitative analysis does not fit well with falsifiable hypothesis, and hence omit explicit hypothesis statements.

Table 1: Participant demographics. IP = degree in progress; $\bar{X}$ is mean; Y is mode.

pID	Age	Gender	First Interview Condition (modality)	Data Intensive Career	Braille Years Exp.	Vision Loss Level	Onset of Vision Loss	Highest Level of Education
P1	37	Female	Heatmap (tactile)	Yes	25	Severe low vision	Lost vision gradually	Master's
P2	32	Male	Heatmap (text)	Yes	29	No residual vision	Blind since birth	Master's
P3	44	Male	Violin (text)	Yes	7	No residual vision	Lost vision gradually	Master's
P4	24	Female	Violin (tactile)	No	18	Light perception	Lost vision suddenly	Bachelor's (IP)
P5	29	Male	Violin (tactile)	No	15	No residual vision	Blind since birth	Bachelor's
P6	57	Female	Heatmap (tactile)	No	52	Light perception	Blind since birth	Associate's
P7	40	Female	Heatmap (tactile)	Yes	37	Severe low vision	Blind since birth	Master's
P8	23	Male	Violin (text)	No	11	Severe low vision	Lost vision gradually	Associate's (IP)
P9	42	Female	Heatmap (text)	No	38	No residual vision	Blind since birth	Master's
P10	26	Male	Heatmap (text)	Yes	17	Light perception	Lost vision suddenly	High School
P11	27	Female	Violin (tactile)	No	26	No residual vision	Blind since birth	High School
P12	28	Female	Violin (text)	No	15	No residual vision	Lost vision suddenly	Master's
	$\bar{X} = 34 \pm 10$	7/12 F		5/12 Yes	$\bar{X} = 24 \pm 13$	Y=No residual vision(6)	Y=Blind since birth(6)	Y=Master's(6)

4.1 Study Design

We followed methodology we previously successfully employed with the target population [59] to conduct semi-structured interviews over Zoom. We used a paired interview technique with one researcher asking questions and another researcher asking follow-ups [1].

Considering the expected length of the interview, we deemed it infeasible to test all four chart types with individual participants. Challenges in recruiting from our desired population made a 4-condition between-subject design that also counteracts order effects equally infeasible. To winnow down our charts, we ranked them by difficulty (from most to least difficult): UpSet plot, clustered heatmap, violin plot, and faceted line chart. To balance the need for evaluating complex charts while avoiding overwhelming participants, we then selected the clustered heatmap and violin plot for testing.

We used a mixed-design approach with two factors, as illustrated in Fig. 2: (1) chart type: clustered heatmap or violin plot and (2) teaching modality: tactile model with exploration instruction (`Tactile+Text`) or textual instruction alone (`Text-Only`). Each participant experienced one chart type with `Tactile+Text` and the other chart type with `Text-Only`. The specific pairing and order of chart type and teaching method were counterbalanced across participants to control for order effects. Participants completed the interview on their personal computer or phone. The length of interviews averaged 110 min ± 25 min (SD). Each participant received a $100 Amazon gift card as compensation.

4.2 Study Material Preparation

For each chart type, participants experienced two datasets in the study, which we refer to as the simple dataset and the complex dataset (see Fig. 2). We used the simple datasets to create the tactile charts and developed the corresponding exploration instructions for the `Tactile+Text` condition (see Appx. F), as well as the textual instructions for the `Text-Only` condition (see Appx. H). To ensure comparability between conditions, we prepared textual instructions by removing tactile chart-specific content from the tactile chart exploration instructions and adapting the text accordingly. We also wrote the alt text for the simple dataset, which we refer to as *simple alt texts* (see Appx. I). The complex datasets we selected are larger and address more specialized topics —Human Development Index (HDI) across continents for the violin plot, or sociocultural values across European countries for the clustered heatmap (see Appx. J). We created charts with Python (see Fig. 2 and Appx. K) and wrote corresponding alt texts, which we refer to as *complex alt texts* (see Appx. L). We followed established guidance [55, 59] and refined them with our blind co-author. We also prepared interview questions (see Appx. M). The questions assess general understanding of the charts and datasets, factual questions targeting specific information in the alt texts, and comparative questions evaluating the two modalities.

4.3 Participants

We recruited 12 participants through social media and by re-engaging participants who had previously expressed interest in participating in further studies [59] . We required participants to be (1) 18 years or older, (2) proficient in English and Braille, (3) legally blind (e. g., a visual acuity of 20/200 or worse), (4) have a valid U.S. mailing address, and (5) be employed or attending school at least part-time. We required student or employment status, because the focus of our study is a professional data analysis context. All participants provided informed consent. Table 1 shows participants' demographic information.

4.4 Procedure

Pre-Interview. After expressing interest in participating, individuals completed a screening phone call to assess eligibility. Eligible participants were then provided with information about the study procedures and consent process, and scheduled for the remote interview. Participants subsequently read and signed the consent form and provided their shipping address. We shipped each participant a well-protected tactile chart [16] with exploration instructions, and a additional link to text instructions for a second chart type (see Appx. G).

We then shipped one tactile chart in well protect package [16] along with its corresponding exploration instructions to each participant. We also included links to text instructions for the second chart type (example packages see Appx. G). All instructions were accessible via QR code and were also linked in an email. Participants were permitted, but not required, to review the instructions for both conditions and explore the tactile chart prior to the interview.

Background Questions (13 ± 3 min). Each interview began with background questions about demographics, vision loss, screen reader and Braille experience, and familiarity with tactile graphics, violin plots, and clustered heatmaps. The researchers then directed the participants to a series of pages via Zoom chat or email. Throughout the interview, participants were permitted to read the current page as many times as needed to feel comfortable with the information. However, they were not allowed to return to a previous page.

Chart Type Introductions (13 ± 5 min). Participants first read a chart type instruction page. Depending on their modality condition, they explore the tactile chart or not. We then asked three understanding questions about the chart type (e. g., "What types of data are best suited for visualization using a violin plot?")

Simple Alt Text (9 ± 3 min). Next, participants read the simple alt text, and answered three questions about it, e. g., "What is the dataset about?" (understanding) or "Which species had the least variation in body mass, and why?" (factual).

Complex Text Description (18 ± 6 min). Next, participants read the complex alt text and again answered seven questions about it, e. g., "What is the dataset about?" (understanding) or "How many clusters were the countries divided into, and which is an outlier?" (factual). Then we asked participants to rate their understanding of the dataset, reflect on any difficulties or surprising aspects, and provide additional comments about their experience with the chart.

Comparative Questions (18 ± 7 min). After completing the above procedure for both chart types, we asked participants to compare the two training formats (`Tactile+Text` or `Text-Only`) and indicate their preference, and elaborate on their reasoning. They then rated various aspects of the tactile model, including its helpfulness, ease of use, and

Table 2: Rate of correct, partially correct, and wrong answers for understanding and factual questions (N = 6).

	Training	Correct	Partially Correct	Wrong
Understanding questions after instructions	**Tactile**	30.56%	50.00%	19.44%
	Text	33.33%	50.00%	16.67%
Understanding questions after alt text	**Tactile**	91.67%	8.33%	0.00%
	Text	83.33%	12.50%	4.17%
Factual questions after alt text	**Tactile**	44.05%	28.57%	27.38%
	Text	50.00%	23.81%	26.19%

potential for building transferable knowledge. Finally, participants provided their opinions on the usefulness of each training format for educational contexts and on the tactile model in general.

4.5 Quantitative Results

In this section, we report our quantitative results: correctness of understanding and factual questions, and the subjective ratings. These results suggest some trends, but should be interpreted with caution, as our small sample size precluded meaningful statistical testing.

Understanding and Factual Questions. Two researchers independently coded the correctness of the answers to these questions and reached agreement through discussion. As shown in Table 2, participants did not perform better on questions related to chart types after `Tactile+Text` training. Participants performed slightly better in the `Tactile+Text` condition related to general understanding of new datasets (91.67% correct vs 83.33% for the `Text-Only` condition). As expected, there was no improvement in factual recall.

Subjective Ratings. We summarize the results of the subjective ratings in Fig. 3. Participants' perceived understanding of complex datasets across the two training modalities and dataset are overall similar, ranging from an average of 3.5 to 3.83 on a 5-point Likert scale (Fig. 3(a)). Regarding the two learning methods, 10 participants preferred `Tactile+Text`, and 2 preferred `Text-Only` (Fig. 3(b)). Participants also rated the tactile charts as easy to explore (Fig. 3(c), $M = 4.42$) and expressed positive perceptions regarding their helpfulness in chart learning (Fig. 3(d)). Specifically, participants see tactile charts as helpful in supporting understanding chart types ($M = 4.67$), interpreting alt texts ($M = 4.42$), and learning transferable knowledge about chart types ($M = 4.67$). As shown in Fig. 3(e), participants rated the perceived utility as high for `Tactile+Text` ($M = 4.83$), and somewhat lower for `Text-Only` ($M = 4.00$). They also find value in tactile charts being freely available (Fig. 3(f), $M = 4.55$) [3].

5 Themes

We analyzed our corrected transcriptions using thematic analysis [7, 8, 50]. The first author began by familiarizing herself with the data, generating initial codes, and grouping them into themes based on our research questions. All authors then reviewed and refined the codes and theme names through an iterative discussion process. During this process, the first author continued to actively construct additional codes through deeper engagement with the data. We finally extracted 5 themes, including how tactile charts support the construction of mental models, the transferability of chart-related knowledge across datasets, the role of tactile models in education, the use of other modalities, and design recommendations for educational tactile charts (see Appx. N for the codebook). The first author drafted the initial report of themes, and all authors collaboratively refined it and contributed to the version reported in this section.

5.1 Building Mental Models of Chart Types

In this section, we discuss how tactile charts support facilitate learning and comprehension of new chart types for BLV individuals. Tactile charts offer direct access to spatial information and enable hands-on data exploration through touch. These benefits enhance the learning experiences of BLV individuals compared to other visual substitution modalities, such as auditory descriptions.

[3] P5 did not rate for (f), but he expressed a negative opinion on this question.

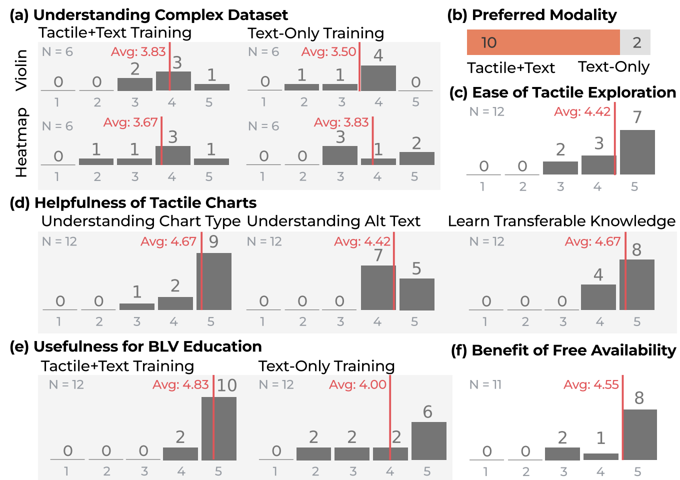

Fig. 3: (a), (b), (d), (e), (f): Histograms of participant ratings on various questions on a 5-point Likert scale (1 = strongly disagree; 5 = strongly agree). (c): Participant preferences between the two learning modalities.

Supporting Mental Model Creation Tactile charts serve as direct substitutes for visual charts for BLV individuals. As P5 described, tactile representations are "*our equivalent*" compared to how sighted people see pictures, and P8 similarly noted exploring the tactile charts as "*like seeing it*". P7 emphasized that tactile charts provide "*an overall understanding of what [the chart] would look like.*" This information can help with the mental model-building process. As P9 described: "*The tactile model helps put it into a picture that you can use, you can create a mental model, to picture things in your head.*"

Even without tactile charts, participants attempted to visualize charts mentally, indicating that creating mental images aligns with their existing learning strategies. However, many participants (P1, P2, P3, P5, P6, P8, P9, P11, P12) noted the difficulty of doing so with only textual instructions. P1 explained, "*sometimes even though I'm listening to the instructions, I still don't get the bigger picture because I can't see what I'm looking at.*" P6 added that even well-written textual instructions are not as effective as tactile models in helping BLV individuals create mental images. P12 was in the `Text-Only` condition for the violin plot, commented: "*I just wish I can see the graph itself, because that would make so much more sense for me, because I think right now, I have a general image. But I'm still not really sure how it looks like visually.*" She then asked us to send her the tactile model after the study.

Participants highlighted that tactile charts are particularly beneficial for those who have never seen a chart before, such as people who were blind from birth, a point raised by both those who are blind since birth (P2, P6, P7) and not (P4, P10).

Understanding chart layout. Several participants shared the difficulty of understanding the spatial layout of chart elements using textual explanation alone. As P9 pointed out, "*not having the tactile representation, you have to draw it in your own mind, so that makes it harder.*" We noticed this difficulty from the reactions of participants in the `Text-Only` condition in our study. For example, P2 struggled with grasping the multidimensional structure of the clustered heatmap: "*When I'm reading things top to bottom, I'm trying to picture them in my mind. Because I have no visual context of what this could even look like, I find myself thinking, "Wait, up and to the left? Up and down?" I'm just trying to imagine all these things, [..] which doesn't always work.*" Reflecting on the learning experience with only textual explanations, P2 noted: "*It's hard to visualize. When you have all those clusters, and this going this way and the other things going on this way on top of that. You lose some of the ability to really analyze it and answer questions about it, and retain the information and really gain insights about it.*" Participants also had difficulty in visualizing violin plots. For example, P8 misunderstood violin plots based on textual information, imagining overlapping violins. P12 tried to visualize a violin plot but was uncertain: "*I still don't really understand how the violin plot looks like, I just end up creating my own visual graph.*" Participants' experiences suggest that while text can convey spatial cues like direction or overlap, it is hard to mentally form a coherent structure from text alone. Thus, text may be insufficient for building mental models.

Understanding shapes. Tactile charts also help participants understand the shapes of chart elements, which is especially important when the chart has a unique shape encoding like the violin plot. Five participants (P6, P8, P9, P10, P12) expressed confusion when first heard "violin shapes." P9 noted that "*sighted people name it in ways that make perfect sense visually, but might not make sense to someone who wouldn't make the visual connection.*" After interacting with the tactile chart, however, participants expressed understanding. As P10 noted, "*I understand now why you call it a violin plot. Makes sense!*" Beyond our study, P9 offered a real-life example, recalling the early pandemic: "*When COVID hit, everybody was talking about flattening the curve. [...] What the hell does that mean? And somebody came up with a tactile representation of flatten the curve because we didn't realize, it's a bell curve and flattening the curve actually meant stopping the increase in COVID cases.*"

Learning by Touch

Tactile charts, as a form of data physicalization, enable learning through material interaction [41]. Eight participants preferred this hands-on learning approach, which supports exploratory and multi-sensory learning. P10 stated, "*I like the hands-on stuff.*" P8 mentioned that "*some people do learn better visually or tactilely than just verbally*" and noted "*My brain would just like to see one.*" P3 describes how this hands-on learning approach aligns with BLV individuals' natural tendencies toward tactile learning: "*Blind people are like children. I want to touch everything.*"

Several participants (P1, P4, P6, P9, P12) identified themselves as "visual, tactile, or kinesthetic learners". Although these labels are debated by cognitive psychologists, they reflect these participants' learning experience and preferences. These participants emphasized that they obtain information better through physical interaction than through auditory input alone. P4 describes her preference for tactile charts over alt texts, stating "*I'm blind, but I do consider myself a visual or a tactile learner in the sense that I'm able to feel what I'm being told. I did fine with the alt text, but I do love the nicely added touch with the tactile*". P6 also explained, "*I'm a visual learner, but not truly visually. I touch things with my hands, and that's how I learned best. [..] When I'm listening, I don't get as much information or don't process it as well.*"

Exploratory learning. Tactile models enable BLV individuals to freely explore tactile charts, as opposed to the prescribed sequence and contents of textual instructions. We found that this autonomy in exploration fosters reflection and insights that might be overlooked in textual or auditory descriptions. For example, P2 described a moment of tactile discovery: "*There was that huge thing in the middle. That thing must represent something in terms of the actual visual data that the text isn't going to give me.*"

Multi-sensory learning. Touching tactile charts while also hearing instructions engages multiple sensory channels, and thus enriches participant's understanding of the data. P7 articulated that "*it just gives you more of a reference point, another way to remember the data. Auditorily is great, but I also like using another sense. [..] Reading it, gives you one perspective, but touching and understanding the different relationships.*" In addition, tactile charts can reinforce and complement textual explanations. P1 emphasized the value of combining touch with audio for building a mental model: "*Being able to feel the map helps me better understand the information I am hearing. When you can't see the visual map, it's almost like you're missing pieces.*" P1 also noted the reassurance that comes from the physical representation: "*You wouldn't have to worry about missing anything, because it's right there in front of you.*" Similarly, P9 shared: "*the tactile diagram really, really reinforces the text, especially when you know what the hell you're looking at. [...] Having something in front of you to look at while JAWS is yammering away, it helps.*"

5.2 Developing Transferable Knowledge

Participants believe the mental models of chart types are reusable and transferable across different datasets. These mental models help them in interpreting new data and alt texts.

Participants reported that tactile chart exploration helped them develop a structural understanding of chart types independent of the dataset, which could be generalized to new contexts. P5 noted this process as "*like getting a mental model of how this particular chart type functions.*" This understanding allowed participants to mentally reconstruct the chart with different data. As P12 explained, "*It helps me understand the chart itself, then it allows me to recreate it mentally with a different data set.*"

This structural mental model also supported participants in understanding alt texts. P1 shared, "*It was different information, but it helped you understand how it could be placed and how you could read it.*" P2 made a comparison to math learning: "*You can use the same type of chart to transfer the information you know about it to be able to understand a different set of information, because it's the same chart. [...] When you learn math, it's the same process to solve a problem. It's just that the numbers are different.*"

Participants emphasized having a reference for comparison helps them understand the new datasets. P4 explained, "*Having one example to feel helped me understand the descriptions of other ones, and understand what they would potentially look like. It definitely helped a lot to have something to compare it to.*" Similarly, P9 explained, "*It gave me a frame of reference to picture the data that I was given. It gave me a model to use, like a mental template. Once you have a concept of a diagram, you can insert other data into that same concept. You have a framework in which to make pictures in your head of the data. If you've never seen the diagram before, you don't have that framework.*"

This idea aligns with our observation that some participants relied on tactile reference points, both physically and mentally, when they encounter new datasets. When interpreting the complex alt text for chart types previously encountered through tactile exploration, participants often referenced their prior tactile experience. For example, P11 said, "*I had that reference point to go back to, because I kept the chart in front of me the entire time.*" We also observed that when asked to imagine the corresponding tactile chart for a new dataset, some participants (P2, P3, P9, P11) used tactile charts they had just explored as a reference in their descriptions. For instance, when P2 was asked to describe a new violin plot about continents after they explored the tactile violin plot about penguins, he said, "*I'm comparing Asia, which has the widest HDI range to the Gentoo penguin on this tactile map because it also had the widest range of body mass.*"

5.3 BLV Visualization Education

Participants discussed barriers that BLV individuals face in learning about data visualizations, their interest in gaining equal access to information, and how tactile charts can support more effective and inclusive visualization education.

Lack of Institutional Support

Participants reported on challenges in their education, where instructors were either unaware of the needs of BLV students or lacked the tools and strategies to support them, consistent with findings by Butler et al. [9]. As a result, BLV learners could be excluded from lessons involving data visualizations. P2 recalled feeling completely lost in a graduate-level visualization course where the instructor made no effort on inclusion: "*He was just writing a bunch of data on the board and drawing it. I had no clue what's going on.*" Even when instructors tried to be inclusive, they could lack effective teaching strategies or resources. As P2 recalled when encountering visualizations in a statistics course: "*They didn't know how to help me. So we just skipped that part of the curriculum for me.*"

Self Exclusion

Some participants noted that BLV students themselves might give up on engaging with visual content. P1 reflected, "*As a blind student, it is so easy for you to say, oh, I'm blind, I can't use this map, and they will let you bypass it.*" However, she also observed positive changes over time: "*Back when I was in school, blind students weren't really pushed. We could opt out of situations that required reading data tables, graphs, and similar materials. But now, with advancements in technology, things are much better in that regard. Blind students are encouraged not to take that cop-out because there are ways to access the information.*"

Interest in Learning Visualizations Participants expressed interest in learning new visualizations and emphasized the importance of equal access to information. For P3, the violin plot offered a clearer alternative to raw data: "*[I think it's a simple way of looking at it rather than having lines and rows of thousands of numbers.*" After exploring the tactile violin plot, P4 shared her enthusiasm: "*This is a really cool format. I've never seen this type of plot for any type of data or information. I really like the concept.*" She also appreciated the clustered heatmap, noting, "*all of this in terms of heatmap, clusters, and dendrograms were new to me, but it was really interesting to learn and see this sort of information be plotted in this way.*" P11 shared similar enthusiasm after interacting with both chart types: "*It is an eye opening experience to see different ways that data are visualized.*" Beyond interest, learning visualizations is important to expend future opportunities. P1 explained: "*Information, like how to read a map or access data, is so important, especially when you get a job. [..] You feel left out when you don't have that information while your peers do.*"

Empowering BLV Education With Tactile Charts Participants discussed the educational value of tactile charts and discussed their availability and potential. P3, an educator herself, emphasized that tactile materials are "*the cornerstone*" and "*the bare baseline,*" stating, "*I think this is extremely valuable.*" P3 pointed out the limitation of relying only on the verbal instructions: "*If you're just teaching by talking to them, for a blind person, they can't get the stimulus, you're missing out on a whole lot of information. It's really difficult to grasp the whole concept. That missing piece causes disengagement. So, the tactile part is absolutely essential.*" Participants also emphasized the potential of tactile charts to support learning and expand future opportunities. P2 noted that tactile charts "*would really change our ability to study a lot of different things,*" and P1 added, "*it is extremely important for students to be able to have access to that, because it just changes the game for you.*" She added that such tools could enable blind students to be "*on the same playing field as their sighted peers.*"

Despite their value, tactile charts are often inaccessible. P6 shared, "*People who are blind don't get exposed to this information, so if I would have had something like this in college, I probably would have done a lot better.*" P9 added, "*It's something that blind people don't often get access to, because they're so expensive to produce.*" Similarly, P1 pointed out the ongoing demand within the BLV community: "*We're always looking for things like this.*" She explained: "*I know a lot of individuals who are blind have requested things like this be put into schools, their workplaces, and their communities—anywhere a sighted person can go and read a map or access data.*"

5.4 Other Modalities

Participants also reflected on alternative modalities for accessing data visualizations, including textual descriptions, raw data, and AI tools. In this section, we discuss participants' experiences with these modalities and highlight how they can complement—but not replace—the need for chart type learning, particularly through tactile charts.

Two participants (P3, P5) preferred the `Text-Only` condition. P3 explained that text can convey all the necessary information and presents a lower barrier to access, serving as a minimal form of support when other modalities are unavailable. For example, P3 noted that not everyone can read Braille: "*Only some very strong braille users would say that they want to look at the braille 100%. [..] If you have a tactile piece with [text]—the more the merrier—but I think [text] meets the threshold. [Text] will 100% give you the information.*" P3 also emphasized that Seeing AI, an accessibility tool he uses, cannot read Braille. He pointed out: "*It's a game of availability. [..] Alternate text is the bare minimum.*" P12 shared a similar view: "*[Text] is better than nothing. But it is really hard to digest and comprehend. It's doable, just takes a lot of energy.*" These perspectives align with our earlier discussions: while textual explanations often fall short in supporting the development of mental models, they offer broad accessibility. P5 preferred AI tools and was not fully satisfied with either training format, but acknowledged the practicality of text: "*Neither of these [modalities] was super effective, but I'd say [I prefer] the text because it summarizes the info I need to know in one easy package.*"

A few participants expressed a preference for raw data in tables over charts. P9 stated that a table might be more accessible: "*As a blind person, you'd probably be more pragmatic just to have a table with the actors and the the movie genres, and then the numbers.*" P5, who prefers using AI tools, advocated for direct access to raw data and the use of AI summaries and question answering: "*When you're trying to take in a data visualization, if I have time I want to take it in as a table, and if I don't have time I need a summary.*" We argue that these workflows are sensible, and our tactile charts are meant to support workflows for arbitrary datasets. In addition, raw datasets are often not available or become impractical when dealing with complex data or layered structures [43]—as seen in many scientific visualizations.

5.5 Design Better Tactile Charts For Learning Chart Type

Participants appreciated our design decisions. For instance, P3, who had prior experience with poorly made charts, noted, "*I'm very, very impressed, because I've seen some bad ones.*" Positive feedback reinforced the importance of thoughtful chart design and construction process. In this section, we identify key design considerations based on participant feedback and provide guidance on how to create more accessible and pedagogically effective tactile charts for BLV learners. We note that in the future, these design suggestions should be validated in real learning scenarios.

Topic Familiarity We observed that familiar content helped participants use prior knowledge to build a mental model of the chart, even when the data was complex. For example, P9, who was more interested in European countries (our complex dataset) than in movies, stated that she could imagine the heatmap for countries but probably not for movies. Hence, we recommend **using topics that are relatable or familiar to the targeted audience in educational tactile charts.**

Clarity of Chart Elements Clear layout and spacing helps reading tactile charts, as suggested by guidelines (e. g., [6]). Participants appreciated the clarity of our chart design. For example, P4 noted that the chart "*has a nice and neat touch*" and added, "*It's clear, legible, and everything is spaced out perfectly. The lines, and all of the different shapes on the graph are easy to identify, and just all of the details were absolutely fantastic.*" These responses highlight the the value of clear organization and visual separation in tactile formats.

Participants also emphasized the value of clear labels. P4 noted that "*it is especially helpful to have the labels along the Y and X-axis*" for the violin plot. P8 also thought the labels of the heatmap columns and rows are very helpful, and further suggested adding "*a more distinct outline, whether between the names or the y-axis columns*" to enhance their separation. We thus recommend designing tactile charts with **clear layout, well-spaced elements, and provide clear labels.**

Braille All participants who commented on the 3D-printed Braille described it as legible and well-formed. P1 and P4 both described it as "*easy to read*" and P3 confirmed that "*Braille dots are not dead. You can read it really well*". P1 further explains that "*the braille is very sharp and crisp, too. That's a good thing.*" These positive responses were reassuring, as we had initially been concerned that 3D-printed Braille might be unpleasant to touch compared with embossed paper.

Beyond readability, participants also discussed the choice between Grade 1 (uncontracted) and Grade 2 (contracted) Braille. We used Grade 1 across all charts in the study. Participants commented that Grade 1 is more accessible (P4, P7, P9), particularly for beginners. However, they also expressed concerns that Grade 1 takes up more space (P7, P9) and may reduce reading speed (P9). P7 further noted that people in advanced classes should be comfortable with Grade 2. These perspectives reflect a trade-off between accessibility and efficiency. In addition, P7 also noted the absence of numeric indicators for the Braille numbers in the heatmap and suggested adding a sentence to indicate that these Braille characters represent numbers to avoid confusion. We thus recommend **selecting the Braille grade based on the target audience's proficiency, and ensuring that all indicators are used correctly or that deviations are clearly explained.**

Production Method Participants expressed appreciation for the 3D-printed tactile charts and identified several advantages of 3D printing. One commonly praised benefit was the sturdiness of the 3D-printed models. P2 noted, "*Regular paper smushes and bends, not helpful at all.*" P4 also explained that the sturdy surface enhanced readability: "*A lot of a lot of tactile stuff that I've seen is flimsy.*" Participants also highlighted the resolution of 3D printing, which allows for more realistic, accurate, and detailed representations, which aligns with prior discussions e. g., [37, 54]. P11 praised our 3D-printed charts: "*It's very realistic looking. [..] That might draw people in. I'm amazed that this can be done.*" P2 contrasted it with embossed paper: "*The problem I always had with them was that you couldn't create highly realistic 3D representations, at least not when I was in school. With 3D printing, you can.*" P9 expressed optimism about improvements in tactile chart quality: "*I'm hopeful that with 3D printing technology [..] that's changing. Back in my day...you rarely found a good tactile representation of something.*" Participants also showed interest in the process behind 3D printing itself. P10 commented, "*I was interested in, surprised that it was printed with a 3D printer. Is that just something you'd have to type in code, and it prints out? [..] Can anyone buy a 3D printer?*" We recommend **using 3D printing to produce tactile charts for complex visualizations for educational purpose.**

Providing a Sighted Version We included a sighted version on the back of the chart to facilitate communication between blind and sighted individuals, which proved helpful. Before noticing it, P3, an educator, asked: "*If a professor is teaching a blind student [..] Would they be able to guide that person based on the tactile model?*"

Exploration Instructions To support independent learning, we provided instructions for tactile charts, which participants appreciated. As P1 noted: "*Someone can explain things to you all day, but being able to look at it yourself opens up a whole new window of information and opportunity.*" While we did not directly compare conditions with and without instructions, many participants (P2, P3, P4, P6, P7, P9, P11) emphasized that guidance was crucial for effective interpretation. Participants often struggled to make sense of the tactile charts before reading the instructions but understood them more clearly afterward. For example, P4 recalled, "*When I first opened this package and I saw what this was, I was like: "What is this? This doesn't make any sense!" But with the instructions, it clicked right away.*" Similarly, P2 said "*having the instructions on how to read it let this makes obviously more sense, and I know what I'am looking at.*" P6 also mentioned that the instructions made the charts "*easy to follow, especially since you guys sent that little instruction thing.*" This impact was reflected in ratings: P3 and P7 rated ease of exploration as 4 without instructions and 5 with them. We recommend **pairing tactile charts with concise exploration instructions and a label referencing the sighted version to support independent learning and communication with sighted individuals.**

Suggestions on Instructions Participants shared what makes effective exploration instructions. They recommended giving a high-level summary before diving into details (P2, P3, P8) and immediately explaining attention-grabbing features of the tactile chart, such as the 3D cells in the heatmap (P3). P2 also emphasized that describing visual features like color is helpful: "*You might not think color is important because we can't see it, but it is still good to know. [..] It would help us understand.*" We thus recommend **structuring exploration instructions to begin with an overview of the dataset and chart structure, followed by a sequence that aligns with the tactile exploration flow. Authors should not avoid describing visual features.**

6 Discussion and Future Work

Our initial quantitative results suggest that `Tactile+Text` and `Text-Only` training support similar levels of understanding of advanced chart types (RQ1). `Tactile+Text`, however, resulted in slightly higher accuracy when interpreting complex alt texts (RQ2). This pattern suggests that while tactile input may not significantly improve immediate basic comprehension, it can support retaining and applying chart type knowledge in more complex or long-term scenarios.

The subjective ratings and qualitative data show a more consistently positive picture. Participants felt that tactile charts helped them develop a better understanding of chart types, and emphasized the benefits of building mental models, understanding chart layouts, learning about shapes, and the advantages of hands-on exploration. These findings align with the benefits of tactile charts shown in prior work (e. g., [13, 20, 20, 28, 29, 33, 45, 81, 85]) and further indicate that tactile models do lead to a better understanding of advanced chart types (RQ1). Furthermore, participants reported that tactile models helped them transfer knowledge to new datasets (RQ4) and even referenced analogous patterns in prior charts, yet self-reported understanding of specific complex datasets did not vary much between conditions, while self-assessment on the helpfulness of tactile charts for learning transferable knowledge was high ($M = 4.67$ out of 5). Preference is clear: most participants (10/12) prefer learning with tactile models (RQ3), which is evident both from the quantitative and from the qualitative data. Only two participants were hesitant about tactile models: one preferred alt text for its lower barrier to access, and the other preferred querying ChatGPT for information. As for the utility in learning, participants strongly believed that tactile template charts are highly useful in education, and reported many personal situations where they could have benefited from them, aligning with previous findings [73]. Taken together, our design and evaluation show the potential of tactile template charts to promote more inclusive access to data. To our knowledge, this is the first empirical study to explore how tactile example charts can be leveraged to teach BLV individuals to interpret complex visualizations, we thus argue that we address a BLV education gap.

Several limitations should be noted in interpreting these results. First, we only evaluated two chart types, limiting the generalizability of our findings. While violin plots and heatmaps allow us to examine the comprehension of different structures, like distributions versus clustering, they do not fully capture the complexity or variation found across all data visualizations. In addition, the interview format creates a structured setting differing from real-world use, where exploration could be self-directed without expert guidance. Third, our study focused on short-term comprehension and did not assess long-term retention, learning outcomes, or educational impact. Finally, participants may have self-selected to participate based on an interest in tactile charts.

Reflecting on our process, conducting online interviews has several advantages with BLV participants. Remote participation made it easier to recruit eligible individuals without geographic restrictions. Participants join the interview using their personal computers, which are already configured with their preferred accessibility tools, such as specific screen readers, settings, and additional software or hardware (e. g., screen magnification, braille display). In addition, future researchers should note the complexity of remote studies involving tactile charts [16]. In our experience, this adds extra logistics, such as an asynchronous consent processes as well as shipping costs and accounting for delivery timelines.

Future work could further explore the educational potential of tactile charts by extending them to additional chart types or modalities (e. g., comparing to or integrating with AI-supported question-answering systems [47, 71]) and by supporting BLV individuals to create them independently [27]. It would also be interesting to explore embedding tactile cues for common interactive features (e. g., on-demand tooltips). Finally, given the importance participants placed on exploration instructions, an automated pipeline that generates such instructions from existing chart specifications could streamline the production of educational tactile charts.

7 Conclusion

We show that tactile charts, when thoughtfully designed and with clear exploration instructions, can be a helpful and preferred educational tool for BLV individuals to learn complex visualizations. These findings suggest a promising research direction toward improving data visualization literacy among BLV individuals with tactile charts and contribute to the broader goal of making information more accessible and inclusive. To this end, we make our models and instructions freely available and hope to build out a library of charts in the future.

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Supplemental Material Pointers

The pre-registrations for our study can be found at `osf.io/uhq68`. We also share our supplementary material at `osf.io/9dwgq` vdl.sci.utah.edu/tactile-charts/, and `github.com/visdesignlab/tactile-charts`.

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Using Tactile Charts to Support Comprehension and Learning of Complex Visualizations for Blind and Low Vision Individuals

Appendix

In this appendix we provide detailed discussion and additional figures that we could include in the main paper due to space limitations or because it was not essential for explaining our approach. .

A Simple Datasets

To help people focus on understanding chart types we used real-world datasets on familiar topics to create the template charts. We refined these datasets by selecting subsets and modifying data to balance the simplicity with sufficient data features for showing each chart type's unique characteristics. In this section, we provide details on the dataset selection and modifications.

A.1 UpSet Plot: The Simpsons dataset

For the UpSet plot, we used a dataset representing attribute overlaps among Simpsons characters. We selected this dataset because it shows various intersection patterns including empty intersections, individual character attributes, and multiple overlapping attributes. We downloaded the original dataset from the UpSet GitHub repository (`github.com/VCG/upset/tree/master/data/simpsons`). This dataset was curated by Alexander Lex and originally sourced from The Simpsons character database (`thesimpsons.com`).

A.2 Clustered Heatmap: Movies by actors and genres

For the clustered heatmap, we used a dataset representing the number of movies performed by five well-known actors across four common movie genres. We selected this dataset because it shows different distribution and clustering patterns. We derived this dataset from the IMDb Non-Commercial Datasets (`developer.imdb.com/non-commercial-datasets/`). To create this dataset, we processed three IMDb datasets: `title.basics.tsv`, `title.principals.tsv`, and `name.basics.tsv`. These datasets refresh daily.We downloaded these original datasets from `datasets.imdbws.com` on November 2, 2024.

A.3 Violin Plot: Penguin dataset

For the violin plot, we used a modified version of the Palmer Penguins dataset, which contains body mass values for three penguin species. We selected and modified this dataset to demonstrate three different distribution patterns. We obtained the original dataset from the Palmer Penguins R package (`allisonhorst.github.io/palmerpenguins`). To show a clearer bimodal distribution, we selectively removed 21 records from the original dataset.

A.4 Faceted Line Chart: Weather dataset

For the faceted line chart, we used a dataset representing daily weather measurements (average temperature, average humidity, average wind speed, and total precipitation) in Austin, Texas during August 2016. We selected this dataset because it shows different types of trend patterns across multiple weather variables. We downloaded the original dataset from Kaggle (`kaggle.com/datasets/grubenm/austin-weather`).

B Python Generated Plots for Template Charts

To create our tactile charts, we first generated visualizations using Python, Matplotlib, and Seaborn. In this section, we present these Python-generated plots.

C Detailed Design Considerations

In this section, we describe our design choices based on tactile chart design guidelines and related research (as we discussed in Sec. 2.3). These considerations primarily concern the spacing and styling of chart elements, and the using of the tactile markers.

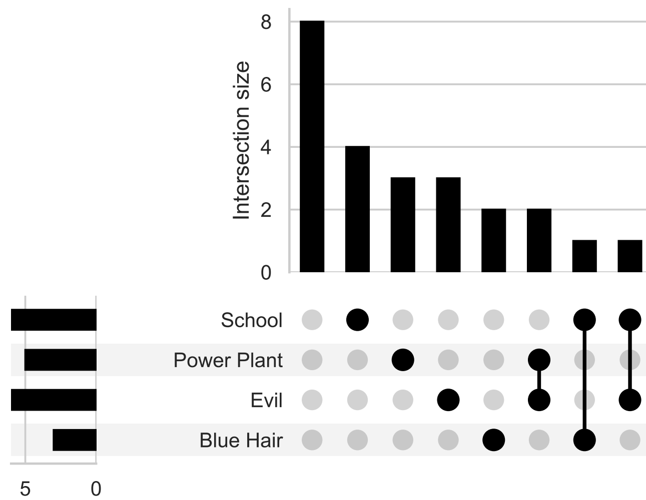

Fig. 4: Python-generated UpSet plot used to create the tactile chart.

Chart Size We chose A4-sized boards, maximizing the size of the chart while keeping it manageable in total size [6]. We consistently placed chart titles and legends (if needed) at the top left of each chart. To indicate orientation, there are two common conventions

Orientation Cues To indicate the orientation of tactile graphics, guidelines suggest two conventions ([67] and www.colorado.edu/project/bbb/creating-tactile-graphics: one is marking the top-right corner with a triple slash ▧, and the other is physically cutting the top-right corner. We adopted the latter for its simplicity.

Chart Elements Follow the guidelines (e. g., [6, 64, 70]) and related research (e. g., [22, 24, 25]) We separate elements by 3-6 mm and also positioned labels 3–6 mm from their referenced components. We differentiated line widths by at least 25%. For dashed lines, we maintained a minimum unit length of 2.5 cm with at least three repetitions of the pattern to ensure clear tactile recognition. For the two bar charts in the UpSet plots, we followed the recommendation for bar charts, and used a bar width of 10 mm. We included both x- and y-axes for plots for violin plots and faceted line plots. We provide the Y-axis labels at the top of the axis (rather than vertically along the axis), while the x-axis labels are placed at the bottom. We avoided arrows at axis endpoints and clearly marked all starting points. We use tick marks only on numerical scales, not on categorical scales. We placed tick marks outside the axis line. UpSet plots and matrices don't have axis, as they are a tabular representation.

Raised Labels We also introduced raised labels to the UpSet plots and clustered heatmaps to guide readers in exploring different parts of the visualization. For example, in the UpSet plots, we labeled the set bar chart, the intersection matrix, and the intersection bar chart as A, B, and C, respectively. We consulted with our blind co-author on this design, and he suggested that for complex charts, when designers wish to highlight or emphasize specific regions or elements, using raised labels can be an effective approach.

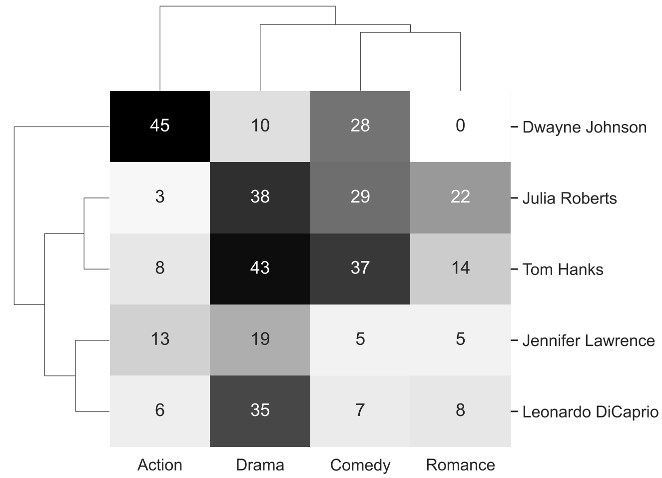

Fig. 5: Python-generated clustered heatmap used to create the tactile chart.

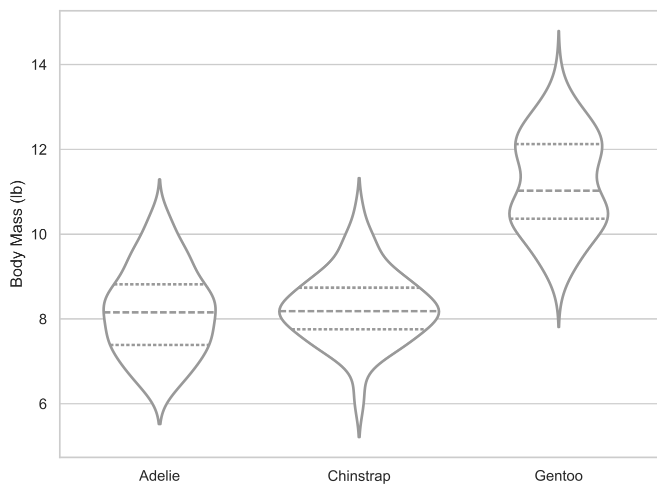

Fig. 6: Python-generated violin plot used to create the tactile chart.

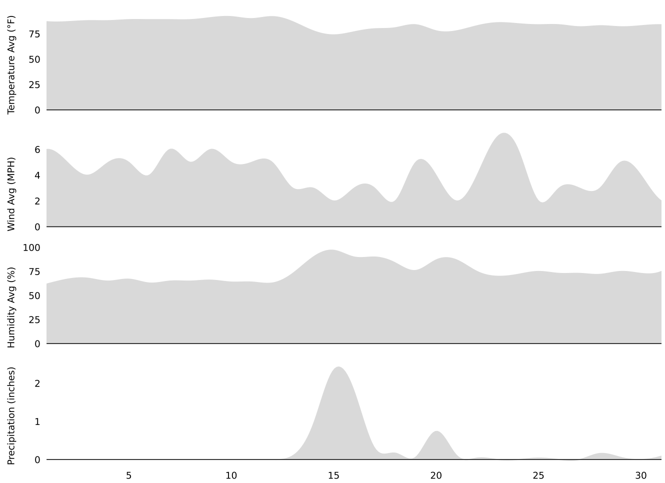

Fig. 7: Python-generated faceted line chart used to create the tactile chart.

Braille We used Unified English Braille (UEB) Grade 1 consistently for all text labels. Grade 1 Braille spells words letter by letter without contractions (as Grade 2 does). While Grade 1 results in longer text compared to Grade 2, it is easier to understand by Braille reading beginners. Braille uses indicators to denote special symbols that follow. These indicators are special Braille characters. We used them as recommended. Specifically, we used the number indicator (⠼) to indicate numeric values, except in contexts where the meaning was unambiguous and space constraints, such as when labeling individual cells in the heatmap. We generally limited the use of capital letters, using it only for cases such as names, where we also included the appropriate capitalization indicators (⠠). For size, we followed standard Braille sizing guidelines (e. g., [6]).

D 3D Model Creation Procedure and Cost

Based on the 2D designs, we created digital 3D models in SolidWorks (available in `osf.io/9dwgq` and on our companion website). These models were then fabricated as 3D-printed tactile charts.

In the first round of model creation, we designed two variations for each of the four chart types, resulting in a total of eight unique designs. We printed five copies of each design, producing 40 models in total. Two UpSet designs were printed at the Merrill Engineering Building (MEB) of the University of Utah with a high-quality large-format printer (Prusa XL), yielding 10 models at a total cost of USD 84.15. Given the substantial number of charts required, we also experimented with commercial 3D printing services. We ordered additional models from a provider listed on Craftcloud (craftcloud3d.com), chosen for its fast turnaround time. The remaining 30 models were printed via this provider at a total cost of USD 311.07 (USD 244.85 for production and USD 66.22 for shipping). All prints used white standard PLA with 20% infill.

To reduce both printing time and cost, we initially used a 5mm base board. Two models printed at the university have a 5mm base (one for each UpSet design). Finding this base thickness stable enough, we transitioned to a 3mm base for the remaining 38 models.

From the first round of printing, we found the quality of the online printing to be inconsistent. For example, some charts required extensive polishing with sandpaper to make them usable. Consequently, for the second round of printing—which included four final designs for each chart type—we only use the printing services from our university. Given that the 3mm base had proven sufficiently stable, we further reduced the base thickness to 2mm. In this second round, we printed 8 violin plots, 8 clustered heatmaps, 2 UpSet plots, and 2 faceted line charts, at a total cost of USD 160.95 (approximately USD 8 per model).

E Tactile Chart Exploration Instructions (Initial Version)

We provide instructions on how to explore the four tactile models. We first drafted an initial version of the instructions and then elicited feedback from our BLV collaborators. Based on their input, we revised the instructions accordingly. In this section, we present the initial version. The initial version corresponds to Design 1 of the tactile chart for each chart type (see Fig. 1).

E.1 Tactile Chart Exploration Instructions (Initial Version): UpSet Plot

Follow these instructions to explore the **UpSet Plot** tactile model. Feel free to stop the exploration at any time or take breaks as needed.

Step 1: Orienting the Chart

- Begin by locating the **cut corner** at the top-right of the page.
- Position the chart so that this corner is at the top-right. This ensures the chart is correctly oriented for your exploration.
- The tactile model is at the front of the chart. There are two stickers on the back, one with a labeled version of the chart, and a round-shaped one with a QR code that can bring you to a companion website, if you scan it with your phone.

Step 2: Introduction to the UpSet Plot

This tactile model represents an UpSet plot, which visualizes how different sets intersect.

Key Concepts:

- **Sets:** Groups of **elements** sharing a specific attribute.
- **Intersection:** The overlap of **elements** between these sets.

Example Context: This example plot uses attributes of Simpson characters:

- Each character represents an element.
- Their attributes (e.g., "School," "Blue Hair") form sets. Characters with a specific attribute belong to that set.
- Intersections represent overlaps of attributes; for example, a character can belong to multiple sets.

Step 3: Overview

To get started, move your hand to the **top-left corner** to feel the **title** of the chart, which reads: "UpSet: Visualizing Intersecting Sets." The **UpSet plot** has three main sections:

1. **Bottom-Left:** A horizontal bar chart representing the size of each set (i.e., how many elements are in each set).
2. **Bottom-Center:** A matrix of circles showing different types of intersections between sets.
3. **Top-Right:** A vertical bar chart showing the size of each intersection (i.e., how many elements belong to each intersection).

Step 4: Exploring the Sections

A-Set Size Bars (Bottom-Left)

1. Move your hand to the **left edge of the chart** and locate **Marker A**.
2. Below this marker are **four horizontal bars**. Each bar represents the size of a set.

How to Explore:

- Labels: On the left end of each bar, feel the Braille labels for set names.
- Bar Lengths: Longer bars represent larger sets.
- Numbers: On the right of each bar, feel the Braille numbers indicating set sizes.

From top to bottom, the sets and their size are:

- School, 6
- Power Plant, 5
- Evil, 6
- Blue Hair, 3

B-Intersection Matrix (Bottom-Center)

1. Move your hand to the **center** and locate **Marker B**.
2. Below and to the right of this marker is the **intersection matrix**, a grid of circles.

Grid Overview:

- **Rows:** Represent sets, aligned horizontally with the set size bars.
- **Columns:** Represent different intersections.

Symbols in the Grid:

- **Filled Circles:** The set is included in the intersection.
- **Empty Circles:** The set is not included in the intersection.
- **Vertical Lines:** Connect filled circles to help trace the columns.

Types of Intersections:

- **Empty Intersection:** A column with no filled circles. **Example:** The first column (leftmost) represents an empty intersection. Trace along the column to feel that all circles are empty. The intersection size is labeled above as **8**, meaning 8 characters have none of the four attributes.
- **Individual-Set Intersection:** A column with only one filled circle. **Example:** The second column from the left represents an individual-set intersection. It has one filled circle (School). The intersection size is labeled above as **4**, meaning 4 characters have only the "School" attribute.

- **Multi-Set Intersection:** A column with multiple filled circles. **Example:** The last column (rightmost) has filled circles in the rows for "School" and "Blue Hair" and empty circles for the other two attributes. The intersection size is labeled above as **1**, meaning 1 character has both attributes but not others.
- **All-Set Intersection:** A column with all circles filled. **Example:** In this plot, no column has all circles filled, meaning no character has all four attributes.

Intersection Degrees:

- The number of sets included in the intersection increases from **empty intersections** to **all-set intersections**,
- **Low-Degree Intersection:** Few sets are included.
- **High-Degree Intersection:** Many sets are included.

C-Intersection Sizes (Top-Right)

1. Move your hand to the **top-right** and locate **Marker C**.
2. Below this marker are eight vertical bars, each corresponding to a possible intersection.

How to Explore:

- **Height:** Taller bars indicate larger intersection sizes.
- **Labels:** Below each bar, the intersection size is written in Braille.
- **Correspondence:** The filled-in cells in the column directly below the bar show which sets are part of that intersection.

Features of Intersections in This Plot:

- The tallest bar (leftmost) represents the **empty set**, with a size of **8**.
- Bars are sorted by size in descending order. Moving from left to right, the bar heights decrease, representing intersection sizes down to **1**.

Step 5: Recap

- Left Section: Horizontal bars show set sizes.
- Center Grid: Circles and lines represent intersections.
- Top-Right Section: Vertical bars show the size of these intersections.

E.2 Tactile Chart Exploration Instructions (Initial Version): Clustered Heatmap

Follow these instructions to explore the tactile model of a **Clustered Heatmap**. Feel free to stop at any time or take breaks as needed.

Step 1: Orienting the Chart

1. Locate the **cut corner** at the **top-right of the page**.
2. Position the chart so this corner remains at the **top-right**. This ensures the chart is properly aligned for your exploration.
3. The tactile model is at the front of the chart. There are two stickers on the back, one with a labeled version of the chart, and a round-shaped one with a QR code that can bring you to a companion website, if you scan it with your phone.

Step 2: Introduction to the Clustered Heatmap

- This tactile model represents a **clustered heatmap**, a chart type that shows patterns and clusters within data.
- The chart combines a **heatmap** (a grid of squares representing data values) with a **dendrogram** (a tree-like structure showing clusters).

Example Context:

- This heatmap represents the number of movies actors have acted in, categorized by genre.
  - **Rows** represent actors.
  - **Columns** represent genres.
- Each square in the grid represents the number of movies:
  - **Higher squares** mean more movies.
  - **Lower squares** mean fewer or no movies.

Step 3: Overview

Move your hand to the **top-left corner** to feel the title: "Heatmap with dendrogram: visualizing clusters." Below the title, explore the **legend**:

- A vertical line of **5 tactile squares** represents different values (from 0 to 50).
- Each square's **height** corresponds to a data value and is labeled in Braille.

You can feel the chart at the right of the legend.
The chart consists of **three main sections:**

1. **Heatmap (Center):** A grid of squares showing the intensity of values.
2. **Row Dendrogram (Left):** A branching structure grouping similar rows (actors).
3. **Column Dendrogram (Top):** A similar branching structure grouping similar columns (genres).

Step 4: Exploring the Sections

Explore the Legend (Top-Left)

- Locate the vertical line of **5 tactile squares**, representing values:
  - **Highest** square=50.
  - **Lowest** square=0.

Explore the Heatmap Matrix (Center)

- Find the grid of squares at the center.
- Rows represent **actors**: Braille labels are along the **right side** of each row.
- Columns represent **genres:** Braille labels are along the **bottom** of each column. Please note that these labels are written vertically. To read them, you'll need to rotate your hand 90 degrees counterclockwise or board orientation by 90 degrees clockwise.

Explore each square:

- Feel its height to determine the value it represents.
  - Higher squares m̄ore movies in that genre.
  - Lower or flat squares f̄ewer or no movies.

Example:

- **Top row (Dwayne Johnson):**
  - **First square (Action):** Very high (many movies).
  - **Second square (Drama):** Low (few movies).
  - **Third square (Comedy):** Medium-high (moderate number of movies).
  - **Fourth square (Romance):** Flat (no movies).

Explore the Dendrograms **Column Dendrogram (Top)**

- Move your hand to the **top edge** of the heatmap.
- Locate **Marker A** at the top of the dendrogram.
- Trace the lines downward toward the heatmap grid.
- Feel how the branches connect, grouping similar genres. **Example:** The **rightmost columns** (Romance and Comedy) group together. Drama joins next, followed by Action, which is the most distinct.

Row Dendrogram (Left)

1. Move your hand to the **left edge** of the heatmap.
2. Locate **Marker B** at the top of the dendrogram.
3. Trace the lines to the right toward the heatmap grid.
4. Feel how branches group similar actors. **Example:**
   - **Dwayne Johnson** is distinct (specializes in Action).
   - **Julia Roberts and Leonardo DiCaprio** cluster together (focus on Drama and Comedy).
   - **Jennifer Lawrence and Tom Hanks** cluster next (focus mainly on Drama).

Step 5: Recap

- The **Heatmap** displays values using a matrix of raised squares.
- The **Dendrograms** show clustering relationships between rows (actors) and columns (genres).
- Together, they illustrate patterns in the data.

E.3 Tactile Chart Exploration Instructions (Initial Version): Violin Plot

Follow these step-by-step instructions to explore the tactile model of the **Violin plot**. Take breaks as needed to ensure a thorough understanding.

Step 1: Orienting the Chart

1. Begin by locating the **cut corner** at the **top-right** of the tactile model.
2. Position the model so that this cut corner is at the **top-right**, ensuring correct orientation for exploration.
3. The tactile model is at the front of the chart. There are two stickers on the back, one with a labeled version of the chart, and a round-shaped one with a QR code that can bring you to a companion website, if you scan it with your phone.

Step 2: Introduction to the Violin Plot

This tactile model represents a **Violin plot**, which visualizes distributions of quantitative data for one or more categories.

Example Context:

- In this model, we are exploring the **body mass (in pounds)** of three penguin species:
  - **Adelie**
  - **Chinstrap**
  - **Gentoo**
- Each **violin shape** shows how body mass varies within each species.

Step 3: Overview

- Move your hand to the **top-left corner** to locate the title, which reads: "Violin plot visualizing distributions across categories."
- Below the title, explore the **legend**. From top to bottom, there are three lines with different thicknesses:
  1. **Thin line**: Represents **Adelie** penguins.
  2. **Middle line**: Represents **Chinstrap** penguins.
  3. **Thick line**: Represents **Gentoo** penguins.
- The species names are in Braille next to each line in the legend.
- To the right of the legend, you will find the **Violin plot**. It has three main areas:
  1. **Y-axis** (Left): A vertical line with Braille tick marks, representing body mass in pounds.
  2. **X-axis** (Bottom): A horizontal line with evenly spaced Braille labels for each species: **Adelie**, **Chinstrap**, and **Gentoo**.
  3. **Violin Shapes** (Center): Three violin shapes, each positioned above a species label, showing the distribution of body masses for that species.

Step 4: Detailed Exploration

Finding the Origin:

- Move your hand to the **bottom-left corner** of the plot. This is where the **Y-axis** and **X-axis** intersect.

Y-Axis and Scale:

- Start at the **bottom-left corner** and trace the **Y-axis** upward.
- Feel the evenly spaced tick marks and their Braille labels, which represent body mass measurements:
  - The bottom tick (at the corner) is **5 pounds**.
  - The next tick above is **6 pounds**, then **8 pounds**, **10 pounds**, and so on, increasing evenly to the top tick, which is **14 pounds**.

X-Axis and Species Labels:

- Return your hand to the **bottom-left corner** and trace the **X-axis** horizontally.
- From left to right, you will feel three Braille labels identifying the penguin species: **Adelie**, **Chinstrap**, and **Gentoo**.
- These labels correspond to the violins directly above them.

Violin Shapes:

- Locate the **first violin** above **Adelie** on the X-axis. This represents the distribution of body masses for Adelie penguins.
- Trace the **outer contour** of the violin with your fingers:
  - The violin is symmetric.
  - Wider parts (more curved sections) represent more penguins with body masses at those values.
  - Narrower parts represent fewer penguins with those body masses.
- Refer to the **Y-axis** or tactile **grid lines** to identify the corresponding body mass values.
- Inside each violin, you will feel a **dashed horizontal line**, which marks the **median body mass** for that species.
- Move your hand to the right and repeat this process for the **Chinstrap** and **Gentoo** violins.
- Touch the three violins. Compare the shapes and medians to understand differences in distribution.
  - **Left violin (Adelie penguins):** The distribution is unimodal, and it has one peak in the middle. The median body mass is about 8.2 pounds, with most Adelie penguins' body masses clustering close to this value.
  - **Middle violin (Chinstrap penguins):** The distribution is also unimodal, with a single peak in the middle. The median body mass is about 8.2 pounds. Most Chinstrap penguins' body masses are concentrated around 8.2 pounds, and their weights are more tightly clustered near the middle compared to Adelie penguins.
  - **Right violin (Gentoo penguins):** The distribution is bimodal. It has two peaks, one near each end. The median body mass of Chinstrip penguins is roughly 11 pounds, which is larger than Adelie and Chinstrap penguins. Gentoo penguins' body masses are concentrated around 10.5 pounds and 12 pounds, which form the two peaks.

Step 5: Recap

- **Y-Axis**: Represents body mass in pounds, increasing from 5 to 14 (vertical scale).
- **X-Axis**: Identifies penguin species (horizontal labels).
- **Violin Shapes**: Show the distribution of body masses, with wider sections indicating higher density and dashed horizontal lines marking the medians.

E.4 Tactile Chart Exploration Instructions (Initial Version): Faceted Line Chart

Follow these step-by-step instructions to explore the tactile model of the **Faceted Area Plot**. Take breaks as needed to ensure a thorough understanding.

Step 1: Orienting the Chart

1. Begin by locating the **cut corner** at the **top-right** of the tactile model.
2. Position the model so that this cut corner is at the **top-right**, ensuring correct orientation for exploration.
3. The tactile model is at the front of the chart. There are two stickers on the back, one with a labeled version of the chart, and a round-shaped one with a QR code that can bring you to a companion website, if you scan it with your phone.

Step 2: Introduction to the Faceted Area Plot

- This tactile model represents a **Faceted Area Plot**, which visualizes trends in multiple related datasets.
- **Example Context:** The model displays weather trends in Austin, Texas, using four variables:
  - **Average Temperature** (°F)
  - **Average Wind Speed** (mph)
  - **Average Humidity** (%)
  - **Total Precipitation** (inches)

Step 3: Overview

Title: Move your hand to the **top-left corner** to locate the Braille title: "Faceted area plot visualizing trends."

Chart Structure:

- The plot consists of **four area charts**, stacked vertically. Each chart represents one variable.
- All charts **share the same X-axis** (at the bottom) but have their **own Y-axis** (on the right).
- The layout can be divided into three vertical sections:
  - **Left:** Braille labels indicating variable names and units.
  - **Middle:** The embossed area chart for each variable.
  - **Right:** The Y-axis with tick marks showing the scale for that variable.

Step 4: Detailed Exploration

Variable Names and Units

- Place your hand on the **left side** of the board and move **vertically**.
- You will feel the Braille labels for each variable, listed from **top to bottom**:
  1. **Average Temperature** (°F)
  2. **Average Wind Speed** (mph)
  3. **Average Humidity** (%)
  4. **Total Precipitation** (inches)

Exploring the X-Axis

- Locate the **bottom of the plot** to find the shared X-axis.
- Move your hand **horizontally** along this axis, which represents the days of the month.
  - Tick marks are **evenly spaced**.
  - **Longer tick marks** indicate intervals of 5 or 10 days.

Exploring an Example Section

Total Precipitation (Bottom Section):

- Start at the **bottom section**, which represents **Total Precipitation (inches)**.
- Move to the **rightmost corner**, where the X-axis and Y-axis intersect.
- Trace the **Y-axis vertically upwards**; the scale ranges from **0 to 2.5 inches**.
- Return to the X-axis and **move your hand to the left** to start tracing the curve.
- Horizontally trace the area curve from **left to right**:
  - Initially, there is no curve (no rainfall for the first half of the month).
  - Around **August 15**, you will feel a **large peak**, indicating the maximum rainfall.
  - Beyond the peak, smaller bumps represent **minor rainfall** later in the month.
- While tracing the curve, refer to the **Y-axis** for rainfall amounts and the **X-axis** for the corresponding dates.

Exploring the Other Variables

Average Humidity%):

- Move your hand **one section up** to find the humidity plot.
- Locate the **Braille label** on the left: "Average Humidity (%)."
- Trace the curve of the area:
  - Humidity is generally **high and stable**.
  - A **slight peak** occurs around the middle of the month.
- Compare this peak with the precipitation section below; you will notice a rainfall event corresponds to increased humidity.
-

Average Wind Speed (mph):

- Move your hand **one section up** to the wind speed plot.
- Locate the **Braille label** on the left: *"Average Wind Speed (mph)."*
- Trace the curve: You will feel **periodic peaks and valleys**, indicating fluctuations in wind speed.

Average Temperature (°F):

- Move to the **top section** of the plot.
- Locate the **Braille label** on the left: "Average Temperature (°F)."
- Trace the curve:
  - Temperature remains **stable throughout the month**, hovering around **85°F**.
  - Even during the mid-month rainfall, temperature changes only slightly, indicating **minimal impact**.

Comparison Between Variables

To compare variables at a specific time, trace **vertically** across the plots. For example, during the mid-month rainfall, compare the **humidity and precipitation peaks** while noting the stable temperature.

Step 5: Recap

- **X-Axis:** Represents days of the month (at the bottom), shared by all area plots.
- **Y-Axis:** Represents the scale for each variable (on the right side of each plot).
- **Faceted Areas:** Show trends for four weather variables:
  - **Top:** Average Temperature.

  - **Second:** Average Wind Speed.
  - **Third:** Average Humidity.
  - **Bottom:** Total Precipitation.

Exploration Tips:

- Trace **horizontally** to observe trends for a single variable.
- Trace **vertically** to compare different variables at the same time.

F Tactile Chart Exploration Instructions (Final Version)

We provide instructions on how to explore the four tactile models. We first drafted an initial version of the instructions and then elicited feedback from our BLV collaborators. Based on their input, we revised the instructions accordingly. The initial version is provided in Appx. E. In this section, we present the final versions, which correspond to the tactile chart design for each chart type (see Fig. 1). These final version instructions are also hosted on our accessible website: vdl.sci.utah.edu/tactile-charts/.

F.1 Tactile Chart Exploration Instructions (Final Version): UpSet Plot

Below is the final version of the tactile UpSet plot exploration instructions, which can also be accessed at vdl.sci.utah.edu/tactile-charts/upset-plot/instructions-tactile.

Follow these instructions to explore the tactile model of a **UpSet Plot**.

Step 1: Orienting the Chart

- Locate the **cut corner** at the **top-right** of the board. Position the chart so this corner remains at the top-right.
- On the back, there are **two stickers**:
  - A **smaller square label** near the cut corner contains a **QR code**. Scanning it with your phone will take you to a companion website.
  - A **larger rectangular label** provides a labeled version of the chart.

Step 2: Introduction to the UpSet Plot

- This tactile model represents an UpSet plot, which visualizes how different sets intersect.
  - **Sets:** Groups of **elements** sharing a specific attribute.
  - **Intersection:** The overlap of **elements** between these sets.
- Move your hand to the top-left corner to feel the title: "UpSet Plot."
- Explore the board to get an overview. The chart is located on the right side of the board.
- The **UpSet plot** has three main sections:
  - **Bottom-Left** of the chart: A horizontal bar chart representing the size of each set (i.e., how many elements are in each set).
  - **Bottom-Center** of the chart: A matrix of circles showing different types of intersections between sets.
  - **Top-Right** of the chart: A vertical bar chart showing the size of each intersection (i.e., how many elements belong to each intersection).
- **The data:**
  - In this model, we are exploring the **Simpson characters** and their attributes: School, Blue Hair, Evil, Power Plant.
  - Each character represents an element.
  - Their attributes (e.g., "School," "Blue Hair") form sets. Characters with a specific attribute belong to that set.
  - Intersections represent overlaps of attributes; for example, a character can belong to multiple sets.

Step 3: Exploring the Sections

Set Size Bars

- Move your hand to the **left edge of the chart**
- There are **four horizontal bars**. Each bar represents the size of a set.
- **Labels:** On the left end of each bar, feel the Braille labels for set names.
- **Bar Lengths:** Longer bars represent larger sets.
- **Reference Lines:** Feel the **lines and holes** within each bar:
  - Each line represents **one unit**
  - Every **fifth unit** is marked with a slightly thicker reference line
  - These tactile markers help you count the total value of each bar
- Numbers: On the right of each bar, feel the Braille numbers indicating set sizes.
- From top to bottom, the sets and their size are:
  - School, 6
  - Power Plant, 5
  - Evil, 6
  - Blue Hair, 3

Intersection Matrix

Move your hand to the **center** of the chart Below and to the right of this marker is the **intersection matrix**, a grid of circles.

Grid Overview:

- **Rows:** Represent sets, aligned horizontally with the set size bars.
- **Columns:** Represent different intersections.

Symbols in the Grid:

- **Filled Circles:** The set is included in the intersection.
- **Empty Circles:** The set is not included in the intersection.
- **Vertical Lines:** Connect filled circles to help trace the columns.

Types of Intersections:

- **Empty Intersection:** A column with no filled circles. This is a special intersection with elements that have none of the attributes. **Example:** The first column (leftmost) represents an empty intersection. Trace along the column to feel that all circles are empty. The intersection size is labeled above as **8**, meaning 8 characters have none of the four attributes.
- **Individual-Set Intersection:** A column with only one filled circle. **Example:** The second column from the left represents an individual-set intersection. It has one filled circle (School). The intersection size is labeled above as **4**, meaning 4 characters have only the "School" attribute.
- **Multi-Set Intersection:** A column with multiple filled circles. **Example:** The last column (rightmost) has filled circles in the rows for "School" and "Blue Hair" and empty circles for the other two attributes. The intersection size is labeled above as **1**, meaning 1 character has both attributes but not others.
- **All-Set Intersection:** A column with all circles filled. **Example:** In this plot, no column has all circles filled, meaning no character has all four attributes.

Intersection Degrees:

- The number of sets included in the intersection increases from **empty intersections** to **all-set intersections**.
- **Low-Degree Intersection:** Few sets are included.
- **High-Degree Intersection:** Many sets are included.

Intersection Size Bars

- Move your hand to the **top-right** of the chart
- There are **eight vertical bars**, each corresponding to a possible intersection.
- **Height:** Taller bars indicate larger intersection sizes.
- **Labels:** Below each bar, the intersection size is written in Braille.
- **Reference Lines:** Same as the horizontal bars.
  - Each line represents **one unit**
  - Every **fifth unit** is marked with a slightly thicker reference line
  - These tactile markers help you count the total value of each bar
- **Correspondence:** The filled-in cells in the column directly below the bar show which sets are part of that intersection.
- **Features of Intersections in This Plot:**
  - The tallest bar (leftmost) represents the **empty set**, with a size of **8**.
  - Bars are sorted by size in descending order. Moving from left to right, the bar heights decrease, representing intersection sizes down to **1**.

Recap

- **Left Section:** Horizontal bars show set sizes.
- **Center Grid:** Circles and lines represent intersections.
- **Top-Right Section:** Vertical bars show the size of these intersections.

F.2 Tactile Chart Exploration Instructions (Final Version): Clustered Heatmap

Below is the final version of the tactile clustered heatmap exploration instructions, which can also be accessed at vdl.sci.utah.edu/tactile-charts/clustered-heatmap/instructions-tactile.

Follow these instructions to explore the tactile model of a clustered heatmap.

Step 1: Orienting the Chart

- Locate the **cut corner** at the **top-right** of the board. Position the chart so this corner remains at the top-right.
- On the back, there are **two stickers**:
  - A **smaller square label** near the cut corner contains a **QR code**. Scanning it with your phone will take you to a companion website.
  - A **larger rectangular label** provides a labeled version of the chart.

Step 2: Introduction to the Clustered Heatmap

- This tactile model represents a **clustered heatmap** of tabular data.
- Move your hand to the top-left corner to feel the title: "Clustered Heatmap."
- Broadly explore the board to get an overview. The chart is located on the right side of the board.
- This chart type combines a heatmap and dendrograms:
  - **The Heatmap is** a matrix of squares representing data values through heights.
  - **The Dendrograms are** Tree-like diagrams positioned above and to the right of the heatmap, showing the similarity between rows and columns.
- **The data:**
  - This clustered heatmap visualizes how frequently actors appear in different movie genres.
  - Similar actors and genres are grouped together.

Step 3: Explore the Heatmap

Locate the Heatmap: On the **right side** of the board, find the matrix of squares (the heatmap).

Rows and Columns:

- **Rows represent 5 actors,** labeled in Braille on the left side of each row, from top to bottom:
  - Dwayne Johnson
  - Julia Roberts
  - Tom Hanks
  - Jennifer Lawrence
  - Leonardo DiCaprio
- **Columns represent 4 movie genres,** labeled in Braille at the bottom of each column using abbreviations, from left to right:
  - a: Action
  - d: Drama
  - c: Comedy
  - r: Romance

Legend: On the top-left of the board, below the chart title, find the legend enclosed in a rectangular frame. It explains the column abbreviations.

Squares:

- **Height:** The height of the squares encodes the number of movies an actor has performed in in a specific genre. High squares indicate many moves, while lower or flat squares indicate fewer or no movies.
- **Braille Numbers:** Each square has a Braille number representing its value.
- **Example Exploration:** Top row (Dwayne Johnson), the four squares from left to right:
  - Action: Very high (45 movies). This is the highest square in the whole heatmap, so it is the biggest value.
  - Drama: Low (10 movies).
  - Comedy: Medium-high (28 movies).
  - Romance: Flat (0 movies). This is the smallest value in the heatmap.

Step 4: Exploring the Dendrograms

Dendrograms show hierarchical grouping based on similarity.

Row Dendrogram (Actor Clusters) Locate the Row Dendrogram: On the right edge of the heatmap, find the tree-like structure. From the right end of each row of the heatmap, you'll feel a line extending to the right. These lines connect rows to each other and group together hierarchically. The more quickly the lines group together, the more similar the two rows are.

Clusters are groups of similar rows with close connections. This chart shows two main clusters among actors.

Cluster 1: Julia Roberts and Tom Hanks (rows 2 and 3 from top):

- Trace their lines to see how they connect to each other quickly.
- Confirm in the heatmap: Feel the similar height patterns of squares in their rows:
  - Both are low in Action (column 1 from left).
  - Both are high in Drama and Comedy (columns 2 and 3).
  - Both are moderately high in Romance (column 4).

Cluster 2: Jennifer Lawrence and Leonardo DiCaprio (rows 4 and 5):

- Similarly, trace their lines to see how they group quickly.
- Confirm in the heatmap: Feel the similar height patterns of squares in their rows:
  - Both are high in Drama.
  - Both are low in other genres.

Outlier: Rows that deviate from the main clusters are outliers.

- This chart shows one outlier among actors.
- Dwayne Johnson (row 1):
  - Trace his line to see how it remains separate for a long time.
  - Confirm in the heatmap: The pattern in row 1 differs significantly from other rows. For example, row 1 shows a very high value in Action (column 1), while other rows show low values in this column.

Column Dendrogram (Movie Genre Clusters) Locate the Column Dendrogram at the top of the heatmap.Lines extend from each column upwards, clustering genres hierarchically. Its principle is the same as the row dendrogram, but this time it applies to the genres in the columns.

Cluster and Outlier:

- The movie genres are clustered incrementally in a step-by-step manner, starting with closely related pairs and gradually incorporating more distinct genres. The tall tree indicates that they are generally not very similar.

- **Romance and Comedy (columns 3 and 4 from left):** These two genres group together first, indicating they are the most similar movie genres among the four genres in terms of actor involvement patterns.
- **Drama (column 2):** Joins next.
- **Action (column 1):** Joins last, being the most distinct genre (outlier).

Recap

- The heatmap displays values using a matrix of raised squares.
- The dendrograms reveal similarity between rows and columns.

F.3 Tactile Chart Exploration Instructions (Final Version): Violin Plot

Below is the final version of the tactile violin plot exploration instructions, which can also be accessed at vdl.sci.utah.edu/tactile-charts/violin-plot/instructions-tactile.

Follow these instructions to explore the tactile model of a violin plot.

Step 1: Orienting the Chart

- Locate the **cut corner** at the **top-right** of the board. Position the chart so this corner remains at the top-right.
- On the back, there are **two stickers**:
  - A **smaller square label** near the cut corner contains a **QR code**. Scanning it with your phone will take you to a companion website.
  - A **larger rectangular label** provides a labeled version of the chart.

Step 2: Introduction to the Violin Plot

- This tactile model represents a **Violin plot**, which visualizes distributions of quantitative data for one or more categories. A distribution describes how values in a dataset are spread out. For example, if you collect the weight of 100 penguins, the distribution will show how many penguins are light, average weight, and heavy, respectively.
- Move your hand to the top-left corner to feel the title: "Violin Plot."
- Explore the board to get an overview. The chart is located on the center of the board.
- **The data:** In this model, we are exploring the **body mass (in pounds)** of three penguin species:
  - **Adelie**
  - **Chinstrap**
  - **Gentoo**
- There are **three violin-plot shapes**, each showing the body mass distribution for a species of penguins.

Step 3: Exploring the Violin Plot

Finding the Origin Move your hand to the **bottom-left corner** of the plot. This is where the **Y-axis** and **X-axis** intersect.

Y-Axis and Scale

- Start at the **bottom-left corner** and trace the **Y-axis** upward.
- The Y-axis is a vertical line with tick marks and Braille labels, encoding body mass in pounds.
- At the top of Y-axis is the y-axis label in Braille: body mass (lb)
- Feel the evenly spaced tick marks and their Braille labels, which represent body mass measurements:
  - The bottom tick (at the corner) is **5 pounds**, which means the Y-axis starts from 5 pounds.
  - The next tick above is **6 pounds**, then **7 pounds**, **8 pounds**, and so on, increasing evenly to the top tick, which is **14 pounds**.
  - The even numbers are marked out with Braille numbers.

X-Axis and Species Labels

- Return your hand to the **bottom-left corner** and trace the **X-axis** horizontally.
- The X-axis is a horizontal line with evenly spaced Braille labels for each species, from left to right: **Adelie**, **Chinstrap**, and **Gentoo**.
- These labels correspond to the violin plots directly above them.

Violin Shapes Three violin shapes, each positioned above a species label show the distribution of body masses for that species.

- Locate the **first violin** from the left. This represents the distribution of body masses for **Adelie** penguins.
- Trace the **outer contour** of the violin with your fingers:
  - The violin is symmetrical left to right.
  - Wider sections of the violin represent more values, meaning that a higher number of penguins have a body mass around this value.
  - Skinnier sections represent fewer values, meaning that few penguins have a body mass around this value.
- Refer to the **Y-axis** or tactile **grid lines** to identify the corresponding body mass values.
- Inside each violin, you will feel a **dashed horizontal line**, which marks the **median body mass** for that species.
- Move your hand to the right and repeat this process for the **Chinstrap** and **Gentoo** violins.

Touch the three violins to compare the shapes and medians to understand differences in distribution.

For the left violin representing Adelie penguins note that:

- The distribution has one peak, meaning that it is unimodal, and is **symmetrical**.
- The widest section is centered at the **median (8.16 pounds)**, where most data points are concentrated, indicating that most Adelie penguins have body masses around this value.
- The density tapers off symmetrically on both sides, showing a relatively balanced distribution with fewer penguins at the lower and upper extremes.

For the middle violin, representing Chinstrap penguins:

- The distribution also has one peak and is **symmetrical**. The peak near the median body mass is about 8.18 pounds.
- The peak is more distinct compared to Adelie penguins. The violin is wider, indicating that Chinstrap penguins' body masses are more tightly clustered around the median. The tails at both ends are skinnier than that of Adelie penguins. This suggests lower variability in body mass compared to Adelie penguins.

For the right violin, representing Gentoo penguins:

- The distribution is **bimodal**, meaning there are two distinct peaks in body mass. The first peak appears around **10.5 pounds**, and the second peak near **12 pounds**, forming two areas of high density. This suggests that Gentoo penguins exhibit greater variation in body mass, possibly due to differences in sex with males having distinctly higher body mass than females.
- The median body mass of **11.02 pounds** is **higher** than that of Adelie and Chinstrap penguins, and about as high as the heaviest penguins of the other species.
  - The median is closer to the lower peak (10.5 pounds) rather than centered between the two peaks, indicating that more Gentoo penguins have body masses around the lower peak than the higher peak. This suggests an asymmetry in distribution, where the higher peak represents fewer but more widely spread heavier penguins.
  - The violin also has a more elongated distribution compared to the other two species, showing Gentoo penguins have a larger body mass range.

Step 4: Recap

- **Y-Axis**: Represents body mass in pounds, increasing from 5 to 14 (vertical scale).
- **X-Axis**: Identifies penguin species (horizontal labels).

- **Violin Shapes**: Show the distribution of body masses, with wider sections indicating higher density and horizontal lines marking the medians.

F.4 Tactile Chart Exploration Instructions (Final Version): Facted Line Chart

Below is the final version of the tactile faceted line chart exploration instructions, which can also be accessed at vdl.sci.utah.edu/tactile-charts/faceted-plot/instructions-tactile.

Follow these instructions to explore the tactile model of a violin plot.

Step 1: Orienting the Chart

- Locate the **cut corner** at the **top-right** of the board. Position the chart so this corner remains at the top-right.
- On the back, there are **two stickers**:
  - A **smaller square label** near the cut corner contains a **QR code**. Scanning it with your phone will take you to a companion website.
  - A **larger rectangular label** provides a labeled version of the chart.

Step 2: Introduction to the Faceted Line Chart

- This tactile model represents a **Faceted Line Chart**, which visualizes trends in multiple related datasets.
- Move your hand to the top-left corner to feel the title: "Faceted Line Chart."
- Explore the board to get an overview. The chart is located on the center of the board.
- **The data:** This faceted line chart visualizes weather trends in Austin, Texas, focusing on four variables:
  - Average Temperature (°F)
  - Average Wind Speed (mph)
  - Average Humidity (%)
  - Total Precipitation (inches)
- **Chart Structure:**
  - The plot consists of **four line charts**, stacked vertically. Each chart represents one variable.
  - All charts **share the same X-axis** (at the bottom) but have their **own Y-axis** (on the right).
  - The layout can be divided into three vertical sections: **Left:** Braille labels indicating variable names and units. **Middle:** The embossed area chart for each variable. **Right:** The Y-axis with tick marks showing the scale for that variable.

Step 3: Exploring the Faceted Line Chart

Variable Names and Units

- Place your hand on the **left side** of the board and move **vertically**.
- You will feel the Braille labels for each variable. Each variable has two parts:
  - A larger rectangular block containing the variable name
  - A smaller rectangular block containing the units
- The variables listed from **top to bottom** are:
  - Average Temperature (F)
  - Average Wind Speed (mph)
  - Average Humidity (%)
  - Total Precipitation (inches)

Exploring the X-Axis

- Locate the **bottom of the plot** to find the shared X-axis.
- At the bottom of the plot, you will feel the Braille labels for the X-axis: "August".
- Move your hand **horizontally** along this axis, which represents the days of the month.
  - Tick marks are **evenly spaced**.
  - **Longer tick marks** indicate intervals of 5 or 10 days.

Exploring an Example Section

Total Precipitation (Bottom Section)

- Start at the **bottom section**, which represents **Total Precipitation (inches)**.
- Move to the **rightmost corner**, where the X-axis and Y-axis intersect.
- Trace the **Y-axis vertically upwards**; the scale ranges from **0 to 2.4 inches**.
- Return to the X-axis and **move your hand to the left** to start tracing the curve.
- Horizontally trace the area curve from **left to right:**
  - Initially, there is no curve (no rainfall for the first half of the month).
  - Around the middle of the month, you will feel a **large peak**, indicating the maximum rainfall.
  - Beyond the peak, smaller bumps represent **minor rainfall** later in the month.
  - While tracing the curve, refer to the **Y-axis** for rainfall amounts and the **X-axis** for the corresponding dates.

Exploring the Other Variables

Average Humidity (%):

- Move your hand **one section up** to find the humidity plot.
- Locate the **Braille label** on the left: "Average Humidity (%)."
- Trace the curve of the area:
  - Humidity is generally **high and stable**.
  - A **slight peak** occurs around the middle of the month.
- Compare this peak with the precipitation section below; you will notice a rainfall event corresponds to increased humidity.

Average Wind Speed (mph):

- Move your hand **one section up** to the wind speed plot.
- Locate the **Braille label** on the left: "Average Wind Speed (mph)."
- Trace the curve: You will feel **periodic peaks and valleys**, indicating fluctuations in wind speed.

Average Temperature (°F):

- Move to the **top section** of the plot.
- Locate the **Braille label** on the left: "Average Temperature (F)."
- Trace the curve:
  - Temperature remains **stable throughout the month**, hovering around **85°F**.
  - Even during the mid-month rainfall, temperature changes only slightly, indicating **minimal impact**.

Comparison Between Variables

- To compare variables at a specific time, trace **vertically** across the plots. The vertical grid lines can help you align the plots.
- For example, during the mid-month rainfall, compare the **humidity and precipitation peaks** while noting the stable temperature.

Recap

- **X-Axis:** Represents days of the month (at the bottom), shared by all line plots.
- **Y-Axis:** Represents the scale for each variable (on the right side of each plot).
- **Faceted Areas:** Show trends for four weather variables:
  - **Top:** Average Temperature.
  - **Second:** Average Wind Speed.
  - **Third:** Average Humidity.
  - **Bottom:** Total Precipitation.
- **Exploration Tips:**
  - Trace **horizontally** to observe trends for a single variable.
  - Trace **vertically** to compare different variables at the same time.

G Example Packages

Fig. 8 and Fig. 9 show the example packages we shipped to participants in our evaluation study (Sec. 4).

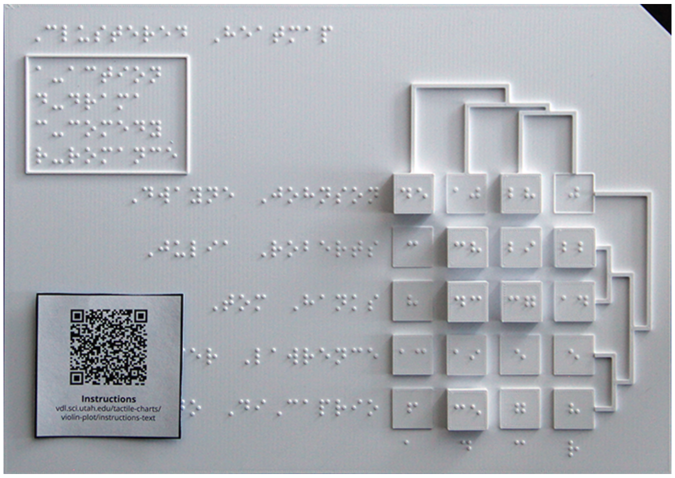

Fig. 8: A package we shipped to a participant in our evaluation study under the tactile clustered heatmap condition.

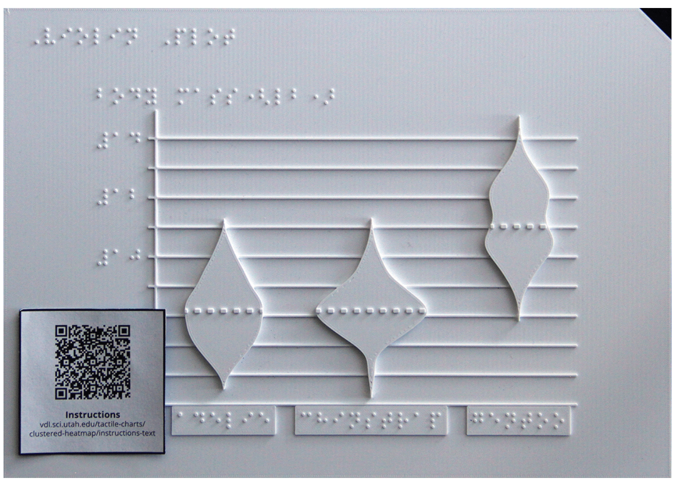

Fig. 9: A package we shipped to a participant in our evaluation study under the tactile violin plot condition.

H Textual Instructions

In our evaluation study (Sec. 4), we used textual instructions of the clustered heatmap and the violin plot for the `Text-Only` condition. To ensure comparability between conditions, we prepared textual instructions by removing tactile chart-specific content from the tactile chart exploration instructions and adapting the text accordingly. In this section, we present these textual instructions used in our evaluation study.

H.1 Textual Instructions: Clustered Heatmap

Step 1: Introduction to the Clustered Heatmap and Chart Overview

- A **clustered heatmap** combines a heatmap and dendrograms:
  - **Heatmap:** A matrix of squares that represent tabular data values through color saturation.
  - **Dendrograms:** Tree-like diagrams positioned above and to the right of the heatmap, showing the similarity between rows and columns.
- **We use an example to explain this chart type.**
  - Imagine a clustered heatmap that visualizes how frequently actors appear in different movie genres.
  - Similar actors and genres are grouped together.

Step 2: What's in the Heatmap

Rows and Columns:

- **Rows represent 5 actors,** from top to bottom:
  - Dwayne Johnson
  - Julia Roberts
  - Tom Hanks
  - Jennifer Lawrence
  - Leonardo DiCaprio
- **Columns represent 4 movie genres,** from left to right:
  - Action
  - Drama
  - Comedy
  - Romance

Each square in the matrix indicates the number of movies an actor has performed in for each genre. The color saturation represents these numbers:

- Darker squares: More movies in a specific genre.
- Lighter or blank squares: Fewer or no movies.

Example: For Dwayne Johnson (his row):

- **Action**: Very dark (45 movies). This is the darkest square in the heatmap, representing the highest value.
- **Drama**: Light (10 movies).
- **Comedy**: Medium-dark (28 movies).
- **Romance**: Blank (0 movies). This is the lowest value in the heatmap.

Step 3: What do Dendrograms Show

Dendrograms show hierarchical grouping based on similarity.

Row Dendrogram The row dendrogram shows similarities between actors. If rows are connected directly with a short branch it indicates that these actors are similar in terms of the movie genres they typically perform in. Clusters are groups of similar rows with close connections. This chart has two main actor clusters.

Cluster 1: Julia Roberts and Tom Hanks

- Both have few Action movies.
- Both have many Drama and Comedy movies.
- Both are some Romance movies.

Cluster 2: Jennifer Lawrence and Leonardo DiCaprio

- Both have many Drama movies.
- Both have few movies in other genres.

Outlier: The elements deviating significantly from the main clusters are outliers.

- This chart has one outlier among actors.
- **Outlier:** Dwayne Johnson * His movie genre pattern is different from other actors. For example, he is heavily involved in Action movies, while other four actors have very low numbers in this genre.

Column Dendrogram The column dendrogram shows similarities of movie genres. The principle is the same as the row dendrogram but applied to the columns. If columns group closer, it means these genres are more similar in terms of actor involvement patterns. Again, groups of similar columns can form clusters.

Cluster and Outlier:

- In this chart, the movie genres are clustered incrementally in a step-by-step manner, starting with closely related pairs and gradually incorporating more distinct genres. The tall tree indicates that they are generally not very similar.
- **Romance and Comedy** group together first, indicating they are the most similar genres.
- **Drama** joins next.
- **Action** joins last, being the most distinct genre (outlier).

Recap

- The heatmap displays values using a matrix of color-saturation coded squares.
- The dendrograms reveal similarity between rows and columns.

H.2 Textual Instructions: Violin Plot

Step 1: Introduction to the Violin Plot and Chart Overview

- **A Violin plot visualizes distributions of quantitative data for one or more categories. A distribution describes how values in a dataset are spread out. For example, if you collect the weight of 100 penguins, the distribution will show how many penguins are light, average weight, and heavy, respectively.**
- We use an example dataset to explain the plot. Imagine a violin plot that compares the body mass distributions (in pounds) of three penguin species: Adelie, Chinstrap, and Gentoo. The chart displays three vertical violin shapes, each representing the distribution of body masses for one penguin species.

Step 2: What's in the Violin Plot

Axes

- **Y-axis:** Represents body mass in pounds. It ranges from **5 pounds** at the bottom to **14 pounds** at the top, with evenly spaced tick marks representing whole numbers (5, 6, 7, up to 14).
- **X-axis:** Lists the three penguin species from left to right: **Adelie**, **Chinstrap**, and **Gentoo**. Each species label is under its corresponding violin shape above it.

Violin Shapes :

- Each violin shows the distribution of body masses for a species:
- **Width:** Wider sections indicate more penguins with body masses around that value; skinnier sections indicate fewer numbers with that body mass.
- **Median:** A dashed horizontal line inside each violin marks the median body mass for that species.

Different violin shapes: **This datasets shows three violins that have different shapes**

- The violin is symmetrical left to right.
- Wider sections of the violin represent more values, meaning that a higher number of penguins will have a body mass around this value.
- Skinnier sections represent fewer values, meaning that that few penguins have a body mass around this value

Adelie penguins:

- The distribution has one peak, meaning that it is unimodal, and is **symmetrical**.
- The widest section is centered at the **median (8.16 pounds)**, where most data points are concentrated, indicating that most Adelie penguins have body masses around this value.
- The density tapers off symmetrically on both sides, showing a relatively balanced distribution with fewer penguins at the lower and upper extremes.

Chinstrap penguins:

- The distribution also has one peak and is **symmetrical**. The peak near the median body mass is about 8.18 pounds.
- The peak is more distinct compared to Adelie penguins. The violin is wider, indicating that Chinstrap penguins' body masses are more tightly clustered around the median. The tails at both ends are skinnier than that of Adelie penguins. This suggests lower variability in body mass compared to Adelie penguins.

Gentoo penguins:

- The distribution is **bimodal**, meaning there are two distinct peaks in body mass. The first peak appears around **10.5 pounds**, and the second peak near **12 pounds**, forming two areas of high density. This suggests that Gentoo penguins exhibit greater variation in body mass, possibly due to differences in sex with males having distinctly higher body mass than females.
- The median body mass of **11.02 pounds** is **higher** than that of Adelie and Chinstrap penguins, and about as high as the heaviest penguins of the other species.
- The median is closer to the lower peak (10.5 pounds) rather than centered between the two peaks, indicating that more Gentoo penguins have body masses around the lower peak than the higher peak. This suggests an asymmetry in distribution, where the higher peak represents fewer but more widely spread heavier penguins.
- The violin also has a more elongated distribution compared to the other two species, showing Gentoo penguins have a larger body mass range.

Step 3: Recap

- **Y-Axis**: Represents body mass in pounds, increasing from 5 to 14 (vertical scale).
- **X-Axis**: Identifies penguin species (horizontal labels).
- **Violin Shapes**: Show the distribution of body masses, with wider sections indicating higher density and horizontal lines marking the medians.

I Alt Text Corresponding to the Tactile Charts (Simple Alt Text)

In our evaluation study (Sec. 4), we wrote the alt text for the simple dataset, which we refer to as *simple alt texts*. These alt texts correspond to the tactile charts, the tactile chart exploration instructions, and the example chart referenced in the textual instructions.

In this section, we present the simple alt texts for the clustered heatmap and the violin plot, which we used in our evaluation study. Alt texts for tactile charts of all four chart types are available on our website (vdl.sci.utah.edu/tactile-charts/.).

I.1 Simple Alt Text: Clustered Heatmap

Below is the simple alt text of the clustered heatmap, which can also be accessed at vdl.sci.utah.edu/tactile-charts/clustered-heatmap/alttext-simple.

This **clustered heatmap** visualizes how frequently actors appear in different movie genres. Similar patterns are grouped together.

- Julia Roberts and Tom Hanks show similar patterns, focusing primarily on Drama and Comedy
- Jennifer Lawrence and Leonardo DiCaprio share a strong emphasis on Drama
- Dwayne Johnson is an outlier in this dataset, with a strong specialization in Action and no Romance films

The visualization combines a data table (heatmap) with tree-like diagrams (dendrograms) on its sides that show how similar rows and columns are. The heatmap displays **five actors** (rows):

- Dwayne Johnson
- Julia Roberts
- Tom Hanks
- Jennifer Lawrence
- Leonardo DiCaprio

And **four movie genres** (columns):

- Action
- Drama
- Comedy
- Romance

Each cell indicates the number of movies an actor has performed in for each genre using color saturation. Dark cells indicate many movies. The rows and columns are **clustered** based on similarity patterns. The most similar clusters of actors and genres are connected with the tree above and to the left of the matrix.

Statistical Information

- **Highest Value**: **Dwayne Johnson**'s contributions to **Action** (45 movies).
- **Lowest Value**: **Dwayne Johnson**'s contributions to **Romance** (0 movies).
- **Most Represented Genre**: **Drama**, with a total of **145 movies** across all actors.
- **Least Represented Genre**: **Romance**, with a total of **49 movies** across all actors.
- **Person Who acted in the Most Films**: **Tom Hanks**, with a total of **102 movies** across all genres.
- **Person Who acted in the Fewest Films**: **Jennifer Lawrence**, with a total of **42 movies** across all genres.

Actor Clusters

The actors are grouped into **two main clusters** and **one outlier** based on their genre preferences:

Cluster 1: Julia Roberts and **Tom Hanks**

- Both actors contributed a lot of movies in **Drama** and **Comedy**.
  - Julia Roberts: 38 Drama, 29 Comedy
  - Tom Hanks: 43 Drama, 37 Comedy
- They have moderate contributions to **Romance**
  - Julia Roberts: 22 Romance
  - Tom Hanks: 14 Romance
- They have low involvement in **Action**.
  - Julia Roberts: 3 Action
  - Tom Hanks: 8 Action

Cluster 2: **Jennifer Lawrence** and **Leonardo DiCaprio**

- Both actors primarily contribute to **Drama**.
- They show some involvement in **Action** but minimal contributions to **Comedy** and **Romance**.

Outlier: Dwayne Johnson

- Dwayne Johnson has lots of contributions in **Action** (45), while other actors contribute to Action only a little.
  - Julia Roberts: 3
  - Tom Hanks: 8
  - Jennifer Lawrence: 13
  - Leonardo DiCaprio: 6

Movie Genre Clusters

The movie genres are clustered incrementally in a step-by-step manner, starting with closely related pairs and gradually incorporating more distinct genres, emphasizing their hierarchical relationships. Generally, genres are fairly distinct.

Comedy and Romance:

- These genres are grouped together first
- Julia Roberts and Tom Hanks are the most prominent contributors to these genres.

Drama:

- Drama is added into the cluster in the next step.

Action:

- This genre is the most distinct and isolated, and it is clustered last.

I.2 Simple Alt Text: Violin Plot

Below is the simple alt text of the violin plot, which can also be accessed at vdl.sci.utah.edu/tactile-charts/violin-plot/alttext-simple.

This is a violin plot showing the distribution of body mass (in pounds) across three species of penguins: Adelie, Chinstrap, and Gentoo. While **Adelie and Chinstrap penguins exhibit unimodal distributions with similar median values**, Gentoo penguins show a **bimodal distribution and a higher median.**

- **Y-axis:** Represents body mass in pounds.
- **X-axis:** Lists the three penguin species from left to right: **Adelie**, **Chinstrap**, and **Gentoo**.
- **Three violins each shows the distribution of body masses for a species**

Distribution Properties

- **Adelie penguins:** The distribution is unimodal, and it has one peak in the middle. Most Adelie penguins' body mass is concentrated close to the median (8.16 pounds).
- **Chinstrap penguins:** The distribution is also unimodal, with a single peak in the middle. Most Chinstrap penguins' body masses are concentrated close to the median (8.18 pounds), and their weights are more tightly clustered near the middle compared to Adelie penguins.
- **Gentoo penguins:** The median body mass of Gentoo penguins is 11.02 pounds, which is larger than Adelie and Chinstrap penguins. The distribution is bimodal. Gentoo penguins' body masses are concentrated around 10.5 pounds and 12 pounds, which form the two peaks.

Statistical Information

Adelie penguins:

- Body mass ranges from 6.28 to 10.53 pounds.
- The first quartile (Q1) is 7.39 pounds.
- The median is 8.16 pounds.
- The third quartile (Q3) is 8.82 pounds.

Chinstrap penguins:

- Body mass ranges from 5.95 to 10.58 pounds.
- The first quartile (Q1) is 7.76 pounds.
- The median is 8.18 pounds.
- The third quartile (Q3) is 8.74 pounds.

Gentoo penguins:

- Body mass ranges from 8.71 to 13.89 pounds.
- The first quartile (Q1) is 10.36 pounds.
- The median is 11.02 pounds.
- The third quartile (Q3) is 12.13 pounds.

J COMPLEX CHART DATASETS

In our evaluation study (Sec. 4), participants experienced two datasets for each chart type, which we refer to as the simple dataset and the complex dataset (see Fig. 2). In this section, we present the details of the preparation of the complex datasets.

J.1 Clustered Heatmap

For the complex clustered heatmap, we used a dataset from the European Values Study [26] and selected countries based on Perin et al.'s work [62] on tabular visualizations. When creating the chart, we normalized each row based on the method described in the Perin et al.'s work [62]. We normalized the percentages independently for each row (country) to a scale of 0 to 1, to emphasize the relative distribution of responses across topics within a country.

J.2 Violin Plot

For the complex violin plot, we used a Human Development Index (HDI) dataset, which is downloaded from data.humdata.org/dataset/human-development-data. We used the data of 2021.

K COMPLEX CHARTS

Based on our complex datasets, we created charts with Python (see Fig. 2 and present them in this section (Fig. 10 and Fig. 11).

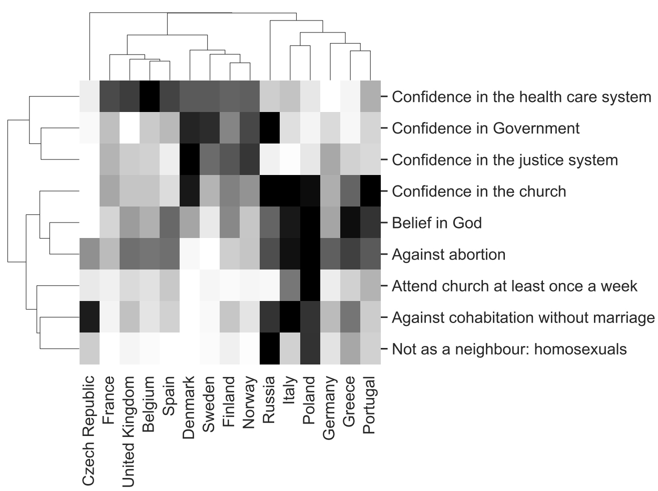

Fig. 10: The clustered heatmap with the complex dataset.

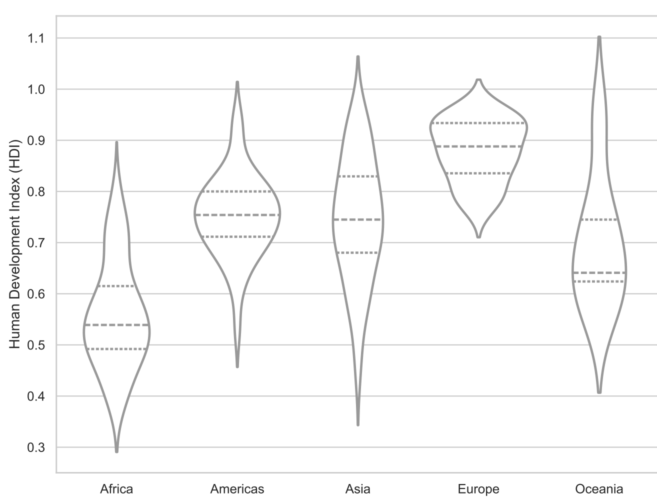

Fig. 11: The violin plot with the complex dataset.

L Complex Alt Text

In this section, we present the alt texts for the clustered heatmap and the violin plot based on complex datasets (see Appx. K), which we refer to as *complex alt texts* in our evaluation study (Sec. 4).

L.1 Complex Alt Text: Clustered Heatmap

This visualization is a **clustered heatmap** comparing the relative proportion of importance citizens from 15 European countries assign to 9 sociocultural and religious topics, such as confidence in the government, belief in god, or cultural issues such as homosexuality.

On a high level, the Nordic countries are the most confident in state institutions and most liberal. Religious values are strongest in Russia, Italy, Poland, Germany, Greece and Portugal. Poland, Italy, and Russia are most conservative on social issues.

The **rows** represent countries, and the **columns** represent topics participants were asked about in a survey. The intensity of color in each **cell** indicates agreement levels, where **darker shades** represent higher agreement and **lighter shades** indicate lower agreement.

Both **countries** and **topics** are clustered based on similarity. The relationships among them are displayed in a **hierarchical tree**.

Topic Clusters Topics are grouped into three main clusters:

Cluster 1: Confidence in the State Institutions, which includes

- Confidence in the healthcare system
- Confidence in the government
- Confidence in the justice system

Cluster 2: Religious Issues, which includes

- Confidence in the church
- Belief in God
- Opposition to abortion

Cluster 3: Conservative Social Issues, which includes

- Attending church at least once a week
- Opposition to cohabitation without marriage
- Opposition to having homosexuals as neighbors

Country Clusters Countries are grouped into three clusters and one outlier:

Cluster 1: Nordic Countries (Denmark, Sweden, Finland, Norway)

- High values on confidence in state institutions (healthcare, government, justice system).
- Moderate values on religious issues, with exceptions:
  - Denmark shows higher confidence in the church.
  - Denmark and Sweden show lower opposition to abortion.
- Finland and Norway have the most similar response patterns among all countries.

Cluster 2: Secular Western European Countries (France, United Kingdom, Belgium, Spain)

- High confidence in the healthcare system.
- Moderate confidence in government and justice, with an exception: The United
- Moderate values on religious issues.
- Low values on conservative social issues, but slightly higher than Nordic countries and lower than the next cluster (Religious European Countries).

Cluster 3: Religious European Countries (Russia, Italy, Poland, Germany, Greece, Portugal)

- **Lower confidence** in state institutions, except **Russia, which has high confidence in the government.**
- **High values** on religious issues.
- **Mixed values** on conservative social issues:
  - **Germany, Greece, and Portugal** form a **sub-cluster**, showing **moderate values** on all conservative social issues (attending church, opposing cohabitation without marriage, and opposing homosexual neighbors).
  - **Italy and Poland** form another **sub-cluster**, with: **Poland** showing **high values** on all conservative social issues. **Italy** showing **high church attendance and opposition to cohabitation without marriage, but moderate opposition to homosexual neighbors.**
  - **Russia** is an **outlier within this cluster**, showing **high opposition** to homosexual neighbors and cohabitation without marriage but **low church attendance.**

Outlier: Czech Republic. It has

- Low confidence in state institutions.
- Low values on issues related to the church and belief in God, but only moderate opposition to abortion.
- Moderate church attendance and opposition to homosexual neighbors, but high opposition to cohabitation without marriage.

L.2 Complex Alt Text: Violin Plot

This is a violin plot showing the distribution of the Human Development Index (HDI) across five continents, Africa, Americas, Asia, Europe, and Oceania, based on data from 2021The HDI aims to capture the overall well-being and development of countries based on health, education, and standard of living. Europe exhibits the highest and most consistent HDI values, while Asia has the widest variability. Africa and Oceania have non-normal distributions, indicating groups of countries with different levels of development. HDI is measured from 0 (low) to 1 (high).

Distribution Properties

Africa:

- The distribution is not a normal distribution but has a wider part at the upper end, in addition to a peak in the middle.
- The majority of African countries have HDI values concentrated around the median of **0.54**, forming a primary peak.
- A smaller wider section is observed around **0.73**, indicating a group of countries with higher HDI.
- The distribution is relatively spread out, spanning from **0.39 to 0.80**.

Americas:

- The distribution is unimodal and symmetrical, peaking around the median **0.75**.
- Most countries' HDI values are concentrated between **0.71 and 0.80**, with fewer extreme values, reflecting a less spread out level of human development across the region.

Asia:

- The distribution is unimodal but highly dispersed, with HDI values spanning from **0.46 to 0.95**, the widest range among all continents.
- The violin is relatively thin with no strong peak indicating that HDI values vary substantially across Asian countries.

Europe:

- The distribution is unimodal but asymmetrical, with a clear peak above the median at **0.89**.
- Europe has the highest median HDI among all continents and the smallest range **0.77 to 0.96**, suggesting high and consistent levels of human development.

Oceania:

- The distribution is elongated and not normal bimodal, with a primary peak around the median of **0.64** and a smaller wider part near **0.94**.
- The range is broad **0.56 to 0.95**, indicating variation in human development levels within the region.

Statistical Information

Africa:

- HDI ranges from 0.39 to 0.80.
- The first quartile (Q1) is 0.49.
- The median is 0.54, the lowest median among all continents.
- The third quartile (Q3) is 0.62.

Americas:

- HDI ranges from 0.54 to 0.94.
- The first quartile (Q1) is 0.71.
- The median is 0.75.
- The third quartile (Q3) is 0.80.

Asia:

- HDI ranges from 0.46 to 0.95, the largest range among all continents.
- The first quartile (Q1) is 0.68.
- The median is 0.75.
- The third quartile (Q3) is 0.83.

Europe:

- HDI ranges from 0.77 to 0.96, the smallest range among all continents.
- The first quartile (Q1) is 0.84.
- The median is 0.89, the highest median among all continents.
- The third quartile (Q3) is 0.93.

Oceania:

- HDI ranges from 0.56 to 0.95.
- The first quartile (Q1) is 0.62.
- The median is 0.64.
- The third quartile (Q3) is 0.75.

M Evaluation Study Scripts

In this section, we present our full interview scripts used in the evaluation study (Sec. 4).

Introduction

Thank you for taking the time to speak with us today. My name is [Researcher A]. I am here with [Researcher B] and we are here to talk with you about tactile models and alternative text for data visualizations.

Let's begin by going over the plan for today's interview. We are focusing on two specific types of data visualizations, which we will examine one at a time. For each visualization type, we will first introduce the chart type to you with a simple example, along with its corresponding alternative text. Then, we will provide an alternative text for a more complex example of the same visualization type. Throughout this process, we will discuss things from your perspective. We expect today to be 2 hours.

Any questions before we begin?

Audio Recording

To help with the accuracy of our notes, we are requesting to record the audio and your screen from today's interview. The only people who will have access to this recording is us and our team. I am going to go ahead and start the recording now.
START SCREEN AND AUDIO RECORDING AFTER PARTICIPANT HAS CONSENTED

Background Questions

We will start by learning about you and your background. I will ask you questions, please answer them by speaking out loud.
ONE EXPERIMENTER: INPUT ANSWERS IN REDCAP

Demographics

- If you would like, please let us know your preferred pronouns.
- Year of birth
- Gender
- What is the highest level of education you have completed?
- What is your current status? Are you working or studying, and is it full-time or part-time? If so, what is your job or major?
- Vision loss level
- How would you describe your vision-loss level? (Blind since birth / Lost vision suddenly / Lost vision gradually)
- How would you describe your vision level (e. g., completely blind, light perception, central vision loss, etc.)?
- (If the participant is not totally blind) If you know, what is your corrected visual acuity in either Snellen (e.g., 20/200) or LogMAR (e. g., 1.3)?
- If you are comfortable sharing, please indicate your visual pathology diagnosis. This information is optional and not required.

Screen Reader Experience

- Which screen reader do you use with your computer or other devices (e.g., NVDA, JAWS, VoiceOver, etc.)
- How long have you been using a screen reader?
- When using a screen reader, what is your preferred rate of speech?
- Do you use other accessibility devices or software in combination with a screen reader, such as screen magnification or a braille display? If yes, please describe all accessibility devices or software you use in combination with a screen reader.
- Braille experience
- How long have you been reading braille?
- How would your rate your skill reading Braille (1 - I can't read Braille / 5 - I'm very proficient at reading Braille)
- In what contexts did you read braille (e. g., work, personal use)?
- Tactile chart experience
- How would you describe your familiarity with tactile charts or graphics? (1 - Not at all familiar / 5 - Extremely familiar)
- Can you describe in which context you have interacted with tactile charts or graphics?

Data Visualization Experience

- How many hours do you use a computer or smartphone each day?
- Would you consider your career to be data-intensive or numbers-driven (e. g., regularly work with large datasets, perform statistical analyses, or make decisions based on quantitative information)?
- How often do you interact with data visualizations, such as those for work, from news articles, in video games, etc.?
- In which context do you encounter data and data visualizations (e. g., work, news, leisure)?
- How do you typically view datasets? (e. g., download to excel, you don't, etc.)

Familiarity with the Two Chart types

In this study, we focus on 2 specific chart types. We want to know how familiar you are with each of them.

- How familiar are you with **clustered heatmaps** - a visualization of tabular data that encodes values by color? (1 - Not at all familiar / 5 - Extremely familiar)
- Have you seen or touched **clustered heatmaps** through a tactile display or an embossed paper before? (Yes / No / I don't know what a clustered heatmap is)
- How familiar are you with **violin plots** - a visualization of a distribution of values? (1 - Not at all familiar / 5 - Extremely familiar)
- Have you seen or touched **violin plots** through a tactile display or an embossed paper before? (Yes / No / I don't know what a violin plot is)
- After you received our package, have you explored the model, or hear any of the instructions?
- Researcher B, do you have any additional questions?
- To ensure that we are both on the same link during today's discussion, do you mind also sharing your screen?

IN ZOOM SETTINGS, MAKE SURE THAT ALL PARTICIPANTS CAN SHARE THEIR SCREEN

Evaluation Part 1

Training

The first chart type we will explore is Clustered Heatmap / Violin Plot.

Chart Type Instructions I am going to send a link in the chat that will tell you more about this chart type. Please take your time to read and understand (and follow it to explore the physical model you received).

After hearing the instructions, I am going to ask you several questions about this chart type.

DEPENDING ON THE CONDITIONS OF THE PARTICIPANT, SEND ONE OF THE FOLLOWING LINKS TO THEM:

- Clustered heatmap tactile chart exploration instructions (Sec. F.2)
- Clustered heatmap textual instructions (Sec. H.1)
- Violin plot tactile chart exploration instructions (Sec. F.3)
- Violin plot textual instructions (Sec. H.2)

Questions for both chart types

- What types of data are best suited for visualization using a Clustered Heatmap / Violin Plot?
- Can you provide an example scenario where you would use a Clustered Heatmap / Violin Plot?
- (Clustered Heatmap) We want to add another movie actor – Arnold Schwarzenegger – to this clustered heatmap. Could you describe how he would appear in the chart and how he relates to the others? You can make up data based on what you know about Arnold Schwarzenegger.
- (Violin Plot) Imagine a new species of very small penguins (little penguins) with its body mass distribution added to the example violin plot. Could you describe how this species would appear in the chart and how it relates to the others? You can make up data based on what you know about penguins.
- Researcher B, do you have any additional questions?

Simple Alt Text I am going to send you another link in the chart. This is an example of alt text, which describes the chart used in the instruction you just heard. You will hear alt text for another dataset of the same chart type later. After hearing the alt-text, I am going to ask you several questions based on it.

DEPENDING ON THE CONDITIONS OF THE PARTICIPANT, SEND ONE OF THE FOLLOWING LINKS TO THEM:

- Clustered heatmap simple alt text (Sec. I.1)
- Violin plot simple alt text (Sec. I.2)

Questions for clustered heatmap

- What is the dataset about?
- Which actor is an outlier in this dataset, and why?
- Which two movie genres are most similar, and why?

Questions for violin plot

- What is the dataset about?
- What is the key difference between the distributions of Gentoo penguins compared to the other two species?
- Which penguin species has the least variation of body mass values and why?

Researcher B, do you have any additional questions?

Do you have any questions about this chart type?

Testing

If you have no more questions, I will send another link to the chat to another Clustered Heatmap / Violin Plot alt text. Please take your time to read and understand the text description. We will have some questions for you once you read it.

Complex Alt Text *DEPENDING ON THE CONDITIONS OF THE PARTICIPANT, SEND ONE OF THE FOLLOWING LINKS TO THEM:*

- Clustered heatmap complex alt text (Sec. L.1)
- Violin plot complex alt text (Sec. L.2)

Now, I am going to ask you a series of questions about the alt text. We want to understand things from your perspective. It's important to highlight that this isn't a test. So do not worry about the right or wrong to any of the questions, and I would like to ask you to be as honest as possible.

Questions for clustered heatmap

- What is the dataset about?
- According to the description, how many clusters are the European countries divided into, and which country is an outlier?
- Name the three main topic clusters and one example from each.
- Which country cluster has the lowest values on social conservative issues?
- If a country strongly opposes having homosexual neighbors, which country cluster is it likely in?
- The Czech Republic is described as an outlier. Why is the Czech Republic an outlier relative to other countries?
- Describe what the corresponding tactile chart or visualization would be like for this dataset (e.g., What labels would be included, what would the height of the squares, etc.).

Questions for violin plot

- What is the dataset about?
- Which continent has the most variability in HDI values?
- Which continents have non-normal distributions in their HDI values?
- Where is the peak for HDI in Africa's distribution relative to the other countries?
- How does the HDI distribution of Asia differ from that of the Americas?
- Which continent has the highest levels of human development?
- Describe what the corresponding tactile chart or visualization would be like for this dataset (e.g., what would the violins look like for the countries, which would be the widest and skinniest plots, etc.)

Questions for both chart types

- Do you feel like you have a good understanding of the dataset? Please rate your understanding on a 5-point scale, where 1 = I don't understand it at all and 5 = I completely understand it.
- What was difficult for you to understand about the dataset?
- What did you find interesting or surprising about the dataset?
- Do you have any additional comments on your experience with the clustered heatmap/violin plot?

Evaluation Part 2

Now we will explore another chart type: Violin Plot / Clustered Heatmap. We will follow a similar procedure.

SAME PROCEDURE AS PART 1

Comparative Questions After Both Charts Were Explored

- You have learned about visualization types in two different ways: one by exploring a tactile model with instructions, and another by only hearing a textual explanation. Which training format do you prefer? Can you explain the reasons for your preference?
- How helpful is the tactile model used in the training for better understanding the chart type?
- After answering the question, could you please rate it on a scale of 1 to 5? (1 = Not helpful at all, 5 = Very helpful)
- Do you think the tactile model helped you understand the alt text of the dataset that was not shown in the chart? After answering the question, could you please rate it on a scale of 1 to 5? (1 = Did not help at all, 5 = Helped a lot)
- How easy was it to explore the tactile model?

- After answering the question, could you please rate it on a scale of 1 to 5? (1 = Not easy at all, 5 = Very easy)
- I believe that tactile models can teach me transferable knowledge about a chart type. After answering the question, could you please rate it on a scale of 1 to 5? (1 = I don't believe this at all, 5 = I strongly believe this)
- How useful is the training format (tactile model with exploration instructions) for BLV education in your opinion? After answering the question, could you please rate it on a scale of 1 to 5? (1 = Not useful at all, 5 = Very useful)
- How useful is the training format (only textual explanation) for BLV education in your opinion? After answering the question, could you please rate it on a scale of 1 to 5? (1 = Not useful at all, 5 = Very useful)
- If these tactile models were freely available, how beneficial would they be for blind or low-vision individuals? After answering the question, could you please rate it on a scale of 1 to 5? (1 = No benefit, 5 = Highly beneficial)
- Do you have any comments or feedback on the tactile models?
- Do you have any other feedback or comments that we didn't touch on today?
- Researcher B, do you have any follow-up questions?

M.0.1 Conclusion

Thank you so much for sharing your insights today. Your feedback has been incredibly valuable and will play a crucial role in helping us improve text descriptions.

Do you have any final questions about the interview process or about our study that you'd like to ask?

One final thing, to help us reach more individuals who may also be eligible for this study, would you be willing to provide contact information for people you know who might be interested and eligible to participate? Of course, sharing this information is entirely voluntary, and will be handled with care.

Alright, if anything comes to mind later, feel free to reach out. We will process your $100 Amazon gift card and send it to your email within the next two weeks. Otherwise, thanks again for your time and have a wonderful day!

END SCREEN AND AUDIO RECORDING

N CODEBOOK

In this section, we present the codebook from our thematic analysis, which includes the themes and corresponding codes. We discussed the themes in detail in Sec. 5.

Theme 1: Building Mental Models of Chart Types

This theme examines the ways in which tactile charts support BLV individuals in building mental models of different chart types.

- Supporting mental model creation
  - Chart layouts
  - Shapes of chart elements
- Learning by touch
  - Exploratory learning
  - Multisensory learning

Theme 2: Developing Transferable Knowledge

This theme examines how BLV individuals transfer and apply the knowledge of chart types acquired through tactile charts.

- Structural understanding of chart types
- Understanding new alt text for the same chart type
- Using template charts as references for comparison

Theme 3: BLV Visualization Education

This theme examines the role of tactile charts in visualization education for BLV individuals.

- Challenges faced by BLV individuals in education
- Interest in learning visualization
- Empowering BLV education with tactile charts

Theme 4: Other Modalities

This theme examines other modalities preferred by BLV individuals.

- Textual descriptions
- Raw data and AI tools

Theme 5: Design Better Tactile Charts For Chart Type Education

This theme examines design considerations for tactile charts intended for chart learning purposes.

- Topic familiarity
- Clarity of chart elements
- Use of Braille
- Production methods
- Supporting blind-sighted communication
- Supporting independent learning

O Template Chart Design Variations

Based on the tactile graphics guidelines, we transcribed the Python generated charts to the 2D designs for tactile charts. In this section, we present the 2D tactile chart designs for the four chart types. We provide two design variations for each chart type. Each chart has three versions: sighted version, Braille version, and a Braille-to-English letter-by-letter translation version (Fig. 12–35).

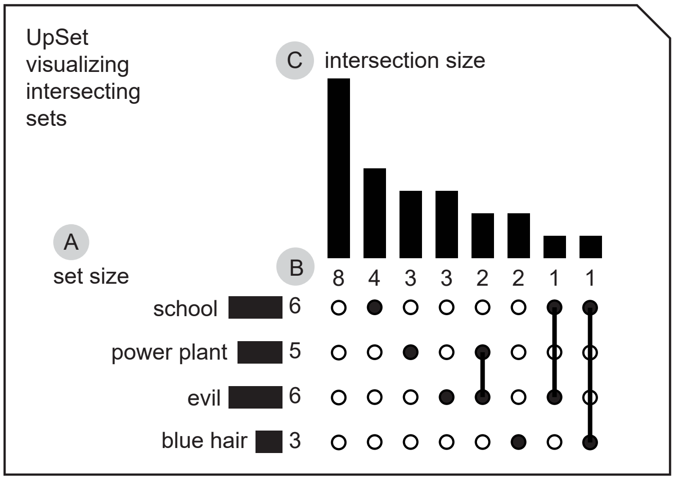

Fig. 12: The tactile chart design for UpSet plot, Design 1, sighted version.

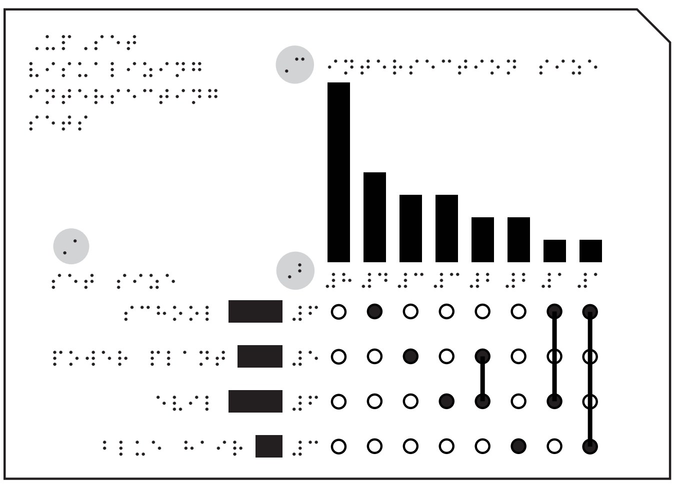

Fig. 13: The tactile chart design for UpSet plot, Design 1, Braille version.

P Template Chart Model Photos Design Variations

In this section, we present the photos of the 3D printed tactile charts for the four chart types in Fig. 65–52. Each chart type has two design variations. We show two views of each model: front view and back view.

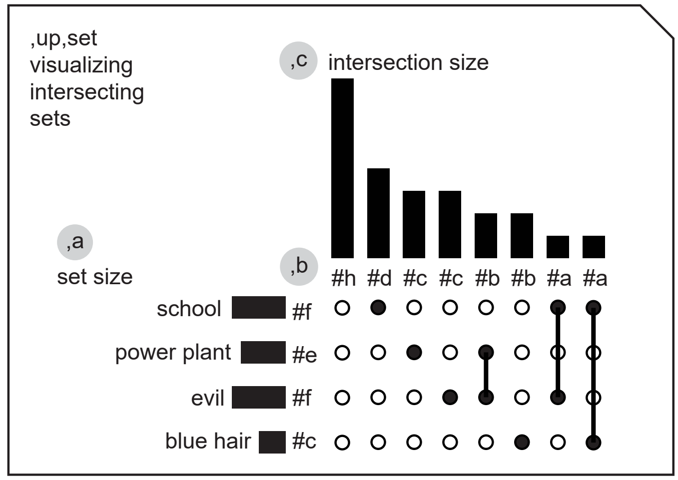

Fig. 14: The tactile chart design for UpSet plot, Design 1, Braille-to-English letter-by-letter translation version.

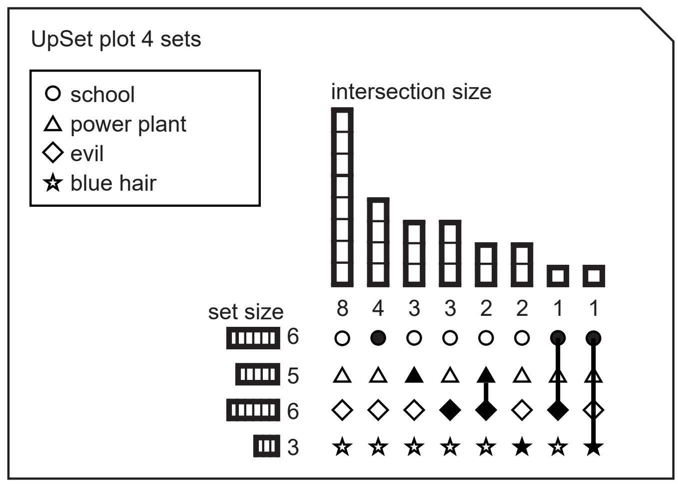

Fig. 15: The tactile chart design for UpSet plot, Design 2, sighted version.

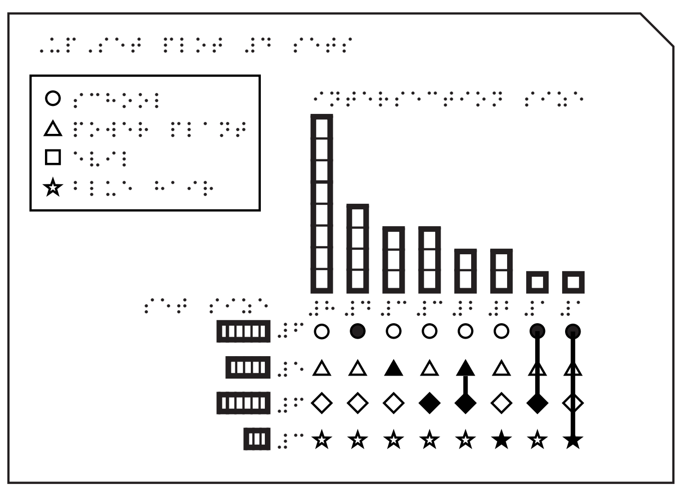

Fig. 16: The tactile chart design for UpSet plot, Design 2, Braille version.

Fig. 17: The tactile chart design for UpSet plot, Design 2, Braille-to-English letter-by-letter translation version.

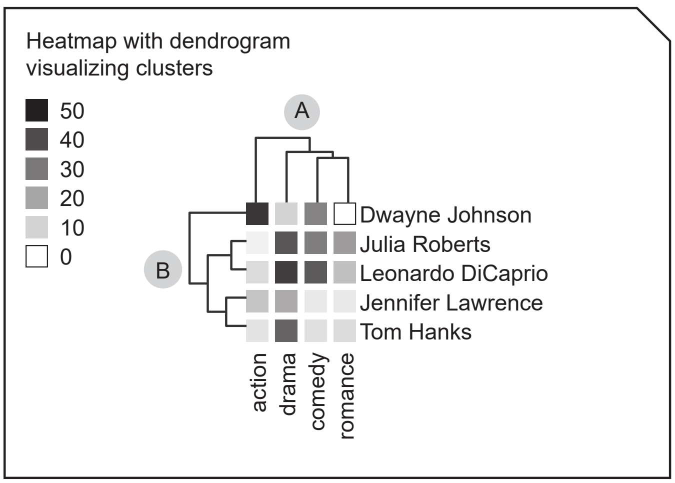

Fig. 18: The tactile chart design for clustered heatmap, Design 1, sighted version.

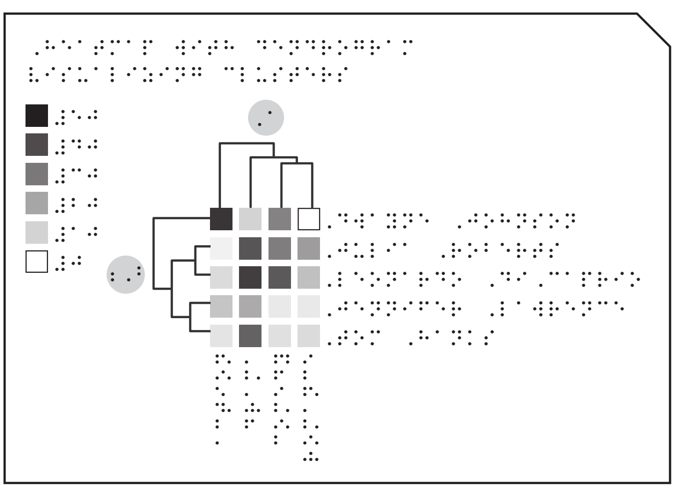

Fig. 19: The tactile chart design for clustered heatmap, Design 1, Braille version.

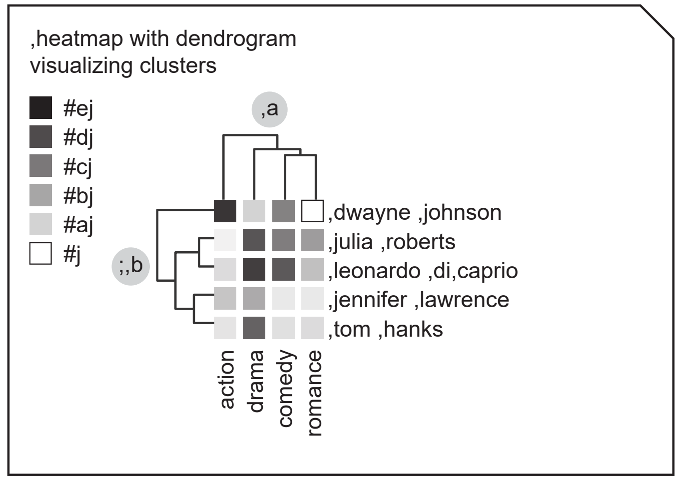

Fig. 20: The tactile chart design for clustered heatmap, Design 1, Braille-to-English letter-by-letter translation version.

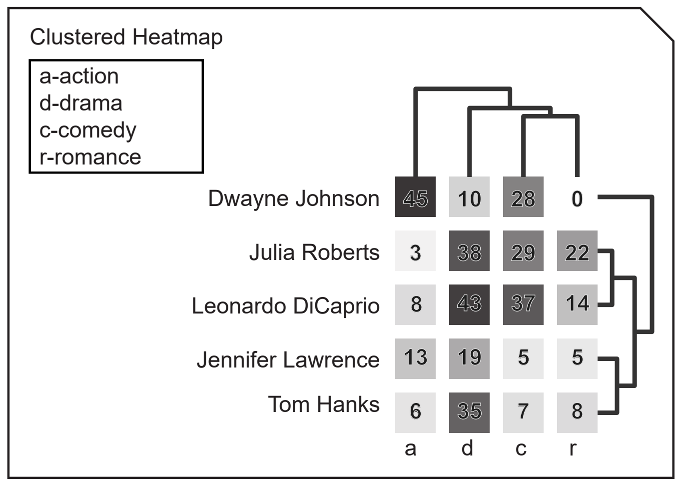

Fig. 21: The tactile chart design for clustered heatmap, Design 2, sighted version.

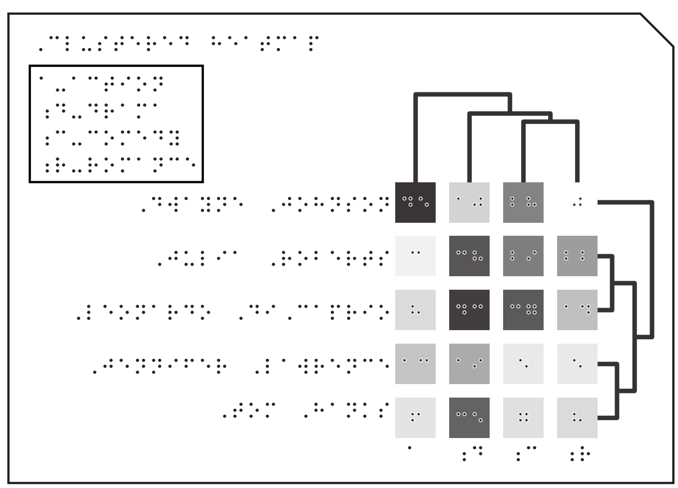

Fig. 22: The tactile chart design for clustered heatmap, Design 2, Braille version.

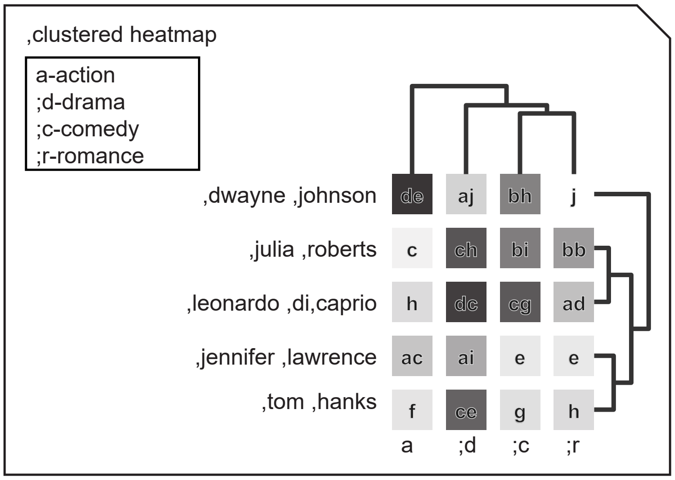

Fig. 23: The tactile chart design for clustered heatmap, Design 2, Braille-to-English letter-by-letter translation version.

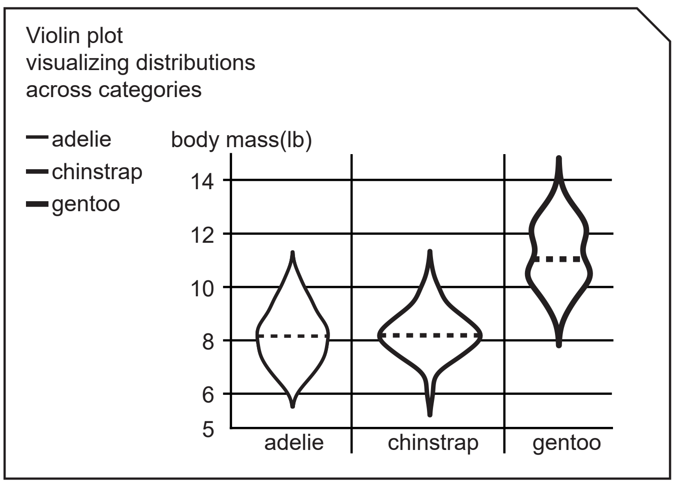

Fig. 24: The tactile chart design for violin plot, Design 1, sighted version.

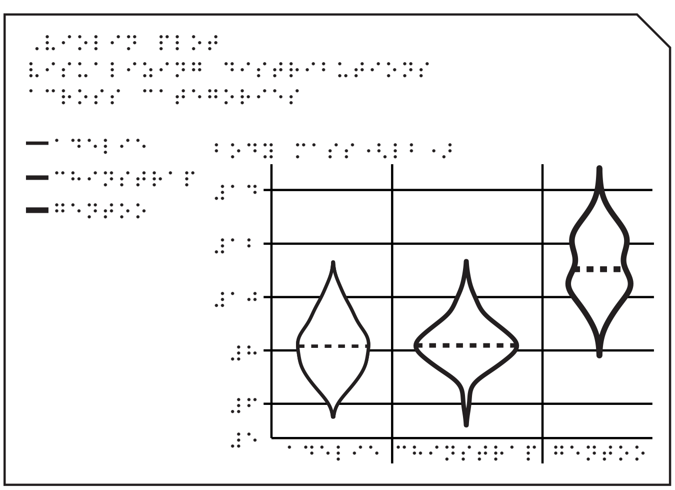

Fig. 25: The tactile chart design for violin plot, Design 1, Braille version.

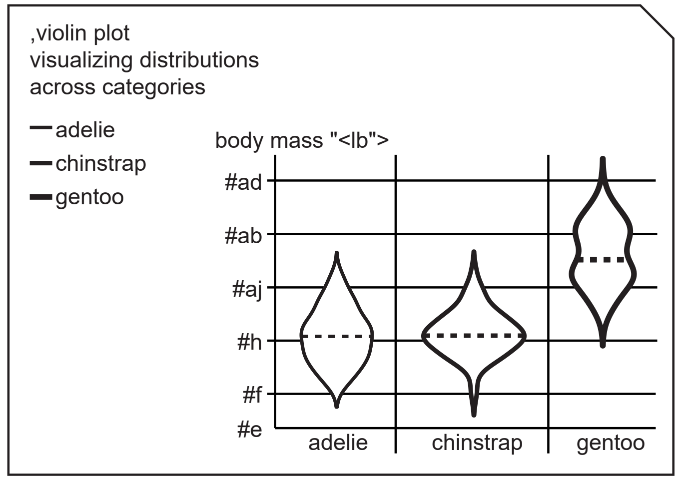

Fig. 26: The tactile chart design for violin plot, Design 1, Braille-to-English letter-by-letter translation version.

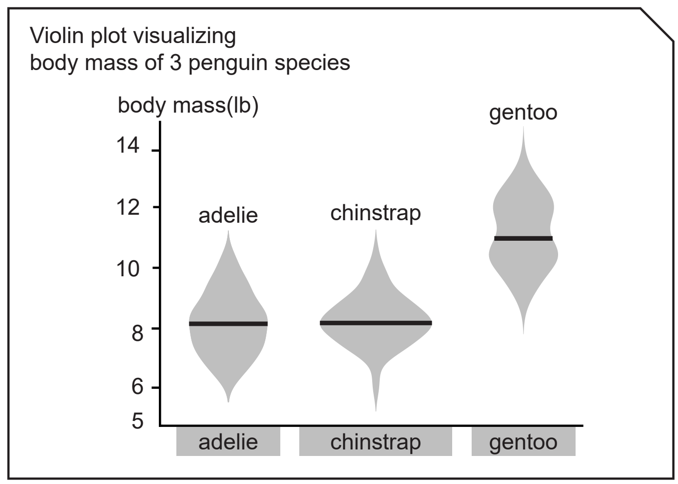

Fig. 27: The tactile chart design for violin plot, Design 2, sighted version.

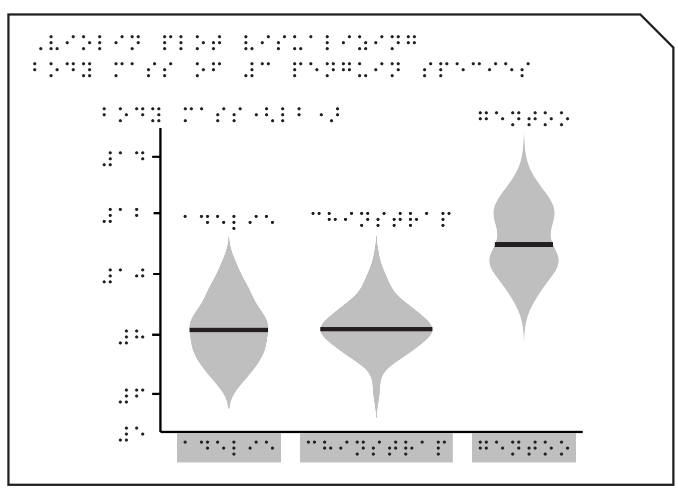

Fig. 28: The tactile chart design for violin plot, Design 2, Braille version.

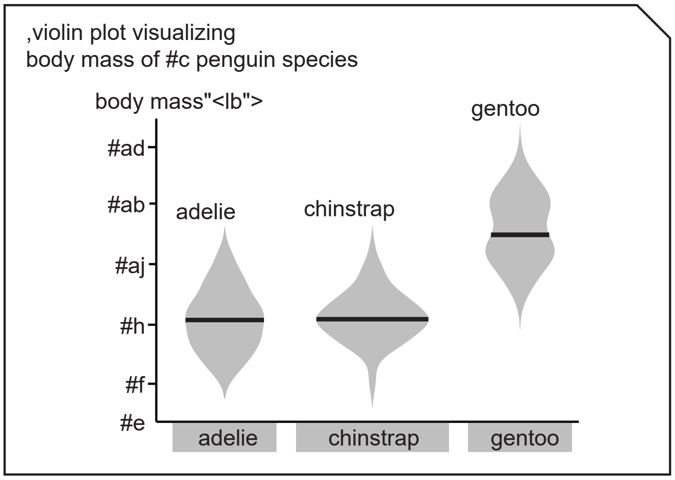

Fig. 29: The tactile chart design for violin plot, Design 2, Braille-to-English letter-by-letter translation version.

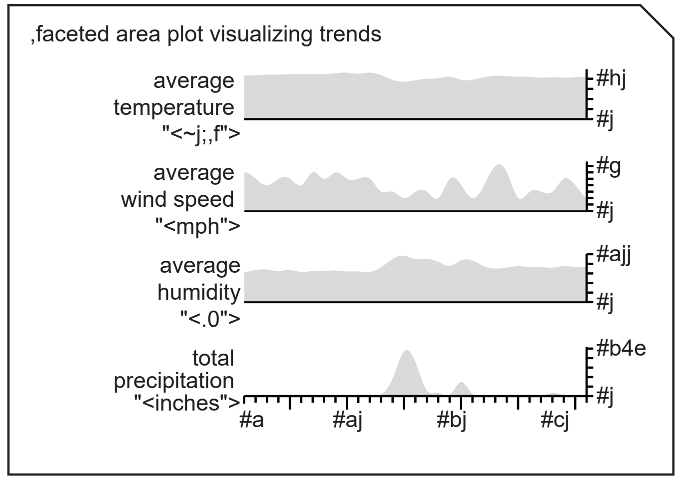

Fig. 32: The tactile chart design for faceted plot, Design 1, Braille-to-English letter-by-letter translation version.

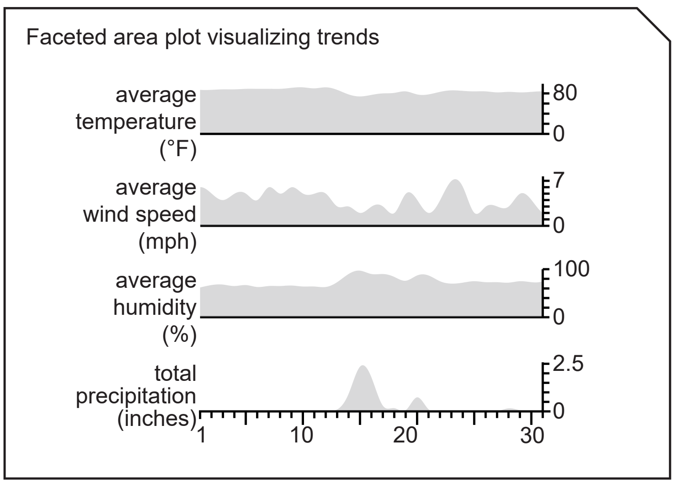

Fig. 30: The tactile chart design for faceted plot, Design 1, sighted version.

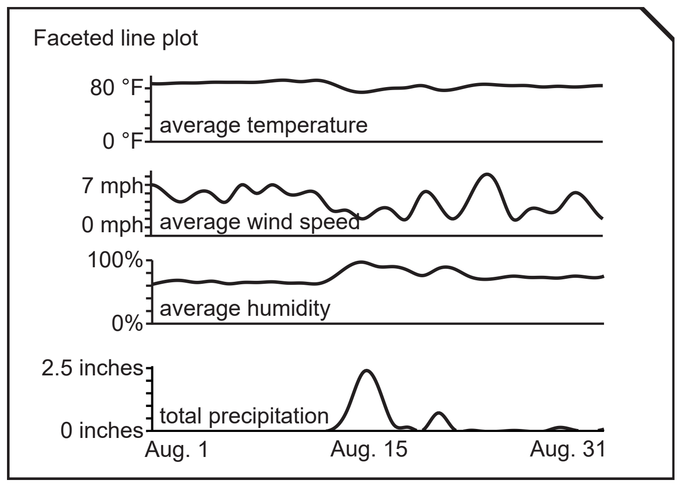

Fig. 33: The tactile chart design for faceted plot, Design 2, sighted version.

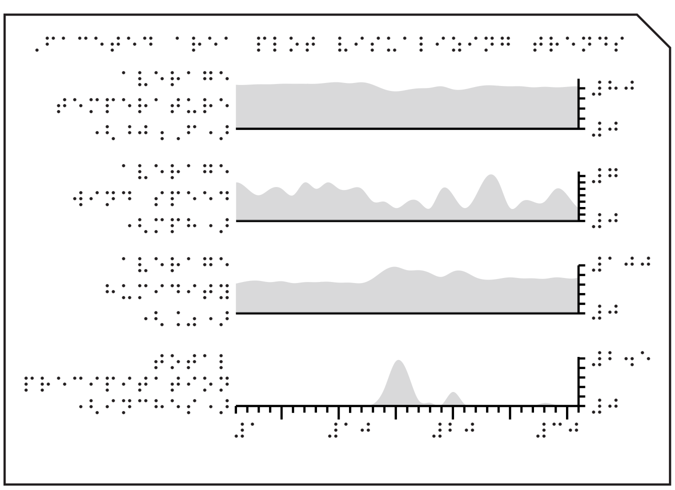

Fig. 31: The tactile chart design for faceted plot, Design 1, Braille version.

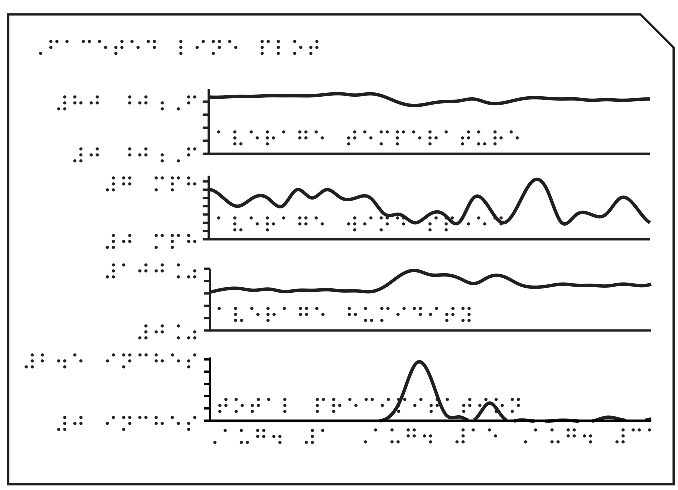

Fig. 34: The tactile chart design for faceted plot, Design 2, Braille version.

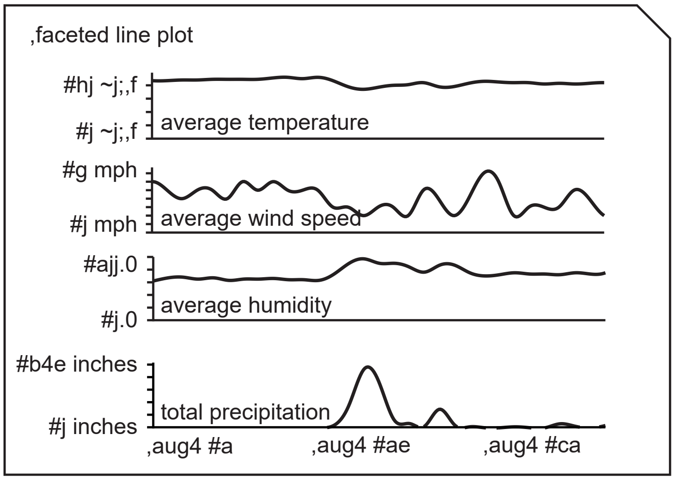

Fig. 35: The tactile chart design for faceted plot, Design 2, Braille-to-English letter-by-letter translation version.

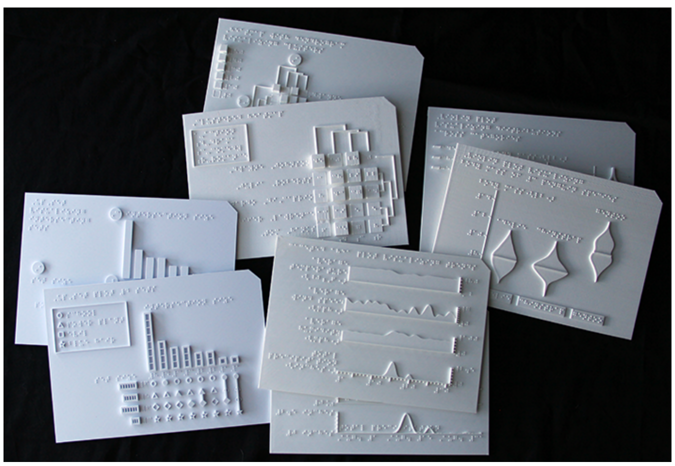

Fig. 36: All eight 3D-printed tactile charts created in our design process, including two design variations for each chart type: UpSet plot, clustered heatmap, violin plot, and faceted line chart.

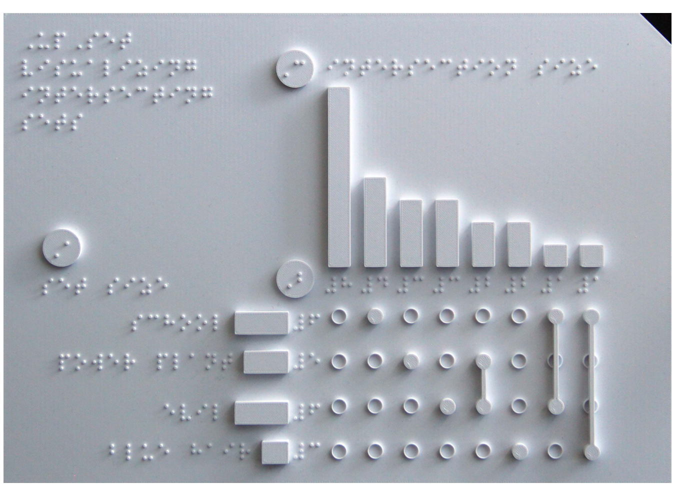

Fig. 37: The 3D printed tactile chart for UpSet plot, Design 1, front view.

Fig. 38: The 3D printed tactile chart for UpSet plot, Design 1, back view.

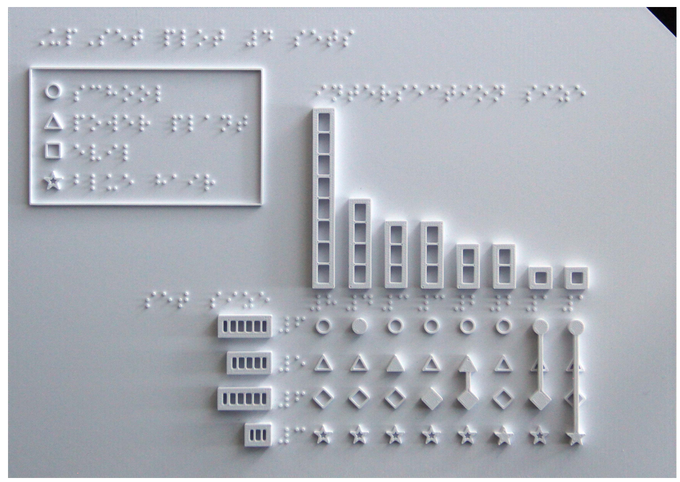

Fig. 39: The 3D printed tactile chart for UpSet plot, Design 2, front view.

Fig. 40: The 3D printed tactile chart for UpSet plot, Design 2, back view.

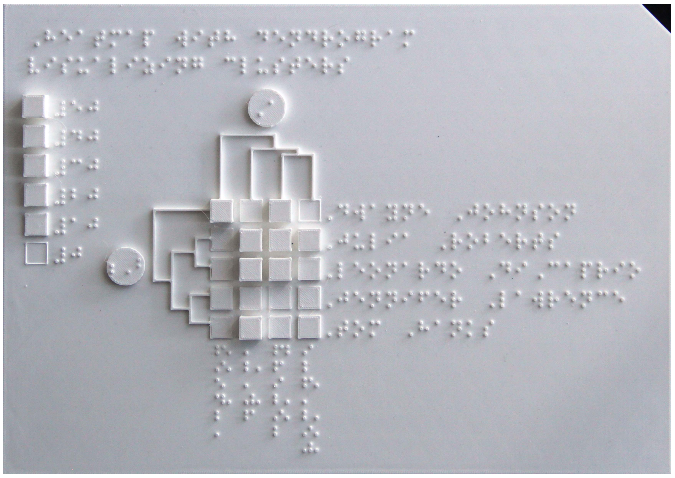

Fig. 41: The 3D printed tactile chart for clustered heatmap, Design 1, front view.

Fig. 42: The 3D printed tactile chart for clustered heatmap, Design 1, back view.

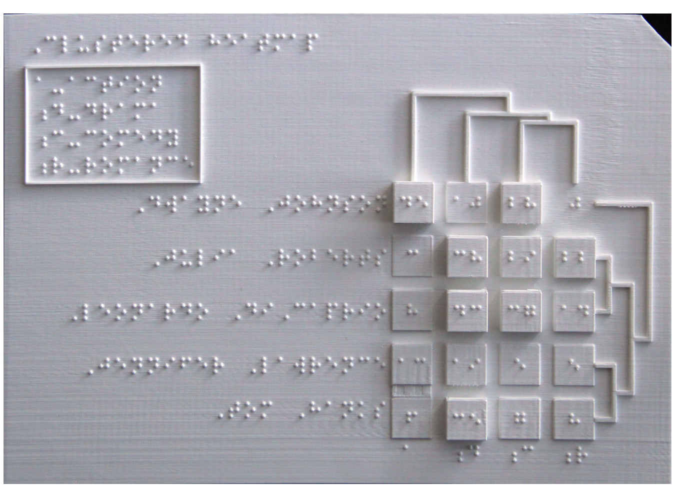

Fig. 43: The 3D printed tactile chart for clustered heatmap, Design 2, front view.

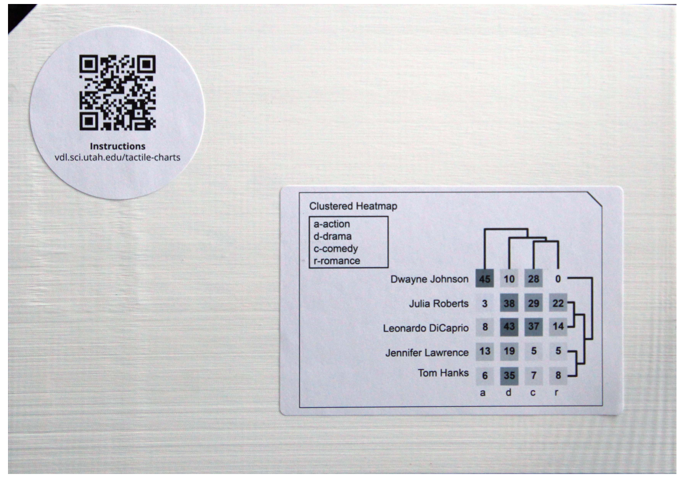

Fig. 44: The 3D printed tactile chart for clustered heatmap, Design 2, back view.

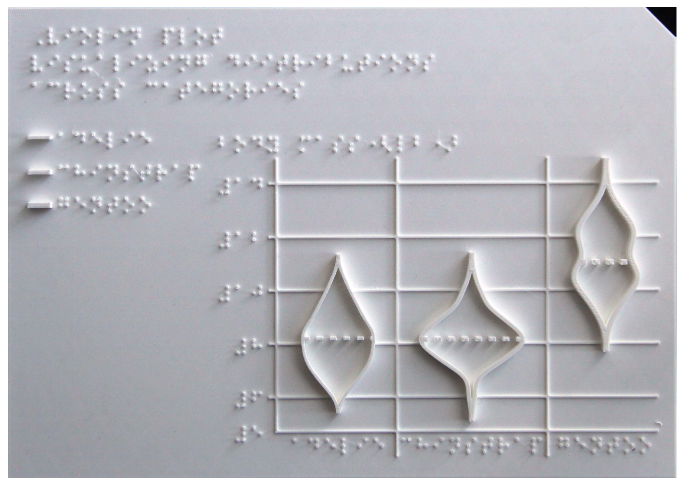

Fig. 45: The 3D printed tactile chart for violin plot, Design 1, front view.

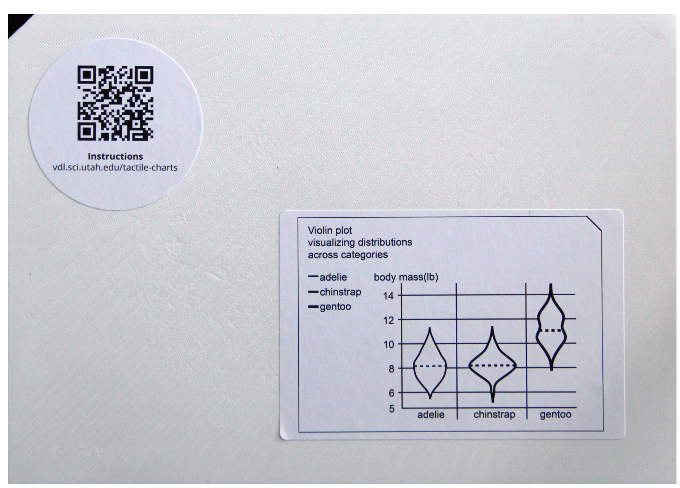

Fig. 46: The 3D printed tactile chart for violin plot, Design 1, back view.

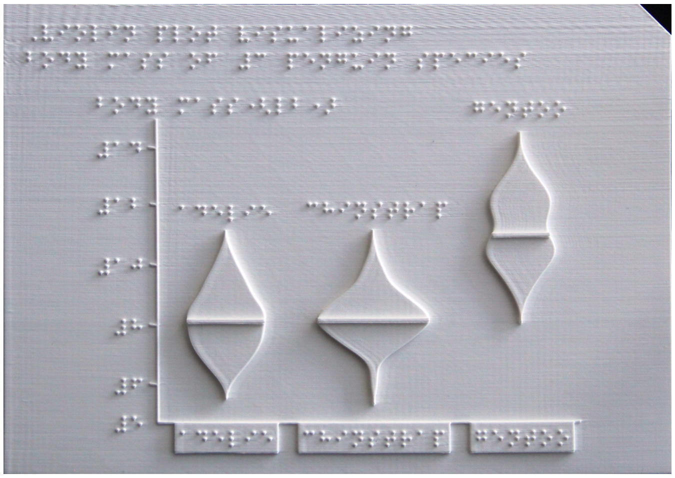

Fig. 47: The 3D printed tactile chart for violin plot, Design 2, front view.

Fig. 48: The 3D printed tactile chart for violin plot, Design 2, back view.

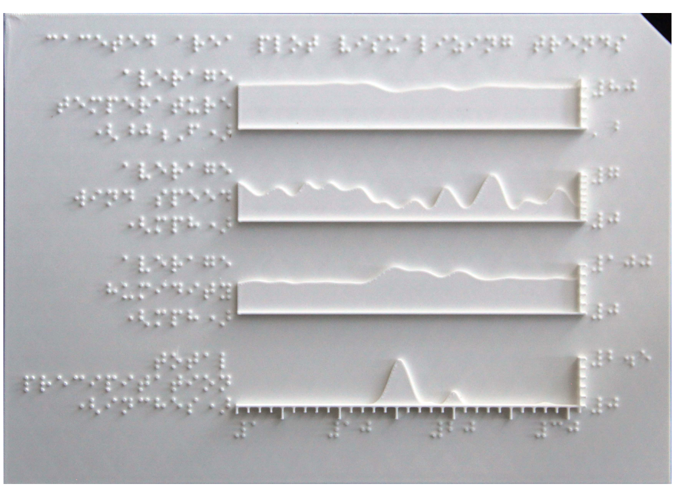

Fig. 49: The 3D printed tactile chart for faceted plot, Design 1, front view.

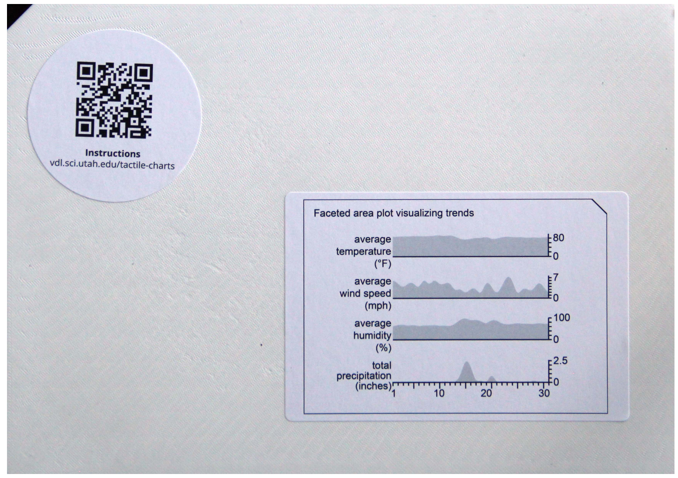

Fig. 50: The 3D printed tactile chart for faceted plot, Design 1, back view.

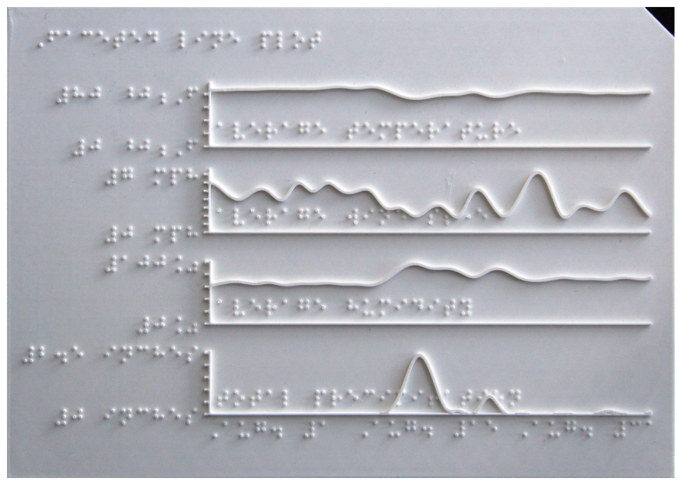

Fig. 51: The 3D printed tactile chart for faceted plot, Design 2, front view.

Fig. 52: The 3D printed tactile chart for faceted plot, Design 2, back view.

Q Template Chart Final Design

Based on the feedback from the consultation sessions with the two blind participants, we made the final design for our four chart types and present them in this section (Fig. 53–64). For each chart, we should three versions: sighted version, Braille version, and a Braille-to-English letter-by-letter translation version.

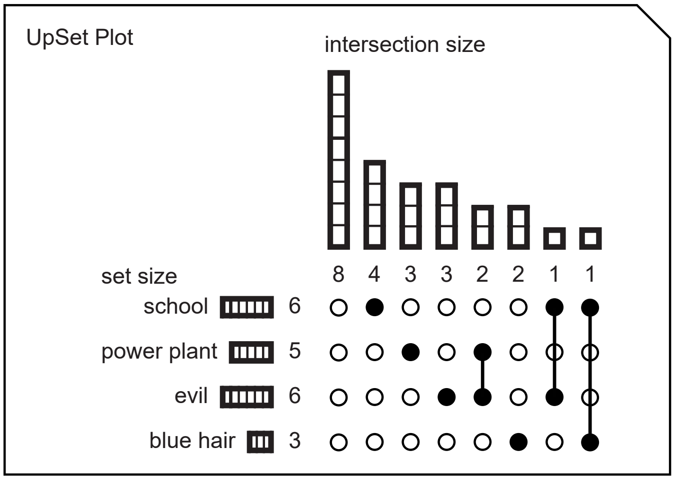

Fig. 53: The final tactile chart design for UpSet plot, sighted version.

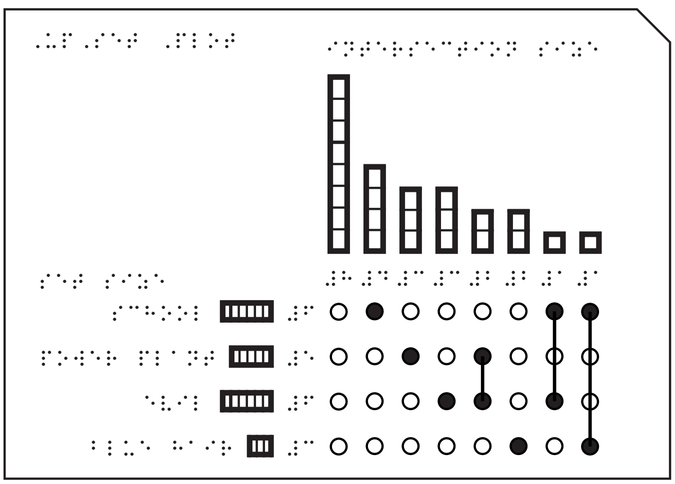

Fig. 54: The final tactile chart design for UpSet plot, Braille version.

R Template Chart Model Photos Final Design

In this section, we present the 3D printed models for the final tactile charts (Fig. 66–73). We show two view of each model: front view and back view.

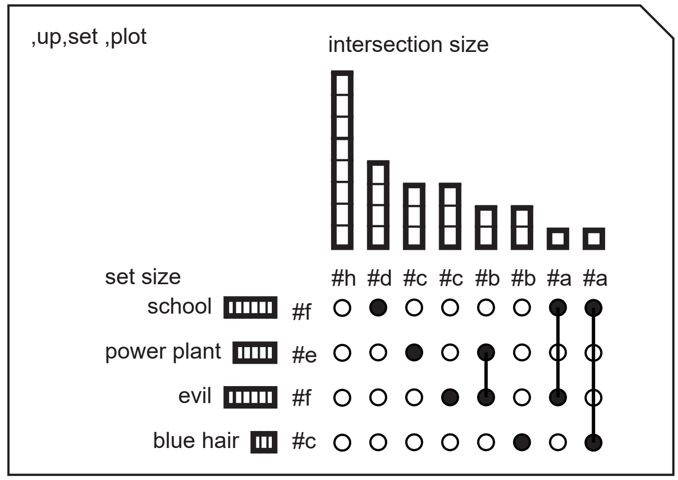

Fig. 55: The final tactile chart design for UpSet plot, Braille-to-English letter-by-letter translation version.

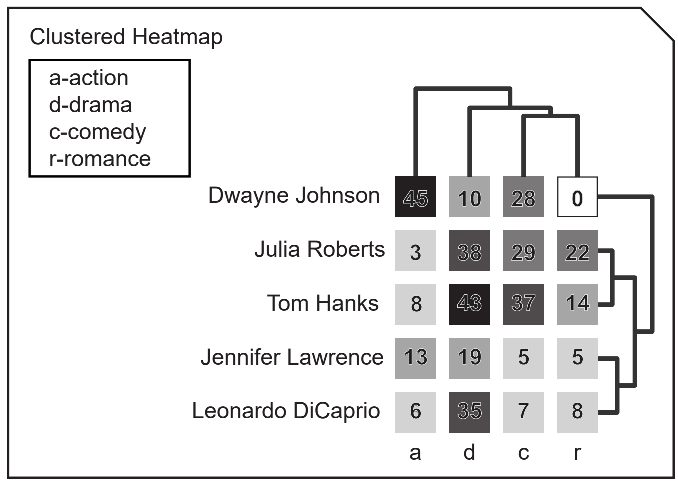

Fig. 56: The final tactile chart design for clustered heatmap, sighted version.

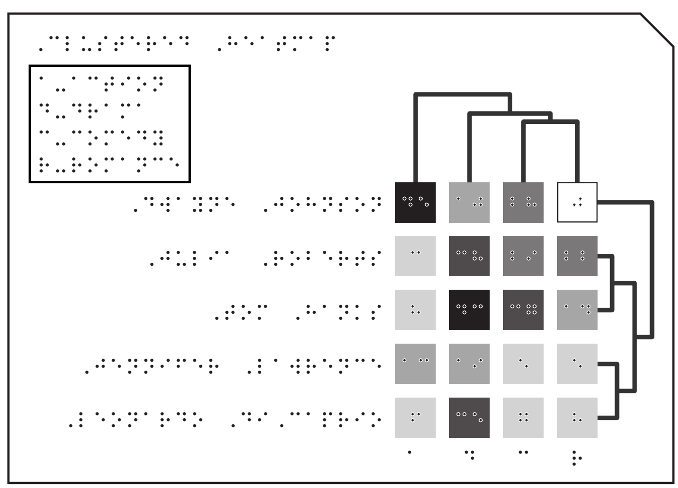

Fig. 57: The final tactile chart design for clustered heatmap, Braille version.

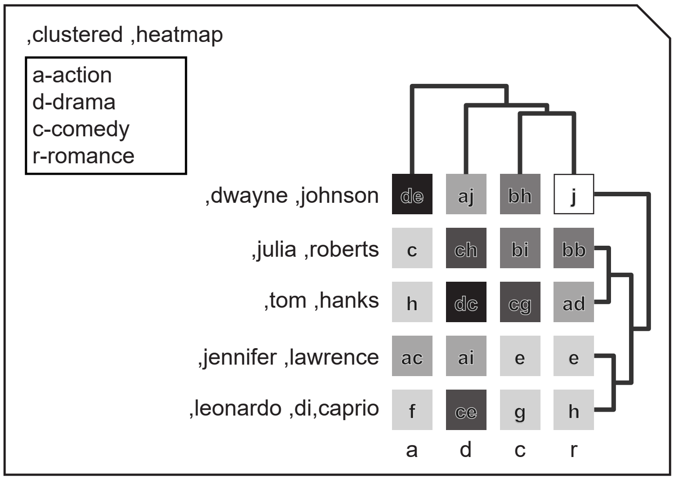

Fig. 58: The final tactile chart design for clustered heatmap, Braille-to-English letter-by-letter translation version.

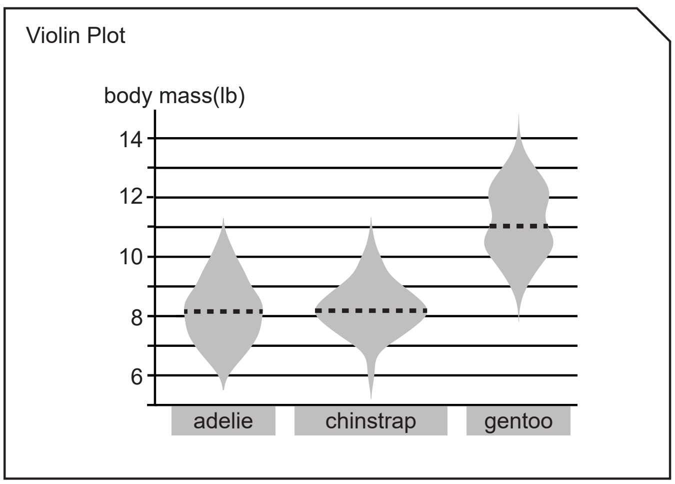

Fig. 59: The final tactile chart design for violin plot, sighted version.

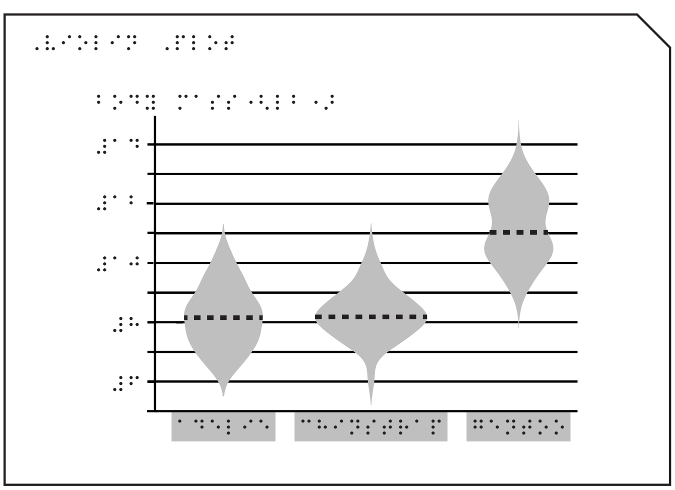

Fig. 60: The final tactile chart design for violin plot, Braille version.

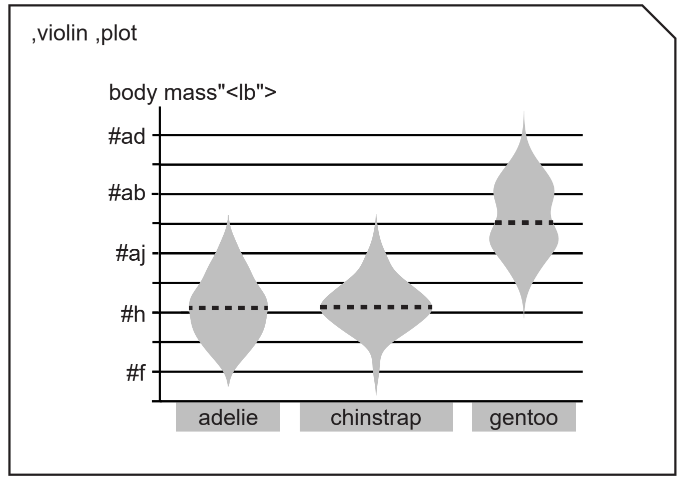

Fig. 61: The final tactile chart design for violin plot, Braille-to-English letter-by-letter translation version.

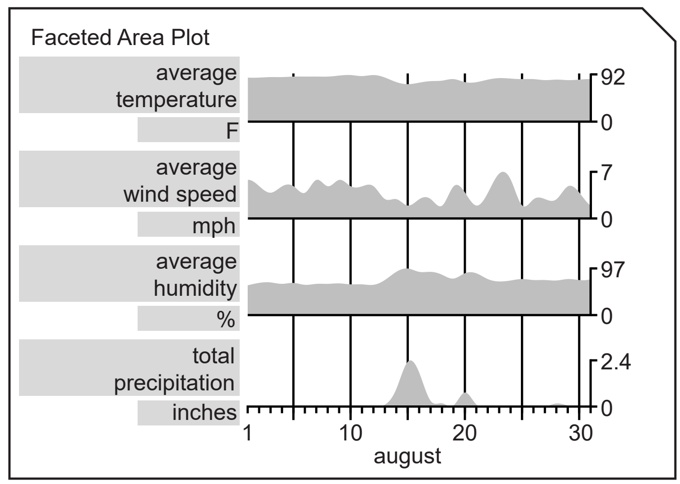

Fig. 62: The final tactile chart design for faceted plot, sighted version.

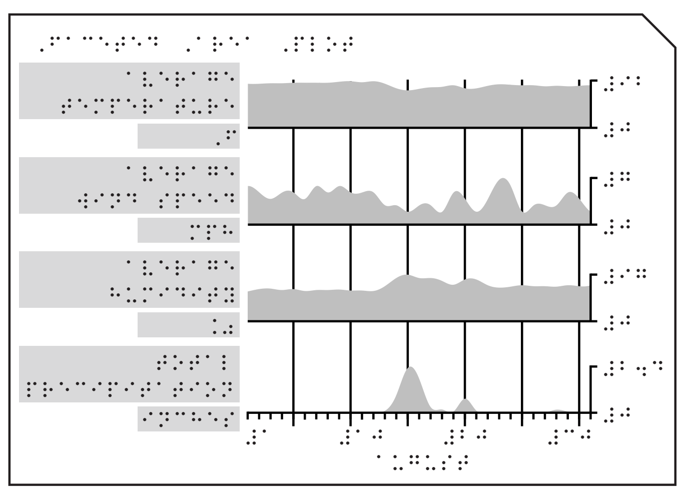

Fig. 63: The final tactile chart design for faceted plot, Braille version.

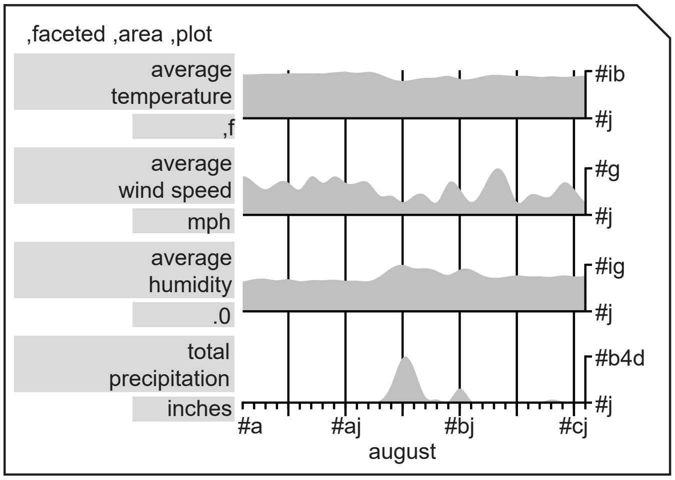

Fig. 64: The final tactile chart design for faceted plot, Braille-to-English letter-by-letter translation version.

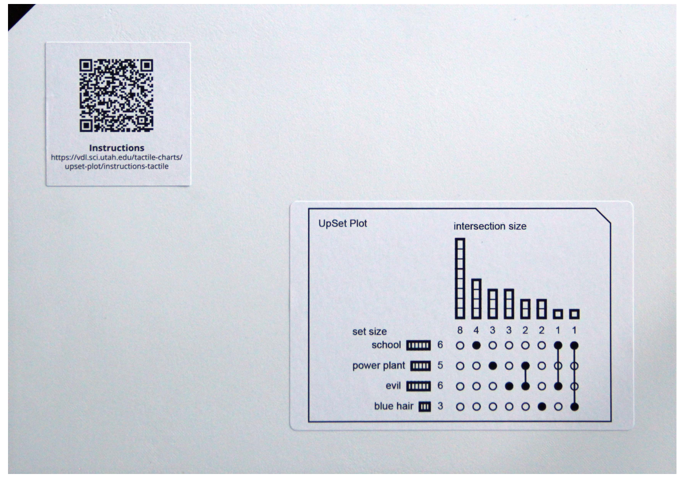

Fig. 67: The 3D printed tactile chart for UpSet plot, final design, back view.

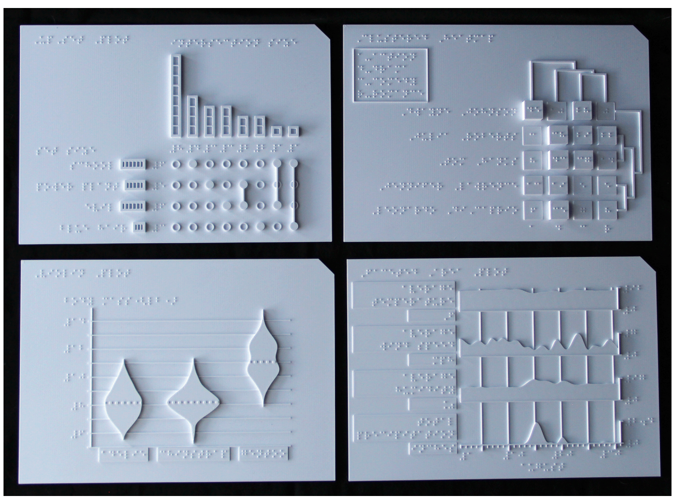

Fig. 65: Four final 3D-printed tactile charts, one for each chart type: UpSet plot, clustered heatmap, violin plot, and faceted line chart.

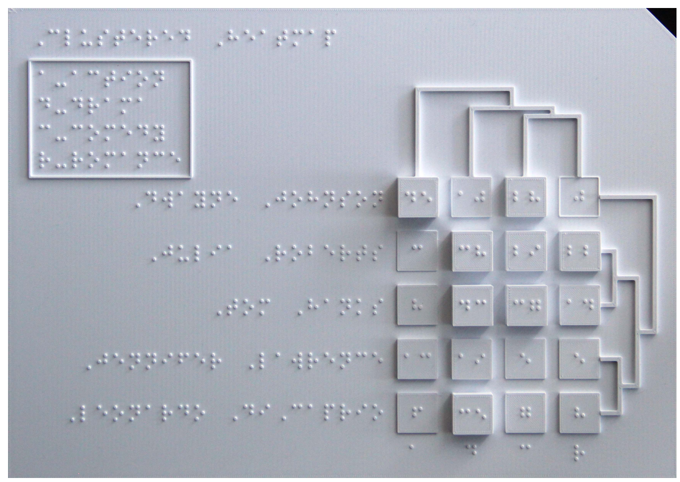

Fig. 68: The 3D printed tactile chart for clustered heatmap, final design, front view.

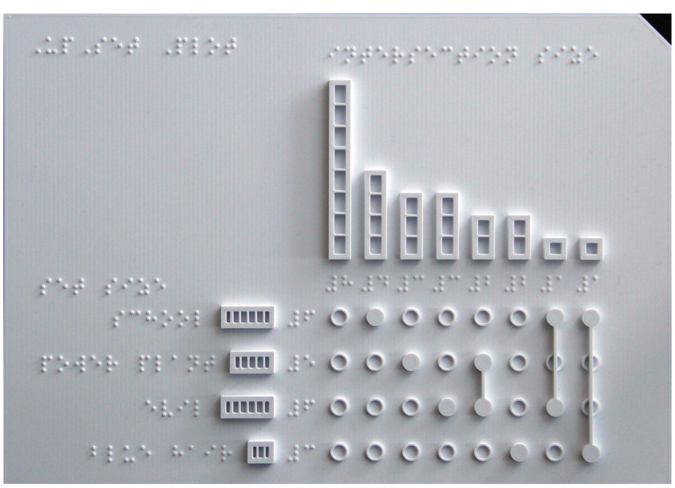

Fig. 66: The 3D printed tactile chart for UpSet plot, final design, front view.

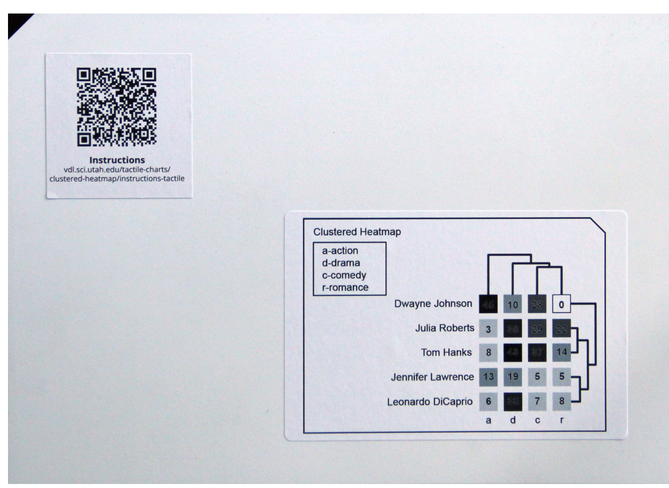

Fig. 69: The 3D printed tactile chart for clustered heatmap, final design, back view.

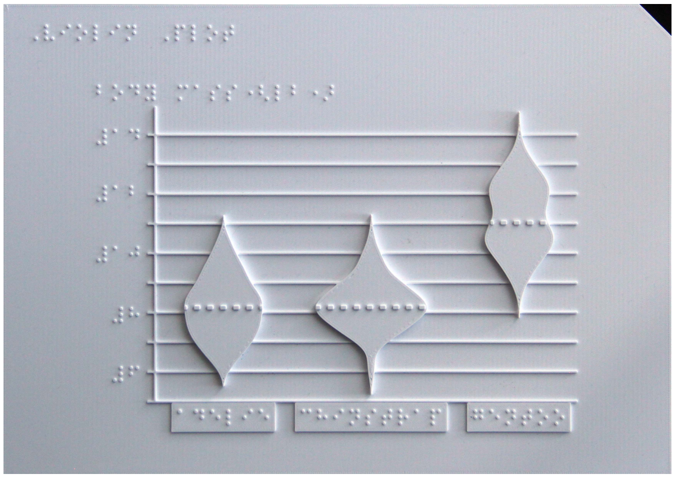

Fig. 70: The 3D printed tactile chart for violin plot, final design, front view.

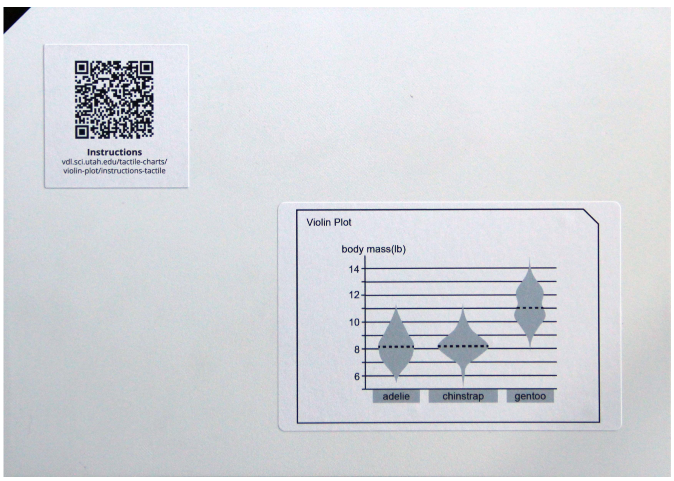

Fig. 71: The 3D printed tactile chart for violin plot, final design, back view.

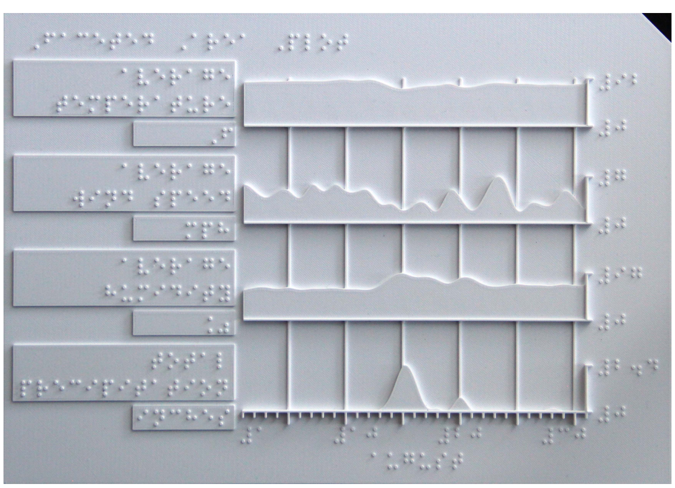

Fig. 72: The 3D printed tactile chart for faceted plot, final design, front view.

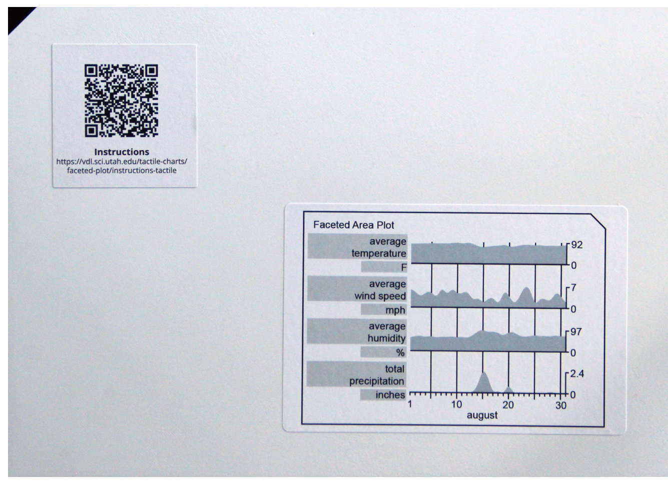

Fig. 73: The 3D printed tactile chart for faceted plot, final design, back view.