Visualization Accessibility in the Wild: Challenges Faced by Visualization Designers

Shakila Cherise Joyner
joynersh@bc.edu
Boston College
Chestnut Hill, Massachusetts, USA

Amalia Riegelhuth
amaliariegelhuth@gmail.com
Boston College
Chestnut Hill, Massachusetts, USA

Kathleen Garrity
kathleen.garrity223@gmail.com
Boston College
Chestnut Hill, Massachusetts, USA

Yea-Seul Kim
University of Wisconsin-Madison
Madison, USA
yeaseul.kim@cs.wisc.edu

Nam Wook Kim
Boston College
Chestnut Hill, Massachusetts, USA
nam.wook.kim@bc.edu

ABSTRACT

Data visualizations are now widely used across many disciplines. However, many of them are not easily accessible for visually impaired people. In this work, we use three-staged mixed methods to understand the current practice of accessible visualization design for visually impaired people. We analyzed 95 visualizations from various venues to inspect how they are made inaccessible. To understand the rationale and context behind the design choices, we also conducted surveys with 144 practitioners in the U.S. and follow-up interviews with ten selected survey participants. Our findings include the difficulties of handling modern complex and interactive visualizations and the lack of accessibility support from visualization tools in addition to personal and organizational factors making it challenging to perform accessible design practices.

CCS CONCEPTS

• **Human-centered computing → Accessibility design and evaluation methods**.

KEYWORDS

inclusive design, data visualization, visual impairment, a11y

ACM Reference Format:
Shakila Cherise Joyner, Amalia Riegelhuth, Kathleen Garrity, Yea-Seul Kim, and Nam Wook Kim. 2022. Visualization Accessibility in the Wild: Challenges Faced by Visualization Designers. In *CHI Conference on Human Factors in Computing Systems (CHI '22), April 29-May 5, 2022, New Orleans, LA, USA.* ACM, New York, NY, USA, 19 pages. https://doi.org/10.1145/3491102.3517630

1 INTRODUCTION

Data visualizations are a critical medium for the public to access and understand data. Many types of organizations such as news media outlets and government agencies use charts and graphs to communicate important information about our society, helping people make decisions on finances, health, and other everyday activities. The power of data visualizations is leveraging visual perception, which offers preattentive information processing not readily available in different modalities. Driven by decades of research in developing new tools and techniques, visualization designers are now creating increasingly complicated visualizations with intricate encodings and interactions. Often, these visualizations in the wild are hardly accessible for visually impaired people, and the complexity of the visualization exacerbates the accessibility problems.

Serving the diverse audiences of data visualizations has recently been recognized as a significant societal problem with the increased popularity of visualizations across disciplines [48]. While people may have trouble accessing visualizations due to various reasons such as limited availability of computers or mobile devices, cognitive and learning difficulties, and motor impairments, visually impaired people are most directly impacted by the inaccessibility of data visualizations. People with visual impairment make up more than 3% of the global population, including people who are blind or have low vision [11]. These conditions are different from color vision deficiency addressed through an accessible color palette [49]. Blind and low vision people face more significant challenges in interpreting and manipulating data visualizations and other related tools due to the absence or severe deterioration of vision. A typical practice for accessible visualizations is to provide alternative text or a data table that may not work well beyond simple charts and may not support analytical tasks [56].

Accessibility has long been investigated for traditional graphical content like maps and diagrams [37, 45, 63, 68]. However, these traditional graphics do not recognize data access as a main problem [49]. Moreover, data visualizations pose unique challenges due to their data-driven content and structure, such as a multitude of data points laid out in interactively coordinated views. Although not extensive, several past research endeavors specifically investigated visualization accessibility for visually impaired people, summarized in a recent survey [42]. A category of work develops new techniques and devices for accessible visualizations, leveraging non-vision modalities such as braille, haptics, tactile graphic, sonification, and speech [1, 23, 29, 55, 72]. The other type of work focuses on understanding the needs of visually impaired people through empirical studies including comparing different charts and

CHI '22, April 29-May 5, 2022, New Orleans, LA, USA

ACM ISBN 978-1-4503-9157-3/22/04…$15.00
https://doi.org/10.1145/3491102.3517630

sensory modalities [53, 74] or examining how they interact with them [21, 30, 40]. Nonetheless, many existing studies are limited to simple charts with a few data points and static visualizations. It is *unclear whether they are kept up to date with the latest development* in the visualization field. More importantly, they *did not address the need of visualization creators* who are supposed to make accessible visualizations.

In this research, we investigate the current practice of accessible visualization design for visually impaired people. Our two main research questions include 1) **how visualizations in the wild are made accessible if at all** and 2) **what makes it challenging for practitioners to create accessible visualizations** for visually impaired people. We employed a three-stage mixed-methods design to tackle these questions.

In the first phase, we collected and analyzed the accessibility practices of existing visualizations, evaluating how they are made accessible through screen readers. We collected the visualizations from diverse sectors, including news media and government. Three sighted researchers inspected each case in detail by running it through screen readers, and conducted an iterative open coding process to derive recurring themes and concepts. We divided the analysis dimensions we identified into visualization and accessibility dimensions.

To mimic the broad spectrum of accessible visualization design space, we balanced the distributions of the visualization dimensions when we collected the visualizations, including sector, chart type, chart format (e.g., `<img>`, `<svg>`), data complexity, and interactions. The accessibility dimensions, which we derived while analyzing, include an alternative text method used, interactions available through screen readers, chart existence and type notification, chart overview, data details, contextualization, and overall informative value.

Overall, through screen-reader usage, the informative value of most visualizations was low. Most visualizations neither convey the type of the chart nor provide underlying data details. Many interactions available to sighted users were not available through screen readers. In general, government and non-profit organizations retained original interactions relatively well, and also provided data tables relatively frequently. News media visualizations typically provide more informative overviews. The interactive visualizations are typically written in `<svg>`, while they rarely leverage the advanced accessibility feature (i.e., `aria`) to make the underlying content easily navigable. The surrounding text often alleviated the inaccessibility of the chart, by redundantly conveying the same information.

In the second phase, we conducted a survey with visualization practitioners in the U.S. to gain insights behind the observed patterns in the first phase. We asked about their awareness of and experience with visualization accessibility for visually impaired users. We collected 144 responses from diverse people including designers, scientists, and journalists. They work in small to large organizations with varying levels of visualization responsibilities.

The respondents indicated they use diverse tools and technologies to create visualizations including programming (e.g., `<svg>`) to visualization tools such as Excel (14%) and Tableau (13%). Most respondents reported having basic knowledge (43%) or familiarity with web accessibility (31%), while most of them have no to little experience (62%) in making visualizations accessible for visually impaired people. About one-third of the respondents said accessibility is not a topic at their workplace (30%). Many of them said they themselves are responsible for providing accessibility for the products they develop (42%). Although many think their visualizations are not very accessible (38%) or just do not know how accessible they are (23%), most respondents agreed on the value of visualization accessibility and that providing it is worth the effort (>50%). The respondents stated that it is okay to not provide accessibility if the associated text conveys the same information (41%), while some others said it is never okay (29%). The most common purpose of using web accessibility features was to convey the general message of the visualization (28%). However, this trend is largely driven by practitioners with no to little experience in visualization accessibility (35%). Amongst experienced practitioners supporting insights into underlying data (33%) and ensuring equal engagement for users irrespective of their visual status (25%) were more frequently listed as main purposes. The experienced practitioners also reported having more accessible visualizations and using a broader variety of strategies to provide accessibility.

Finally, in the third phase, we conducted semi-structured interviews with ten visualization practitioners. We recorded the interviews and performed a thematic analysis. We first assigned themes inspired by our research questions to the interview transcripts and then identified emerging codes. After coding, we used these annotations for close reading of the transcript passages and summarizing of statements assigned to the codes. The interview showed that practitioners differ, especially regarding the user groups they consider, ranging from one focusing only on colorblind users to others including low vision and blind users. We further uncover a problematic grey zone. Some practitioners adhere to accessibility standards but may not provide efficient accessibility that meets user needs. Amongst other factors, a lack of expertise, a lack of robustness of visualization tools (e.g., unsatisfactory support of keyboard navigation), and insufficient feedback on the quality of their accessibility practices play into this. Furthermore, participants reported on hurdles that stand in the way of more widespread accessibility. These include a lack of awareness amongst visualization practitioners, an unsupportive environment and infrastructure at the workplace, and insufficient provision of resources such as time, budget, training, and expertise. While novices in visualization accessibility describe being overwhelmed by making complex or interactive visualizations accessible, practitioners with more experience frame this challenge as a design task for which systematic solutions exist. Lastly, practitioners envisioned tools and features that could support them in their workflow. Most commonly, this was real-time in-browser feedback pointing out accessibility issues and simulating users' experience with different needs.

Our work advances the understanding of the accessible design practice for the visually impaired in light of recent advanced visualizations and the challenges of visualization *creators*. More specifically, this paper makes the following contributions:

- The analysis of the visualizations collected in the wild to surface existing accessibility considerations
- The analysis of the survey showing how practitioners position themselves in regards to visualization accessibility

- The findings from the interviews that shed light on practitioners' visualization design process, working definition of accessibility, and motivators and hurdles for providing accessibility

2 RELATED WORK

We provide a background on web accessibility for visually impaired people and examine prior work on analyzing web content accessibility. We review the current status of *visualization* accessibility and articulate where our work lies.

2.1 Web Accessibility for Visually Impaired People

Alternative text, commonly referred to as alt text, has been a de facto method for web accessibility. The alt attribute was first introduced in HTML 2.0 and used inside `<img>` tag to provide an image description for screen readers. If it is necessary to provide a longer description, the `longdesc` attribute is used in addition to the `alt` attribute. WCAG (Web Content Accessibility Guidelines) provide guidelines for creating useful alt attribute content for images [67]. For complex images including graphs and charts, the WCAG suggests providing both a short alt text that briefly describes the chart as well as a long description that substitutes the chart and provides the same content and functionality [39]. Although not specifically designed for accessibility, HTML5 semantic tags, including `<figure>` and `<figcaption>`, can convey the structure and role of web content helpful for accessible navigation. Recently, interactive and dynamic web applications are increasingly common. To improve the accessibility of such rich web content, ARIA (Accessible Rich Internet Applications) has recently become a W3C (World Wide Web Consortium) recommendation. For instance, a developer can assign a `role` and `aria-label` to any element in an HTML document (e.g., a data point represented via `<div>`) that is dynamically changing based on user input. More specific ARIA specs for SVG-based charts [18] are currently being proposed, such as roles (e.g., `graphics-legend`) and attributes (e.g., `aria-datatype` and `aria-datascales`). Proprietary tools that are often embedded in web pages (e.g., Microsoft Power BI [50] and Tableau Dashboards [59]) follow the WCAG standards, while it is still not clear if the final outcome is accessible for visually impaired users.

Screen readers are widely used and affordable assistive technologies that can read the alternative text markup. While third-party screen readers such as JAWS and the free of cost software NVDA have been available for a long time, recent devices and platforms provide their own screen readers without any cost, such as TalkBack for Android, Voice Over for macOS & iOS, Narrator for Windows. These screen readers provide similar features by using keyboard shortcuts to navigate web content. Screen readers use speech as the main output modality and thus are limited to sequential information processing. Since the web content is visually spatial, the limited processing capability leads to a higher cognitive load [10]. In addition, the many keyboard commands for operating screen readers make them challenging to master [60]. However, it is reported that common frustrations of using screen readers typically arise from the web content rather than the assistive technology's limitations. They include confusing and complex page layouts, poorly labeled forms, absence of alt text for images, and misleading links [5, 46]. Previous studies indicated that visually impaired people employ various strategies to cope with these problematic situations [10, 66]. Examples include proactive probing, increasing speech rate, fast tabbing to skip inaccessible content, inferring roles of controls, and finally asking for assistance or giving up [10, 66]. Interestingly, the most common strategy for coping with dynamic content was evading it completely [6]. However, this is not because users are not interested in the dynamic content but because the content is typically inaccessible [42].

The previous research on alternative text and screen readers informed our *analysis framework for evaluating visualization accessibility on the web*. We run over data visualization articles using screen readers and also inspect the underlying HTML/SVG code to see if and how alternative texts are provided. Other accessible output and technologies such as non-speech audio and braille displays provide complementary benefits that alternative text and screen readers cannot provide. However, they are still costly and not universally used, and we leave those for future work.

2.2 Evaluating Web Content Accessibility

The web is constantly and rapidly evolving, introducing new media content and platforms such as complex images and social networks. Ever since the first WCAG specification was available in 1999, existing studies have investigated how well web content is made accessible. For instance, Bigham et al. analyzed web pages from various venues and found that government organization websites have a higher percentage of labeled images than other high-traffic websites [7]. On the other hand, Johnson and Castro [25] recently reported that about one-third of the U.S. government websites still need to improve their accessibility based on automated accessibility testing [20]; common issues include absent, inaccurate, repetitive, and confusing captions. Similarly, Goodwin et al. compared the web accessibility of national websites from the United Nations and found that implementing anti-disability discrimination laws might help ensure accessibility [31]. Using the Internet Archive's Wayback Machine [3], Hackett et al. studied how web accessibility changed over time, finding that the increased technology complexity raises the accessibility barriers [35]. In addition to the general web content accessibility, other studies investigate the accessibility of content on social network sites [13, 26, 27, 52, 57, 61], productivity tools [12, 19, 73], and COVID dashboard web pages [56]. Most of these analysis studies use surveys and observations to collect experiential feedback from visually impaired users [19, 27, 56, 57, 61, 73]. Others analyze image descriptions and content structures [7, 26, 35, 52] and perform simulations through screen readers [12]. Some studies investigate ways to derive quality metrics as an effort to derive an objective, comparative evaluation framework [2, 65], such as using WCAG [67] as a basis.

While previous research examines regular images, we specifically focus on the accessibility of data visualizations. Data visualizations are systematically generated from data and are often interactive and dynamic, coordinating multiple views based on user input. Such differences afford different ways of writing alternative text and supporting navigation [32]. We do not consider non-data maps and diagrams as visualizations and exclude them from our accessibility analysis. Moreover, our work goes beyond static image-based visualizations by examining more advanced and interactive visualizations. Also, rather than simply evaluating alternative text content, we analyzed detailed visualization accessibility dimensions, including the accessibility of underlying data details and the relationship with the surrounding text.

2.3 Visualization Accessibility for Visually Impaired People

Visually impaired people nowadays frequently encounter data-driven media [56], contributing to the expanded user base of data visualizations beyond scientists and analysts [48]. However, accessibility for people with visual impairment, as well as other disabilities, is relatively less explored in the visualization research community thus far [49]. Recently, Kim et al. provided an overview of visualization accessibility research from 1999 to 2020 [42]. They derive seven key dimensions of visualization accessibility—user, task, chart type, interaction, information granularity, sensory modality, and assistive technology—and put together a preliminary model for accessible visualization design consisting of four stages: 1) notifying existence, 2) providing an overview, 3) offering details on request, and 4) bringing context when needed. Practitioners have also recognized the increasing importance of visualization accessibility and developed an extended version of accessibility guidelines specifically for data visualizations, dubbed Chartability [32], and maintain relevant resources [33].

A variety of assistive technologies and sensory modalities have been explored, such as touch-enabled tablets [17, 47], tactile graphics [44, 74], and data sonification [16, 53]. Among those, screen readers were the most common assistive technology due to their availability [15, 28, 55]. On the other hand, several other studies investigate novel multi-modal interactions, overcoming the limitations of screen readers or a single modality. For instance, RoboGraphics combines a touch tablet with tactile overlays and small mobile robots [34], while GraVVITAS integrates the speech modality with multi-touch, haptic feedback [29]. Although most research focuses on tackling one or a few specific charts (e.g., bar and line charts), several studies have developed scalable frameworks producing accessible visualizations. For instance, ASVG augments SVG with additional metadata (i.e., intention tree) encoding underlying data semantics (e.g., data values, trends, maximum, minimum, etc.) [72]. Godfrey et al. provide a similar system in the R statistical environment, using a library of external tools to support metadata annotation, interactive navigation, and braille and speech output [28]. EvoGraphs [55] is another example that accepts a chart spec and produces a corresponding accessible chart. Similarly, efforts have also been made for APIs. These include Vega-lite [64] and Highcharts [38] which have done extensive work to make visualizations more accessible for people with vision impairments and who provide comprehensive accessibility API modules. iGraph-Lite also provides a generalizable navigation architecture, although only demonstrated for a line chart [23]. In these tools, textual information is embedded in the chart output that screen readers can read.

While less available compared to systems research, empirical studies investigated how visually impaired people interact with data visualizations. Many of them explore the experience of tactile graphs, such as identifying suitable textures [70], comparing different charts and design variations [21, 74], and comparing against other sensory modalities such as audio [30, 71]. A majority of other studies examined non-speech modality [1, 62, 69], while one compares that to speech modality [53]. For chart descriptions, Ault et al. provide guidelines for describing charts [4], while the recent study by Jung et al. offers a more comprehensive set of recommendations for alternative text [40] by analyzing the figure captions of academic publications and interviewing visually impaired people. Siu et al. recently noted that simply offering alt text and tables does not support data-oriented tasks well, necessitating the further need to utilize the capability of screen readers (e.g., facilitating jumping between different parts of the graph) [56].

While most prior studies are focused on studying the experiences of visualization *readers* (i.e., visually impaired people), our goal in this work is to understand the needs and wants of visualization *creators* who are responsible for making visualizations accessible for visually impaired readers. Thus, we conducted surveys and interviews with visualization practitioners, asking about their awareness, attitude, and struggles.

3 ANALYZING VISUALIZATION ACCESSIBILITY PRACTICES IN THE WILD

As a first step to understanding the challenges of visualization accessibility, we aim to inspect the current state of accessibility practices in existing visualizations in the wild. We are interested in how visualizations are made accessible to visually impaired users across different venues, what practices are employed to handle the varying levels of interactivity and data complexity, and how contextual information surrounding a visualization supports accessibility.

3.1 Data Collection

Our goal was to curate a sample that best reflects the heterogeneous spectrum of visualizations and the range of approaches taken for making them accessible. Our annotated set of examples of accessibility practices found in the wild is open to access in the supplemental material. We adapted the list of source sectors from Borkin et al. [9] who composed an extensive in-the-wild set of visualizations of different types and from different sources. We manually gathered visualizations from government websites, news media, scientific journals & academic publications, and non-profit organizations & blogs. Thereby we mimic the broad range of topics users may come across on the web. These visualizations were typically embedded in articles or parts of dashboards. Considering the fast-evolving web technology, we limited our collection to visualizations published after 2014. We excluded non-data-driven graphics such as infographics and graphical diagrams.

We collected an initial set of 65 visualizations and coded them based on venues (e.g., news media, government websites), data complexity, interactivity, format (e.g., `<img>`, `<svg>`, `<canvas>`), and chart type. We further collected additional visualizations to improve the initial set in regards to those category dimensions. We aimed to achieve a similar distribution of venue sector and chart type in Borkin et al [9], while also including a variety of intricate modern visualizations with rich data, advanced encodings, and interactive elements created in different formats. Adding these examples in addition to standard and static visualizations resulted in a comprehensive set of 95 visualizations.

3.2 Method

To analyze the accessibility practices of the visualizations collected, we employed a systematic coding process adopted from grounded theory [58] and qualitative content analysis [14, 41]. We created a codebook with initial code categories and their definitions inspired by the accessibility model from Kim et al. that outlines different stages of accessibility [42]. These included venue, chart type, interactivity, and format. Three researchers inductively and collaboratively expanded the codebook with additional categories that emerged from the analysis of a few visualization examples. They deductively and independently applied the codes to the remaining examples. Throughout the process, conflicts were resolved through discussion. The codebook was updated if needed, fostering consistent coding between the researchers. For cases where no consensus could be reached, a senior researcher was consulted. The senior researcher finally inspected all visualizations to confirm the consistency and validity of the final categories and codes.

To evaluate each case, we used *screen readers* to inspect what information is available through the speech output and how the information can be navigated using keyboard shortcuts. We also inspected the underlying source code. Moreover, we evaluate not only the target visualization but also contextual information surrounding it (i.e., text, caption, table), considering that they all are used to communicate relevant information on the visualization and its underlying data to screen reader users. We additionally checked whether or not each venue published an accessibility statement. These serve as summaries outlining what the organization has done to make its websites accessible for people with disabilities, and how their website has tried to adhere to current standards.

3.3 Results

We separated the dimensions we used and identified from the analysis into visualization dimensions and accessibility dimensions. The visualization dimensions are those we balanced during the data collection, while the accessibility dimensions are the ones we derived through the coding process. After analyzing each type of dimension, we inspected how the visualization dimensions relate to the accessibility dimensions.

3.3.1 Overview of Visualization Dimensions. Table 1 shows the overview of visualization dimensions: sector venues, chart types, chart formats, data complexity, and available interactions for sighted users. From these, we further deduce additional dimensions, such as whether a visualization is interactive, involves multiple views, and is basic or advanced (see Table 2). We consider bar, line, and pie graphs as basic charts and treat other ones as advanced ones, including scatter plots. We also tagged if any external tool was used (e.g., Tableau) and categorized the role of the visualization in the whole article (e.g., is it the main content?). A majority of articles (87%) we selected were published after the latest WCAG guidelines had been published in 2018.

News media takes up a majority of sector venues in our collection (49/95), while government and non-profit organizations (NPOs) are also frequent (28/95). Example news media sources include Financial Times, Pew Research Center, New York Times, and Vox. The government and non-profit categories include WHO and OECD, WebAIM, and Wikipedia. Our collection also contains visualizations from individual blogs (10/95) and science articles (8/95) to reflect the composition of various visualization articles in the wild. The blog articles are written by private companies and individuals, while the science category includes articles from Nature and Science.

To reflect the distribution of chart types in the wild, we referred to the in-the-wild visualization collection by Borkin et al. As a result, our distribution generally follows a similar trend, with a majority of charts being standard ones, including line charts (32/95), bar charts (26/95), and maps (15/95). Scatter plots (8/95 and their variants, such as bubble charts (7/95), are also common. Overall, there are 56 basic and 39 advanced charts. When we look at the format, most charts use `<img>` (50/95) and SVG (37/95). A few charts use HTML tags (4) and canvas (4). Eleven of these charts have multiple views that are often coordinated through interactions. Seven charts use external tools, including Tableau (4), Power BI (1), Highcharts (1), and Flourish (1).

In most cases, visualizations play an additional role (40), providing information not available in other surrounding elements. For instance, the text may only mention a few specific data points, while the chart shows a bigger picture with all trends and enables comparisons. In other cases, they play supporting roles (29), summarizing the same information provided elsewhere in the accompanying article. There are 26 cases where visualizations are the main content, such as dashboards.

To approximate the underlying data complexity, we counted the number of marks visible and classified them into three categories: high (> more than 30 marks), medium (8-30 marks), low (less than eight marks) [51]. We later used this dimension to see how the complexity impacts overall accessibility (see Section 3.3.3). Although other visual encoding variables exist, such as color and size, the number of marks was a good approximation for the overall complexity of a visualization. To make all data accessible, screen readers should at least describe each data point behind each mark. The proportions of data complexity categories are comparable: low (34/95), medium (19/95), and high (42/95), reflecting our intention to include modern complex visualizations.

Most visualizations are still static (55/95). Nevertheless, a significant portion of interactive visualizations is included as well (40/95). We categorized what interactions are available for sighted users based on the taxonomy by Heer & Shneiderman [36]. Selecting (34/95), filtering (17/95), and sharing (9/95) are the most common interactions. An example of selecting interaction includes hovering to reveal a tooltip, while sharing is mainly exporting data. Typical filtering is through user interface elements such as checkboxes and dropdown menus, while other advanced interactions involved encoding different types of charts (7/95), coordinating more than one chart view (7/95), navigating content such as zooming (5/95), and recording a visualization snapshot (2/95).

3.3.2 Overall Quality by Accessibility Dimensions. Table 3 shows an overview of the accessibility dimensions we identified and

Sector		Chart Type		Chart Format		Data Complexity		Interaction	
News Media	49	Line	32	Image	50	High	42	No	55
Government	17	Bar	26	SVG	37	Low	34	Select	34
Non Profit	11	Map	15	HTML	4	Medium	19	Filter	17
Blog	10	Point	8	Canvas	4			Share	9
Science	8	Circle	7					Visualize	7
		Distribution	3					Coordinate	7
		Diagram	3					Navigate	5
		Area	3					Sort	2
		Grid & Matrix	2					Record	2
		Tree & Network	1						

Table 1: Overview and Frequencies (n=95) of Visualization Dimensions

Is Advanced Chart		Is Multi-View		Is Interactive		Tool Used		Purpose	
No	56	No	84	No	55	Tableau	4	Additional	40
Yes	39	Yes	11	Yes	40	Power BI	1	Supporting	29
						Highcharts	1	Main Content	26
						Flourish	1		

Table 2: Overview and Frequencies (n=95) of *Deduced* Visualization Dimensions

Table 4 shows the frequencies of properties within the dimensions. For the alternative text method, many charts take advantage of HTML elements (42/95) that are accessible to both sighted users and visually impaired. These HTML elements are mostly headers (e.g., <h1>-<h6>) and subtitles and other explanations (e.g., <p>). The `alt` attribute for <img> (31/95) is also commonly used, while `aria` (7/95) is rarely used. We also observed <figcaption> (13/95), <text> in SVG (4/95), and the `title` attribute in <img> (2/95) that are visible as tooltips. <text> are typically data labels, while the common use case of `aria` is using `aria-describedby` to refer to a separate caption. While we expected that `aria` might be used to improve the accessibility of SVG (e.g., `aria-label` for a data value or axis), that is not the case in our collection.

Among the 40 visualizations with interactions, 18 interactions are completely inaccessible through screen readers. Seventeen cases only partially retain original interactions in screen readers. Five out of the 40 visualizations fully retain interactions in screen readers. We identified two aspects that accompanied the retention of interactivity: the degree of interactivity and the interaction type. In cases where full interactivity is provided, the degree of interactivity is kept relatively simple compared to others. For example, four of the five cases had single interactions (*navigate*, *select*, *filter*), while the other one had both *select* and *sort*. Among all interaction types, *record* and *sort* are fully accessible for both sighted users and screen reader users alike as these two interactions are implemented using typical HTML buttons. In other words, if interactions are implemented in standard user interface elements (e.g., <input>), they mostly remain accessible for screen readers as well.

The existence and type dimension indicate whether the user is informed of the chart or its type at any point. This information is important in order to construct a mental model of the visualization. More than half of the web pages (55/95) do not notify the existence of the chart or the chart type. The notification of existence and chart type is typically available in the first few words of an alternative text (e.g., "Graph showing ...", "Line chart of..."). In some other cases, they are hidden somewhere in the surrounding text, which is not easily accessible. At times, screen readers can catch the mentions of underlying visual mark types such as "lines" and "bars", but this may not be enough to convey the chart type (9/95).

The overview dimension refers to the first description that a screen reader reads when encountering the chart. The overview can support users in deciding whether they want to further engage with a visualization and is often the title or the alt text. Fifteen articles do not describe the chart, effectively making it a "phantom visualization", meaning that it is not perceivable through non-visual access. We observed three different types of overview: non-descriptive, descriptive, and informative. Examples are provided in Figure 1. A descriptive overview typically explains the visual encoding of the chart, such as axes and data labels (54/95), while non-descriptive ones typically include unrelated or unhelpful text for understanding the chart (e.g., a caption like "credits: ..." or a simple title like "Presidential Election Interactive Map") (11/95). On the other hand, an informative overview provides a trend or message of the chart (15/95). While the message can be useful at times, providing it without access to the underlying data might incite a biased conclusion [43] or feelings of being manipulated or patronized for visually impaired people.

The data detail dimension indicates how the underlying data of the chart is accessible. More than half of the charts leave their underlying data inaccessible (54/95). Sometimes, an alternative text mentions a few selected data points (15/95). Occasionally, all data points are read out through screen readers (15/95), although this is mostly for simple charts with a few data points. 14 out of 54 charts provide separate tables for accessing the whole data navigable by screen readers. However, since the raw data table is not the same as the original visualization in terms of structure, users may not extract

Dimension	Dimension Meaning	Property	Property Meaning
Accessibility Statement	Whether the venue published an accessibility statement.		
Alternative Text Method	The types of elements used to convey the alternative text.	See Section 2.1	
Interaction via Screen Reader	The types of interactions available through the screen reader.	See Heer & Shneiderman [36]	
Existence	Measures if at any point the user will be informed that they are dealing with a chart.	No	It is never made clear that the user is dealing with a visualization.
		Somewhat	Screen reader reads out terms that hint at the type (e.g. "lines", "bars").
		Existence	Screen reader reads out a general word like chart/graph/visualization.
		Type	Screen reader at any point reads aloud the type of the visualization.
Overview	Refers to the first description the screen reader reads out when encountering the chart.	No	No description is read. The chart is not perceivable in a non-visual way.
		Non-descriptive	The description is not descriptive at all.
		Descriptive	The description explains the chart content such as axes.
		Informative	The description gives trends of the data and conveys a message.
Data Detail	Measures if someone can access the underlying data through the screen reader.	None	No data points are readout.
		Selected	At least one data point is read out while interacting with the chart (e.g., max).
		Table	The underlying data table is provided.
		All	Every data point is read out while interacting with the chart.
Contextualization	Evaluates how the orientation within the chart and the context is supported.	No	None of the below apply.
		Uninformative Marks/Axes	Screen reader reads aloud data values or axes of the chart without context.
		Supporting Context	In the surrounding paragraphs, there is a mention of information related to the chart.
Informative Value	Evaluates the information provided by all elements that can be picked up by the screen reader.	Low	It does not go beyond basic elements of the chart. The purpose of the chart is not clear.
		Selective	There is some mention of a trend but it does not capture the whole value of the chart.
		Comprehensive	It captures the whole message and all the trends of the chart, as well as its purpose.

Table 3: Description of the Accessibility Dimensions

the same meaning out of it. These results suggest that conveying the underlying data may not be the main intention of practitioners when making visualizations accessible.

Contextualization refers to how orientation within the chart and its context is supported for screen readers. Many articles provide supporting context describing the chart (47/95), although it might not explicitly refer to the chart. This supporting text is helpful,

AltTextMethod		InteractionScreenReader		InformativeValue		HasAccStatement	
HTML	42	No	18	Low	45	Yes	49
img:alt	31	Filter	9	Selective	28	No	46
No	20	Share	7	Comprehensive	22		
figcaption	13	Select	3				
aria-	7	Visualize	3				
<text>	4	Sort	2				
img:title	2	Navigate	2				
		Record	2				
ExistenceType		**Overview**		**DataDetail**		**Contextualization**	
No	55	Descriptive	54	None	54	Supporting Context	47
Existence	19	No	15	All	15	No	36
Type	12	Informative	15	Selected	15	Uninformative Marks/Axes	21
Somewhat	9	Non-descriptive	11	Table	14		

Table 4: Overview and Frequencies (n=95) of Accessibility Dimensions

particularly when the corresponding chart is not very accessible. On the other hand, screen readers often read chart elements such as marks and axes without the possibility to gain context (21/95). This can leave the user confused and also overwhelmed if the screen readers pick up too many data points and tick labels. This is usually common with SVGs as they have underlying elements available. Although providing access to underlying data is desirable, it would be necessary to orient the user where they are located in the chart.

The informative value dimension evaluates the information provided by all elements that can be picked up by the screen reader, including the alt text, other visible and surrounding texts, and tables. This dimension is to assess if the informative value of the graph comes across through the screen reader. Visualizations with low informative values (45/95) have no mention of the reason why the chart was provided in the first place. They do not go beyond describing the very basic elements of the chart and provide no information on the underlying structure. Selective information value (28/95) does slightly better, mentioning some aspects of the chart. Comprehensive value (22/95) indicates that screen readers can pick up the core value of the chart, including all trends in the chart and why it is used on the web page. However, the comprehensive value does not necessarily indicate the full accessibility of the chart (e.g., interactions or complete data may still not be accessible).

3.3.3 Relationship between Visualization and Accessibility Dimensions. We inspected how the visualization dimensions relate to the accessibility dimensions to identify prominent patterns. We investigated: how visualization accessibility is approached in each sector and how the complexity and interactivity of the chart impact accessibility.

Government (Gov) and non-profit organizations (NPOs) demonstrated similar approaches. For instance, Gov (11/17) and NPOs (4/11) support the chart existence and type notification relatively frequently, compared to news media (10/49). Gov (10/19) and NPOs (9/12) also provide underlying data details (e.g., tables) more frequently. Only one out of 49 news media charts provides a data table, while none of the science charts provide underlying data details. On the other hand, news media offer more informative overviews (13/49), while Gov (12/17) and NPOs (11/11) focus on descriptive overviews. While sample sizes are small, the informative value of blogs (7/10) and science sectors (7/8) is generally low.

We also observed differences in low-complexity and high-complexity charts. The low-complexity charts are mostly images (27/34) and also have less diverse interactions (only three interaction types: *filter*, *select*, *navigate*). They use `alt` attributes for alternative text quite frequently (19/34). Even though less complex, they have informative overviews (10/34) and comprehensive informative values (14/34) relatively often. However, they rarely provide data tables (1/34). Instead, they often make all data values available since the number of data points is not high (8/34). High-complexity charts use SVGs more frequently (27/42). They typically do not use `alt` attributes for alternative text (3/42) and have no informative overviews (0/42). Instead, they provide underlying tables more frequently (12/42). Still seldom are they of comprehensive informative value (6/42). Another issue is that high-complexity charts have many uninformative marks or axes (16/42), compared to low-complexity ones (1/34).

Our analysis revealed differences in accessibility between static and interactive charts. Contrary to general recommendations, most interactive charts do not leverage the `aria` functionality but rather rely on nearby HTML elements for the alternative text (29/40), such as using `h1` and `<p>`. As expected, uninformative marks/axes are recurring issues with interactive charts leveraging SVG and HTML, exposing the underlying elements (17/40). In fact, 90% (36/40) of the interactive charts used SVG and HTML, while 91% (50/55) of the static charts were images. Interestingly, interactive charts (13/40) provide data tables more frequently than static charts (1/55). However, static charts provide informative overviews (15/55) more frequently than interactive ones (0/40). One possible explanation for these differences is that interactive charts are more frequently main

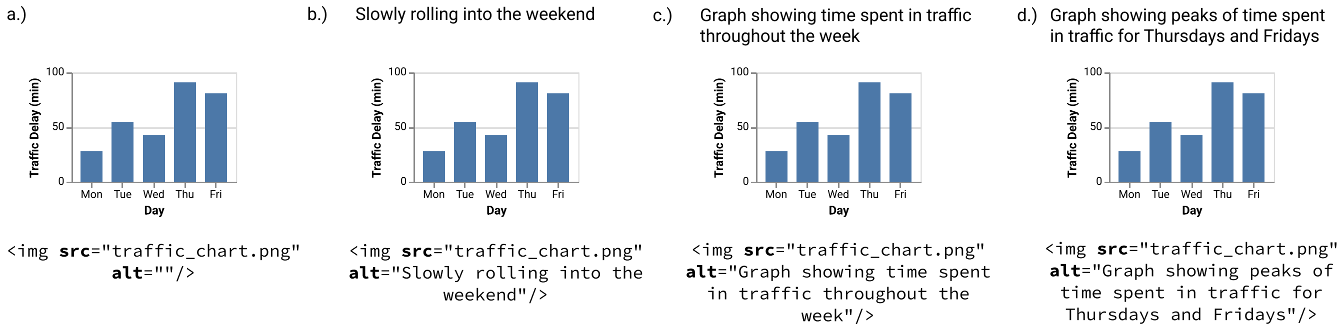

Figure 1: Illustrative example chart with different overview types. (a) Phantom visualization: The visualization is an image, and its overview is not embedded in the alt-text leaving the graph non-perceivable through the screen reader. (b) Non-descriptive: The title contains no information on the content of the graph. (c) Descriptive: The overview contains the axes and data labels. (d) Informative: The overview contains the overall trend and main message of the chart.

content such as dashboards (21/40), while static charts support existing text content (24/55).

3.4 Accessibility Statement Analysis

About 60% of the venues we analyzed had published accessibility statements. 55% of them explicitly mention accessibility measures for visually impaired users but none of the accessibility statements we collected specifically mentioned making data visualizations more accessible.

3.5 Takeaways

The results indicate that accessibility for many in-the-wild charts is provided inconsistently for visually impaired users. The informative value of visualizations for screen reader users is typically low and further underlying data is seldom exposed. This raises the question of if designers consider providing insight into the data to be important or prioritize communicating other information. Challenges also seem to lie in complex and interactive charts that are typically written in SVG. SVG has the capability to enable the navigation of underlying data compared to static images. However, most existing charts did not leverage advanced accessibility features to the fullest extent such as the `aria` attributes. Simply providing underlying tables does not sufficiently address accessibility. Directly leveraging the chart structure would be still better than navigating the tables. While we did find that some interactions can be retained if they are kept relatively simple and are implemented using standard user interface elements, it remains still unclear how to support efficient engagement with highly interactive and complex charts using screen readers. We often observed phantom visualizations which are not perceivable for screen reader users at all. What remains unclear is whether these are unintentional omissions or deliberate attempts to avoid inaccessible charts that hamper web experience. Government and non-profit sectors seem to support accessibility more consistently than private sectors. It would be interesting to dig deeper into the cause of these differences, such as whether they enforce stricter internal rules for web accessibility [31].

4 UNDERSTANDING PRACTITIONERS' AWARENESS AND EXPERIENCE

We conducted an online survey with visualization practitioners to understand the rationale behind the design choices we observed in the first phase. Questions that were left unanswered in Section 3 include: what is the rationale behind phantom visualizations? Between conveying insights into data and providing more general information, e.g., on the message of a visualization, what are practitioners' priorities? And what are the differences in the importance of accessibility in different sectors? We were also interested in learning about how designers position themselves regarding visualization accessibility and what role their experience in visualization accessibility plays.

4.1 An Online Survey with Visualization Practitioners

We recruited visualization designers in the U.S. through social media, data visualization forums, personal networks, and invitation emails. Participation was voluntary. Thus, the sample may show a volunteer bias, that people who are interested in the topic or inclined to exhibit pro-social behavior may be more likely to volunteer. To diversify our sample we actively encouraged both novices and experts on the topic to share their perspectives. To achieve this, we introduced accessibility as a challenge that could be addressed in a non-uniform manner among practitioners. The survey took approximately 10 minutes. Respondents did not receive compensation. After giving their informed consent, participants were asked questions about their background (e.g., age, experience, etc.), their expertise (e.g. "How much experience do you have in making data visualizations accessible for people with visual impairments?"), and their design practices (e.g. "What strategy do you typically follow to make sure that the content/products you create are accessible?"). Participants could skip any question they did not feel comfortable answering. All survey questions can be found in the supplemental material.

4.2 Respondents

We collected a total of 144 responses (Gender: *male=58% female=36% non-binary=4% others: 2%*; Age: *21-29=35%, 30-39=44%, 40-49=15%, 50-59:4%, others=2%*; Ethnicity: *White=64%, Asian=12%, Black=8%, Hispanic=5%, Multiracial=4%, Native American=1%, others=5%*). In terms of professional backgrounds, respondents identify themselves (multiple selections allowed) as visualization designers or developers (38%), data scientists (37%), people who hold positions in an organization with some visualization job responsibilities (36%), and other roles that include academics/teachers (22%), students (10%), data journalists (10%), and hobbyists (7%).

Most of our respondents work in the private sector (46%), academia (31%) and research (28%), or in the public sector (13%), non-profit (10%), and journalism (8%). A majority of respondents were in their early-to-mid career (<2 years%=11%, 2-4=26%, 5-7 years=32%), while some had more than 8 years of experience (8-10=14%, >11 years=17%). Their primary purposes of making visualizations were to analyze and communicate data (30% and 26% respectively), while research, education, and marketing were also part of the purposes (22%, 15%, and 7% respectively). More than half of the respondents work in organizations with more than 500 employees (55%), while others work in mid-to-small organizations (100-499=12%, 20-99=18%, <20=9%, one person=6%). About 22% of the respondents said data visualization is their main job, while 32% of them said it is important but not the main job. Others said it is one of several other things they do (35%) or only a small part (10%). Most respondents were sighted (91%), while only a few respondents have color blindness (6%), low vision (1%), and blindness (1%).

4.3 Results

4.3.1 Participants' awareness of visualization accessibility. To learn about participants' awareness of accessibility, we asked **how familiar they are with web accessibility** and the features and characteristics that make web content accessible. Answer options and results are shown in Figure 2(b). Most respondents reported having at least basic knowledge (43%) or intermediate level of expertise being familiar with web accessibility and the relevant features (31%). Others were novices on the topic, as they reported having heard about it but not knowing much about it (15%) or not being familiar at all (4%). On the other hand, 7% of the respondents identify themselves as experts. When asked about **their experience with making visualization accessible** to users with visual impairment, more than one-third of the respondents indicated that they are novices that do not have any experience at all (35%) or at a basic level with only little experience (27%). 30% of the respondents place themselves on an intermediate level having some experience, while 6% said they are experts. 2% do not know their level of experience.

4.3.2 The role of accessibility at the workplace. Regarding **how accessibility is supported at their workplace**, 30% stated that as far as they know, accessibility is not a topic at their workplace. However, no one said that they are not supposed to spend time, effort, and resources on web accessibility. Twenty-seven percent of the respondents said they do not have accessibility guidelines, but it is considered important (e.g., topic in meetings, hiring, planning projects). On the other hand, 18% of the respondents said that they do have accessibility guidelines, but it does not matter too much if they do not always follow them. Lastly, 24% of them noted that accessibility is essential; e.g., they have accessibility guidelines and are held responsible for following them.

We inspected the support for accessibility across different sectors. In the public sector, including government organizations, 58% said that accessibility guidelines are in place at their workplace. Furthermore, 21% of the participants said that accessibility is very important, and they are held responsible for following them. On the other hand, 36% of journalist participants said that guidelines are in place at their organization, although only 9% said that the guidelines are being enforced. In the private sector, 47% reported having guidelines, and 35% said the guidelines are enforced. Participants working in NPOs mostly said that they do not have guidelines, but accessibility is still discussed as an important topic (73%).

When asked **who is responsible for providing accessibility**, 12% of the respondents said that anyone needing assistance is expected to apply their own tools and methods to support accessibility. Another 42% of them acknowledged that they themselves are responsible for providing accessibility for the websites/products they develop. Around 8% of the respondents said that another coworker/their employer is responsible for ensuring accessibility to all websites/products, including the ones they develop. Furthermore, another 8% of them said they have a dedicated accessibility specialist overseeing the quality of accessibility. Lastly, about 40% of the respondents said they were unsure who is responsible for ensuring accessibility.

We asked **how accessible they think their visualizations are for people with visual impairments**. Answer options and results are shown in Figure 2(a). About 38% of the respondents stated that they are typically not accessible at all (10%) or not very accessible (28%), while 23% said they do not know. Around 32% of the respondents said their visualizations are mostly accessible at least to some extent, and another 6% said that their visualizations are typically very accessible. A closer look at the respondents who said that they do not know the level of accessibility of their visualizations shows that 91% of those have no to little experience with accessible visualizations.

4.3.3 Designers' valuation of visualization accessibility. To learn about the value practitioners place on visualization accessibility, we asked **how important they would say it is that people with visual impairments can access data visualizations on the web**. One respondent (1%) noted that it is not important in general as visually impaired users do not need access to visualizations. Three respondents (2%) similarly said it is often not that important that visually impaired users can access visualizations, while 18% said they are unsure. However, still, a majority of the respondents think that it is vital in many cases (22%) or very important (56%) that visually impaired users can access visualizations.

We asked the 94 participants with experience in providing accessibility features about **the trade-off between the time & effort and the importance** of making visualizations accessible to visually impaired users. Figure 2(c) shows answer options and results. Most respondents said it is very much worth the effort (47%), quite worth the effort (30%), and somewhat worth the effort (18%). None of the respondents said it is not worth the effort at all, although 5% said it is rather not worth the effort.

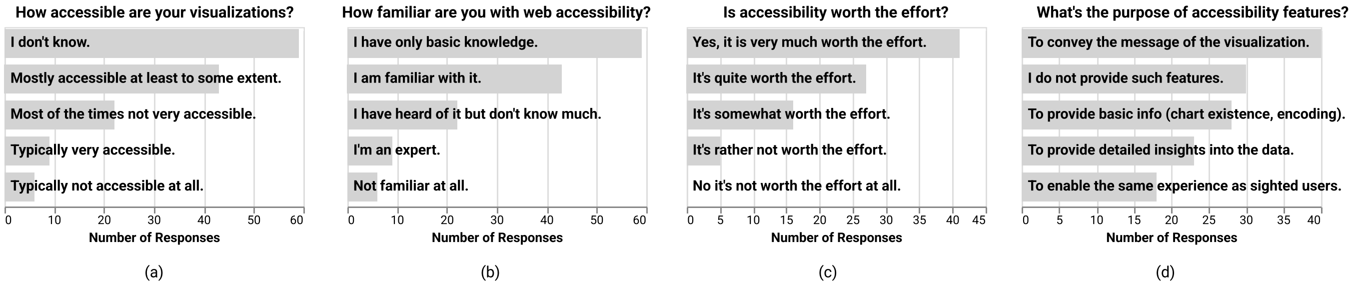

Figure 2: Example survey questions. (a) Most respondents do not know how accessible their visualizations are (b) They mostly have only basic knowledge about web accessibility (c) Most of them think that it is worth the effort to make visualization accessible (d) Many think the purpose of web accessibility features is to convey the main message of the visualization.

4.3.4 Designers' accessibility practices. The respondents indicated that they use diverse **tools and technologies to make data visualizations** on the web. About 40% of the times creating custom visualizations (e.g., `<canvas>`, `<image>`, `<svg>`) was selected. Respondents also said they use external tools such as Excel (14%), Tableau (13%), Power BI (8%), Datawrapper (5%), and Flourish (3%). While not provided as an option, many respondents indicated they use R.

31% of the 89 practitioners with no to little experience do not provide accessibility features to their creations at all. Only 2% of practitioners with more experience stated this. Instead, when asked **which accessibility strategies they follow**, the 52 more experienced practitioners frequently presented extensive lists. Besides applying their own knowledge (94% of practitioners with experience), they refer to WCAG (50%), follow company-internal guidelines (37%), use software to check for accessibility issues (57%), and use features automatically provided by their visualization tools (29%).

On the other hand, 44 of the 89 participants who have no to little experience in making visualizations accessible still apply their own knowledge (49%), some at times reference company guidelines (15%), WCG (19%), use tools to check for accessibility (20%) or visualization tools that automatically provide features (16%).

When asked about **the purpose of using accessibility features** such as `alt`, `aria`, and other text descriptions. We also observed some differences between experts and novices. Among the 89 practitioners with no to little experience 29% do not provide such features, 22% do so in order to provide the basic information, 35% to convey the general message, 8% to give insights into data, and 6% to ensure equal engagement for users with or without visual impairment. Whereas amongst the 52 more experienced practitioners, 6% do not provide such features, 17% do so to provide the basic information, 19% to communicate the general message, 33% to allow insights into underlying data, and 25% to ensure equal engagement irrespective of visual status. Among all participants, the most commonly stated intention when attempting to provide accessibility through textual descriptions is to communicate the message of the visualization (28%) or even just the basic information (20%) and not so much to convey important data values and data relations (17%) (see Figure 2(d)). This is in agreement with the lack of data insights we observed in Section 3.

We specifically asked about **potential target audiences** they have in mind when adding accessibility features. About 28% of respondents said they target blind users, while 18% said their goal is to support low vision people. Other respondents stated that they use such features for other reasons (13%), such as using the alt attribute to replace the image if the web page is not rendered properly, or for other impairments such as hearing, motor, or cognitive impairments (2%). Most participants did not have a specific target audience in mind (39%).

Finally, we asked about **when it is okay not to provide accessibility** for a visualization. Almost one-third of the respondents stated "never", irrespective of whether they had more or less experience (31% of 52 and 29% of 89, respectively). Others said when the associated text provides the same information (41%), the visualization is too complex (22%), and the majority of the target audience is sighted (14%). Respondents also said it is unnecessary when the visualization is not too important (14%) or if it is not a project requirement (17%). Only 6% said it is not necessary for visualization in general. Thus, about 71% of all participants could think of reasons to withhold accessibility features which may explain the occurrences of phantom visualizations observed in Section 3.

4.4 Takeaways

The survey results provide valuable insights into the practitioners' awareness, thoughts, and workplace practice. They agree that visualization accessibility for visually impaired users is important, although most do not have much experience in making accessible visualizations. We found that many practitioners seem to consciously decide not to provide accessibility features, although it is unclear whether they expect this to benefit visually impaired users. We also observed differences between practitioners with more experience in visualization accessibility and novices. It was mostly people with less experience that placed little value on conveying underlying data. This sparks interest in exploring practitioners' mental models of an accessible visualization, which we investigate in more detail in the next section. The results also reiterate the finding in the content analysis that accessibility is supported differently across sectors. Moreover, our survey results indicated the lack of support and the diffusion of responsibility at the workplace, which we take a deeper look at in the next section. Many of the respondents said they use existing visualization tools, pointing to the importance of accessibility support from the tools.

5 UNDERSTANDING CHALLENGES IN ACCESSIBLE DESIGN PRACTICE

We conducted follow-up interviews with selected participants to further understand the rationale and context behind the accessibility practices we observed in Section 3 and Section 4. Open questions from our previous studies were: What are practitioners' intentions for visualization accessibility? Why may practitioners decide not to provide accessibility features? And what does organizational support look like? In addition, we were interested in understanding practitioners' difficulties and their ideas on how to overcome these challenges.

5.1 Interviews with Visualization Practitioners

We selected interviewees from a sub-pool of survey respondents who had offered their participation. We aimed to include participants with a broad spectrum of experience (i.e., novice to experienced and across different industry sectors) of different genders, ages, and races. We conducted ten semi-structured remote interviews of 30 to 45 minutes in which we asked questions on the context behind the survey responses and specific challenges in ensuring accessibility in practice. The full interview protocol can be found in the supplemental material. We compensated each participant with a $50 Amazon gift card.

5.2 Data Analysis

Each interview was led by one researcher and conducted with one interviewee individually. We recorded and transcribed interviews. One to three researchers took notes during the interview sessions. After the interviews, we consolidated verbatim transcripts and all interview notes into a summarized transcript. The researchers initially collaboratively annotated the summarized transcripts in a top-down manner using pre-defined themes inspired by the research questions and interview guide for this study. They refined the themes throughout the process based on concepts emerging from the transcripts and constructed a codebook. The themes included "stages of the design process", "understanding of accessibility", "accessibility practices and features", "personal valuation", "relevant tools", and "organizational support". In an iterative coding process, one researcher then assigned the themes to the summarized transcripts and identified lower-level codes. For example, a quote assigned to the higher-level theme "relevant tools" was further coded for "issues with tool", "support from tool" and "request". We then used these annotations for close reading of the transcript passages associated with each theme, to summarize the statements assigned to the codes.

5.3 Results

5.3.1 *Professional and Personal Experience with Visualization.*

What are participants' backgrounds and experiences? Table 5 shows the ten interviewees and their backgrounds. Three participants self-identified as female, the other seven as male. One self-identified as Asian or Pacific Islander, one self-identified as Black or African American, and eight self-identified as White or Caucasian. The youngest participant was between 21 and 29 years of age and the two oldest participants were between 40 and 49 years of age.

Participants worked in different fields such as academia, the private sector, journalism, or research and had various occupational roles, including data journalists, data scientists, visualization designers, and developers. They reported engaging with visualization as creators, by developing tools and features for visualization software or through other responsibilities. These include working on personal visualization projects as hobbyists and managing resources or project groups to promote visualization accessibility within their company. The visualizations they create vary in types and complexity, including both static and interactive charts. Their visualizations span a broad spectrum of use cases such as exploratory visualizations and dashboards but also narrative visualizations such as those found in data-driven articles and other web applications. The participants have experience in creating visualizations for many different target audiences, such as internal reports, the members of large institutions or specific companies, and the general public.

5.3.2 *Visualization Design Process.*

What are the common steps in the design process? We observed common steps that creators follow within their design process. Whether they choose raw data to be visualized or are tasked with creating a visualization for clients, they first familiarize themselves with the material. The familiarization process includes gathering detailed requirements or trying out different visualizations to find out how to represent the data graphically. Two of our interviewees explained that they have company-wide standards to follow (e.g., particular aesthetics to communicate brands). Almost all go through rounds of feedback and review through senior colleagues, colleagues from adjoining departments such as researchers and editors, as well as business partners and clients.

How do they consider accessibility in the design process? How accessibility is considered in the design process is highly inconsistent, both across participants and within individual design practices. For example, one participant (P2) stated that they do not incorporate accessibility for the visualizations they create as they do not feel responsible. Others typically provide limited accessibility for internal visualizations (e.g., only use adequate color palettes) and may put more thought into accessibility for a public audience. P3 and P9 followed such an approach and shared that if necessary for public projects, they could consult accessibility experts. P3 has a disability resource center at their organization, and P9 has a colleague who has more experience with visualization accessibility that could give advice. On the other hand, two participants said providing accessibility features is a standard step in their design process, such as adding descriptive alternative text. However, even for those participants, thoroughly providing accessibility beyond the minimum requirements is an afterthought. One of these practitioners stated that, as they produce visualizations for the government, any final product published must conform to official accessibility standards and would additionally be reviewed by external experts.

5.3.3 *Defining Accessibility.*

How do they define accessibility in their own terms? P10 described "The term accessibility is so broad that a lot of people don't know what that means". We asked for interviewees' personal definitions

PID	Role in Organization	Experience Vis.	Experience Web Acc.	Experience Vis. Acc.	Organization Size
1	VDe, DS, SDVJ	5-7 years	Expert	Expert	100 - 499 employees
2	DJ, DS, SDVJ	2-4 years	Novice	Basic	20 - 99 employees
3	VDe, DS, DVH, AT	8-10 years	Basic	Basic	20 - 99 employees
4	VDe	8-10 years	Intermediate	Basic	500+ employees
5	VDe, SDVJ, DVH	11 or more years	Basic	Basic	500+ employees
6	VDe	8-10 years	Expert	Intermediate	500+ employees
7	VDe, DS, STU	5-7 years	Expert	Expert	500+ employees
8	VDe	2-4 years	Intermediate	Intermediate	500+ employees
9	DJ, SDVJ	5-7 years	Intermediate	Intermediate	20 - 99 employees
10	VDe	2-4 years	Intermediate	Intermediate	500+ employees

Table 5: Overview of Interview Participants. Columns show participants' roles as AT = Academic/Teacher, DJ = Data Journalist, DS = Data Scientist, DVH = Data visualization hobbyist, SDVJ = Position in an organization with some data visualization job responsibilities, STU = Student, VDe = Visualization Developer/Visualization Designer; their self-evaluated level of experience with visualization, experience with web accessibility, and experience with visualization accessibility; and organization size.

and encountered two aspects most have in common. Most frequently, the participants highlight the goal of communicating the same information to anyone. Secondly, they describe that interacting with the visualization should be supported, saying that engaging with the data or drawing conclusions should also be possible for those who use assistive technology. More specifically, anything that can be done with a mouse should be achievable with an alternate input device.

Who are their target audiences? Most respondents focus on one or more of three user groups with specific vision-related needs. The first group includes people with less than average visual acuity or color vision deficiency who need more inclusive color palettes or benefit from magnification. The second group comprises low vision users who due to more severe deterioration of vision can leverage only some residual vision and thus may use assistive technology for support. The third group includes blind users who seek non-visual access, e.g., through audio-based keyboard navigation. P10 pointed out other aspects of accessibility, including different locations, infrastructure, and devices. P7 did not have a target user but instead followed core accessibility heuristic principles to include people with a broad spectrum of experiences. P6 corroborated this thought, explaining that when designing visualization software, it is important to give visualization designers the tools that allow them to cater to any audience they choose, including people with various abilities.

How do they provide accessibility for visually impaired users? Following the findings from our content analysis, participants focus on screen reader access and keyboard navigation when incorporating accessibility. Participants did not use other modalities such as sonification. Most focus on providing textual descriptions, accurate labels, and a logical structure for a meaningful auditory experience. Furthermore, the approaches of constructing textual descriptions mirror findings from prior research [40]. In general, respondents describe multiple levels of information that can be communicated, including a high-level summary of the visualization, stating key trends and patterns on an intermediate level, and naming low-level elements such as the chart type. P7 described multiple intricate linguistic considerations: the omission of punctuation, the overall reduction of words, and consistent and easily understandable order. These approaches aim to provide a smoother screen reader experience and minimize cognitive effort by reducing demands on working memory.

Participants also elaborated on supporting meaningful keyboard navigation. They spoke about providing labels for main chart elements and arranging HTML elements and their labels in a logical order (e.g., the screen reader reads out elements from top to bottom and left to right). They also mentioned grouping elements into chunks to avoid overload (e.g., not more than 20 elements). Another frequently employed approach is providing data tables. Again, they need to carefully consider the order and amount of elements to allow for efficient navigation. Another pitfall P3 pointed out is data privacy, prohibiting sharing the entire data publicly. Frequently used features that we had not investigated in our content analysis were color palettes (e.g., adequate contrast) and large enough font size.

How do they handle complex visualizations? The way practitioners deal with more complex visualizations shows the tension between the desire to create advanced visualizations with many data points and their accessibility. P6 explained how this already begins with the issues visualization software faces when handling a large number of items. They generally have a progressive loading scheme of elements to maintain performance speed, although this may interfere with some accessibility requirements of having the complete set of elements immediately available upon opening the page. Especially practitioners with less experience in accessibility reported struggles with complex visualizations. Some of them explained that they might try to make a complex visualization accessible but will "give up" if it becomes too burdensome. One participant admitted that their most complex visualizations are not accessible. Another participant concluded that they would not simplify a complex visualization only because they did not know how to make it accessible. This reflects the standing of accessibility as an afterthought, instead of an indispensable component. On the other side, accessibility experts seem more ready to take on this challenge. P1 voiced that it is always possible to provide a description, even if they may require more time breaking down into smaller subsets and explaining each fragment.

How do they handle interactive visualizations? Regarding interactive visualizations, participants' difficulties revolve around the two aspects of "functional interactivity", where both the interface element and the result of the interaction are accessible. Regarding the first aspect, multiple participants explained that it is unclear how to support mouse-driven capabilities such as click, drag, hover, and navigating complex data structures through a keyboard interface. One of the visualization experts presented an elaborate solution to the limited semantic support of SVG. For instance, interactive affordances and feedback that is inherent to SVG elements can be accessed by screen readers if assigning aria-roles to SVG elements.

Other issues relate to the second aspect of functional interactivity, the communication of the result of the interaction. P10 explained that providing summaries and data tables is a viable accessibility feature for static charts. However, they do not know of a satisfactory solution for exploratory visualizations with dynamic data sets that are updated based on user selection. For instance, P6 mentioned cross-filtering across multiple views as a challenging accessibility problem, e.g., how can we indicate a change in the view using a non-visual cue? Other participants reported similar issues about interactive spatial visualizations like maps. Adding labels to each map element that a screen reader reads would effectively equal a data table, losing the original spatial interactivity. One suggestion from participants was to expose interactions into standard accessible user interface elements such as a dropdown menu to supplement interactions within the visualizations.

When should visualization accessibility be provided? Few participants described that they do not think that visualization is of interest for visually impaired users. Still, all acknowledged that there is a demand for making the underlying data accessible. One participant recalled that other colleagues justify a lack of accessibility features with the overall intention of providing a smoother experience for screen reader users. This practice would correspond to a deliberate creation of phantom visualization. However, none of our interviewees confirmed this practice of consciously withholding accessibility features. We asked participants for times when they had not provided any accessibility features. The only occasions where interviewees actively decided not to incorporate accessibility were related to the project requirement, e.g., within an application aimed at a purely sighted audience or if the client specified it due to budget or time restraints. More frequently cited reasons for why designers did not provide accessibility were unconscious lapses and omissions due to a lack of awareness.

Lastly, respondents mentioned insufficient support in the tools and technologies used. One participant described that "One of the biggest frustrations web developers have is the lack of a holistic explanation of accessibility. (...) Did I get it, and how do I know?!" Often designers seemed to be moving within a grey zone between conformance to standards and effective accessibility. "I'm not sure if I'm considering the specific needs of these users. I am guessing that this is what their experience is, but I haven't met them, yet I haven't seen them on the site." P3 described having a disability resources center that promotes accessibility across all areas of the organization. This is a valuable resource as the resource center would also test the accessibility of their products. One of the most commonly voiced needs was an excellent single resource to educate on the challenges of accessible visualizations, including a concise overview of guidelines and requirements specific to visualization design.

How much effort does it take to ensure accessibility? One participant explains that sometimes more theoretical considerations are required before approaches can be implemented. It might be the case if a project is complex and standard accessibility features are insufficient or hard to apply. They say that, in those cases, it can take multiple days to a week to make a product accessible. At the same time, others noted that applying routine features such as adding alternative text and choosing color palettes does not take as much time. Extra training may be necessary initially, but practice and consistency can speed up the process. Another relevant factor is the creators' valuation of accessibility. P7 said that it should not take any extra time to incorporate accessibility because it should be an indispensable part of a visualization by default. They compared saving time for sacrificing accessibility with "cheating and making things that aren't viable products." The extent to which a creator wants to provide accessibility will also determine the time it takes. P10 explained, "It's one of the 85 - 15 things. You get to 85% of what's required in 15% of the time, and then the last 15% takes 85% of the time." Multiple participants reported that applying accessibility features adds about 15% to 30% to the overall workload. Overall we found that the time it takes designers to add accessibility features varies greatly and depends on multiple factors, showing that accessibility is, as P3 put it, "also a matter of time and who is willing to pay for it".

5.3.4 Motivators and Hurdles for Accessibility.

What role does personal valuation play in visualization accessibility? Eight out of the ten people we talked to described some personal association towards providing widespread access that made them value visualization accessibility. Many empathized with visually impaired users as they or someone they knew needed special assistance in other situations. Others simply saw it as their human responsibility to support equality through equal access in any domain of life. P5 commented, "Personally, I think it is the right thing to do". In the context of visualization accessibility, this is amplified because of their significant role in communicating information. As P8 put it, "People who are in a position of spreading information or sharing knowledge or expertise should try to structure things so that it is as accessible as possible to as wide a range of types of people or types of thinking as possible. (...) I think it's unfair that people can message information in a way that only reaches a specific target audience and then that target audience has an unfair advantage or other audiences have an unfair disadvantage."

Furthermore, to many, incorporating accessibility is a part of doing their job right. P3 said, "Good design is universal design.", while P10 elaborated on this, stating that "making sure that our navigation and the information is clear to someone using assistive technology, always helps the design, it makes it clear to people who have full vision and use the site with a mouse and their eyes as well. Having everything labeled just helps everyone understand what they're seeing or listening to." However, this personal valuation must be proceeded by awareness, which, as our participants described, is not yet as widespread. P8 commented, "I think one challenge, globally, is making people aware of accessibility and making people care about accessibility. If you don't even know about it, you're not gonna do anything". P5 similarly stated, "The first step of making people aware of why it's important, is something that will have a big impact. If we can make them care about it, then it's going to be a lot easier to get people to do the things that will make things more accessible for more people."

What role does the organization play in visualization accessibility? Organizations benefit from accessibility as they can attract a broader audience and fulfill their legal and moral obligations. However, P5 described that there is lots of talk about accessibility but not a lot of repercussions if standards of accessibility are not reached. Accessibility is often still more a recommendation at the workplace that is not well enough supported. Some participants experience back push when wanting to incorporate accessibility. P2 said, "I would say it's not necessarily a priority at my job, and I think spending a lot of time making a visualization accessible or thinking about it wouldn't be as highly valued. To emphasize accessibility, you would have to push for a big change in terms of changing the standard color palette for our brand or push back against what designers have decided looks good." To foster accessibility at their workplace, P5 argued that setting examples would help others learn best practices, while P2 commented on the need for having company-wide accessibility guidelines. The story of P6 supported this idea. P6 initially considered accessibility one of the minor tasks, but soon they realized how it improves the experience for everybody, and now they see it as more important.

Another institutional issue was the insufficient provision of resources. One participant complained about the lack of centralized support and wished for more software packages, tools, expertise, and feedback to make more accessible visualizations. The participant said, "if I needed the IT group to test a visualization with a screen reader, they could not do that for me", highlighting the potential value of support from a dedicated accessibility team and specialists. Other participants also mentioned the necessity of accessibility training to make company-wide changes.

What role do visualization tools play in accessibility? Multiple participants expressed dissatisfaction about the accessibility of the visualizations created by the tools they use. They noted unsatisfactory support of interactions such as hovering or inefficient keyboard navigation. They commented, "If these tools do anything at all, they do the bare minimum and often make it a worse experience. Some people think of it as meeting a certain level of compliance. You can have all your boxes checked and still have a bad visualization experience."

Most frequently, participants wished for a feature that gives them more clarity and oversight in their design process through real-time in-browser feedback. P8 described it as "A browser-based tool or add-on that would enable you to both simulate various accessibility challenges and can help structure how to go through your work and check." Similarly, P7 said, "I wish that in the developer tools in a browser when you open up the console or using the element inspector, you could click something, and then see what different screen readers would read." Participants also suggested features for the earliest stages of the design process, such as prompting questions asking to enter the goal and main trends of the visualization or even automated annotation of chart elements. Three interviewees pointed out that many problems could be solved if the end-users had more control over how a visualization is presented. This could be through on-demand requests, such as choosing different levels of detail for a description or different types and levels of redundancy for visual marks. Others also commented on personalization, "If you could set your default preferences and then anytime you access a visualization it's going to bring it up in a way that's most usable to you, that would be really good.".

5.4 Takeaway

The interviews provided richer and multifaceted insights behind the accessibility design practices observed in the wild. First, we observed various views on accessibility. While participants agree on the overall goal of communicating the same information, they differ in who they consider as target audiences and the approaches to address their specific needs. A different understanding of what accessibility means can lead to the mere "checking off boxes" to follow standards without actually providing efficient accessibility to visually impaired users. An example is the provision of tables, which may be a helpful feature, but without careful consideration of the complexity of data, it will not offer a meaningful experience. This suggests the need for spreading more specific yet consistent and illustrative guidelines for practitioners beyond the generic ones such as WCAG, that explain the practical implications of design choices for visualizations. Experts in visualization accessibility describe more favorable mindsets towards accessibility than practitioners with less experience. They frame accessibility challenges not so much as unsolvable problems but more as design tasks that are regular aspects of creating a visualization. They are willing to expend time and effort and apply intricate and creative solutions to foster accessibility. The interviews also highlighted multiple hurdles that may still hinder accessibility. For instance, even after designers are aware of the need and value for providing accessibility, they still face difficulties related to the limitations of the tools they use and resource constraints by their organizations and clients.

6 DISCUSSION

6.1 Three layers of uncertainty affecting designers

Our research has identified uncertainty of the evaluation and execution of accessibility as a common issue for visually impaired users browsing the web. This uncertainty affects users as they can't be sure of whether the information they seek on a website does not exist, is not made accessible, or could be retrieved with more persistent effort [8]. Our findings suggest that uncertainty also extends to visualization designers. We shed light on a sequence of uncertainty layers affecting practitioners.

On a *personal* level, there is significant uncertainty regarding when user needs are met sufficiently. Our findings remind us that data visualization might not be the main part of their job for most practitioners. While some creators may have some knowledge of web accessibility, many do not have experience with visualization accessibility and frequently cannot assess how accessible their visualizations are. To address these issues, visualization accessibility must become a concept inextricably linked to the idea of a viable data visualization. For instance, it could be implemented into the curriculum of data visualization classes and introduced to visualization novices alongside other basic visualization principles.

On an *operational* level, there is uncertainty on how to use the available tools effectively. This is especially the case when it comes to complex and interactive visualizations. Designers may wish to provide a certain accessibility feature but do not know how to achieve it. Participants also expressed the need for training and expert feedback; their employers could provide these or tackled as community efforts.

On an *organizational* level, there is often uncertainty on the expectations and responsibilities and the time and resources that can be allocated to making visualizations accessible. Accessibility was not a topic at the workplaces of many participants. Our interviewees explained that decision-makers in higher positions need to set in motion changes for company-wide improvements. It remains unclear if people on higher levels of the organizational hierarchy understand it as their responsibility to address visualization accessibility or if the diffusion of responsibility persists and they see it as a design choice that they expect others to consider. These decision-makers and their views should be identified to compose strategies that benefit everyone.

6.2 Organizational support for visualization accessibility

Restraints in resources such as time, budget, guidelines, and other support are known factors hindering practitioners from providing accessibility [22]. Our findings show how these issues accumulate when it comes to data visualizations. Our results point towards the vital role the organization plays. We found differences between sectors similar to those reported in the accessibility literature [7], with government organizations providing accessibility guidelines more consistently. Guidelines that all members of an organization must adhere to may encourage more diligent implementation of accessibility.

Our work highlights distinctive features of visualization accessibility and points out that these are not accounted for in company accessibility statements. Features that set visualizations apart from other web content, including the relevance of underlying data and ensuring equal engagement through interactive components, are not considered enough. Company design guidelines and accessibility statements should incorporate elements such as definitions, expectations, and references specific for visualization accessibility.

We also noticed differences in the resources allocated towards accessibility depending on the size of the organization. This may lead to tension between practitioners' personal motivation to make accessible visualizations, other job responsibilities, and support from the organization. While smaller companies with fewer resources may not make their employees feel appreciated when spending time on accessibility, larger institutions can offer services such as disability teams that introduce software, training, and expertise on accessibility. We found that practitioners with more expertise approach the topic with more strategies and a favorable mindset and create more accessible visualizations. Accessible visualizations are also often described as 'better,' more robust, and understandable for sighted users as well. It would be interesting to further explore the overall value of accessible data visualizations, e.g., reflecting an organization's quality or trustworthiness.

6.3 Accessibility guidelines for advanced visualizations and visualization tools

Our findings showed that data-dense and interactive visualizations pose challenges for accessibility. Often designers seek to resolve these by providing alternative text, data tables, and contextual information surrounding the visualizations. However, in the interviews, participants explained that they do not always know or have the time to make very complex visualizations accessible. While the WCAG provides relatively well-established guidelines and instructions for simpler static charts [39], many practitioners still long for technical guidelines for handling dynamic data visualizations with multiple layers of graphical content. In theory, ARIA features could be used to support efficient navigation, but as our data collection reflects, they are not applied widely. Existing efforts within the visualization accessibility community such as Chartability [32] providing heuristics and tests to evaluate interactive visualizations, and other instructions and guides shared by individuals (e.g. [24]) still remain less known. Guidelines either not being applicable to advanced visualizations, unknown to practitioners, or lacking practical demonstrations and examples remains a problem in itself. We encourage future research to take on this challenge of complementing and amplifying existing guidelines. Given that there may be many possible ways to navigate through dynamic data, it would be valuable to conduct empirical studies to find out what navigation order makes the screen reader experience more meaningful.

6.4 Accessibility support from visualization creation tools

The surveys and interviews indicated that practitioners often rely on external tools to create visualizations. Therefore, the outcome visualizations are limited by the capability of the tools. It may be true that a majority of visualization creators who are not familiar with computer programming are users of these tools. While not many, we had some examples in our collection that use Power BI, Tableau, Highcharts, and Flourish. Highcharts provide a separate accessibility module that the developer can configure to provide an optimized screen reader experience [38]. Other than Highcharts, other tools did not seem to support screen readers well, while more in-depth research would be necessary to evaluate the accessibility of existing visualization tools. Ideally, the visualization tools should automatically add accessibility while the designer can focus on creating visualizations. Like Highcharts, the designer should be able to customize the default accessibility support to meet their target audiences (e.g., skipping the complex data content). As the interviewees pointed out, testing the screen reader experience of their visualizations during the design process would be valuable.

6.5 The phenomenon of phantom visualizations

A number of visualizations in our collection were "phantom visualizations". That is, they are not at all perceivable through the screen reader. This supports recent findings by Sharif et al. who similarly observed a frequent number of visualizations that cannot be detected by screen readers [54]. We further investigated this phenomenon to see what the underlying design rationale is. Our analysis did not find any accessible signals communicating the importance or relevance of the phantom visualizations in the surrounding texts. The phantom visualizations might reflect a conscious design choice, signaling screen reader users to move on instead of further engaging with the visualization. Indeed, our survey showed that a big part of practitioners sees justifications for phantom visualizations in certain situations. However, it may still be desirable to provide options for visually impaired users to ensure information equality. Future research may investigate what an effective cue for the relevancy of a visualization is. Perhaps even considering currently underused modalities such as sonification.

6.6 Limitations

In our content analysis, the sighted coders examined information coming through screen readers. This inspection might be different from the natural reading experience of visually impaired users. Therefore, the focus of this work was to inspect the procedures and communicative signals designers use to incorporate accessibility. Likely, those that took the time to participate in our survey were already more interested in accessibility than others. This may lead to the underrepresentation of people against or not interested in accessibility. Thus, the actual state of accessibility practice might be even less favorable than what our results depicted. The experience and skills of the respondents were still diverse, however, and the results should allow valuable insights into the mindsets of those practitioners that would at least to some extent be willing to promote accessibility.

7 CONCLUSION

We report on our analysis of visualization accessibility practices in the wild, our survey on designers' attitudes towards it, and a series of interviews on practitioners' challenges behind their design practices. Our work provides insights into the thoughts and struggles of "visualization creators". Furthermore, it points out what hinders widespread visualization accessibility for visually impaired users. We hope that these findings will be helpful for future researchers to address the needs of visualization practitioners, such as building better guidelines and tools to ensure accessibility for visually impaired users.

REFERENCES

[1] Cengiz Acartürk, Özge Alaçam, and Christopher Habel. 2014. Developing a Verbal Assistance System for Line Graph Comprehension. In *Proceedings of the Third International Conference on Design, User Experience, and Usability. User Experience Design for Diverse Interaction Platforms and Environments - Volume 8518*. Springer-Verlag, Berlin, Heidelberg, 373–382. https://doi.org/10.1007/978-3-319-07626-3_34

[2] Patricia Acosta-Vargas, Luis Antonio Salvador-Ullauri, and Sergio Luján-Mora. 2019. A Heuristic Method to Evaluate Web Accessibility for Users With Low Vision. *IEEE Access* 7 (2019), 125634–125648. https://doi.org/10.1109/ACCESS.2019.2939068

[3] Internet Archive. [n.d.]. Wayback Machine. https://archive.org/web/. Online; accessed 23 August 2021.

[4] H. K. Ault, J. W. Deloge, R. W. Lapp, M. J. Morgan, and J. R. Barnett. 2002. Evaluation of Long Descriptions of Statistical Graphics for Blind and Low Vision Web Users. In *Proceedings of the 8th International Conference on Computers Helping People with Special Needs (ICCHP '02)*. Springer-Verlag, Berlin, Heidelberg, 517–526. https://doi.org/10.5555/646269.684495

[5] Rakesh Babu, Rahul Singh, and Jai Ganesh. 2010. Understanding blind users' Web accessibility and usability problems. *AIS Transactions on Human-Computer Interaction* 2, 3 (2010), 73–94. https://doi.org/10.12691/ajis-2-2-2

[6] Jeffrey P. Bigham, Anna C. Cavender, Jeremy T. Brudvik, Jacob O. Wobbrock, and Richard E. Ladner. 2007. WebinSitu: A Comparative Analysis of Blind and Sighted Browsing Behavior. In *In Proceedings of the 9th International ACM SIGACCESS Conference on Computers and Accessibility (ASSETS '07*. https://doi.org/10.1.1.119.2417

[7] Jeffrey P Bigham, Ryan S Kaminsky, Richard E Ladner, Oscar M Danielsson, and Gordon L Hempton. 2006. WebInSight: making web images accessible. In *Proceedings of the 8th International ACM SIGACCESS Conference on Computers and Accessibility*. 181–188.

[8] Jeffrey P. Bigham, Irene Lin, and Saiph Savage. 2017. The Effects of "Not Knowing What You Don't Know" on Web Accessibility for Blind Web Users. In *Proceedings of the 19th International ACM SIGACCESS Conference on Computers and Accessibility* (Baltimore, Maryland, USA) *(ASSETS '17)*. Association for Computing Machinery, New York, NY, USA, 101–109. https://doi.org/10.1145/3132525.3132533

[9] Michelle A Borkin, Zoya Bylinskii, Nam Wook Kim, Constance May Bainbridge, Chelsea S Yeh, Daniel Borkin, Hanspeter Pfister, and Aude Oliva. 2015. Beyond memorability: Visualization recognition and recall. *IEEE transactions on visualization and computer graphics* 22, 1 (2015), 519–528. https://doi.org/10.1109/TVCG.2015.2467732

[10] Yevgen Borodin, Jeffrey P. Bigham, Glenn Dausch, and I. V. Ramakrishnan. 2010. More than Meets the Eye: A Survey of Screen-Reader Browsing Strategies. In *Proceedings of the 2010 International Cross Disciplinary Conference on Web Accessibility (W4A)* (Raleigh, North Carolina) *(W4A '10)*. Association for Computing Machinery, New York, NY, USA, Article 13, 10 pages. https://doi.org/10.1145/1805986.1806005

[11] Rupert RA Bourne, Seth R Flaxman, Tasanee Braithwaite, Maria V Cicinelli, Aditi Das, Jost B Jonas, Jill Keeffe, John H Kempen, Janet Leasher, Hans Limburg, et al. 2017. Magnitude, temporal trends, and projections of the global prevalence of blindness and distance and near vision impairment: a systematic review and meta-analysis. *The Lancet Global Health* 5, 9 (2017), e888–e897. https://doi.org/10.1016/S2214-109X(17)30293-0

[12] Maria Claudia Buzzi, Marina Buzzi, Barbara Leporini, Giulio Mori, and Victor MR Penichet. 2010. Accessing Google docs via screen reader. In *International Conference on Computers for Handicapped Persons*. Springer, 92–99. https://doi.org/10.1007/978-3-642-14097-6_17

[13] Silvia Canelón and Elizabeth Hare. 2021. *Revealing Room for Improvement in Accessibility within a Social Media Data Visualization Learning Community*. https://doi.org/10.5281/zenodo.4743271 The goal of this talk for csv,conf,v6 was to share our findings after scraping the alternative (alt) text from data visualization tweets shared as part of the TidyTuesday online learning community. Repository: https://github.com/spcanelon/csvConf2021.

[14] Ji Young Cho and Eun-Hee Lee. 2014. Reducing confusion about grounded theory and qualitative content analysis: Similarities and differences. *Qualitative Report* 19, 32 (2014). https://doi.org/10.46743/2160-3715/2014.1028

[15] Jinho Choi, Sanghun Jung, Deok Gun Park, Jaegul Choo, and Niklas Elmqvist. 2019. Visualizing for the Non-Visual: Enabling the Visually Impaired to Use Visualization. In *Computer Graphics Forum*, Vol. 38. Wiley Online Library, 249–260. https://doi.org/10.1111/cgf.13686

[16] Stephen H. Choi and Bruce N. Walker. 2010. Digitizer Auditory Graph: Making Graphs Accessible to the Visually Impaired. In *CHI '10 Extended Abstracts on Human Factors in Computing Systems*. Association for Computing Machinery, New York, NY, USA, 3445–3450. https://doi.org/10.1145/1753846.1753999

[17] Robert F. Cohen, Arthur Meacham, and Joelle Skaff. 2006. Teaching Graphs to Visually Impaired Students Using an Active Auditory Interface. *SIGCSE Bull.* 38, 1 (mar 2006), 279–282. https://doi.org/10.1145/1124706.1121428

[18] The World Wide Web Consortium. [n.d.]. SVG Accessibility. https://www.w3.org/wiki/SVG_Accessibility. Online; accessed 23 August 2021.

[19] Maitraye Das, Darren Gergle, and Anne Marie Piper. 2019. "It Doesn't Win You Friends": Understanding Accessibility in Collaborative Writing for People with Vision Impairments. *Proc. ACM Hum.-Comput. Interact.* 3, CSCW, Article 191 (nov 2019), 26 pages. https://doi.org/10.1145/3359293

[20] Deque. [n.d.]. axe™ - The Standard in Accessibility Testing. https://www.deque.com/axe/. Online; accessed 23 August 2021.

[21] Christin Engel and Gerhard Weber. 2018. A user study to evaluate tactile charts with blind and visually impaired people. In *International Conference on Computers Helping People with Special Needs*. Springer, 177–184. https://doi.org/10.1007/978-3-319-94274-2_24

[22] Glen Farrelly. 2011. Practitioner Barriers to Diffusion and Implementation of Web Accessibility. *Technology and Disability* 23 (01 2011), 223–232. https://doi.org/10.3233/TAD-2011-0329

[23] Leo Ferres, Gitte Lindgaard, Livia Sumegi, and Bruce Tsuji. 2013. Evaluating a Tool for Improving Accessibility to Charts and Graphs. *ACM Trans. Comput.-Hum. Interact.* 20, 5, Article 28 (nov 2013), 32 pages. https://doi.org/10.1145/2533682.2533683

[24] Sarah L. Fossheim. [n.d.]. How (not) to make accessible data visualizations, illustrated by the US presidential election. https://fossheim.io/writing/posts/accessible-dataviz-us-elections/. Online; accessed 01 December 2022.

[25] Information Technology & Innovation Foundation. [n.d.]. Improving Accessibility of Federal Government Websites. https://itif.org/publications/2021/06/03/improving-accessibility-federal-government-websites. Online; accessed 23 August 2021.

[26] Cole Gleason, Patrick Carrington, Cameron Cassidy, Meredith Ringel Morris, Kris M. Kitani, and Jeffrey P. Bigham. 2019. "It's almost like they're trying to hide it": How User-Provided Image Descriptions Have Failed to Make Twitter Accessible. In *The Web Conference*. ACM. https://www.microsoft.com/en-us/research/publication/its-almost-like-theyre-trying-to-hide-it-how-user-provided-image-descriptions-have-failed-to-make-twiter-accessible/

[27] Cole Gleason, Amy Pavel, Xingyu Liu, Patrick Carrington, Lydia B Chilton, and Jeffrey P Bigham. 2019. Making memes accessible. In *The 21st International ACM SIGACCESS Conference on Computers and Accessibility*. 367–376. https://doi.org/10.1145/3308561.3353792

[28] A Jonathan R Godfrey, Paul Murrell, and Volker Sorge. 2018. An accessible interaction model for data visualisation in statistics. In *International Conference on Computers Helping People with Special Needs*. Springer, 590–597. https://doi.org/10.1007/978-3-319-94277-3_92

[29] Cagatay Goncu and Kim Marriott. 2011. GraVVITAS: Generic Multi-Touch Presentation of Accessible Graphics. In *Proceedings of the 13th IFIP TC 13 International Conference on Human-Computer Interaction - Volume Part I* (Lisbon, Portugal) *(INTERACT'11)*. Springer-Verlag, Berlin, Heidelberg, 30–48. https://doi.org/10.5555/2042053.2042060

[30] Cagatay Goncu, Kim Marriott, and John Hurst. 2010. Usability of Accessible Bar Charts. In *Proceedings of the 6th International Conference on Diagrammatic Representation and Inference* (Portland, OR, USA) *(Diagrams'10)*. Springer-Verlag, Berlin, Heidelberg, 167–181. https://doi.org/10.5555/1884734.1884758

[31] Morten Goodwin, Deniz Susar, Annika Nietzio, Mikael Snaprud, and Christian S Jensen. 2011. Global web accessibility analysis of national government portals and ministry web sites. *Journal of Information Technology & Politics* 8, 1 (2011), 41–67. https://doi.org/10.1080/19331681.2010.508011

[32] DatavizA11y group. [n.d.]. Chartability. https://chartability.fizz.studio/. Online; accessed 23 August 2021.

[33] DatavizA11y group. [n.d.]. DataViz Accessibility Advocacy and Advisory Group. https://github.com/dataviza11y/Why-We-Exist. Online; accessed 23 August 2021.

[34] Darren Guinness, Annika Muehlbradt, Daniel Szafir, and Shaun K Kane. 2019. RoboGraphics: Dynamic Tactile Graphics Powered by Mobile Robots. In *The 21st International ACM SIGACCESS Conference on Computers and Accessibility*. 318–328. https://doi.org/10.1145/3308561.3353804

[35] Stephanie Hackett, Bambang Parmanto, and Xiaoming Zeng. 2003. Accessibility of Internet Websites through Time. In *Proceedings of the 6th International ACM SIGACCESS Conference on Computers and Accessibility* (Atlanta, GA, USA) *(Assets '04)*. Association for Computing Machinery, New York, NY, USA, 32–39. https://doi.org/10.1145/1028630.1028638

[36] Jeffrey Heer and Ben Shneiderman. 2012. Interactive Dynamics for Visual Analysis. *Commun. ACM* 55, 4 (apr 2012), 45–54. https://doi.org/10.1145/2133806.2133821

[37] Sabine Hennig, Fritz Zobl, and Wolfgang W. Wasserburger. 2017. Accessible Web Maps for Visually Impaired Users: Recommendations and Example Solutions. *Cartographic Perspectives* (Nov. 2017), 6–27. https://doi.org/10.14714/CP88.1391

[38] Highcharts. [n.d.]. Accessibility module. https://www.highcharts.com/docs/accessibility/accessibility-module. Online; accessed 23 August 2021.

[39] Web Accessibility Initiative. [n.d.]. Web Accessibility Tutorial: Complex Images. https://www.w3.org/WAI/tutorials/images/complex/. Online; accessed 23 August 2021.

[40] C. Jung, S. Mehta, A. Kulkarni, Y. Zhao, and Y. Kim. 2022. Communicating Visualizations without Visuals: Investigation of Visualization Alternative Text for People with Visual Impairments. *IEEE Transactions on Visualization & Computer Graphics* 28, 01 (jan 2022), 1095–1105. https://doi.org/10.1109/TVCG.2021.3114846

[41] Inhwa Kim and Jasna Kuljis. 2010. Applying Content Analysis to Web-based Content. *CIT* 18 (01 2010). https://doi.org/10.2498/cit.1001924

[42] NW Kim, SC Joyner, A Riegelhuth, and Y Kim. 2021. Accessible visualization: Design space, opportunities, and challenges. In *Computer Graphics Forum*, Vol. 40. Wiley Online Library, 173–188. https://doi.org/10.1111/cgf.14298

[43] Ha-Kyung Kong, Zhicheng Liu, and Karrie Karahalios. 2018. *Frames and Slants in Titles of Visualizations on Controversial Topics*. Association for Computing Machinery, New York, NY, USA, 1–12. https://doi.org/10.1145/3173574.3174012

[44] Richard E. Ladner, Melody Y. Ivory, Rajesh Rao, Sheryl Burgstahler, Dan Comden, Sangyun Hahn, Matthew Renzelmann, Satria Krisnandi, Mahalakshmi Ramasamy, Beverly Slabosky, Andrew Martin, Amelia Lacenski, Stuart Olsen, and Dmitri Groce. 2005. Automating Tactile Graphics Translation. In *Proceedings of the 7th International ACM SIGACCESS Conference on Computers and Accessibility* (Baltimore, MD, USA) *(Assets '05)*. Association for Computing Machinery, New York, NY, USA, 150–157. https://doi.org/10.1145/1090785.1090814

[45] Megan M. Lawrence and Amy K. Lobben. 2011. The Design of Tactile Thematic Symbols. *Journal of Visual Impairment & Blindness* 105, 10 (2011), 681–691. https://doi.org/10.1177/0145482X1110501014

[46] Jonathan Lazar, Aaron Allen, Jason Kleinman, and Chris Malarkey. 2007. What frustrates screen reader users on the web: A study of 100 blind users. *International Journal of human-computer interaction* 22, 3 (2007), 247–269. https://doi.org/10.1080/10447310709336964

[47] Jonathan Lazar, Suranjan Chakraborty, Dustin Carroll, Robert Weir, Bryan Sizemore, and Haley Henderson. 2013. Development and Evaluation of Two Prototypes for Providing Weather Map Data to Blind Users through Sonification. *J. Usability Studies* 8, 4 (aug 2013), 93–110. https://doi.org/10.5555/2817919.2817921

[48] Bongshin Lee, Eun Kyoung Choe, Petra Isenberg, Kim Marriott, John Stasko, and Theresa-Marie Rhyne. 2020. Reaching Broader Audiences With Data Visualization. *IEEE Comput. Graph. Appl.* 40, 2 (mar 2020), 82–90. https://doi.org/10.1109/MCG.2020.2968244

[49] Kim Marriott, Bongshin Lee, Matthew Butler 0002, Ed Cutrell, Kirsten Ellis, Cagatay Goncu, Marti Hearst, Kathleen McCoy, and Danielle Albers Szafir. 2021. Inclusive data visualization for people with disabilities: a call to action. *Interactions* 28, 3 (2021), 47–51. https://doi.org/10.1145/3457875

[50] Microsoft. [n.d.]. Overview of accessibility in Power BI. https://docs.microsoft.com/en-us/power-bi/create-reports/desktop-accessibility-overview. Online; accessed 23 August 2021.

[51] George A. Miller. 1956. The magical number seven plus or minus two: some limits on our capacity for processing information. *Psychological review* 63 2 (1956), 81–97. https://doi.org/10.1037/h0043158

[52] Meredith Ringel Morris, Annuska Zolyomi, Catherine Yao, Sina Bahram, Jeffrey P. Bigham, and Shaun K. Kane. 2016. "With Most of It Being Pictures Now, I Rarely Use It": Understanding Twitter's Evolving Accessibility to Blind Users. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems* (San Jose, California, USA) *(CHI '16)*. Association for Computing Machinery, New York, NY, USA, 5506–5516. https://doi.org/10.1145/2858036.2858116

[53] Prabodh Sakhardande, Anirudha Joshi, Charudatta Jadhav, and Manjiri Joshi. 2019. Comparing User Performance on Parallel-Tone, Parallel-Speech, Serial-Tone and Serial-Speech Auditory Graphs. In *IFIP Conference on Human-Computer Interaction*. Springer-Verlag, Berlin, Heidelberg, 247–266. https://doi.org/10.1007/978-3-030-29381-9_16

[54] Ather Sharif, Sanjana Shivani Chintalapati, Jacob O. Wobbrock, and Katharina Reinecke. 2021. *Understanding Screen-Reader Users' Experiences with Online Data Visualizations*. Association for Computing Machinery, New York, NY, USA. https://doi.org/10.1145/3441852.3471202

[55] Ather Sharif and Babak Forouraghi. 2018. evoGraphs — A jQuery plugin to create web accessible graphs. In *2018 15th IEEE Annual Consumer Communications Networking Conference (CCNC)*. 1–4. https://doi.org/10.1109/CCNC.2018.8319239

[56] Alexa F. Siu, Danyang Fan, Gene S-H Kim, Hrishikesh V. Rao, Xavier Vazquez, Sile O'Modhrain, and Sean Follmer. 2021. COVID-19 Highlights the Issues Facing Blind and Visually Impaired People in Accessing Data on the Web. In *Proceedings of the 18th International Web for All Conference* (Ljubljana, Slovenia) *(W4A '21)*. Association for Computing Machinery, New York, NY, USA, Article 11, 15 pages. https://doi.org/10.1145/3430263.3452432

[57] Abigale Stangl, Meredith Ringel Morris, and Danna Gurari. 2020. " Person, Shoes, Tree. Is the Person Naked?" What People with Vision Impairments Want in Image Descriptions. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*. 1–13. https://doi.org/10.1145/3313831.3376404

[58] A. Strauss and J.M. Corbin. 1997. *Grounded Theory in Practice*. SAGE Publications. https://books.google.com.br/books?id=TtRMolAapBYC

[59] Tableau. [n.d.]. Build Accessible Dashboards. https://help.tableau.com/current/pro/desktop/en-us/accessibility_dashboards.htm. Online; accessed 23 August 2021.

[60] Mary Frances Theofanos and Janice Redish. 2003. Guidelines for accessible and usable web sites: Observing users who work with screen readers. *Interactions* 10, 6 (2003), 38–51.

[61] Garreth W. Tigwell, Benjamin M. Gorman, and Rachel Menzies. 2020. Emoji Accessibility for Visually Impaired People. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*. Association for Computing Machinery, New York, NY, USA, 1–14. https://doi.org/10.1145/3313831.3376267

[62] Brianna J. Tomlinson, Jared Batterman, Yee Chieh Chew, Ashley Henry, and Bruce N. Walker. 2016. Exploring Auditory Graphing Software in the Classroom: The Effect of Auditory Graphs on the Classroom Environment. *ACM Trans. Access. Comput.* 9, 1, Article 3 (nov 2016), 27 pages. https://doi.org/10.1145/2994606

[63] Márcio Josué Ramos Torres and Regina Barwaldt. 2019. Approaches for diagrams accessibility for blind people: a systematic review. In *2019 IEEE Frontiers in Education Conference (FIE)*. IEEE, 1–7. https://doi.org/10.1109/FIE43999.2019.9028522

[64] vegalite. [n.d.]. Make charts more accessible #4244. https://github.com/vega/vega-lite/issues/4244. Online; accessed 01 December 2022.

[65] Markel Vigo and Giorgio Brajnik. 2011. Automatic web accessibility metrics: Where we are and where we can go. *Interacting with Computers* 23, 2 (2011), 137–155. https://doi.org/10.1016/j.intcom.2011.01.001

[66] Markel Vigo and Simon Harper. 2013. Coping Tactics Employed by Visually Disabled Users on the Web. *Int. J. Hum.-Comput. Stud.* 71, 11 (nov 2013), 1013–1025. https://doi.org/10.1016/j.ijhcs.2013.08.002

[67] W3C. [n.d.]. Resources on Alternative Text for Images. https://www.w3.org/WAI/alt/. Online; accessed 23 August 2021.

[68] Jakub Wabiński, Albina Mościcka, and Marta Kuźma. 2020. The Information Value of Tactile Maps: A Comparison of Maps Printed with the Use of Different Techniques. *The Cartographic Journal* 0, 0 (2020), 1–12. https://doi.org/10.1080/00087041.2020.1721765

[69] B. N. Walker and L. M. Mauney. 2010. Universal Design of Auditory Graphs: A Comparison of Sonification Mappings for Visually Impaired and Sighted Listeners. *ACM Trans. Access. Comput.* 2, 3, Article 12 (mar 2010), 16 pages. https://doi.org/10.1145/1714458.1714459

[70] Tetsuya Watanabe and Naoki Inaba. 2018. Textures suitable for tactile bar charts on capsule paper. *Transactions of the Virtual Reality Society of Japan* 23, 1 (2018), 13–20. https://doi.org/10.18974/tvrsj.23.1_13

[71] Tetsuya Watanabe and Hikaru Mizukami. 2018. Effectiveness of tactile scatter plots: comparison of non-visual data representations. In *International Conference on Computers Helping People with Special Needs*. Springer, 628–635. https://doi.org/10.1007/978-3-319-94277-3_97

[72] Markus Weninger, Gerald Ortner, Tobias Hahn, Olaf Drümmer, and Klaus Miesenberger. 2015. ASVG- Accessible Scalable Vector Graphics: intention trees to make charts more accessible and usable. *Journal of assistive technologies* (2015). https://doi.org/10.1108/JAT-10-2015-0027

[73] Brian Wentz, Harry Hochheiser, and Jonathan Lazar. 2013. A Survey of Blind Users on the Usability of Email Applications. *Univers. Access Inf. Soc.* 12, 3 (aug 2013), 327–336. https://doi.org/10.1007/s10209-012-0285-9

[74] Yalong Yang, Kim Marriott, Matthew Butler, Cagatay Goncu, and Leona Holloway. 2020. Tactile presentation of network data: Text, matrix or diagram?. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*. 1–12. https://doi.org/10.1145/3313831.3376367