Beyond Alternative Text and Tables: Comparative Analysis of Visualization Tools and Accessibility Methods

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Abstract

Modern visualization software and programming libraries have made data visualization construction easier for everyone. However, the extent of accessibility design they support for blind and low-vision people is relatively unknown. It is also unclear how they can improve chart content accessibility beyond conventional alternative text and data tables. To address these issues, we examined the current accessibility features in popular visualization tools, revealing limited support for the standard accessibility methods and scarce support for chart content exploration. Next, we investigate two promising accessibility approaches that provide off-the-shelf solutions for chart content accessibility: structured navigation and conversational interaction. We present a comparative evaluation study and discuss what to consider when incorporating them into visualization tools.

CCS Concepts
• *Human-centered computing* → *Empirical studies in visualization; Visualization systems and tools;*

1. Introduction

Data visualizations have become a mainstream medium for communicating data on the web, such as news media outlets and government websites [LCI*20]. They leverage the preattentive processing of human visual perception, which provides a large amount of information bandwidth compared to other sensory modalities and enables efficient decoding of intricate data patterns. However, relying solely on vision can unintentionally exclude audiences with decreased or absent vision capabilities, limiting their ability to access and comprehend data visualizations.

Blind and low-vision (BLV) people come across data visualizations frequently as they use screen readers (e.g., VoiceOver, Narrator, JAWS, and NVDA) to browse the web [srs]. Recent studies report that many data visualizations on the web are inaccessible for BLV people [FSR*22, SCWR21]. The screen reader users often have to spend more time only to extract less quality information from the visualizations [SCWR21]. The information can be critical if it relates to people's health during times of crisis, such as accessing daily COVID-19 cases in their neighborhood [FSR*22].

Many practitioners heavily use existing software and programming libraries to create data visualizations [JRG*22]. But the extent to which these tools support accessibility is unclear. Do they provide options for adding alternative text (alt text) and data tables? Modern visualizations often require more complex data and advanced visual encodings. Alt text does not support data exploration, while data tables strip away the benefit of data visualization. What do these tools provide beyond the standard methods?

How can they enable BLV people to access underlying visualization content as sighted people would?

We tackle these questions in a two-phase investigation. First, we collected existing popular tools for online visualizations through a keyword-based web search, including Tableau and HighCharts, and analyzed what accessibility features they provide. Through a thematic analysis, we classified the features into four major categories: alternative text & data tables, keyboard navigation of visualization content, dynamic & large data handling, and low vision support. Overall, most tools did not even support basic accessibility, reaffirming why many visualizations on the web were not accessible [JRG*22, FSR*22]. In addition, we found only a few tools support navigating underlying chart content. Among the supported tools, the mode of navigation and the level of information detail were not consistent.

To explore chart content accessibility options for visualization tools, we investigated two recently proposed off-the-shelf solutions: structured navigation [ZLL*22] and conversational interaction [SWM*22]. We ran a within-subject user study using data tables as a baseline, in which blind and low-vision participants tested each method to answer task questions (two extremum searches, two comparisons, two summaries, and one insight takeaway). We analyzed the results to compare task performance, user preference, and observations & comments, and found unique aspects of each method, common frustrations, and coping techniques. Structured navigation produced the highest quality insights, while conversational interaction and data tables worked better for analytical ques-

tions. The result was aligned with the participants' preferences and comments. We discuss design considerations for incorporating these methods into existing visualization tools.

2. Related Work

2.1. Accessibility Experiences with Online Data Visualizations

Screen readers (e.g., JAWS, NVDA, VoiceOver) are the most popular method used for BLV individuals to browse the web, as they do not require any special hardware such as refreshable braille displays and haptic feedback devices. Government agencies such as the national federation of the blind in the U.S. [Blib] and the World Health Organization [Blia] share demographic statistics on blindness. WebAIM publishes screen reader usage statistics for blind people [Blia] and low vision people [Web]. There have been numerous research reports on how people use screen readers to navigate the web and what kinds of barriers they face (e.g., the impact of sentence length [KE20] and redundant information [GTS18], common frustrations [LAKM07], browsing strategies [BBDR10], and coping tactics [VH13, VH14, MVPA18]). A few research studies have reported the accessibility status of government websites [HR13], social media [VAWL16], and workplaces [WWB18]. Others investigated differences from sighted users regarding information-seeking [STS12], awareness of information existence [BLS17], browsing behavior [BCB*07, PPS*13], and moods caused by inaccessibility [PRGC14].

Online data visualizations have grown rapidly in recent years, but research on accessibility has lagged behind [MLB*21, KJRK21]. It is only recently there has been an influx of research on visualization accessibility. A recent survey and interview reported blind people's struggles during the pandemic when navigating and interpreting data visualizations on the web [FSR*22]. Sharif et al. discuss similar challenges of screen reader users in comparison to sighted people [SZS*22]. They also reported what questions blind people ask about the chart to extract information [SWM*22]. Recent research examined the accessibility status of data visualizations by inspecting them through screen readers [FSR*22, JRG*22]. Other studies analyzed and evaluated the quality of alternative texts [WdGH*22, JMK*22, LS21, ADL*02]. The primary sensory modality for screen readers is speech output. Several studies provide insights on how the speech modality compares with tactile presentation [GMH10, WM18] and sonification [AAH14, SJJJ19]. While all these studies focus on understanding the broad experiences of typical blind people, researchers also studied the perspectives of blind scientists [CBF*22] and accessibility experts [CPR*22], struggles and expectations of visualization practitioners [JRG*22, EBM22].

In this work, we aim to understand accessible design support from visualization programming and software tools as these tools contribute to the majority of visualizations on the web [FSR*22, JRG*22]. Unlike the previous work analyzing the accessibility of visualizations in the wild [FSR*22, JRG*22], we specifically examine the scope of accessibility features provided by the tools.

2.2. Accessible Methods for Online Data Visualizations

The prior literature on visualization accessibility presents novel accessibility technologies using different modalities like tactile, haptic, and multimodal techniques [KJRK21], but these custom hardware options are expensive and not easily available. Therefore, screen readers remain the most popular and affordable assistive technology, which use speech output or sonification as their primary output modality."

Previous research has investigated the automatic generation of alternative text descriptions for various types of charts. For example, SIGHT systems generate summaries of line charts [MSMC14], bar charts [DOS*10], and stacked bar charts [BCES19] by extracting salient features of the charts through linguistic analysis and statistical methods. In contrast, the iGraph-Lite system uses templates to generate line chart summaries [FVL*07, FLST13], assuming that a structured representation of the chart and underlying data is available. Other systems utilize computational pipelines to extract chart features and produce human-friendly summarizing text [KM18, KOM21, MKCS22, CJP*19]. More recently, a system has been developed that uses narratives to structure alternative text and sonification in a meaningful sequence [SSHKOF22].

The alternative text does not allow blind people to explore the chart content on their own. Several past systems investigated ways to enable the navigation of the chart and its underlying data. Most of these systems represent a chart in a hierarchical accessible tree from a top-level summary to axes and data values [GMS18, ZLL*22, WOH*15, FVL*07]. For instance, the most recent system structurally divides chart content based on higher-level encoding variables (e.g., positional axes and color legends) and lower-level individual data points, while the user can use arrow keys to navigate the hierarchy [BZS, ZLL*22]. In addition to the structural navigation approach, another recent system demonstrated conversational interaction enabling blind people to inquire about the chart [SWM*22]. Although iGraph-Lite [FVL*07] and interactive SIGHT [DOS*10] systems afford similar back-and-forth interactions, they are activated by shortcut key commands and buttons with predefined functions rather than verbal commands.

The two recent approaches, structured navigation [ZLL*22] and conversational interaction [SWM*22], provide promising alternatives for limited chart content accessibility in existing visualization tools. In this work, we conducted a user study to understand the potential benefits and disadvantages of these methods against data tables as a baseline.

3. Accessibility Analysis of Visualization Tools and Toolkits

Many practitioners rely on existing visualization tools to create data visualizations on the web. Our goal is to understand the degree of accessible design support existing visualization software and programming libraries provide to practitioners. The question guiding our analysis is: "what are existing accessibility features, and how are they supported across different tools?"

3.1. Data Collection

To collect visualization software and libraries to be analyzed, we used a web search with keywords such as "data visualization,"

"chart," "libraries," "tools," "software", and "web." Example search results returned include "top 15 visualization libraries" and "complete overview of the best data visualization tools." After we visited the top search results, the list of tools quickly converged. We limited our data collection to tools that produce visualizations for the web; e.g., mobile development frameworks and Python libraries are excluded. The initial collection consists of 97 tools, including 33 software and 64 programming libraries.

We further filtered the tools based on several exclusion criteria. First, we excluded software mainly used for internal analytics & monitoring (e.g., IBM Watson and SAP Analytics Cloud). We also excluded generic graphics libraries such as D3.js, Three.js, and Fabric.js and software with different purposes, such as spreadsheets and slide presentations (e.g., Excel and PowerPoint), that are not specifically designed to produce data visualizations. For the feasibility of our qualitative analysis without loss of generality, we did not include programming libraries that only support single chart types (e.g., financial line charts, maps, or networks). Finally, we filtered several low-usage libraries based on the GitHub Star count. The final collection consists of 39 tools, including 30 programming libraries and nine visualization software.

3.2. Analysis Method

We used a systematic content analysis process via open coding [CL14]. To kick-start the coding process, we started the analysis with tools that are already known for accessibility support, such as HighCharts. This early analysis provides fruitful initial codes for the rest of the analysis. We also referred to the recent surveys to inspire the initial codes [FSR*22, JRG*22, KJRK21]. Moreover, we guided our codes toward the extent of accessibility support for underlying chart content beyond simple alternative text, such as keyboard navigation of the content. We inspected documentation and tutorials for accessibility if they existed. We examined user interfaces for creating data visualizations and analyzed resulting data visualizations created by us or available in example galleries. One junior researcher and one senior researcher collaborated on the coding process. The junior researcher led the major portion of the initial code establishment in consultation with the senior researcher. Finally, the senior researcher reviewed all codes to resolve conflicts and inconsistencies and break down or merge codes as necessary.

3.3. Results

Figure 1 shows the final collection of the tools along with accessibility codes. Unsurprisingly, the overall accessibility support from the existing software and programming libraries was generally low. Most of the tools did not even support basic alternative text and data tables, while only a few supported beyond the standard methods. In the following sections, we discuss our findings based on the themes and codes identified from the analysis.

3.3.1. Accessibility Statements & Guidelines

An accessibility statement describes the commitment to accessibility. Typically, it cites existing standards to demonstrate the intended level of accessibility. Examples include *Web Content Accessibility Guidelines (WCAG) 2.0* [CCR*08] (or *W3C's Web Accessibility Initiative*), *Section 508 Amendment to the Rehabilitation*

Act of 1973 [sec22], and *EN 301 549 Accessibility requirements suitable for public procurement of ICT products and services in Europe* [Ins21]. The statement is required for public-sector organizations but not necessarily for the private sector (only required if they provide services for public agencies). Several tools, such as PowerBI and AnyCharts, often include conformance reports describing how they address the accessibility requirements outlined in the standards. In the case of software tools, accessibility conformance is addressed not only for data visualization outcomes but also for authoring interfaces. An example compliance check for non-text content (WCAG 2.0 1.1.1 and Section 508 1194.22 1) ranges from simply saying *Partially supports*—Power BI or *All charts produced add an "aria-label" for all elements*—AnyChart.

In addition to the statement and conformance reports, existing tools also provide guidelines on their accessibility features, if they have any. For instance, HighCharts provides comprehensive guidelines from tutorials, use cases, and demonstrations. PowerBI and Tableau also maintain in-depth documentation on designing and consuming accessible dashboards. Flourish and DataWrapper publish blog articles on best accessibility practices for their tools. Many programming libraries such as AnyChart, FusionCharts, Apache ECharts, and amCharts provide examples of accessible data visualizations along with code snippets.

3.3.2. Standard Alt Text & Data Tables

Alternative text provides a high-level summary of the chart (e.g., `alt` in `<img>`), while data tables allow screen reader users to explore the underlying data. Although they are considered de-facto standards for accessible charts, a majority of the tools still do not support them well. Among the 39 tools, only ten charting libraries and three software provide explicit APIs and user interfaces for adding alternative text to the charts they produce. On the other hand, support for data tables is even lower; three programming libraries (HighCharts [hig], Visa Chart [visa], and AnyChart [any]) and two software (Tableau and PowerBI) support it. Toast UI Chart [toa] and DataWrapper [dat] instead provide a data export, such as in CSV and XLS. Although one can imagine employing a manual workaround to programmatically embed alt text and tables under the hood, we found it is not easy as it seems. Many programming libraries provide their own chart encapsulation and interfaces, and thus directly modifying the accessibility attributes such as `aria-label` is not easily possible. Mostly, alternative text is automatically generated by the chart title if provided. Some tools, such as Apache ECharts [ech] and DataWrapper [dat], provide advanced generation based on titles, axes, annotations, and data. Flourish [flo] supports adding a speech narration to their charts.

3.3.3. Keyboard navigation of Chart content

ARIA roles and attributes are used to convey rich semantics for more complex and interactive applications such as modern data visualizations. For instance, the WAI-ARIA Graphics Module [BRESS18] provides three roles that could be used for data visualizations, i.e., `graphics-document`, `graphics-object`, and `graphics-symbol`. Additionally, `aria-roledescription` can provide a human-readable description for each role.

Legend:
⚒ : programming library
🖥 : software tool
● : full support
○ : partial support

	Highcharts	Semiotic	Vega-lite	Visa Chart	amCharts	FusionCharts	AnyChart	Chart.js	Apache ECharts	Observable Plot	G2Plot	Victory	Nivo	ngx-chart	Plotly.js	Google Charts	Taucharts	ApexCharts	Toast UI Chart	VX	Recharts	React-vis	V Charts	Frappe Charts	Flot	roughViz.js	Billboard.js	Plottable	Vizzu	NVD3	Flourish	Power BI	DataWrapper	Infogram	Tableau	Visme	ChartBlocks	Raw Graphs	Looker Studio
Tool Type	⚒	⚒	⚒	⚒	⚒	⚒	⚒	⚒	⚒	⚒	⚒	⚒	⚒	⚒	⚒	⚒	⚒	⚒	⚒	⚒	⚒	⚒	⚒	⚒	⚒	⚒	⚒	⚒	⚒	⚒	🖥	🖥	🖥	🖥	🖥	🖥	🖥	🖥	🖥
Accessibility Guides	●	●	●	●	●	●	●	●	●	●		●																			●	●	●		●				
Alt Text	●	●	●	●	●	●	●	●	●	●																					●	●	●						
Alt Text Generation	●	●	●	●	●	●	●	●		●	●																								●				
Table	●		●		●														○												●	○			●				
Keyboard Navigation	●	●	●	●	●	●	●			●		●	○	○																	○	●	○		○				
Navigation Order	●			●						●		●																				○			○				
Aria Label Customization	●		●	●	●	●	●			●		●	○																										
Label Parameterization	●		●		●	●	●			●		●																											
Dynamic Data	●		●																													●							
Large Data	●																																						
Patterns Fills	●			●	●	●	●					●							●																○				
High Contrast Handling	●			●																												●							
Focus Highlight	●			●	●																											●							
Sonification	●																																						
Narration																															●								
Voice Control	●																																						

Figure 1: *The accessibility analysis result includes 30 programming libraries and nine visualization software tools. In addition to standard alternative text and data tables, advanced accessibility support includes keyboard navigation, interactive and dynamic data handling, and low-vision support. HighCharts and PowerBI are the most accessible visualization tools.*

```
<rect role="graphics-symbol"
      aria-roledescription="bar" .../>
```

One can embed `aria-label` for each visual mark to convey its associated data value.

```
<rect ... aria-label="value: 34" .../>
```

Alternatively, marks can refer to corresponding data labels using `aria-labelledby`:

```
<text id="bar1-val">34</text>
<rect aria-labelledby="bar1-val" ... />
```

Graphical elements (e.g., `<rect>` and `<circle>`) are often ignored by screen readers. To make them keyboard-navigable, one needs to add `tab-index`.

```
<rect ... tab-index="0" .../>
```

In practice, a data visualization may contain a much more complex structure involving multiple data series in different groups and guiding elements such as axes and legends. Currently, there is no convention on how the underlying accessible structure should be formatted and navigated in what order.

Several programming tools allow users to interact with the chart through a keyboard. The level of access often varies. For instance, Vega-lite [veg] and ObservablePlot [obs] allow for navigating to individual data points and guide elements such as axes. Some other charts, such as HighCharts [hig], FusionCharts [fus], and Visa Chart [visa], allow multi-level navigation from alternative text to data series to individual points. Axes are often skipped except HighCharts [hig], in which a developer can add axes descriptions if needed. AnyChart [any] and AmCharts [amc] only support single-level navigation from the root to the data series without going through axes and individual data points. The keyboard navigation of the underlying content is mostly supported by the libraries that produce SVG outcomes. One exception we found is AmCharts [amc] which implements custom navigation on top of HTML Canvas. Tools like Vega-lite [veg] can produce both SVG and Canvas; keyboard navigation is not available for Canvas output. Likewise, other Canvas-based libraries can only provide alternative text at best (e.g., Apache ECharts [ech] and Chart.js [cha]).

Programming libraries that support keyboard navigation provide default descriptions for alternative text, data series, and data points. The default descriptions tend to be minimal based on data table columns. Oftentimes, the programming libraries provide options to customize the descriptions. For instance, Vega-lite exposes a Boolean `aria` property to toggle the visibility of an element from the ARIA accessibility tree (e.g., hiding axes) and `description` property to modify text content. These properties can be domain-specific expressions so that the alternative text content can be parameterized by data variables; e.g., HighCharts [hig] expose context variables such as a datum index and value for the value descriptor callback and series name and data for the series descriptor callback. Most libraries did not support changing the navigation order of elements in the chart. No libraries, except HighCharts [hig], amCharts [amc], and Victory [vic], allow for modifying the default navigation order. For instance, HighCharts [hig] maintains an `order` array that contains an ordered list of chart elements such as series, legends, and user custom components.

For software tools, only PowerBI [pow] seems to truly support keyboard navigation. Other tools like Flourish [flo] and DataWrapper [dat] present visible text elements in a random order in SVG. Visme [visb] internally uses amCharts [amc] and thus keyboard navigation works but rather randomly. PowerBI [pow] and Tableau [tab] make it possible to change the navigation order of

higher-level components such as views and filtering controls not the accessible order of elements within the chart.

In terms of keypads used for navigation, several tools (e.g., FusionCharts [fus] and Visa Chart [visa]) leverage tabs to navigate to landmarks such as charts, legends, series, and axes, and then used arrow keys to navigate elements within the groups. To enter and exit the groups, PowerBI [pow] and Visa Chart [visa] used Enter and ESC keys, while others relied on default screen reader keys (e.g., Ctrl+Option+Shift down and up arrows.) To facilitate across-group navigation, HighCharts [hig] supports remembering the focus item in the previously visited series, enabling navigating the same data category across different series groups.

3.3.4. Dynamic and large data handling

Modern data visualizations are interactive and involve many data points, bringing unique accessibility challenges. For dynamic chart updates, HighCharts [hig] provide a way to announce new data to the user and customize the announcement content format using the data. Visa Chart provides a data change handler but what to do with the change is mainly up to the developer.

For large data, we found only HighCharts [hig] provide explicit control of the data count threshold to disable the navigation of individual data points. While other libraries do not provide such support, a developer might achieve something similar by removing or not specifying aria labels for individual data points. Software tools do not provide this option, while providing a guideline to reduce the number of marks [tab] or hiding the chart content [flo].

3.3.5. Low Vision Support

Pattern fills were relatively more common than other low-vision support features in programming libraries. No software tools provide this option. PowerBI [pow], HighCharts [hig], and AnyChart [any] provide adaptations of their visuals to the high-contrast mode in Windows. In addition, while navigating content, a few tools offer focus highlighting using opacity [hig] and bounding box [visa, amc, pow].

3.3.6. Beyond Speech Output Modality

HighCharts [hig] is the only one that supports sonification. It also claims to support tactile export, but we found this is simply SVG output (e.g., no text-to-braille conversion).

3.4. Takeaways

The tool analysis results indicate that tools rarely support even the minimum requirement of alternative text and data tables, let alone keyboard navigation of chart content. The result also confirms why so many visualizations in the wild were not accessible [JRG*22, FSR*22]. There was a meaningful trend on how to support keyboard navigation (e.g., multi-level hierarchical navigation). Still, no convention exists calling for the collective effort of the visualization community to establish the best practice for what information should be accessible and how to interact with a chart.

4. Comparative Analysis of Accessibility Strategies

The most notable issue we observed was the lack of consistent and established support for underlying chart exploration. In a follow-up user study, we set out to investigate two recently proposed accessibility methods that can provide off-the-shelf solutions to improve the accessibility of visualization tools: 1) structured navigation [ZLL*22] and 2) conversational interaction [SWM*22]. Our goal is to compare and contrast the accessibility methods against data tables as a baseline and investigate strategies to incorporate them into visualization tools.

4.1. Stimuli

We prepared four data visualizations available in the Vega-lite gallery [SMWH17] (see Figure 2) and made them accessible based on data table, structured navigation, and conversational interaction methods. We used conventional HTML tags for data tables accessible on default for screen readers. We also used consistent alternative text format for all chart types and kept them minimal (e.g., chart name and title) as we focused on exploring the chart's inner content.

4.1.1. Structured Navigation

For the structured navigation condition in our study, we adapted the most recent technique proposed by Zong et al. [ZLL*22]. It provides the most comprehensive and systematic navigation of complex chart content, among other keyboard-based navigation approaches (Section 2 & 3). We modified the code from [ZLL*22] to accept a Vega-lite spec [SMWH17] and generate an accessible tree consistently, rather than writing custom code for each visualization. Figure 3 shows an example navigation using the stacked bar chart. The user can use the tab to focus on the chart, which will read its alternative text. They can use up and down arrows to go between different levels of information from the root to encoding-level and data category nodes. Likewise, left and right arrow keys are used to move laterally across siblings. The navigation remembers which node was focused, so the cursor starts at the last focused point when navigating back to it.

4.1.2. Conversational Interaction

We adapted VoxLens, a conversational approach where a user can ask natural language questions about the chart [SWM*22]. Question & answering is not new, and several systems have tackled the semantic understanding of a chart [KHA20, SSL*22]. VoxLens is a much-simplified version compared to existing computational approaches but is the first to be applied in the visualization accessibility context.

The original VoxLens is initialized with data and chart encodings (e.g., data field names mapped in the x-axis and y-axis) and can answer simple queries about data values, extrema, and aggregates. It is limited to a single data series: one categorical variable and one numerical variable, meaning it can only handle a simple bar or line chart (or simple query like "what is the maximum?"). To ensure a fair comparison with the structured condition, we modified VoxLens to accept up to two numeric and two categorical variables. Figure 4 shows several example questions supported by our modified version, such as filtering by a category name.
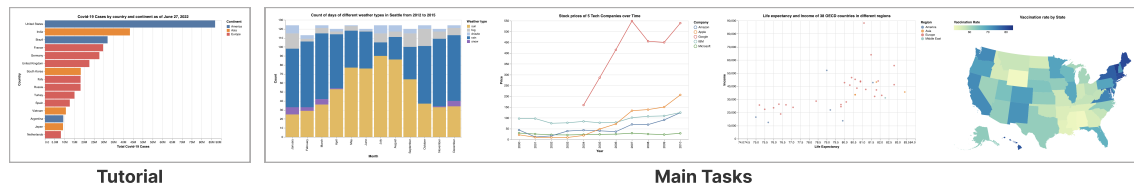
Figure 2: *Visualization stimuli. One tutorial chart and four visualizations used for main tasks. The tutorial chart showing COVID-19 cases by country and continent. The stacked bar chart showing the count of days for different weather types by each month, from 2012 to 2015. The multi-series line chart showing stock prices of 5 tech companies over time. The scatter plot showing life expectancy and income per person for 38 OECD countries in different regions. The U.S. map showing vaccination rates of all states in the U.S.*
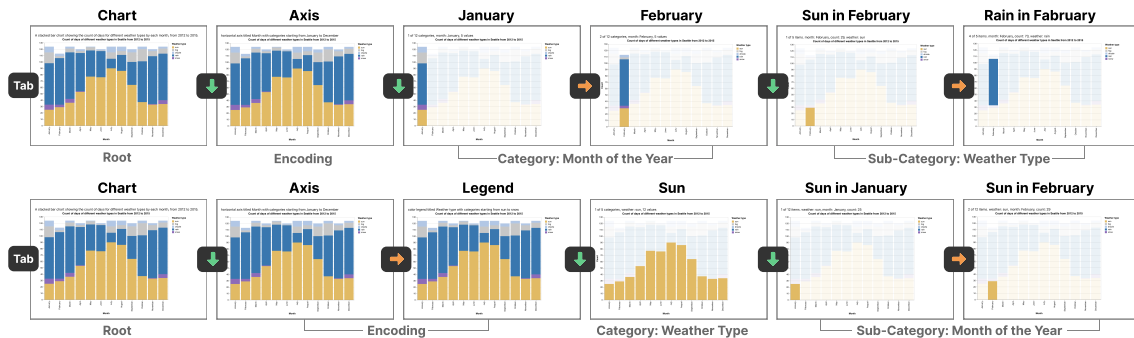
Figure 3: *Structured navigation based on Zong at el. [ZLL*22]. A user can use tab to focus on the chart, up and down arrows to navigate different levels of information, and left and right keys to move between sibling items.*

We also made several other changes, mainly to ensure the validity of comparisons in the study. For instance, it is challenging to ask a question if a person does not know what is available in the chart. Thus, our version of a chart summary includes visual encodings, such as available categories and axes ranges, rather than listing all data patterns, such as maximum and minimum, which we intend to be answered interactively. We also discarded some mathematical operations such as mode, variance, and standard deviation that we believed were too complex to be useful. We also excluded sonification to simplify the comparison setup in the study.

To interact with the chart, we maintain the same interface. The user can press shortcuts to get instructions, a chart summary, and initiate a natural language query. The user has to grant permission to access the microphone. Alternatively, we provide a text box where they can type their query.

4.2. Experiment Design & Procedures

Two junior researchers conducted all sessions remotely via Zoom and prepared an experiment website that blind participants could access remotely. The remote study setting made it easier to reach out to broader participants (see Sec 4.3). Upon entering the website, participants gave their informed consent. We then asked them to share their screen and instructed them to move through the study website. Participants underwent a background survey, the main task, and a final reflection survey. The background survey included demographics, a technical setup, and levels of experience in screen readers, tables, and charts.

The main task had three randomized blocks, each representing an

accessibility strategy among the data table, structured navigation, or conversational interaction; we used a within-subjects experiment design to mitigate individual differences. A block is divided into a tutorial, the main trial, and a post-task survey. In each tutorial, participants read instructions on how to use each accessibility method. The tutorial chart made accessible with the method appeared on the screen. Participants could familiarize themselves with the method and were given three practice questions (finding extrema, comparison, and summarization). The researcher observed how they engaged with the chart, encouraged them to try all functionalities of the method, and clarified any open questions. Participants could move on to the main trial only after correctly solving the practice questions. We chose this design based on our pilot, where we observed participants did not explore the method enough and struggled in the main trial.

In the main trial, we presented a new chart made accessible with the same method in the tutorial. The chart was either a bar chart, a line chart, a scatter plot, or a map, chosen at random without repetition across the blocks. We prepared seven questions for each chart, two extrema questions, two comparison questions, two summarization questions (e.g., median, trend), and one insight question in the order of their appearance. Table 1 shows a list of questions for the stacked bar chart. The format of the questions was consistent across the chart types. We arranged the questions based on their presumed difficulty level. All questions were multiple-choice except the insight question, in which they were asked to summarize the main takeaways. Each multiple-choice question had three data-specific options and two default options: "None of the above is the correct answer" and "Unable to extract information", similar to Sharif et
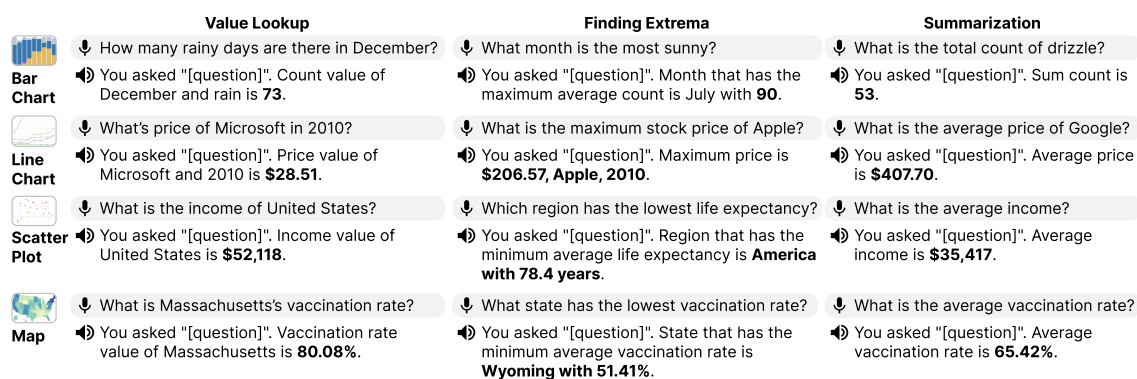
	Value Lookup	Finding Extrema	Summarization
Bar Chart	🎤 How many rainy days are there in December? 🔊 You asked "[question]". Count value of December and rain is **73**.	🎤 What month is the most sunny? 🔊 You asked "[question]". Month that has the maximum average count is July with **90**.	🎤 What is the total count of drizzle? 🔊 You asked "[question]". Sum count is **53**.
Line Chart	🎤 What's price of Microsoft in 2010? 🔊 You asked "[question]". Price value of Microsoft and 2010 is **$28.51**.	🎤 What is the maximum stock price of Apple? 🔊 You asked "[question]". Maximum price is **$206.57, Apple, 2010**.	🎤 What is the average price of Google? 🔊 You asked "[question]". Average price is **$407.70**.
Scatter Plot	🎤 What is the income of United States? 🔊 You asked "[question]". Income value of United States is **$52,118**.	🎤 Which region has the lowest life expectancy? 🔊 You asked "[question]". Region that has the minimum average life expectancy is **America with 78.4 years**.	🎤 What is the average income? 🔊 You asked "[question]". Average income is **$35,417**.
Map	🎤 What is Massachusetts's vaccination rate? 🔊 You asked "[question]". Vaccination rate value of Massachusetts is **80.08%**.	🎤 What state has the lowest vaccination rate? 🔊 You asked "[question]". State that has the minimum average vaccination rate is **Wyoming with 51.41%**.	🎤 What is the average vaccination rate? 🔊 You asked "[question]". Average vaccination rate is **65.42%**.

Figure 4: *Example natural language queries we support in our modified version of VoxLens [SWM*22]. The original version only supports questions of a single data series (e.g., no filtering by another category).*

	Task Type	Difficulty	Question	Options and Answer
1	Extrema	Medium	In which month, was the highest count of days for a single weather type observed?	September / **July** / May / None of the above is the correct answer / Unable to extract information
2	Extrema	Medium	Which month has the fewest rain days?	**July** / May / September / None of the above is the correct answer / Unable to extract information
3	Comparison	Easy	Were there more days with rain in March or in September?	They are the same / **More rainy days in March** / More rain days in September / None of the above is the correct answer / Unable to extract information
4	Comparison	Easy	In September, were there more days of sun or days with rain?	They are the same / More rainy days / **More sunny days** / None of the above is the correct answer / Unable to extract information
5	Summarization	Hard	What is the average number of days with sun? Please try to choose the closest answer.	35 / 44 / **53** / None of the above is the correct answer / Unable to extract information
6	Summarization	Hard	What is the overall trend of days with rain?	It remains steady throughout the year / It increases toward the summer / **It increases toward the winter** / None of the above is the correct answer / Unable to extract information
7	Insight	Hard	Imagine you are summarizing the chart and its data for your colleague. Interpret the data and write about the main takeaway insights and conclusions. You can go back to the chart and further improve your understanding of the overall message.	

Table 1: *Seven task questions we asked to study participants for the stacked bar chart in the order of appearance. We had two questions for each task type (finding extrema, comparing categories, and summarizing data trends), while the final question was about summarizing takeaways.*

al. [SCWR21]. Participants were instructed to find the correct answer as quickly as possible and informed that their responses would be timed.

In the post-task survey in each trial, participants were asked to rate their experience with the accessibility method. We adapted the survey used in Zong et al. [ZLL*22] and asked about perceived enjoyment, ease of use to look up and locate values, ease of use to browse and explore, learnability of the method, the usefulness of the method, and the certainty that their answers had been correct. Participants gave their responses to each question on a 5-point Likert scale.

In the final reflection survey after the three experiment blocks, participants shared which method they liked best and least and what they liked and disliked about the methods. They also had the opportunity to share any additional feedback while the researcher clarified any other open questions. Participants were compensated with a $50 Amazon gift card for completing the study. Each session took approximately one and a half hours to two hours.

4.3. Participants

We recruited 30 online participants through the National Federation of the Blind [Blib]. Five of them were part of our initial pilot investigation from August to September 2022. The main study was run from September to October 2022. Two had to drop out of the session due to their time limit. Two had technical issues and only partially completed their sessions. The final study result we report in this work includes 21 participants.

Most participants used JAWS (15), while others also used NVDA (3) and VoiceOver (2). Also, many of them used Chrome as their primary browser (15), and some others used Microsoft Edge (3), Safari (1), and others (1). A majority of our participants had more than basic screen reader experience: one intermediate user (uses it from time to time), 14 advanced users (uses it almost daily), and five expert users (can perform complex tasks). Regarding their experience with data tables, two participants said they barely engaged with data tables, eight rated themselves as having basic knowledge of what data tables are and how they are constructed, seven said they had intermediate experience in navigating tables, and three claimed advanced expertise, such as performing data analysis. The trend was similar when we asked about their experience with charts. Five participants said they had no to little experience, seven reported basic knowledge of what charts are and how they are constructed, seven rated themselves as having intermediate expertise in understanding charts, and one person indicated having advanced experience, such as creating charts.

Twelve participants were female, and eight were male. Age distribution was only slightly skewed toward the younger population:

18-24 (2), 25-34 (6), 34-44 (3), 45-54 (4), 55-64 (3), and 65 or older (2). Nine participants developed blindness with later onset. Nine participants were blind since birth. Two participants had low vision since birth. The formal diagnosis of their eye condition was varied, ranging from Optic atrophy (3), Glaucoma (3), Retinopathy of prematurity (3), Microphthalmia, Retinoblastoma, Corneal Scarring & Nystagmus, Juvenile Uveitis, and Leber Congenital Amaurosis, and Retinitis Pigmentosa. One participant did not submit their demographic survey part; our background survey was optional.

4.4. Results

4.4.1. Task Performance Comparison

For multiple-choice questions (Q1-Q6), we computed the overall accuracy of each method for each participant by computing the ratio of correct answers. When aggregated across all participants, the mean accuracy for speech interaction and data tables were 0.794 (std=0.163) and 0.786 (std=0.212) respectively, that are significantly higher than 0.603 (std=0.220) of structured navigation using Kruskal-Wallis test(H=15.60, p<0.05) followed by Dunn's test (p<0.05). When aggregated for task types, the mean accuracy for comparison (identify) was 0.856 (std=0.353), 0.718 (std=0.452) for extrema questions, and 0.619 (std=0.488) for summarization; this confirms the validity of our presumed difficulty ratings of the task questions.

Figure 5 shows the overall accuracy broken down by the task type and method. We computed the average time for each method by aggregating over all questions. Overall, data tables and speech interaction took 1.917 (std=1.414) and 1.728 (std=1.617) minutes respectively, that were significantly lower than 2.330 (std=1.704) minutes of structured navigation, when tested using Kruskal-Wallis test(H=15.60, p<0.05) followed by Dunn's test (p<0.05). When aggregated by the task type, extrema questions took 2.512 (std=1.787) minutes, while comparison and summarization task questions took 1.783 (std=1.505) and 1.691 (std=1.363) minutes, respectively; i.e., participants spent more time on initial questions. Figure 5 shows the overall time broken down by the task type and method.

When we looked at how their prior experience and expertise on screen readers, data tables, and charts impacted the result, we did not find significance differences across the experience and expertise levels. While there were no significance differences in accuracy across chart types, the map ($mean$=1.487, std=1.140) took significantly less time than the bar ($mean$=1.926, std=1.636), line ($mean$=2.134, std=1.638), and scatter ($mean$=2.343, std=1.749) charts; there was also a significant difference between the bar chart and the scatter plot. The test was conducted using Kruskal-Wallis test (H=11.207, p<0.05) followed by Dunn's test with p<0.05.

For the last insight question (Q7), we rated the quality of descriptions: 1. neutral information (mostly irrelevant to the context of the chart), 2. neutral + elementary information (chart type, encodings, axes, labels, etc.), 3. elementary information only, 4. elementary and statistical information (extrema, outliers, correlation, comparisons), and 5. elementary/statistical/perceptual information (trends and patterns). When we compared the average quality ratings of the three methods, we found that structured naviga-
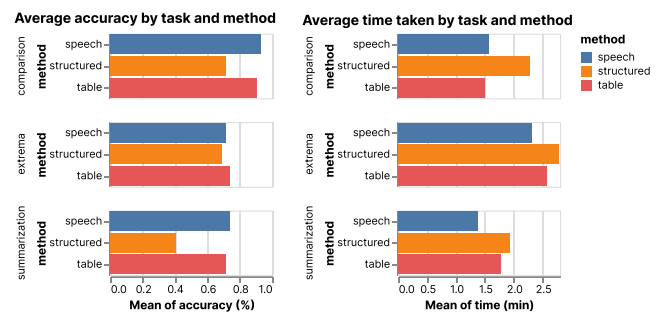
Figure 5: *Average accuracy and completion time for task questions, categorized by accessibility methods and task types.*

tion was the highest ($mean$ = 3.238, std=1.023), while data tables ($mean$ = 3.088, std=1.519) and speech interaction ($mean$ = 2.677, std=1.335) were lower; the rating for speech interaction was significantly lower than the others when tested using Kruskal-Wallis test (H=11.207, p<0.05) followed by Dunn's test (p<0.05). The time taken followed a similar trend: structured ($mean$ = 4.836 minutes, std=3.505), table ($mean$ = 4.467, std = 1.967), and speech ($mean$ = 4.398, std=3.376), although there was no significant difference across the methods when tested using Kruskal-Wallis test (H=3.928, p>0.05).

4.5. Participants' Preference Comparison

Generally, the participants' preference trend was in line with the task performance result. In the final reflection survey, ten participants chose data tables as the most liked method, nine participants chose conversational interaction, and two participants chose structured chart navigation. When asked about the least liked method, eight people chose structured chart navigation, seven chose conversational interaction, and six chose data table.

Figure 6 shows the result of the post-task survey after each trial block. The response trend was, by and large, consistent with the final reflection. Participants found data table and speech interaction were more enjoyable, easier to learn, and more engaging. They found conversational interaction and data tables easier to use when they knew what information they were trying to find. On the other hand, when they did not know which information they were trying to find, they found speech interaction and structured navigation generally more difficult than data tables.

4.6. Comparative Observations & Comments

4.6.1. Participants favored speech interaction and data tables

We noticed participant observations and comments that are aligned with the aforementioned quantitative result. Participants made positive comments on conversational interaction compared to structured navigation. For instance, P31 said, "I like this one better because it is interactive. ... I just asked what is the lifespan of all the countries and I figured that out." P32 similarly commented, "I like the speech the best. It was quite easy to type in the questions and get the answer right away". P43 expressed, "With greater program flexibility, I would like the speech interaction method best. But it
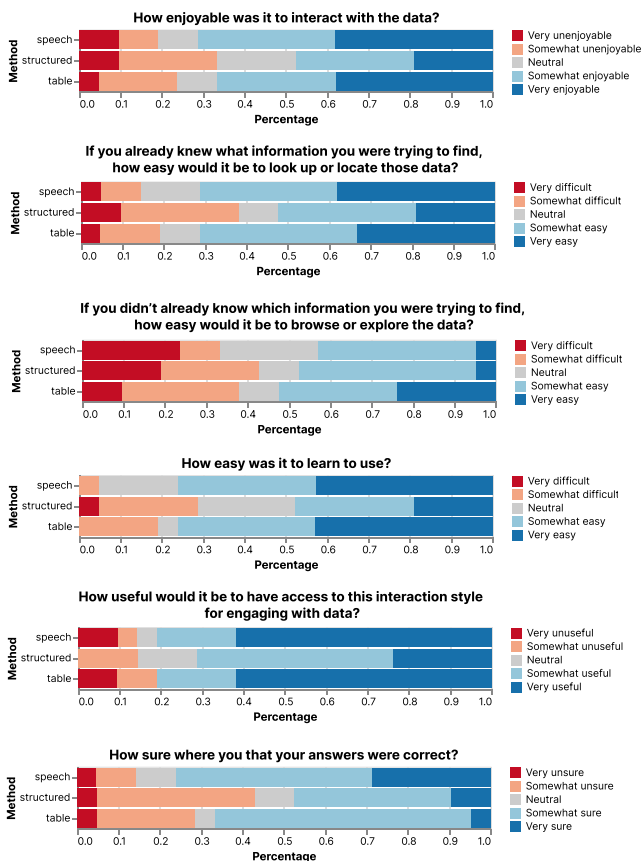
Figure 6: *Participants responded to preference survey questions after trying each method. The results showed that conversational interaction and data tables were generally preferred, which aligns with the task performance result.*

is limited now because of parameters, but the fact that it can recognize questions easily gives it potentially unlimited ability." We observed participants often simply repeat, or copy and paste, the task questions. Not always, but sometimes the system was able to articulate the answer at the first attempt. For example, P40 inputted the question "In which year was the highest price for a share reached?" directly in the text prompt; we observed a similar behavior from P41.

On the other hand, for structured navigation, participants expressed the method as, "It potentially takes the longest to find information"—P26 and "It is hard to detect trends based on what I've seen of the chart. This is partly because there are a lot of numbers, and going through each ... takes too much time"—P28. Other participants specifically commented on the confusion in navigation, such as "...it was confusing to navigate ... out of all of the three methods"–P44, "...It was hard figuring how to get to the information", "All the layers are difficult to keep track of"—P35, and "there was a lag between the arrow keys and the speech, which was a bit confusing. Also, it was easy to get lost within the different levels"—P20.

All that being said, P26 had shown their preference for struc-

tured over speech interaction and data table by saying "potentially takes the longest to find information, but it presents the most realistic depiction of a chart". In a follow-up discussion, the participant further elaborated, "I tend to be more of the visual type person, so I like the structured chart. The speech is great and I like to see that as an option for being able to use that, just I have some doubts as to whether or not the speech commands are understood correctly..."

Participants generally made favorable comments about data tables. P30 said, "it would be nice to have the data table anyways just in case one person wants to explore and see like everything they have that option. I was faster with that because that is how we typically do it with JAWS right?". P41 and P45 wrote, "I had control over the data, could review it easily and find information in a variety of ways" and "I enjoyed the granularity I could exercise with the information", respectively. P35 similarly noted, "I feel the data table is simple to use. Though more complex data can take longer to navigate, having all of it readily available in an intuitive form is extremely helpful." But often, we observed several complaints about data tables as well, such as "There was too much information. It was kind of overwhelming and hard to find answers quickly"—P37 (who liked speech interaction the best) and "it took more time to focus on what I wanted"—P43 (who liked data tables least).

4.6.2. Repetition and recall are frequent frustrations

Frustrations with speech interaction often came from the need to repeatedly try different questions when the initial questions were not successfully recognized. Similarly, participants also often had to go back and forth between the task question and query formation. For instance, for the comparison question of "Which state's vaccination rate is higher, New York or California?", P18 first asked about California and had to revisit the question as they forgot about New York. Having to recall task questions and question options was a problem for data tables and structured navigation as well; e.g., while attempting to answer the question *Which continent's highest income country has longer life expectancy, America or Europe?*, P23 struggled to respond — "Like this question, I feel it has a few parts and am trying to remember all the parts and remember like which category..." In addition, P31 expressed the difficulty of recalling information, ""As a blind person, it is a lot of numbers to try to memorize and correlate, but it is possible to go back...I would probably have a separate sheet to take notes as I cannot take a quick glance and would need to write down a number and then go researching to compare it to another number."

4.6.3. Uncertainty and discoverability in speech interaction

We witnessed unique frustrations regarding conversational interaction. For instance, several participants indicated the issue of uncertainty on the recognition of their speech queries or the correctness of responses they received. P26 said, "I think the speech is great, but for me to be able to use that I have some doubts as to whether or not the speech commands I am giving are actually understood correctly or it is giving me the correct information." P26 continued to evaluate, "I said Australia maybe I did and then I don't know whether I was hearing for Austria and then the second time I just wanted to verify that it was actually hearing me correctly."

In addition, P41 reported the limitation of the control over the

speech method as "I couldn't grasp the data, couldn't get a picture of it...I have no idea what this chart contains, what it shows, or how to get that information. I can't get a picture of it by simply asking these questions." The same participant compared it to data tables, "I had control over the data, could review it easily." P26 also similarly mentioned, "It doesn't really give an understanding of what the map or the chart looks like."

Others commented on the discoverability of possible speech commands. P30 said, "I think at the beginning, I was a bit slower because I didn't remember all the commands of the speech part but I think if you get to know it a little bit ... it would be really easy to use." On the other hand, P34 complained, "I found it cumbersome to try and come up with the exact wording to produce the desired results." For instance, P18 initially attempted to ask a question, but the current system is unable to answer it.: "What are the vaccination rates of New York and California?" After the speech response had told them the command was not recognized, they attempted to formulate different questions.

4.6.4. Frustrations lead to ill-formed assumptions

In all three methods, participants sometimes make assumptions about underlying data without returning back to the chart. For instance, in structured navigation with the summarization question "What is the relationship between income and life expectancy?", P28 selected "None of the above" and commented, "I wasn't exactly sure how to answer that. But it seemed like the answer was what I saw ... I kind of, I knew about the topic from experience I guess ... I could as well say that like I didn't know. But I thought it would just be worth for me to say that neither is true." On the other hand, participants who thoroughly explored the chart could quickly answer some following questions without revisiting the chart.

5. Discussion

5.1. Keep data tables as default

Many participants had a good understanding of how to navigate and explore the data table. The familiarity was a strong advantage for data tables. Moreover, screen readers are well-established for interacting with data tables, providing unique shortcuts to jump across the tables. This makes data tables as an ideal default strategy or as a fallback to other methods. To handle the issue of large data points, providing sorting, as well as other filtering methods [WWJK22], would be critical for data table accessibility.

5.2. Tailor affordances and feedback for blind people

Even if we thoroughly tested structured navigation and conversation interaction methods in pilot stages, we observed participants consistently had issues with discovering the methods and interpreting system responses. For instance, some participants went straight to question headings and got confused with what to do. An accessible method should be detectable despite unusual navigation strategies of screen reader users (e.g., jumping through headings and or tabbing through focusable items). The issue was more noticeable for conversational interaction. Making the speech system more explicit about what commands are accepted and more robust to different phrasing of questions would improve its usability. Moreover,

making non-visual feedback more friendly to blind people would be important. Our decision to just repeat the user's question does not seem enough to address the gulf of evaluation. What are alternatives to visual cues or information scents for blind people?

5.3. Allow control for level-of-detail and orientation

Redundant information cues (e.g., repeating a higher-level category name in a lower-level data value) in structured navigation were often more confusing than helpful, as observed in the original paper [ZLL*22]. Often, the verbose speech feedback could not keep up with participants' fast keystrokes. Future work should investigate what the appropriate amount of information is at each level of the hierarchy. Moreover, several participants had a hard time matching their mental image to the navigation model. Should the tree navigation be vertical or horizontal? What kinds of spatial cues would be helpful for orienting participants? It is also possible that a one-size-fits-all may not work and user-driven customization would be necessary.

5.4. Leverage prior knowledge and experience

We observed that participants frequently rely on prior knowledge and attempt to guess the answers. Often, it was the last resort after consistent failures but also happened without any notable issues with the accessibility methods. We wonder if this is blind people's coping strategy. Instead of preventing it, there may be opportunities to leverage it. Can the prior experience be used to offload the burden on their memory? What if there was a quicker way to just confirm their prior knowledge rather than going through all data points?

5.5. Integrate all methods to support multi-modal interaction

The distinctive characteristics of the accessibility methods present an opportunity for advanced multi-modal interaction; familiarity with data tables, fast turnaround for conversation interaction, and maximum insight with structured navigation. P45 succinctly summarized this unique opportunity, saying "The structured method spat out too much information for each key press, creating information overload. The speech method was excellent, but it required an understanding of the proper syntax. Despite my preference for the data table, I could see all of these being highly useful ways of engaging with larger sets of information".

6. Conclusion

In this paper, we explored the accessibility features of existing visualization tools, focusing on how they make inner chart content accessible. In a follow-up user study, we investigated the pros and cons of two representative approaches: structured navigation and conversational interaction, using data tables as a baseline. The result of this work highlights what to consider when we integrate these methods into data visualization tools. For future work, we will further investigate what paths are typically taken in structured navigation and what questions are asked in conversational interaction. Finally, we hope to explore the design space of multi-modal approaches complementing and addressing the limitations of each method.

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