The Accessibility of Data Visualizations on the Web for Screen Reader Users: Practices and Experiences During COVID-19

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Data visualization has become an increasingly important means of effective data communication and has played a vital role in broadcasting the progression of COVID-19. Accessible data representations, however, have lagged behind, leaving areas of information out of reach for many blind and visually impaired (BVI) users. In this work, we sought to understand (1) the accessibility of current implementations of visualizations on the web; (2) BVI users' preferences and current experiences when accessing data-driven media; (3) how accessible data representations on the web address these users' access needs and help them navigate, interpret, and gain insights from the data; and (4) the practical challenges that limit BVI users' access and use of data representations. To answer these questions, we conducted a mixed-methods study consisting of an accessibility audit of 87 data visualizations on the web to identify accessibility issues, an online survey of 127 screen reader users to understand lived experiences and preferences, and a remote contextual inquiry with 12 of the survey respondents to observe how they navigate, interpret, and gain insights from accessible data representations. Our observations during this critical period of time provide an understanding of the widespread accessibility issues encountered across online data visualizations, the impact that data accessibility inequities have on the BVI community, the ways screen reader users sought access to data-driven information and made use of online visualizations to form insights, and the pressing need to make larger strides towards improving data literacy, building confidence, and enriching methods of access. Based on our findings, we provide recommendations for researchers and practitioners to broaden data accessibility on the web.

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CCS Concepts: • **Human-centered computing → Empirical studies in accessibility**; **Visualization application domains;**

Additional Key Words and Phrases: Accessibility, data visualization, accessible data visualization, web accessibility, blind, visually impaired, user experience, audit

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1 INTRODUCTION

The use of data visualizations has grown rapidly throughout the past decade, serving as a way to identify and communicate data-driven insights. The COVID-19 pandemic has highlighted the important role data visualizations play in guiding important decisions by policy-makers, businesses, and the general public [105]. *Flattening the Curve*, for example, was a central public health strategy popular during the early months of the pandemic that used visual graphics to demonstrate the importance of slowing down the spread of the virus [99]. Many other visualizations also played a vital role in promoting awareness, informing the public, guiding policy, and predicting future outcomes [66, 105, 133].

While online visualizations have flourished with the aid of several web tools and libraries [15, 26, 27, 128], these methods have largely relied on representations that leverage visual modalities for consumption, which leaves large parts of the news and information on the web inaccessible to people who are **Blind and Visually Impaired (BVI)** [39, 54, 79]. Anecdotal evidence reported in the general media captured some of the barriers faced by the BVI community in obtaining proper access to vital data visualizations and information about their local communities during the COVID-19 pandemic [39, 61, 66, 73]. In response, a number of websites were independently launched in an effort to provide more accessible alternative representations to the BVI community [39]. These efforts provided alternative modalities for data consumption such as comprehensive alternative text (alt text) [10], data sonification [9, 10, 14], and access to tabular data [9, 75].

Prior research on accessible visualization has investigated natural language descriptions [36, 67, 76], data sonification [124, 134], and haptic graphs [41, 91], mostly in controlled settings. Considerably fewer works have examined the experiences of BVI users when interacting with data visualizations on the web, but several recent works have begun to explore this research gap. Sharif et al. investigated how accessibility issues reduced task performance across three common web-based visualization libraries [102]. Holloway et al. found that many visual graphics do not provide sufficient textual summaries and that blind and low vision users often rely on news sources that do not provide direct access to data [62].

However, there still lacks a systematic and detailed understanding of specific accessibility gaps in current, highly encountered visualizations and the types of content, context, navigation, and interactivity that these visualizations provide for screen reader users. Moreover, while a number of websites provide data through alternative representations (e.g., comprehensive alt text and sonification) to meet accessibility needs, little is known about how well the needs of BVI users are met through these representations and whether additional challenges remain.

In this work, we use in-the-wild COVID-19 websites as a tool to study the current accessibility gaps relating to online visualizations and strategies employed by BVI users to retrieve data-driven information.

Specifically, we ask the following research questions:

- RQ1 How accessible are current implementations of data visualizations on the web for screen reader users (with respect to content, context, navigation, and interactivity)?
- RQ2 What are BVI users' current experiences (needs, gaps, and challenges) and preferences (for modalities and technology) when accessing data-driven media on the web?

RQ3 How do "accessible" online data representations address these needs? How do they help BVI users navigate, interpret, and gain insights from the data?

RQ4 What are the practical challenges that limit BVI users' access and use of data representations on the web?

As the breadth and diversity of these questions makes answering them through a single research method difficult, in this work, we adopted a mixed-methods approach and report on three complementary studies consisting of an accessibility audit, a survey, and a contextual inquiry. Findings from these three studies provide complementary perspectives on the current state of data accessibility on the web.

To understand how accessible widely accessed data visualizations are on the web for screen reader users [RQ1], we conducted an accessibility audit of popular sites. Audits have been used to assess web accessibility conformance, uncover additional accessibility limitations to web content, and offer improvements on current solutions [17, 52, 90]. However, no widespread audit of web visualizations has been done to date. The COVID-19 crisis provided a unique opportunity to examine a large quantity of visualizations that were constructed by a diverse set of organizations for public consumption within the past three years. We selected 76 visualizations across 28 high-ranked Google-search results websites that were released by several international and government organizations, research institutions, corporations, and news sources, which we call *Top Results* websites and visualizations. Additionally, we sought to investigate how websites designed specifically for screen reader access provided data information, which we call *Born Accessible* websites and visualizations. Auditing both groups allowed us to compare between the current practices of *Top Results* and *Born Accessible* websites and uncover insights into how practices can be improved and what limitations remain.

While the audit exposed data accessibility gaps in the current implementations of websites, we also wanted to understand screen reader users' perceptions of access and preferences to recognize the impact of those gaps [RQ2]. Towards this goal, we conducted a survey of 127 screen reader users to inquire about their experiences, preferences, and strategies for accessing data-driven information, both about the COVID-19 pandemic and in general. This quantitative and qualitative survey allowed us to broadly understand how well current data access needs are being met, areas of unmet needs, and screen reader users' strategies and preferences towards meeting those needs.

Both the audit and survey provide a high-level view of accessibility gaps, but to understand how visualizations are used to gain insight, we needed to observe users directly. While previous studies of accessible data graphics have been conducted on visualizations from general-use data visualization libraries [102], they have not examined how screen reader users interact with *Born Accessible* visualizations that are designed to be accessible. By conducting a contextual inquiry with screen reader users accessing these sites, we hoped to understand how "accessible" representations might help BVI users navigate, interpret, and gain insights from data [RQ3], and whether additional practical challenges remain [RQ4].

Taken together, these components provide a broader understanding of online data accessibility that bridges how information is conveyed (Section 3: Audit), how information is broadly encountered by screen reader users (Section 4: Survey), and how users interact with and form insights based on what is currently provided (Section 5: Contextual Inquiry). While these studies are grounded in the COVID-19 crisis, we position our results in the context of broader accessibility needs on the web. We begin by presenting findings from the audit despite having performed the audit before the survey and contextual inquiry. We hope that details about the accessibility features and issues of current visualization practices described in the audit section will provide additional context to the user experiences reported in the later sections. In the general discussion, we synthesize findings across the three investigations into broader themes (Section 6). Each theme concludes with broad and practical recommendations based on implementation details and user experiences to improve current practices and advance research in online data accessibility.

This article is an extension of Siu et al. [108], which was presented at the 18th International Web for All Conference in 2021. Portions from the Related Work (Section 2), Survey (Section 4), Contextual Inquiry (Section 5), and General Discussion (Section 6) have been reproduced from the conference publication. Individual data files for each figure are included as csv files in the supplementary materials.

2 RELATED WORK

We review prior work investigating the experiences of **people with disabilities (PWD)** on access and impact from COVID-19. Additionally, we review work on accessible data representations, web accessibility, and data literacy.

2.1 COVID-19 and the Impact on People with Disabilities

In past historical times of crisis and rapid change, PWD have often suffered disproportionate impact [117]. A number of recent studies have reported on the early and immediate impact sweeping policies and behaviors enacted at the onset of the pandemic (e.g., the move to online education, lockdowns, shelter-in-place orders) have on PWD [50, 62, 98, 132]. A Twitter analysis conducted by Gleason et al. found that improper dissemination of public health information was one domain that negatively impacted PWD [50]. Of the 55 government agencies' tweets that contained public health guidance information, only 12 agencies employed alt text descriptions, resulting in only 56% of images being accessible. Another study conducted in March 2020 investigated the experiences of BVI adults during the start of the COVID-19 pandemic through a large-scale survey [98]. While the study examined a broad range of topics, one of the findings revealed that BVI users more often rely on information channels that summarize information (e.g., summaries provided by news anchors or sighted relatives) rather than those that provide direct access to the data. One possibility for resorting to these sources of information is a profusion of access barriers. Preliminary findings from Holloway et al.'s survey comparing the experiences and needs between sighted and blind users accessing COVID-19 information revealed similar findings [62].

Anecdotal evidence reported in the general media also captured barriers that BVI people faced when seeking proper access to vital COVID-19 information in their communities [39, 61, 66, 73]. Jeffries et al. used automated tools to analyze the accessibility of each of the 50 US states' websites disseminating COVID-19 data in April 2020 [66] and found that all contained accessibility issues ranging from low contrast text to missing labels. Holloway et al. found that online graphics used to communicate COVID-19 information was often missing alt text [62]. Ensuring the accessibility of information on government agency websites is particularly crucial, because people may rely on these sites during times of crisis.

2.2 Web Accessibility for Screen Reader Users

Screen readers are the most common assistive technology used by BVI users to access web-based content [72]. The screen reader reads information and meta-information (e.g., heading levels, the role of different UI elements) of web pages in a linear fashion, imposing an order and temporal distance between web elements. Websites need to be designed and programmed thoughtfully to ensure proper access with screen reader technology. The **Web Accessibility Initiative (WAI)** of the **World Wide Web Consortium (W3C)** defined the **Web Content Accessibility Guidelines (WCAG)**, which is a set of guidelines on for making web content more accessible to all, including screen reader users [7]. Power et al. found that only 50% of problems were addressed by the guidelines, revealing that meeting accessibility criteria does not ensure screen reader users have access to the information [94]. In other words, there is a gap between what is deemed technically accessible and what is practically usable.

The lack of accessibility across the web has been a documented problem [25, 72], from government websites [52, 90], to social media [49, 86], to productivity tools [32, 37, 126]. Various studies highlight the intricate relationship between accessibility and usability and its impact on screen reader users' navigation of the web [21, 74, 118]. Sharif et al. found that many visualizations were not discoverable through screen reader access and identified several needs and techniques of screen reader users [102]. Through a second controlled experiment, they found that screen reader users extracted information 61% less accurately and spent 211% more time interacting with online data visualizations compared to non-screen-reader users due to inaccessibility of the visualizations explored.

Empirical studies have sought to characterize screen reader users' browsing strategies, challenges, and coping mechanisms or workarounds to recommend solutions that improve both web accessibility and usability for BVI users [19, 23, 25, 46, 48, 72, 77, 87, 112, 120]. Borodin et al. provided an overview of screen reader navigation strategies used by BVI users when dealing with inaccessible content and described how developers have often focused on making non-visual browsing accessible but not efficient [25]. Aizpurua et al. conducted a similar observational study but focused their analysis on how expectations, subjectiveness, and prior experiences impacted blind users' perceptions of web accessibility challenges [19]. The findings showed that when faced with inaccessible content, users often draw from prior experience to guess at a solution, and users often have higher expectations from websites branded as accessible. Vigo and Harper identified coping tactics used by screen reader users and found that more experienced users had better developed effective tactics to help them overcome screen reader shortcomings [120]. A common theme across these studies is the need to provide users with better ways to more efficiently navigate to relevant content. A number of systems address this problem by providing enhanced web functionality for filtering information [48], obtaining an "aural glance" of a web page [46], and skimming through automated web summaries [18, 58].

Understanding the challenges encountered by BVI users on the web in various application domains has led to important recommendations and systems that help improve web accessibility. In this work, our goal is to make similar observations and recommendations towards improving BVI users' access to data-driven information on the web.

2.3 Accessible Data Representations

BVI people most often rely on labels and alternative text (alt text) on web images and charts [24, 84], which provide a textual alternative to graphical content in web pages. WCAG provides general guidelines for the creation of alt text [7], while the National Center for Accessible Media provides more specific guidelines for describing STEM images including data charts [56]. For data-driven content, guidelines also recommend including the source data in tabular form. Using these guidelines, Morash et al. developed and evaluated a template-based description generator for data charts that produces more standardized word usage and structure [84].

Text-based and numerical descriptions of graphics are less precise, more error prone in their interpretation and require more cognitive load than a perceptual interface that directly renders the same information through touch, sound, or vision [53, 111, 119]. Sonification is another method that exploits sound to make data graphics more accessible by transforming data relations into perceived relations in an acoustic signal [122]. Zhao described a set of **Auditory Information Seeking Actions (AISA)** and design considerations to support such actions for users interacting with data through sound [134]. Wang et al. evaluated the accuracy of different mappings between sound and data attributes among people with visual impairments [124]. Various plugins, such as the SAS Graphics Accelerator for Google Chrome [14] and for Excel [95], allow users to import data tables and explore sonified graphs. Additionally, various systems have investigated the use of multimodal interfaces to enable users to understand different data charts [51, 80, 130, 135]. For example, the iSonic system allows blind users to find facts and discover trends in georeferenced data by supporting sonified representations of maps with tightly coordinated access to the tabular data [135].

An alternative or complementary approach to audio is tactile graphics [30, 53, 70]. While tactile graphics are well suited for conveying spatial information, technology for tactile displays that would enable dynamic access to tactile images over the web is still immature and thus not widely available [12, 44, 109]. In this work, we focus on data representations that are currently available through the web and the strategies BVI users can employ to understand data through those representations.

2.4 Visualization Literacy and Gaining Insights from Data

Data visualizations have become omnipresent in the mainstream media. Examples include online infographics and visual explainers, news articles enriched with interactive data, and reports from organizations presenting progress data or findings [97, 101]. Data and visualization literacy refers to one's ability to translate questions into task queries and gain insights from data representations [28]. As information becomes more quantitative and as society relies increasingly on computing devices, data and visualization literacy has become an essential set of skills [34].

When interacting with data, users often perform several elemental tasks with the goal of answering questions from the data [136]. Studies have looked at not only how people perform those queries, but also how people construct mappings between the data and visual representations [64] and how these representations support spatial reasoning tasks [60, 114]. Another goal of interacting with data is for users to draw insights [78, 89], and various studies have reported on strategies used by sighted users to draw insights from data visualizations [35, 55, 110, 129]. Yi et al. identified different processes through which users gain insights (Provide Overview, Adjust, Detect Pattern, and Match Mental Model) and recommended their use in designing and evaluating visualization systems [129].

Few works have examined how accessible data representations are used in practice by screen reader users and what strategies users are able to employ to draw insights from the data [102]. This work aims to understand BVI people's preferences when accessing data representations and the extent of what can be accomplished with existing tools.

3 DATA ACCESSIBILITY AUDIT OF COVID-19 WEBSITES

To investigate how accessible current implementations of visualizations are on the web for screen reader users [RQ1], we worked in close collaboration with access technology and web accessibility experts to conduct an accessibility audit of COVID-19 visualizations. The audit was performed between September 2021 and January 2022, covered 26 criteria, and evaluated 87 visualizations across 2 groups of websites. The first group consisted of *Top Results* websites that were high-ranked Google search results for *"COVID-19 Data."* The second group consisted of *Born Accessible* websites, which were designed from the ground up to meet accessibility needs. The *Born Accessible* websites served as a reference to understand existing deficiencies in the *Top Results* websites and provide a model for improving these websites through current web tools. Accessibility challenges shared by both groups reveal general limitations of existing web visualizations that should be addressed by the broader visualization and research communities.

3.1 Audit Criteria

We developed a list of 26 criteria to test the presence of specific accessibility features. We based the criteria on Chartability, a set of heuristics for assessing the accessibility of data visualizations developed by Frank Elavsky and the Dataviza11y group [40].

We made several modifications to accommodate the scope of the study that were informed by discussions with our access technology specialist co-author, reflections from a pilot audit, and independent pre-audit reviews from the three web-accessibility specialists who performed the audit. Modifications involved (1) omitting criteria that do not apply to screen reader users, (2) rephrasing Chartability's heuristics as questions to be more approachable for auditors to quickly comb through, (3) breaking down several of the criteria to reduce ambiguity in interpretation, and (4) creating intermediary criteria for questions that compare visual and alternative forms of access so blind individuals could perform the audit.

We found that our modified criteria fit well within four umbrella categories that are also general attributes of visualizations when explored using screen readers. These categories are: content, context, navigation, and interactivity. Content criteria focus on what and how data information is conveyed. Context criteria evaluate whether important context about the data is accessible. Navigation criteria relate to how screen reader controls may be used to interact with visualizations and whether visualization designs provide important cues to support effective navigation. Interactivity criteria evaluate whether interactive features within visualizations are accessible when encountered with screen readers. Feedback from our access technology co-author confirmed that grouping and ordering criteria under these categories provide a suitable way for auditors to work through the criteria list. Appendix Table 9 shows the final 26 criteria used for the study.

For each visualization, auditors assessed each of the criteria on a "yes," "partial," and "no" format. Because implementations of visualizations are diverse, we added a "not applicable" option for visualizations in which specific criteria do not apply and an "I don't know" option for specific cases auditors were unsure of. A final question asked auditors to assign an overall accessibility rating to the visualization on a 5-point Likert scale (not at all accessible, slightly accessible, moderately accessible, very accessible, extremely accessible). All criteria included a free response field for auditors to elaborate on their choices.

3.2 Visualization and Website Selection

We compiled two groups of online visualizations for the audit to evaluate and facilitate comparisons between the accessibility of *Top Results* visualization and *Born Accessible* visualizations.

For the *Top Results* group, we used Google searches for "COVID-19 Data" to select visualizations that were popular, high-visibility, and relevant. As the top search results presented a large number of state government-hosted websites, we limited the number of state government-hosted websites to six to sample from other categories of organizations. The websites were hosted by several different types of organizations that include major government agencies, research institutions, and news organizations. Many of the websites relied on data visualization services including Microsoft BI [3], ArcGIS [1], and Tableau [15] to present data.

For the *Born Accessible* group, we selected websites created specifically for screen reader accessibility. *Born Accessible* websites were elicited from or explored by screen reader users in the survey (Section 4) and contextual inquiry (Section 5).

In both groups, many of the websites contained a large number of visualizations (>8). To sample across a number of websites and different visualization types, we limited the sampling of visualizations to three per website, and each visualization needed to be of a different type.

Applying these filters, we ultimately selected 76 visualizations across 28 websites within the top 41 Google sites returned for a search for "COVID Data" on October 14, 2021, for the *Top*

Results group. Within the 76 visualizations, 62 visualizations had accessibility statements, 11 had no accessibility statements, and 3 were a part of a web page that used an accessibility overlay. The *Born Accessible* group consisted of 11 visualizations across 5 websites. None of the *Born Accessible* websites overlapped with websites in the *Top Results* group.

Appendix Section B contains breakdowns of visualizations by organization type (Table 5), visualization type (Table 6), visualization service (Table 7), as well as a complete list of audited visualizations (Table 8).

3.3 Auditors

Three auditors were hired to perform the audit between December 2021 and January 2022. All auditors work as senior accessibility specialists or accessibility leads, are CPACC certified [5], and have 3+ years of experience in web accessibility. Accessibility professionals were chosen to provide nuanced understandings of the technical accessibility details related to screen readers and audited visualizations. Two of the auditors are sighted and one is blind. Table 4 shows the demographic breakdown of each auditor. Auditors were compensated on an hourly rate basis at the current market rate for hiring accessibility professionals.

3.4 Audit Data Collection

Audit data was collected using Qualtrics after exploring the accessibility of several data collection platforms. Javascript compatibility enabled automatic population of visualization title, type, a screenshot of the visualization, alt text for the screenshot, a link to the website, and screen reader instructions for accessing each visualization when auditors selected a visualization to audit from a dropdown list. For flexibility, a separate spreadsheet was also provided to each auditor containing the same information about audited visualizations.

3.5 Audit Procedure

Before conducting the audit, researchers hosted a 90-minute training session with the three auditors to introduce the project. In the session, researchers and auditors performed a sample audit of a training visualization together to develop a shared understanding of the criteria. After the training session, each auditor was provided with a list of 38 visualizations across 19 websites to audit. Of those visualizations, 12 visualizations across 5 websites were shared among all auditors for computing an inter-rater reliability score. Three of the five overlapping websites were from the *Top Results* group, one of which contained an accessibility overlay. The remaining two websites were from the *Born Accessible* group.

Auditors and researchers communicated through a shared mailing list to form additional consensus and resolve ambiguities. Auditors were encouraged to use screen readers and browsers they are most comfortable with so audits were performed with familiar tools. Auditor 1 (A1) used NVDA with Firefox and Auditor 2 (A2) used JAWS with Microsoft Edge. Auditor 3 (A3) initially used Mac Voiceover with Safari, then switched to using NVDA with Firefox and Chrome midway, having encountered too many difficulties using Mac Voiceover. Auditors also informed researchers if visualizations from the list were absent. Only one such visualization was removed from the list and is not included in the total visualization count (n = 87). Auditors on average spent 25 minutes per visualization and 78 minutes per website.

3.6 Audit Data Preparation

Researchers prepared the data following three steps: The first step involved transforming responses from a "yes/partial/no" response scheme to a "pass/partial/fail" grade scheme to align response polarities, as "yes" responses did not always reflect greater accessibility. Additionally, reading through and interacting with entire web pages can often require hundreds of screen reader actions and several hours. We encouraged auditors devote approximately 30 minutes per visualization and 1.5 hours per website to go through the criteria. If auditors were not successful finding accessibility features, then we declared the criteria as a fail. The second step involved cross-referencing responses with visual access to determine whether visual features were not conveyed through screen readers. In the third step, researchers manually reviewed every audit response as a final stage of member checking. The review involved revising entries and resolving "I don't know" responses using details that auditors provided in the optional text-entry fields based on consensus formed through mailing list discussions. This step was necessary, because the many different visualization types and implementations prompted auditors to continue refining criteria interpretations, which needed to be reflected in the already-completed audit submissions.

3.7 Audit Data Analysis

We first computed the inter-rater reliability between each pair of auditors across the shared visualizations using an unweighted Cohen's Kappa. To represent each visualization only once in our group, as some sites were audited by multiple auditors for agreement scoring, we chose to include the audit with the highest agreement to the other two audits for each visualization. For three auditors, this was the audit that was shared among the two highest Cohen's Kappa scores.

We used descriptive statistics to summarize the frequency distribution of passes, partials, and fails among the *Top Results* and *Born Accessible* groups, as well as breakdowns by visualization type. We define ***"pass rate"*** **(PR)** as the percent of "pass" grades out of the sum of "pass," "partial," and "fail" grades. A model comparison approach was used for hypothesis testing. Likelihood ratio tests compared a complex model to a reduced model with and without the effect of interest to determine the significance of these effects. For comparing overall ratings between different groups, a mixed effects ordinal logistic regression was applied with auditor as a random effect. For comparing pass rates between different groups, a mixed effects linear regression was applied with auditor as a random effect. Bonferroni-correction was used for pairwise post hoc comparisons.

We complement quantitative results with descriptions provided by auditors while they performed the audit. The descriptions contribute two types of findings: rationales behind criteria grades and additional accessibility considerations. To provide rationale behind specific criteria grades, two researchers aggregated and labeled responses by shared meaning within each criteria. Several labels were modified by cross-referencing their contents with related visualizations and web pages to provide additional context. We directly report on common labels under each criteria. To identify important accessibility considerations, two researchers gathered labels across all of the criteria that provided additional information. Researchers inductively formed themes based on latent interpretations of the labels and their implications on the relevant visualizations and web pages. To ensure credibility and exploration of various aspects of the data, repeated discussions and debriefings were conducted among members of the research team. We report on these themes in Section 3.11.

3.8 Audit Results

We first present results on inter-coder reliability between the auditors and relationships between criteria grades and the overall accessibility rating auditors provided each website. We then convey general findings related to the accessibility of *Top Results* and *Born Accessible* visualizations audited in the study. We group the results as follows:

- **Section 3.8:** Inter-coder reliability between the auditors and relationships between criteria grades and the overall accessibility rating

Table 1. Pairwise Cohen's K between Auditors across All Shared Visualizations and Criteria

Auditor Pair	Cohen's K	95% CI	Screen Reader	Browser
A1 - A2	0.58	[0.51 0.65]	NVDA - JAWS	Firefox - MS Edge
A2 - A3	0.60	[0.53 0.67]	JAWS - NVDA & Mac Voiceover	MS Edge - Chrome, Safari, Firefox
A1 - A3	0.65	[0.58 0.71]	NVDA - NVDA & Mac Voiceover	Firefox - Chrome, Safari, Firefox

- **Section 3.9:** Comparing overall ratings and criteria grades between *Top Results* and *Born Accessible* visualizations
- **Section 3.10:** Comparing accessibility across different visualization types for *Top Result* visualizations
- **Section 3.11:** Additional considerations web accessibility specialists highlighted while auditing the study visualizations

Criteria grades for all of the audited visualizations are shown in Appendix Figure 12 and Appendix Figure 13.

3.8.1 Inter-coder Reliability. Figure 1 shows how each auditor rated the shared visualizations. Most visualizations were detectable through auditors' screen reader and browser combinations. However, several visualizations in the *Top Results* websites could not be detected by at least one auditor through their screen reader and browser combination (these visualizations are coded as LA1, LA2, and CDC2 in Figure 1).

Inter-rater agreement was assessed on 312 pairs of observations between each pair of auditor. Table 1 shows the Cohen's Kappa inter-rater reliability scores between each pair of auditors, which are 0.58, 0.60, and 0.65, respectively, representing near-substantial to substantial agreement [71].

3.8.2 Relationship between Criteria Grade and Overall Rating. Figure 2 shows strong linear relationships between the proportion of pass rates and the overall accessibility rating on a 5-Point Likert scale (1 = "not at all accessible," 5 = "extremely accessible") auditors provided to each visualization. Pearson's r values for auditors A1 to A3 are $r(36) = 0.80$, $p < .001$, $r(36) = 0.94$, $p < .001$, and $r(36) = 0.93$, $p < .001$, respectively.

3.9 Comparing Visualizations in *Born Accessible* and *Top Results* Websites

Figure 3 shows the overall accessibility rating auditors gave to the visualizations across *Top Results* and *Born Accessible* groups. 82% (9/11) of *Born Accessible* visualizations were rated as very or extremely accessible, while only 14% (11/76) of *Top Results* visualizations achieved the same ratings.

There was a significant difference between *Born Accessible* and *Top Results* visualization ratings ($\chi^2(1) = 26.31$, $P < .001$). The ordinal logistic regression model predicted nearly a 30-fold likelihood of rating increase between for *Born Accessible* visualizations over *Top Results* visualizations (OR = 29.06, 95% CI = [125.16, 7.31]).

Figure 4 and Appendix Table 10 show the grade breakdown of the criteria in the *Top Results* and *Born Accessible* groups. "NA" entries indicate when the criteria does not apply to the visualization, such as if the visualization does not support interactivity or animation through any modality.

In the *Top Results* group, the majority of applicable visualizations received passing grades only in 3 of 26 criteria. The three majority-passing criteria relate to whether visualizations are detectable (PR = 68%, 52/76), provide access to the title (PR = 55%, 42/76), and do not contain custom keyboard commands that override screen reader settings (PR = 100%, 76/76). Of the 22% of detectable visualizations in the *Top Results* group, 13% of the visualizations were completely undiscoverable through auditors' screen readers and browsers, and 18% of the visualizations were difficult to detect through the screen reader. Many of the difficult-to-access visualizations required auditors to expand accordions, navigate into non-obvious frames, select unlabeled tabs, or use

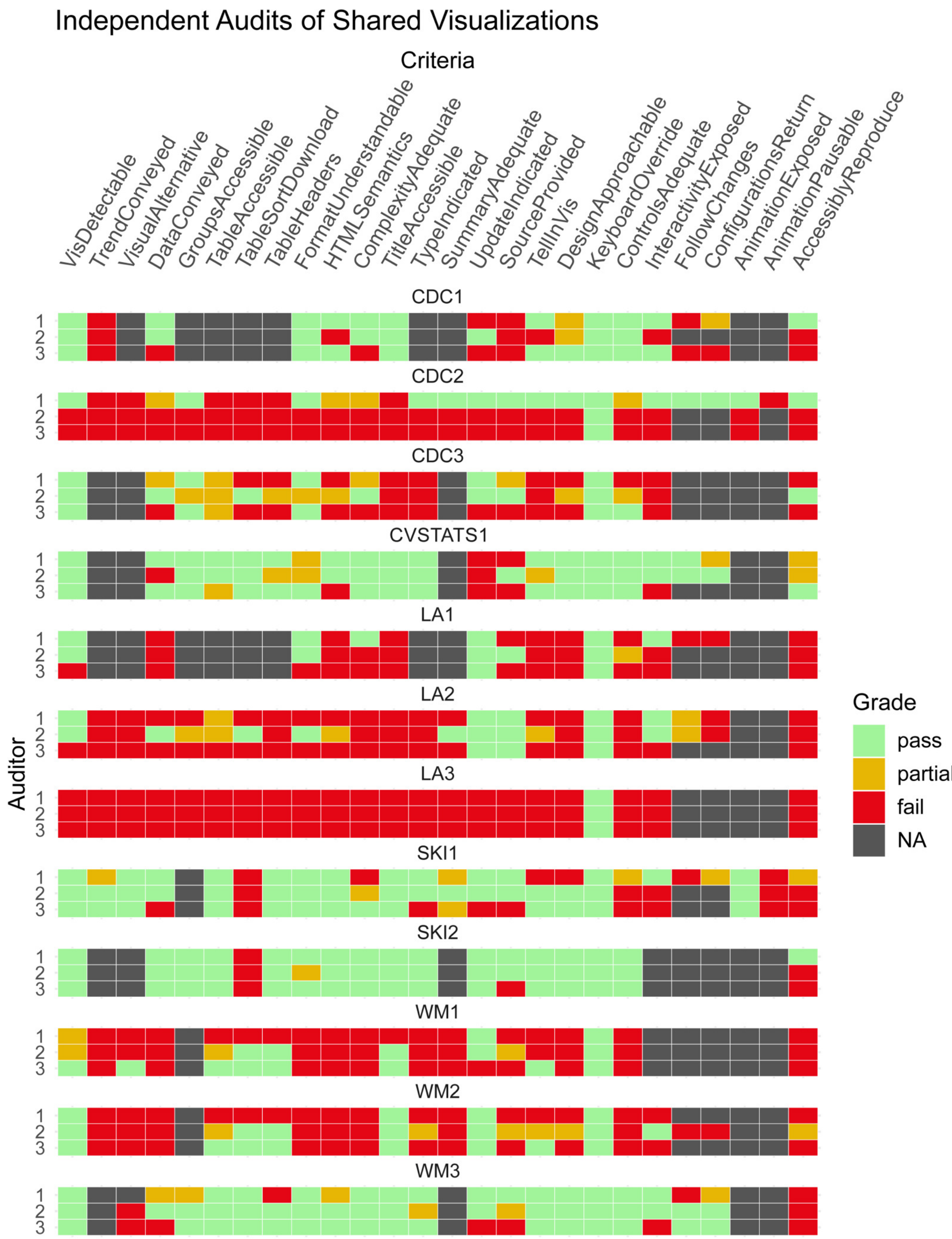

Fig. 1. Audits of 12 shared visualizations show near-substantial to substantial agreement between auditors. Three visualizations were detected by some auditors through their screen reader and browser combinations but not others.

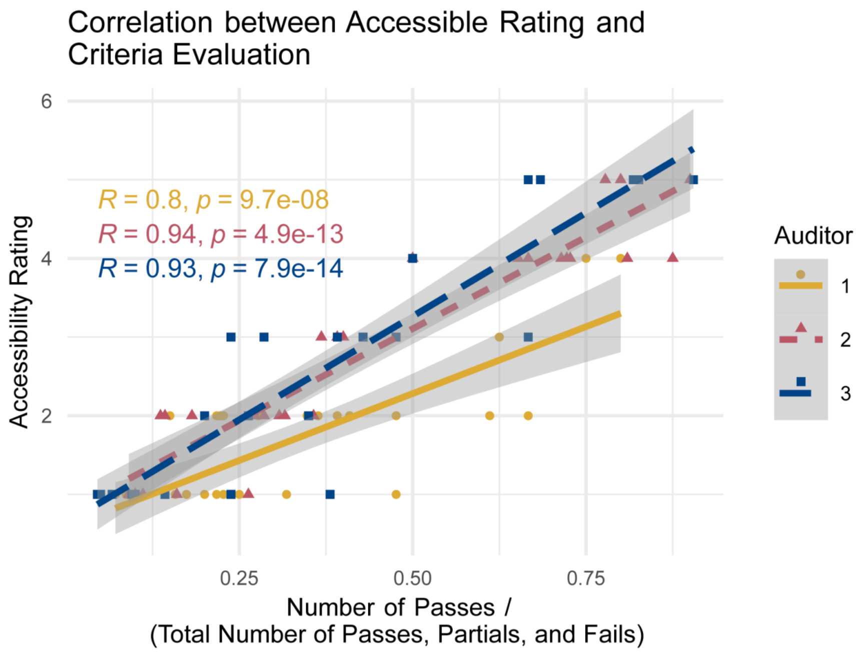

Fig. 2. Linear regression shows a strong linear relationship between criteria pass rate and the overall accessibility rating auditors assigned to audited visualizations.

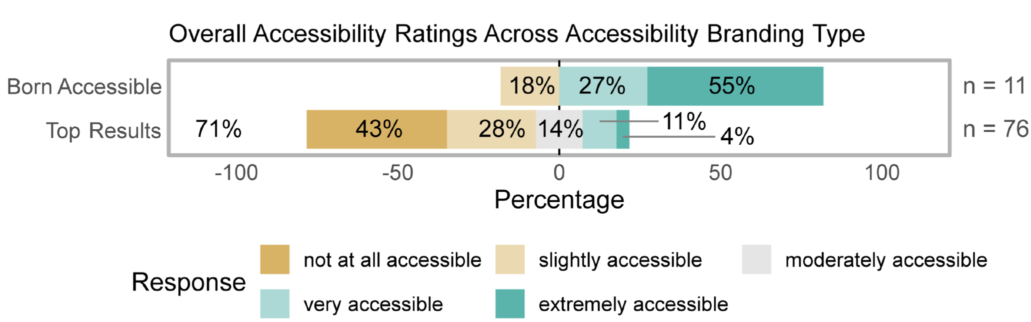

Fig. 3. The majority of *Born Accessible* visualizations were rated as very to extremely accessible while a small minority of *Top Results* visualizations were rated as very to extremely accessible. Differences in ratings between the two groups were statistically significant.

special keyboard commands. In comparison, pass rates were over 50% for 21 of the same 26 criteria in the *Born Accessible* group.

The proportion of pass grades for *Born Accessible* visualizations was also significantly greater than the proportion of pass grades for *Top Results* visualizations across the content ($\chi^2(1) = 32.84$, P < .001), context ($\chi^2(1) = 16.59$, P < .001), navigation ($\chi^2(1) = 33.35$, P < .001), and interactivity criteria ($\chi^2(1) = 8.76$, P = .003). We used Bonferroni adjusted alpha levels of .013 for these tests. Table 2 shows the mean, standard deviation, and confidence intervals for pass rates between the visualization groups for the criteria categories.

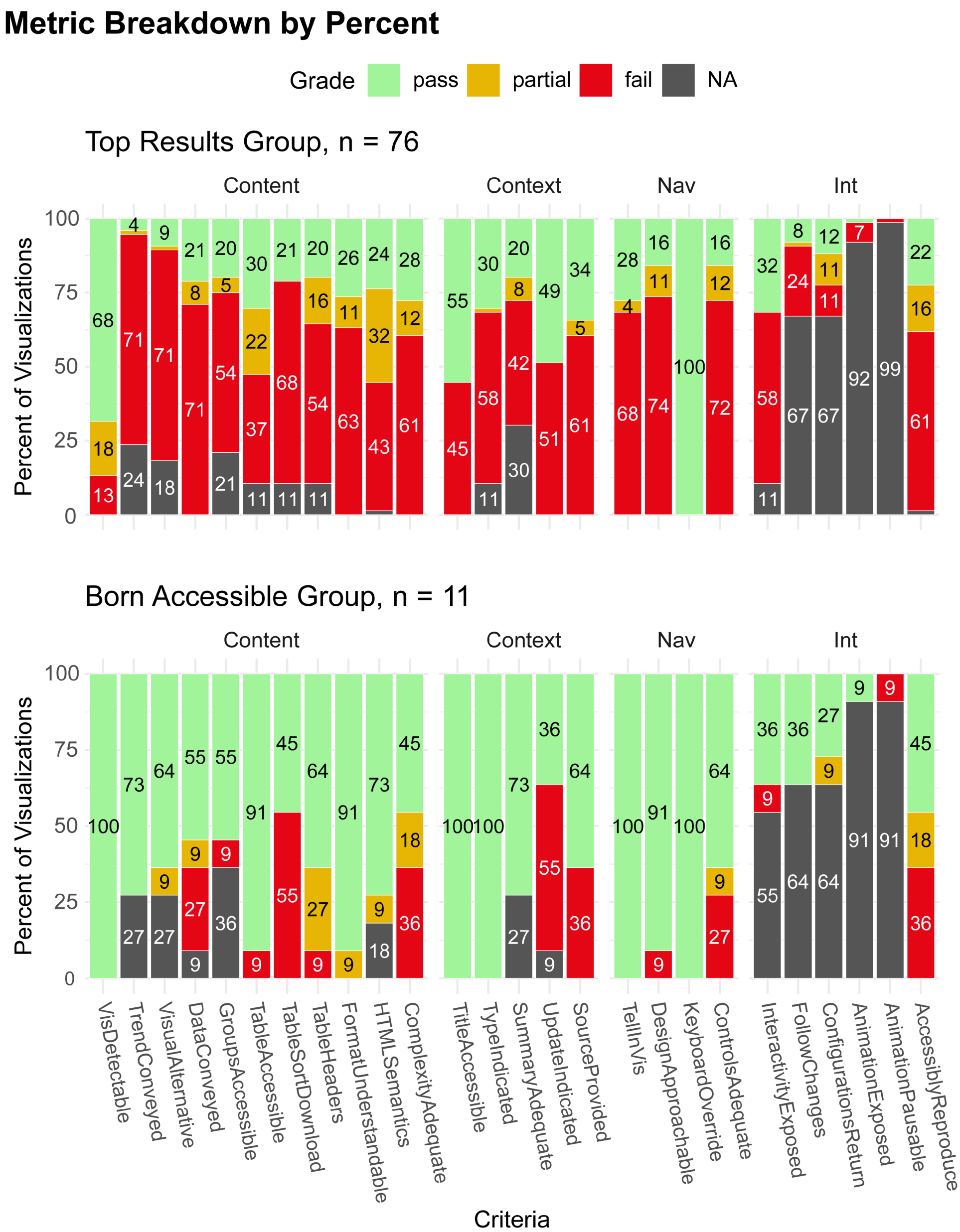

Fig. 4. Pass rates for content, context, navigation, and interactivity criteria were significantly higher for *Born Accessible* visualizations than for *Top Results* visualizations. Appendix Table 10 is a tabular version of this figure.

Thematic coding of auditors' descriptions revealed several areas of challenges for both *Top Results* and *Born Accessible* visualizations, as well as aspects in which *Born Accessible* visualizations performed better. We organize these findings by the criteria categories: content, context, navigation, and interactivity; though many of these considerations have implications across several categories.

Table 2. Pass Rate for Categories of Criteria between the *Top Results* ("TR") and *Born Accessible* ("BA") Groups

Criteria Category	TR Mean	TR SD	TR 95% CI	BA Mean	BA SD	BA 95% CI	χ^2	P
Content	0.24	0.26	[0.18, 0.30]	0.74	0.10	[0.68, 0.81]	32.84	.001
Context	0.41	0.30	[0.34, 0.48]	0.80	0.16	[0.69, 0.90]	16.59	.001
Navigation	0.40	0.25	[0.34, 0.45]	0.89	0.17	[0.77, 1.00]	33.35	.001
Interactivity	0.21	0.29	[0.15, 0.28]	0.52	0.48	[0.20, 0.85]	8.76	.003

3.9.1 Accessibility of Content Measures. Based on our audit, the majority of visualizations in the *Top Results* group did not provide screen reader access to many types of visualization content. Trends (PR = 5%, 3/58), visual features (PR = 12%, 7/60), and specific data points (PR = 21%, 16/76) were largely inaccessible through screen readers. Many visualizations in this group did not provide accessible tables to complement visualizations (PR = 41%, 28/68). Among tables that were provided, 43% (17/40) of them were difficult to find and were encountered accidentally, 40% (16/40) could not be sorted or downloaded in an accessible format, and 38% (15/40) did not articulate row and column headers during navigation.

Many of the visualizations relied on **Scalable Vector Graphics (SVGs)**, a standard markup language that is used for defining two-dimensional graphics. However, auditors observed that those SVGs were not labeled or organized in ways that support understanding through screen readers. A common challenge involved inferring what the SVG elements represented, because groupings appeared arbitrary and it was *"hard to semantically connect it (back) to the groups (A2)."* For example, several visualizations provided all of the numerical values across different axes and categories before any of the axes titles or category labels. Auditors flagged additional challenges with HTML semantic elements, such as improper use of HTML buttons, unlabeled and mislabeled HTML elements, and bad page design, such as the use of *"multiple footer regions (A2)"* or *"navigation buttons...that for which I can't find buttons or links (A2)."*

In contrast to the *Top Results* visualizations, for *Born Accessible* visualizations, most content-based criteria (9/11) had majority pass rates, including ones evaluating the accessibility of trends (PR = 100%, 8/8), visual features (PR = 88%, 7/8), and data points (PR = 60%, 6/10). Auditors particularly appreciated the levels of detail in the summaries provided for these visualizations. Summaries of visualizations that were rated as *"very accessible"* or *"extremely accessible"* often described graphical features, the range of dates covered in the data, statistical and categorical breakdowns, group and overall trends, and information about colors used in the representation.

The *Born Accessible* websites provided information through combinations of textual summaries, tables, and/or sonification. However, auditors described several accessibility barriers with the *Born Accessible* visualizations. These barriers include the lack of access to datapoints for sonifications of trends and the lack of access to trends in provided data tables. Auditors also flagged occasions when data formats were overly verbose. For example, in some cases, the screen reader read table values in "full comma delimited" format (i.e., the screen readers announced "one comma zero zero zero" instead of "one thousand").

3.9.2 Accessibility of Context Measures. Almost half of the visualizations in the *Top Results* group did not provide screen reader access to the visualization title (PR = 55%, 42/76), and the majority of visualizations did not provide easy screen reader access to the visualization type (PR = 34%, 23/68), data source (PR = 26%, 20/76), or when the data had last been updated (PR = 49%, 37/76). When presented, this information was often difficult to find on the page, as it was located away from the visualization, such as in a heading after the visualization, on a different page, or in the summary at the start of the web page.

Auditors also reported that only a small fraction of visualizations provided adequate summaries of the visualization (PR = 28% 15/53) due to a lack of detail describing data structures, overall trends, or important contextual information about the chart. Summaries were sometimes difficult to find on websites, because they were placed after the visualization or required unique keystrokes to access.

In the *Born Accessible* group, all visualizations indicated the title and type of visualization through screen reader accessible text, provided an adequate summary when visual information was present, and the majority of visualizations provided information about the source of information (PR = 64%, 49/76). However, the details in summaries were not consistent across all audited *Born Accessible* websites. Auditors described having access to only detailed numerical values for a few websites and trends without data values in others.

3.9.3 Accessibility of Navigation Measures. Distinguishing between visualizations was a challenge for the majority of *Top Results* visualizations (PR = 28%, 21/76). Auditors described using the heading as a reference for where the visualization started, but for many websites, they had difficulty identifying if the content they were reading was a visualization. They were also often unable to distinguish between grouped visualizations, particularly if located within the same data dashboard. For several visualizations, the screen reader focus jumped from data values of one visualization to that of another without providing any indication for several dashboards. Auditors did not find most visualizations to have approachable designs (PR = 16%, 12/76), which we defined to either be following best practices or providing an adequate explanation of the design. Described design issues include a lack of sufficient textual description about the graph, a lack of instructions on how to use control features of the graph, and difficulty in understanding the meaning and relations in the announced data.

In the *Born Accessible Group*, auditors felt that it was easy to identify when the screen reader focus was in the visualizations for all audited visualizations. All but one visualization were indicated to have an approachable design.

3.9.4 Accessibility of Interactivity Measures. In the *Top Results* group, 89% (68/76) of the visualizations had interactive features, such as sorting, filtering, panning, zooming, highlighting, and changing the display of groups and encodings, but only a fraction of those visualizations (PR = 35%, 24/68) exposed interactive features to the screen readers auditors used. Exposed features tended to include buttons, dropdown links, and sortable columns. Unexposed interactions often included click to highlight, hover to highlight, scroll zoom, and filter interactions. Of the visualizations with interactive features that were exposed, auditors found understanding changes difficult in 25% (6/24) of those visualizations. Challenges described by auditors include the lack of obvious indication that an element was an input element, poor labeling, lack of indication of what changed in the representation, and complete inaccessibility of the control functions using a keyboard.

55% (42/76) of visualizations in the *Born Accessible* group did not have interactive features. However, for those that did, auditors found it easy to follow changes for all of the visualizations. One visualization used sonification to provide overviews of the trendline, but the sonified clip could not be paused after starting.

3.10 Accessibility across Visualization Types

Figure 5 shows overall accessibility ratings auditors gave to different types of visualizations in the *Top Results* and *Born Accessible* groups. In the *Top Results* group, several visualizations were only represented once in the group, including pictorial fraction charts (rated very accessible), bubble maps (rated not at all accessible), and pie charts (rated not at all accessible). Of the remaining visualization types represented by over ≥ 6 visualizations, tables (n = 13) were the only type of

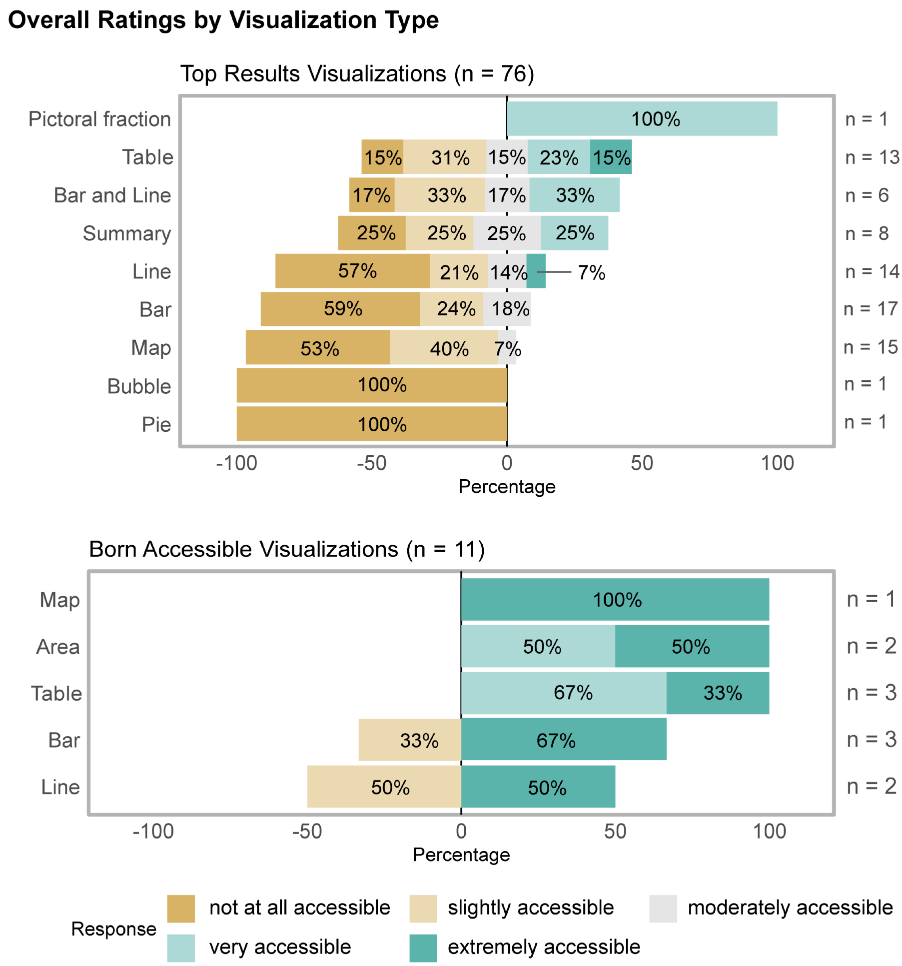

Fig. 5. Overall ratings of different visualization types in *Top Results* and *Born Accessible* visualizations. In the *Top Results* group, auditors rated tables significantly higher than maps.

representation in which the majority of visualization were rated moderately to extremely accessible (54%, 7/13). Many of the inaccessible tables did not follow standard HTML table tag structure, but used specific dashboard libraries or presented information in image format. 50% (3/6) of bar graphs with line overlays, 50% (4/8) of summary panels of spatially oriented statistics, 21% (3/14) of line graphs, 18% (3/17) of bar graphs, and 7% (1/15) of maps were rated moderately to extremely accessible.

With a much smaller sample size, 100% of maps (1/1), area graphs (2/2), and tables (3/3) in the *Born Accessible* group were rated to be very or extremely accessible. 67% (2/3) of bar graphs and 50% (1/2) of line graphs were also rated as very or extremely accessible. Six of these graphs allowed users to explore the data through sonification.

Visualization type was a significant predictor of auditor rating ($\chi^2(5) = 17.04$, P = .004) for the major groups of visualization types ($n \geq 6$) in the *Top Results* group. Post hoc pairwise comparisons (with a Bonferroni adjusted alpha level of 0.0033) showed significant differences in overall accessibility ratings comparing tables with bar graphs (z.ratio = 2.97, P = .003), maps (z.ratio = 2.97,

Table 3. Mean Pass Rates of Visualization Types in the *Top Results* Group

(a) Content Criteria

Visualization Type	Mean	SD	95% CI
Bar (n = 17)	0.18	0.19	[0.08, 0.27]
Bar and Line (n = 6)	0.23	0.20	[0.02, 0.45]
Line (n = 11)	0.19	0.20	[0.07, 0.30]
Map (n = 15)	0.09	0.14	[0.01, 0.16]
Summary (n = 8)	0.38	0.36	[0.08, 0.68]
Table (n = 13)	0.45	0.32	[0.25, 0.65]

(b) Context Criteria

Visualization Type	Mean	SD	95% CI
Bar (n = 17)	0.31	0.22	[0.19, 0.42]
Bar and Line (n = 6)	0.57	0.39	[0.16, 0.97]
Line (n = 11)	0.39	0.25	[0.24, 0.53]
Map (n = 15)	0.37	0.31	[0.19, 0.54]
Summary (n = 8)	0.44	0.43	[0.08, 0.79]
Table (n = 13)	0.53	0.31	[0.35, 0.72]

(c) Navigation Criteria

Visualization Type	Mean	SD	95% CI
Bar (n = 17)	0.35	0.15	[0.27, 0.43]
Bar and Line (n = 6)	0.50	0.32	[0.17, 0.83]
Line (n = 11)	0.32	0.21	[0.20, 0.44]
Map (n = 15)	0.27	0.06	[0.23, 0.30]
Summary (n = 8)	0.47	0.31	[0.21, 0.73]
Table (n = 13)	0.58	0.31	[0.39, 0.77]

(d) Interactivity Criteria

Visualization Type	Mean	SD	95% CI
Bar (n = 17)	0.18	0.25	[0.05, 0.30]
Bar and Line (n = 6)	0.25	0.22	[0.02, 0.48]
Line (n = 11)	0.20	0.30	[0.02, 0.37]
Map (n = 15)	0.24	0.24	[0.11, 0.38]
Summary (n = 8)	0.19	0.37	[−0.12, 0.50]
Table (n = 13)	0.25	0.41	[0.00, 0.50]

P < .003), and marginally significant differences between tables and line graphs (z.ratio = 2.81, P = .005). No other pairwise comparisons were significant. For significant pairwise comparisons, ordinal logistic regressions predicted a 9-fold likelihood of rating increase for tables compared bar graphs (OR = 9.26, 95% CI (40.28, 2.13)) and a 9-fold likelihood of rating increase for tables compared to maps (OR = 9.10, 95% CI (39.04, 2.12)).

Figure 6 shows the proportion of pass, partial, fail, and NA grades for major groups of visualization types in the *Top Results* group. Visualization type was also a significant predictor on the proportion of pass grades across content ($\chi^2(5)$ = 30.05, P = .001) and navigation criteria ($\chi^2(5)$ = 17.27, P = .004), but not context ($\chi^2(5)$ = 5.22, P = .389) and interactivity ($\chi^2(5)$ = 0.78, P = .979) criteria for major groups of visualization. Post hoc pairwise comparisons (with a Bonferroni adjusted alpha level of 0.0033) showed significant differences between tables and maps for both content (t.ratio(65.5) = 3.99, P < .001) and navigation (t.ratio(66.8) = 3.03, P = .004) criteria. For content criteria, marginally significant differences was observed between tables and bar graphs (t.ratio(66.8) = 3.03, P = .004) and between tables and line graphs (t.ratio(65.2) = 2.88, P = .005). For navigation criteria, marginally significant differences were observed between tables and line graphs (t.ratio(65.1) = 3.01, P = .004). Table 3 shows the the mean, standard deviation, and confidence intervals for pass rates between the visualization types for the criteria categories.

3.10.1 Tables. Auditors generally found it easier to navigate to tables, because some screen readers provide default shortcuts for navigating to tables. Auditors also found it easy to tell when the screen reader focus was inside of a table. However, many tables in the *Top Results* group contained poorly labeled elements and lacked a clear reading order that resulted in significant time and effort required to discern what the data communicated. In comparison, auditors found all tables (n = 3) in the *Born Accessible* group to be easy to use. They were able to move around the grid using announced data, headers, and labels as references when reading specific data points.

Auditor comments also highlight that tables in both groups of visualizations did not explicitly convey trend, type of visualization, and design. As A2 described, *"only the number of rows/columns in the table are announced, and not a summary of what's in the table,"* and that the trend in the data was *"discernable [sic] but requires a lot more work"* when reading a table. However, if presented with an informative description in the summary and announcements that supported navigation in the grid, then tables were described by auditors to be more accessible.

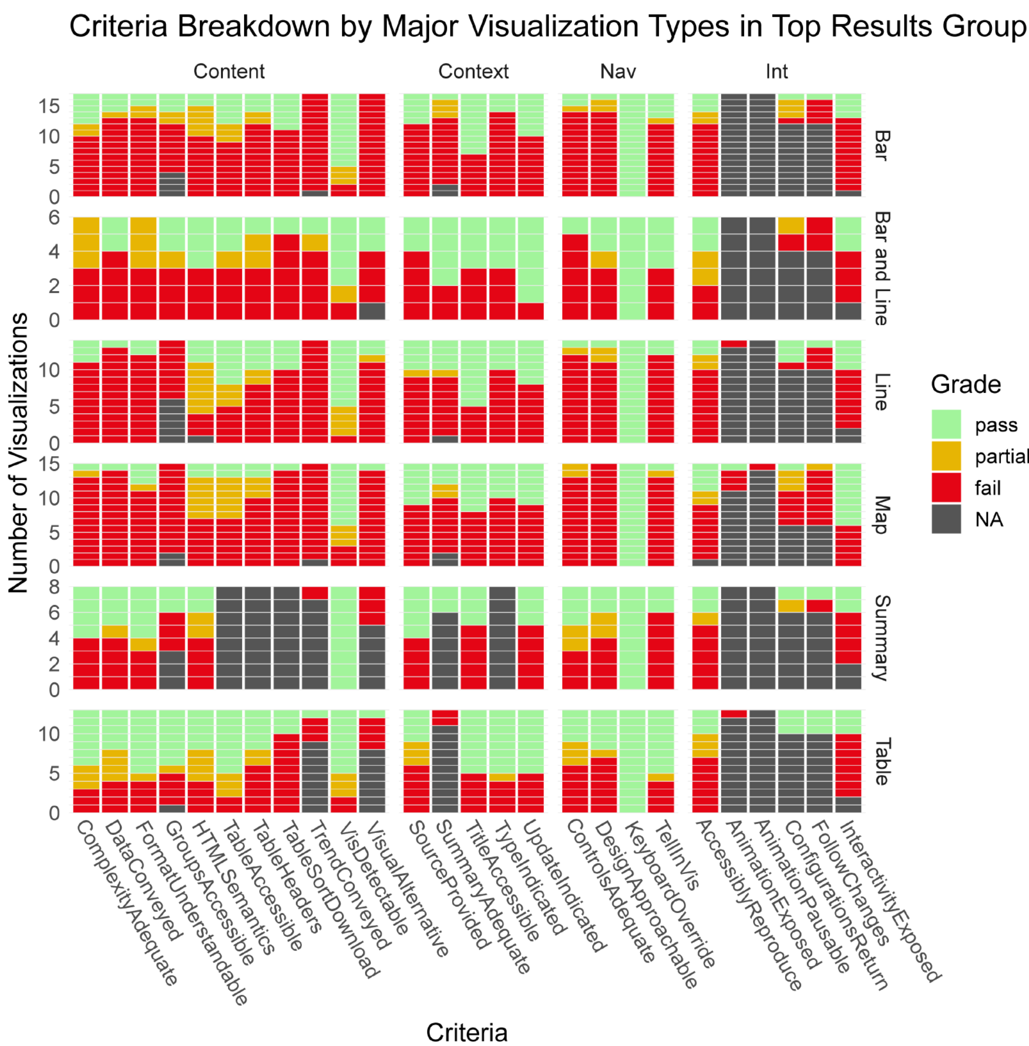

Fig. 6. Proportion of pass, partial, fail, and NA grades across all criteria for major groups of visualization types in the *Top Results* group.

3.10.2 Maps. None of the audited maps in both groups directly conveyed complexity in the data, higher-level patterns, or supported filtering and sorting interactions. Users could not access specific data points when navigating maps using keyboards. Additionally, controls provided to manipulate the maps lacked explanations about what they do. Overall, the visual benefits of map-based data representations did not translate to screen readers.

However, in the *Born Accessible* map, A2 felt that the summary description, high-level statistics, supporting table, and small sample size of data made the information depicted on the map extremely accessible.

3.10.3 Line Graphs. Except for Microsoft BI-based line graphs, auditors could not interact with any line graphs from the *Top Results* websites, and it was easy to miss the visualization altogether. Auditors had to rely on the summaries and supporting data to learn about the details in the visualization. *Born Accessible* visualizations either provided more in-depth summaries of the line graphs or used sonification to make trends more accessible.

3.10.4 Bar Graphs. For bar graphs, auditors struggled to access bar elements of the graph. Auditors often described using implicit information such as position and order of announcement to infer meaning that was not directly available for data points in bar and line graphs. As A3 described, *"groups and values are available but data is not semantically connected to group and I have to depend on positioning of the [bars] to understand which value is connected to which group."* In comparison, tables provided direct access to the data points and their spatial relation in the grid.

3.11 Accessibility Considerations for Visualization Implementations

In this section, we highlight several additional accessibility considerations synthesized from descriptions auditors provided while completing the audit. These considerations were developed through the qualitative analysis methodology described in Section 3.7.

3.11.1 The Need to Make the Presence of Visualizations Explicit. Information about the presence of visualizations was often not explicitly made available to screen reader users. Several visualizations took time to load, but the loading process was only perceivable through a visual icon. None of the visualization was accessible while loading, and no screen reader notification was provided after loading. Auditors *"[had] to explore to discover the data (A3)"* and perceive its presence. Several other visualizations were hidden in hierarchical structures that were much more apparent visually. Auditors had to spend time reading over all the website elements until they reached the specific element to access the visualization. A3 described that *"A screen reader user would not be able to find this graph; I had to use vision to select the right things; 'vaccinations' main tab, then [the] 'who is getting vaccinated' button, then [the] 'age' button."* A few visualizations were not perceivable through screen reader at all. While designers can justify such measures by arguing this improves overall readability of the web page, it also exacerbates the access gap between screen reader and sighted users. As A2 described, *"the creators knew enough about accessibility to be dangerous."*

3.11.2 The Need for Screen Reader Access to Implicit Visual and Spatial Information. Visual representations make use of spatial properties to group and connect information. Screen readers are not spatial, but rely on reading order, navigation structures, and explicit wording to communicate groupings and make connections between values and labels. Auditors observed how many of the websites rated poorly for data accessibility do not communicate these spatial relationships to screen reader users, resulting in disorientation and confusion, both when exploring within and navigating between visualizations.

When exploring within visualizations, auditors described having to make inferences about groupings between labels and values based on reading order, which sometimes led to misinterpretation of these groupings altogether, especially if the reading order is illogical or inconsistent. For example, one visualization presented clusters of statistics with their labels underneath. When using the screen reader *"the order of the group name and its values are read in reverse order...it is a little difficult to understand immediately (A2)."* When several of these groupings were presented in sequence, A2 described how they initially associated the name of one group with the value of another.

When reading between visualizations, data dashboards often use spacing and visual elements to distinguish between multiple visualizations. Auditors described how for several websites with multiple visualizations, no delimiter was provided to screen reader users, making it difficult for users to identify which visualization the data belongs to. As A2 described, *"I have to rely on the* *headings and titles above the graphs for orientation. There are multiple graphs on the page and they all look similar without the reliance I mentioned."*

3.11.3 The Need for Orientation and Guidance Cues for Screen Readers to Navigate Visualizations in the Context of Web Pages. A common analogy relates the screen reader experience to looking at a screen through a straw because only a small portion of the page is read at a time. Additionally, the location of the screen reader focus is often not conveyed. Together, these limitations makes situating screen reader focus within the context of the web page and understanding changes outside of the screen reader focus difficult. As A2 explained *"it was easy to get lost due to a lack of cues to help orienting."* Navigation was especially challenging, as audited websites often contained multiple visualizations across many sections that may require hundreds of interactions to read through. However, websites that conveyed information through extensive passages without an overall hierarchy posed additional barriers. A2 described how it was easy to get lost in the list, but was afraid of skipping past it and missing crucial information.

3.11.4 The Need for Explicit Connection between Visualizations and Surrounding Contextual Information. Information about the data source, update frequency, download options, contextual summaries, and tabular alternatives were often not grouped with the visualization, but scattered throughout the page and difficult to access and associate with the visualization when using a screen reader. In one example, A2 *"had to search through all the ads, frames and other material. [They] found the table by accident when [they] felt something was missing in the visualization, so [they] explored the entire page."* Even when the information is found, its relationship to the visualizations are often unclear. In another example, A2 described how *"there is a summary of the data...but the relationship to the data is implied and [do] not have a semantic association."* In content-dense web pages, knowing where contextual and supplementary information is located and what visualization they are associated with is often difficult, if not impossible.

3.11.5 Infrastructural Barriers to Access. Auditors observed infrastructural challenges that also increased the barrier for accessing and understanding visualizations. These infrastructural challenges include requiring installation of specific software or add-ons to consume the visualization and requiring users to learn unique sets of keyboard interaction techniques to access and interact with visualizations. A3 described how they *"had to research keys I could use to enter the Microsoft Power BI window. Otherwise none of the data could be accessed. There is no help file or information on the page. I had to do an internet search on Power BI."* Pop-up blockers also prevented A1 from perceiving the accessibility overlay of one website. Other auditors described how the accessibility overlay did not change the presentation of already inaccessible visualizations to their screen readers, despite claiming to "adjust the website to be compatible with screen readers."

3.12 Audit Takeaways

Findings from the audit reveal that among top-ranked websites returned by *"COVID-19 Data"* Google searches, few of the audited visualizations provide screen reader access to content, context, effective navigation, and interactive features. Many of the *Top Results* visualizations do not convey any data content through screen reader access. Several visualizations were conveyed through dynamic dashboards produced from libraries without screen reader support, and most do not provide adequate summaries or access to tables of the underlying data. The general inaccessibility of these high-visibility websites across multiple organizations and visualization types during the COVID-19 pandemic supports prior reports of data inaccessibility [39, 61, 66, 73, 73].

We find that overall ratings and criteria performance for *Born Accessible* visualizations were significantly higher than for *Top Results* websites. *Born Accessible* visualizations often provided detailed high-level summaries of trends, tables of specific data values, additional modalities of consumption (e.g., sonification), delineations between different sections of information (both in the visualization and corresponding web pages), accessible references to the surrounding content, or some combination thereof. These *Born Accessible* websites demonstrate improved accessibility of visualizations; however, many have yet to support a level of interactivity that prior work suggests could enable users to gain broader levels of insight [20, 68].

Of the major groups of visualization types audited, tables, particularly ones that used standard HTML tagging, were found to be most accessible. Pairwise comparisons reveal marginally significant to significant differences of tables when compared to bar graphs, line graphs, and maps. Screen reader support for line graphs, bar graphs, and maps is less standardized, which places the onus on content creators to be intentional about including accessibility features.

Some of the *Born Accessible* visualizations provided in-depth summary descriptions of graphs and maps, while other visualizations and libraries presented SVG elements in a structured order with axes labels. We find that this type of presentation, which resembles screen reader experiences navigating through a table, does not provide the rich and expressive high-level information expressed through maps and graphs. The accessibility of maps, line graphs, and bar graphs are known challenges in the research literature [38], and our audit demonstrates how these challenges are reflected in practice. There is a need to integrate qualities identified from other modalities, such as haptics and sound [92, 121], into common visualization tools and libraries for content creators to use.

We identified several additional considerations during the audit, which include (1) making evident the presence of visualizations, (2) providing access to implicit spatial information, (3) providing orientation and guidance cues for visualizations in the context of web pages, (4) connecting visualizations and their surrounding context, and (5) reducing infrastructural barriers to access. The last consideration highlights how the burden still often falls on screen reader users themselves to request data in accessible formats. While prior work has identified similar challenges relating to web accessibility [72] and online data visualizations [102], our findings emphasize the need to consider the screen reader experience while accessing visualizations within the context of the web page structure.

3.13 Audit Limitations

There were several limitations to this audit. First, web accessibility is known to vary by screen reader and browser combination [59], and auditors used different screen readers and browsers to perform the audit. The overall grades and criteria ratings that auditors provided of the visualizations likely represent between the worst-case and best-case screen-reader-to-browser combination for each visualization. As many different screen readers and browsers are used in practice, these results may provide a better reflection of users' general experiences interacting with visualizations on the web.

Second, non-probabilistic judgement sampling was used to compile the visualizations in the *Top Results* group. While the sample may not be a direct reflection of visualizations people encounter while trying to access data-driven information about the pandemic, they represent a set of high-visibility and high-relevance websites that provide information about the pandemic.

Third, two of the auditors performing the audit are sighted, which may provide an advantage for finding features to test through their screen reader. To mitigate this, auditors provided descriptions of cases when the use of vision was important for discovering those features. Researchers also worked with a blind accessibility specialist to eliminate the dependence on vision for completing the audit and provided information about pertinent visual information both through alt text and video-conference to the blind auditor. While pairwise inter-rate reliability ratings only fell within

0.07 of each other, we do note that the inter-rater reliability score between the two sighted auditors was the highest.

Finally, the audit was performed from the perspective of web accessibility specialists with years of professional experience using screen readers, all of whom expressed frustration at the current state of visualization accessibility on the web after completing the audit. In multiple cases, auditors inspected the source code or leveraged multiple screen reader techniques to gain a better understanding of whether information was present and how it was organized. As many of the auditors pointed out, investigating the experiences of everyday screen reader users could reveal many additional challenges that extend from how users seek access to and interact with data-driven information online. We investigate these challenges through a survey and contextual inquiry described in the following sections.

4 SURVEY OF DATA ACCESSIBILITY NEEDS, PREFERENCES, AND EXPERIENCES

To investigate BVI user's preferences and current experiences when accessing data-driven media on the web [RQ2], we conducted an IRB-approved online survey between June–July 2020 through Qualtrics. While the audit focused is on the accessibility of how visualizations are implemented, the survey focused on the experiences of screen reader users. Grounding audits with observations of users' interactions and workflows are a powerful way to reveal important accessibility considerations that may not be obvious when assessing web features in isolation [57].

The survey was organized into five sections: demographics (9 questions), data access methods and modality preferences (10), data and web accessibility (8), access to COVID-19 sources of information (14), and graph concepts (6). Questions included both Likert questionnaire items (unipolar and bipolar scales) and free form responses when applicable.

Non-probability-based sampling was used to recruit survey respondents. We circulated an IRB-approved announcement through mailing lists managed by local and nationwide blindness organizations in the US. The eligibility criteria included: being at least 18 years of age, identifying as blind or visually impaired, and being a fluent speaker of English. To accommodate a flexible number of respondents, respondents could opt-in to a raffle for a chance to win one of 20 gift cards with a 15 USD value. All questions were optional and survey completion was not necessary to enter the raffle.

4.1 Survey Data Analysis

The overall number of registered responses (171) was filtered down to 127 total responses to remove responses that were empty or did not meet the eligibility criteria. For Likert scale and categorical questions with short responses, we used descriptive statistics to summarize frequency distributions of those responses.

To analyze responses to open-ended questions, we used reflexive **thematic analysis (TA)** [29] to construct overarching themes. Responses were coded by at least two authors through four rounds. The first round focused on what people said (semantic) and the underpinning assumptions (latent) to deconstruct responses into singular observations. Authors validated each others' coding in the second round. In the third round, the two first authors used affinity diagrams to group codes and inductively generate patterns and initial themes that relate to the primary research goals. The themes were discussed and iteratively refined among the broader research team in the fourth round.

4.2 Survey Participants

Participant ages ranged from 18 to 84 years old, with a median age of 40, and a mean of 42. 68% (86/127) identified as female, 30% (38/127) as male, and 2% (3/127) preferred not to disclose information about gender. When describing their level of vision, 43% (54/127) described themselves as totally blind, 32% (40/127) as legally blind, 20% (25/127) as having some shape or light perception, and 6% (8/127) described having very low vision. All users (127/127, 100%) relied on a screen reader as their primary assistive technology for accessing information on the web. Additionally, 19% (24/127) used their screen reader in combination with screen-magnifying technologies.

4.3 Survey Findings

4.3.1 Importance of Access to Data. Figure 7(a) shows that 63% of respondents answered positively that having access to data-driven news articles is very important (26/126, 21%) to extremely important (54/126, 43%). Similarly, 65% of respondents reported encountering data-driven media regularly on a weekly (51/127, 40%) to daily basis (31/127, 24%), and no participant reported not having encountered data-driven media (Figure 7(b)). In contrast to both of these reports, 73% of respondents did not agree that data-driven media encountered was typically accessible with their use of assistive technology, with 44% (56/127) of responses in the strongly disagree category (Figure 7(c)).

Most issues reported around incompatibility with users' choice of screen reader have been documented by prior literature throughout the past two decades [25, 72, 87, 90] or addressed by accessibility guidelines that are available to content creators (e.g., WCAG [7], NCAM [56], Section 508 [4]). Respondents described that alt text and tabular data were often missing despite being considered best practice, in addition to insufficient image descriptions and table formatting issues.

4.3.2 Modality Preferences & Experience. When asked about preferred methods for accessing data graphics, the most frequently indicated method was through tactile graphics (n = 50), followed by Braille (n = 25), then audio (n = 15), screen reader (n = 7), and sighted assistance (n = 4). However, when asked about current methods of accessing data graphics, the most frequently indicated method was through screen readers (n = 20), followed by Braille (n = 18), then audio and sound (n = 15), sighted assistance (n = 14), and tactile graphics (n = 5) (Figure 9).

The majority of respondents agreed that both tactile (117/126, 93%) and audio-based methods (105/127, 83%) are helpful for *"exploring data-driven graphics"* (Figure 8(a)). The proportion of respondents who strongly agreed that tactile graphics are helpful (75/126, 59%) is higher than for audio-based methods (33/127, 26%).

55% (70/127) of respondents reported their expertise in interpreting data through tactile graphics in the Competent to Expert range, while 23% (29/125) of participants reported the same categories for audio-based methods (Figure 8(b)). However, when asked how regularly either modality is used to explore data, both tactile (117/127, 92%) and audio (117/125, 94%) were reported as not frequently used (Figure 8(c)).

We asked respondents what tasks they would use tactile and audio-based maps, graphs, and charts for if they were readily available for little to no charge. Figure 10 shows free-response answers coded by categories. *Orientation and mobility*-related tasks was the most popular response for both modalities (e.g., understanding layouts, support route navigation), followed by *data-related media* (e.g., news, finance, public health, scientific journals), then *education related* (e.g., understanding academic subjects, learning instructions), *work related* (e.g., managing timelines and people, completing work-related tasks), and *personal tasks* (e.g., personal finance, personal health), and finally tasks related to *art and music* (e.g., drawing, knitting, design, music).

4.3.3 What Screen Reader Users Enjoy, Find Challenging, and Recommend Improving. We asked respondents what aspects of data-driven information screen reader they enjoy. They commented on several areas, which include having access to raw data to verify information and draw their own conclusion (15/85, 18%), good descriptive text summarizing the information (11/85, 13%), accessible pages with proper style, content, and layout (6/85, 7%), and being able to provide transformations to the data (4/85, 5%). Frequently described challenges that respondents indicated include the lack

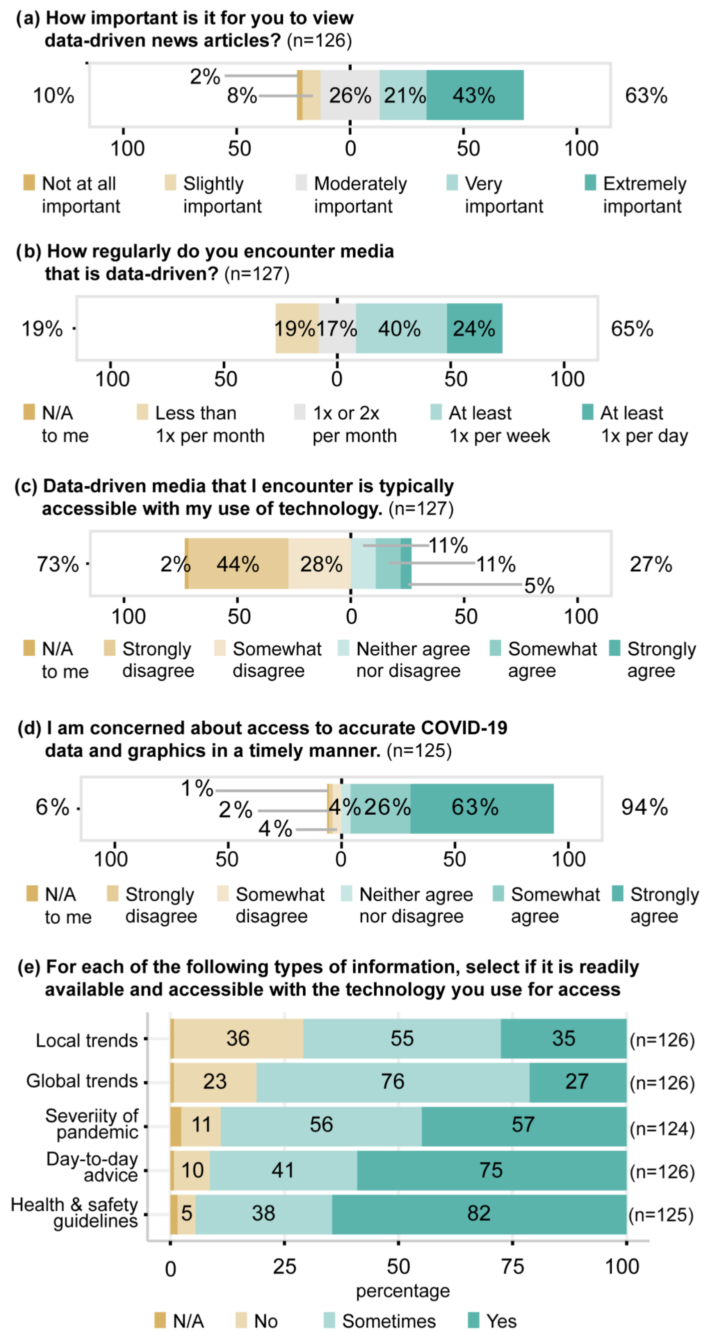

Fig. 7. The majority of survey respondents reported (a) access to data-driven new articles is very or extremely important, (b) they encounter data-driven media regularly or all the time, (c) they encounter data-driven media that is typically not accessible with their use of technology, and (d) they have concerns about accessing local COVID-19 data and graphics in a timely manner. (e) Respondents reported local trends and global trends as most commonly inaccessible types of COVID-19 information.

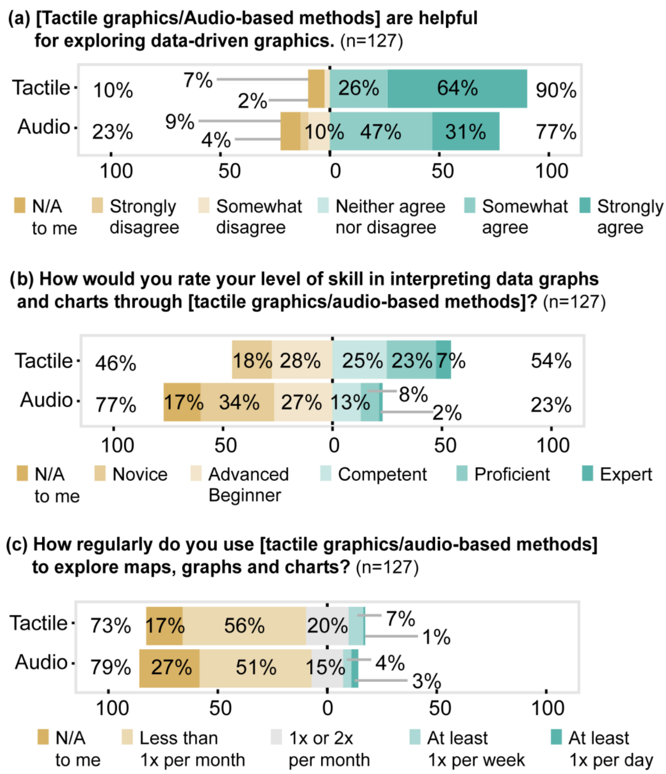

Fig. 8. The majority of survey respondents indicate that (a) tactile and audio-based methods are helpful for exploring data-driven graphics, (b) that their level of skill in interpreting data graphs and charts is competent or above for tactile but the same was not indicated for audio-based methods, and (c) tactile and audio-based methods are not regularly used to explore maps, graphs, and charts.

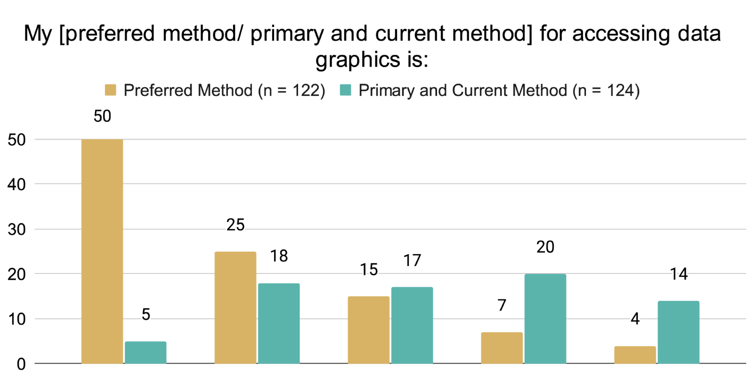

Fig. 9. Preferred and primary ways of access: 50 survey respondents indicate that tactile methods were preferred for accessing data graphics, but only 5 respondents indicate that tactile methods were primarily used.

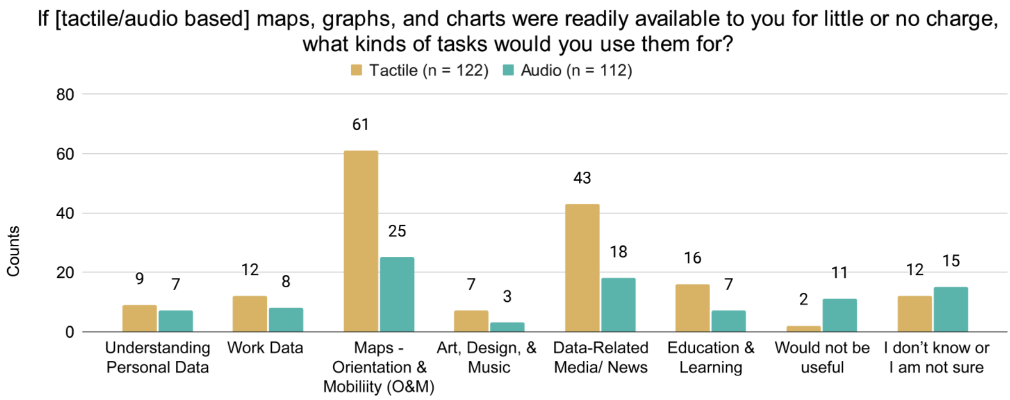

Fig. 10. Uses of tactile and audio-based spatial graphics: respondents indicated a variety of use cases for maps, graphs, and charts if readily available and affordable.

of good descriptions (20/93, 22%), the lack of compatibility with their use of assistive technology (17/93, 18%), poorly formatted tables that are difficult to navigate (12/93, 13%), and the lack of supporting context for data-driven information. Areas in need of improvement include greater access to high-quality descriptive text (28/85, 33%), alternative modalities of consumption (19/85, 22%), raw data (6/85 7%), and screen reader compatible content (6/85 7%).

4.3.4 Concerns about Access to Timely COVID-19 Information. In regards to consumption of COVID-19 information, 94% (117/125) agreed they have concerns about accessing accurate information in a timely manner, with 63% (79/125) of responses in the Strongly Agree category (Figure 7(d)). 98 of 125 respondents provided commentary on the types of information to which access could be improved. The majority of responses related to improving access to data-driven graphs and statistics (77/98, 79%). For example, respondents commented on the lack of access to pandemic progression trends particularly in their local community, comprehensive descriptions of infographics and informative videos, and location and testing hotspots typically available as visual maps. Other respondents commented on needing "better access to everything" (6/98, 6%), more clear guidelines and advice (6/98, 6%), "not sure" (8/98, 8%), and none (1/98, 1%). When asked to rank the accessibility of types of information, respondents ranked *global trends* and *local trends* as most commonly inaccessible, followed by information on the *severity of the pandemic*, *day-to-day advice*, and *health and safety guidelines* (Figure 7(e)).

To address access barriers encountered through mainstream channels, respondents commented on a number of approaches they took, such as:

(1) looking for accessibility branded COVID-19 data dashboards [9, 75] and news websites (e.g., NFB Newsline) created to meet the needs of the BVI community where *"the data has been returned to its numeric form" and "text format"* (15/52, 29%);
(2) learning to interpret data using sonification techniques and tools [14] to *"access graphics and chart[s]"* (13/52, 25%);
(3) listening more to podcasts and news videos where overall trends are *"better described"* (11/52, 21%);
(4) relying more on live visual interpretation services (e.g., AIRA) or help from relatives to *"describe the data to me"* (8/52, 15%);
(5) looking for download access to raw tabular data (5/52, 10%).

4.4 Survey Takeaways

The experiences reported by BVI users in our survey provide insight into the broad impact that accessibility gaps identified in the audit can have. Survey findings revealed that while BVI users place high importance on the consumption of data-driven media, several barriers prevent proper access. During this time of crisis, 94% of survey respondents agreed they had concerns about accessing accurate COVID-19 data and related graphics in a timely manner, while only 16% of respondents agreed that the data-driven media they encounter is typically accessible with their use of technology. Several studies conducted around the same time validate these observations [62, 102]. Particularly, respondents indicated a lack of access to up-to-date trends and geospatial data often used to illustrate the progression of disease in local communities or locations for access to testing, a gap also identified from the audit. Needs that respondents expressed include good summary descriptions, tables for drawing their own conclusions, alternative audio and tactile methods of consumption, and improved screen reader compatibility, which were also common issues identified in our accessibility audit (Section 3). While tactile graphics are infrequently used to consume data graphics, they are most frequently described as the preferred method. In contrast, screen readers are the most commonly described access method. Taken together, these results affirm the need to improve data experiences for screen readers, all the while expanding the availability of tactile modes of exploration.

Education and training for BVI users to assist them in interpreting data graphs and charts through tactile and audio-based graphics also needs to be improved. 54% of respondents indicated that they were at least competent interpreting data graphs and charts through tactile graphics, compared to only 23% for audio-based methods. Over 77% somewhat or strongly agreed that these methods are helpful. The lack of experience users may have with consuming data through audio-based methods should be considered when implementing audio-based tools such as sonification.

4.5 Survey Limitations

While our online survey reached 127 BVI people and provided an informative sample of perspectives, there are limitations when considering the findings in light of our sample and study design. First, the range of visual abilities is diverse, and users rely on different assistive technologies in different ways. All respondents were screen reader users. Second, the space of data visualization and journalism on the web is broad. The perspectives we heard from users through the survey may be limited by what users have been aware of or encountered. For example, we did not hear from any survey respondents about their interaction with data graphics using SVG elements, which have become prevalent with interactive web visualizations. It might be that given the lack of accessibility in this domain, users do not seek out this particular type of content. Third, self-selection bias could have affected the range of perspectives captured by our study. Respondents that opted to participate might have a particular interest in the topic. Several respondents took alternative approaches when encountering access barriers through mainstream channels, such as listening to podcasts and videos where overall trends are "better described," relying more on visual interpretation services, looking to access raw tabular data, learning to use sonification tools, and looking for websites with more accessible means to access information. We investigated how well these sources fulfill BVI peoples' needs in the contextual inquiry described in the next part of the study.

5 CONTEXTUAL INQUIRY WITH *BORN ACCESSIBLE* WEBSITES

To investigate how accessible data representations on the web address users' access needs, we recruited 12 survey participants to carry out a contextual inquiry. We were also interested in determining how well websites help users navigate, interpret, and gain insights from the data [RQ3];

and understanding practical challenges that limit BVI users' access and use of data representations on the web [RQ4]. In contrast to the survey (Section 4), which reports on broad experiences accessing data-driven content, the contextual inquiry provides a window into specific interactions users have with data. The more in-depth ethnographic approach taken through the contextual inquiry provides a lens to understand not only specific accessibility implementations but also how they are impacted by specific users' behaviors and background [96].

The pandemic created a unique situation where numerous websites were developed to meet the needs of BVI users by providing alternative representations to information that was otherwise more challenging to access through mainstream data trackers [39]. These *Born Accessible* websites all provided access to similar datasets tracking the progression of disease but leveraged different representations and modalities.

Through an IRB-approved study, we made use of these in-the-wild *Born Accessible* COVID-19 websites as well as public interest in the pandemic as a *site* to observe whether there are remaining challenges that limit BVI users' engagement with data, even with websites that were *Born Accessible*, and if so, understand how they could be improved.

5.1 Contextual Inquiry Procedure

The study was conducted remotely over Zoom and scheduled for 90 minutes. Throughout the contextual inquiry, we used a Synchronized Concurrent Think-Aloud Protocol [113] to understand participants' thought processes and actions. Participants shared their screen and audio and used Google Chrome.

First, participants completed a walkthrough of websites they had previously visited to access information about the pandemic. If participants reported any website(s), then we asked them to access the website, reflect on the last time they had accessed it, and show us what information they looked for. Appendix Table 12 summarizes accessibility features present in all the websites visited in the contextual inquiry.

To have a common ground across observations, we also asked participants to visit a set of three predetermined *Born Accessible* COVID-19 tracking websites, which was a subset of the *Born Accessible* group from the accessibility audit (Section 3). We describe our website selection process in the next section (Section 5.2).

For the observation, we provided participants an open-ended prompt following North et al. [89], which encouraged participants to interact with different aspects of the data in the way they chose and reflect on the insights they received. Constructed to be simple to understand and applicable across all three websites, the prompt asked participants to use each website to consider the severity of the COVID-19 pandemic in two predetermined U.S. states and make a decision on which one they would choose to relocate to. The prompt was repeated for each of the three websites but with different states to consider. Participants explored each website to collect and reflect on information until they made a decision. After reaching a decision, we asked participants open-ended questions about their experience and strategies used to understand the information available.

5.2 Selection of *Born Accessible* COVID-19 Websites

To make observations of BVI users' access to data on the web, we predetermined a set of three *Born Accessible* websites that were branded as accessible and provided a variety of alternative representations related to the tracking of COVID-19 data (Figure 11). These websites were primarily designed with screen reader accessibility in mind. In particular, we focused on representations mentioned most frequently by survey respondents as important: tabular data, chart descriptions, and sonification of graphs. In the selection of these websites, we reviewed survey responses for websites frequently indicated by respondents for accessing information about COVID-19. Websites were

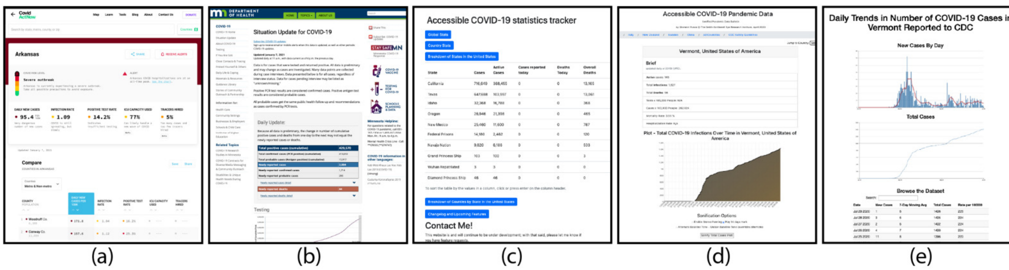

Fig. 11. A selection of COVID-19 websites and data dashboards visited by participants. (a) and (b) were examples of sites that individual participants used frequently (COVID Tracking Project [11], MN Department of Health Situation Update [13]). (c), (d), and (e) were branded as accessible and explored by all participants for the contextual inquiry (CVStats [75], covid.ski [9], AccessibleData [2]). Larger screenshots of the websites are in Appendix Figure 14.

coded by their accessibility features and representations (Appendix Table 12). Websites provided either summary statistics and/or timeseries data showing the progression of key statistics over time (e.g., daily new cases, total deaths). Timeseries charts covered similar dates but differed in trends across different states.

The two *Born Accessible* websites most often mentioned by survey respondents were *CVStats.net* [75] and *COVID.SKI* [9], which presented data using tables and sonification, respectively. These websites matched two methods respondents recommended for interacting with data on the web. Our website coding revealed that none of the websites provided comprehensive descriptions as suggested by guidelines for data graphics [56] and indicated as important by respondents. Thus, in addition to observing how users navigate through *CVStats.net* and *COVID.SKI*, we created a third website, *Accessible COVID-19 Data* [8], that presented data with alt text and tables following guidelines for data-related graphics [56]. To ensure a standardized word usage and structure in the descriptions, we used a template-based description generator for data charts [84].

5.3 Contextual Inquiry Data analysis

We employed a reflexive thematic analysis [29] to analyze the collected data consisting of notes and verbatim transcriptions. Data extracts were separated into single observations and coded using both semantic and latent approaches. Initial codes were framed as processes that lead to data insights (overview, adjust, detect pattern, match mental model) [129]. Additional codes were iteratively added, which relate to usability observations, accessibility observations, and participant values. Next, codes were grouped by their shared meaning to generate sub-themes followed by overarching themes. To ensure credibility and exploration of various aspects of the data, repeated discussions and debriefings were conducted among members of the research team. To report on the themes, we use supporting extracts both illustratively and analytically and note participants from whom the extracts were collected from.

5.4 Contextual Inquiry Participants

Participants were recruited from the pool of survey respondents who indicated interest in being contacted for a follow-up interview. From 103 participants who indicated interest, 36 were randomly selected and contacted. 16 participants followed up and 12 participated in the interviews. Participants received a 30 USD Amazon gift card as compensation for their time.

Participant ages ranged from 18 to 74 years, with a median age of 40, and a mean age of 42. Seven (58%) participants self-identified as female, and five (42%) identified as male. The majority of participants used JAWS (9/12, 75%) as their primary screen reader, followed by NVDA (2/12, 17%), and VoiceOver (1/12, 8%). Five (42%) participants also used a Braille display. Participants' self-reported expertise in tactile graphics ranged from Advanced Beginner to Expert. Participants' self-reported expertise in audio graphics ranged from No Experience to Expert. Appendix Table 11 contains a breakdown of demographics by participant.

5.5 Contextual Inquiry Findings

We organize our findings to first discuss observations specific to the impact of COVID-19 information inaccessibility and participants' strategies to overcome any access barriers. We then discuss general themes based on participants' experiences and preferences towards accessing and gaining insights from data representations online. The findings are grouped as follows:

- **Section 5.6:** *Efforts to access COVID-19 data*: how users accessed timely information and addressed inaccessibility
- **Section 5.7:** *Strategies for completing tasks*: what strategies users employed for completing data tasks
- **Section 5.8:** *Impact of data literacy on understanding*: how prior knowledge and experiences impact users' interactions with data
- **Section 5.9:** *Sources of tension between accessible vs. useful data representations*: how useful accessible representations of data are on the web and factors that impact usefulness
- **Section 5.10:** *Factors that affect confidence*: how participants gain confidence in the insights they draw from data
- **Section 5.11:** *Diversity of preferences for consumption*: what users' preferences towards data are and how these preferences affect individual interactions and takeaways

5.6 Efforts to Access COVID-19 Data

More than half of the study participants (P1, P7–P12) had specific websites they recurrently accessed to gain up-to-date information about the pandemic. The websites ranged from local government to independent volunteer-based and nonprofit services (Table 12). At the onset of the pandemic in the United States (March–April), most participants checked for daily data updates (P7–P12). At the time this study was conducted (September), some had reduced their frequency to a weekly to monthly basis (P1, P8, P9, P12). Given this relatively long period of recurrent use, all participants commented on noticing how the accessibility of websites had improved over time and how they had gained more confidence in understanding the data and insights (P7–P12). Participants described that access had initially been more difficult, and similar to findings in the survey, most commonly described challenges in navigation. Several participants described how they had experienced a large range of websites that provided COVID-19 data *"in some way, shape or form"* in search of the more accessible and useful ones (P7, P8–P12).

Participants also discussed their advocacy efforts to ensure the available tools were made fully accessible. One participant described how initially their state's local website *"didn't have any numbers that JAWS could read"* (P8). She described how most changes to improve the website's accessibility had been enacted as a result of their group's advocacy. Another participant described how she had reached out to the website creators to complement their efforts but also advocated for more thorough accessibility changes (P7).

Despite applauding the improvements made to the websites' accessibility, all participants also discussed several remaining barriers. One participant commented that while now they had access to the daily case count in their local community, they recognized that they are *"not really getting the full picture,"* because they still do not have *"any kind of representation or any way to look [at the data]* *day to day"* or more holistically (P1). Supporting findings from the survey, participants reaffirmed that spatial information (e.g., trends and map hotspots) are most difficult to find and thus have low expectations for their accessibility. One participant described that *"there are probably ways to look for the trend but I never look because I expect it to be inaccessible"* (P8). During times of emergency where access to data-driven information is important, people not believing the information might be accessible to them is a real concern.

Other participants described having to actively seek out and complement multiple sources of information to get a fuller picture since *"there's no perfect website"* (P7–P10, P12). For example, one strategy participants described was *"gleaning on any accessible details from one COVID-19 website"* and using that in complement with the accessible details in another website or dashboard to interpret and understand what the data was saying. Another strategy described was complementing inaccessible graphics in news articles with data representations available through blindness organizations or accessible-branded websites, highlighting how accessible data dashboards provide a way for users to verify and follow along statistics or graphs referred to in mainstream news articles that often don't maintain proper accessibility standards.

5.7 Strategies for Completing Tasks

Participants used a diverse number of access-technology and representation-based strategies to understand how the data was presented, what the data conveyed, and to make comparisons to complete the tasks.

5.7.1 Understanding How the Data Is Presented. Participants often sought overviews before performing drill-down actions to explore new web page or representation structures. When approaching new websites, many participants used headings to gain overviews of web pages or representations (P1, P3–P6, P9, P10, P12) before visiting specific pieces of information. Several participants then made use of linked lists (P2–P4) or search functionality (P2, P7–P12) to access specific pieces of information relevant to the task, such as U.S. states or questions that are relevant to making a comparison. One participant, however, was disoriented after using the find option after they navigated into a table without being notified of being in a table. For tables, most participants read through all of the column headers to first understand the table format and content (P1, P3, P5, P6, P9, P10, P12) before exploring specific values. For unfamiliar and unspecified interactive options, two participants (P6, P10) interacted with the visualization with and without the interactive parameters selected to infer the purpose of the interaction. One participant described how they imagined a tactile graphic to understand how sonification was presented (P3). Another described how they would use Google to clarify unfamiliar terms (P10).

5.7.2 Understanding What the Data Conveys. All of the websites provided multiple representations to convey information about the pandemic. Many participants used these multiple representations to confirm and clarify information, such as using alt text to validate what they heard through sonification (P4–P7, P10, P11), tables to clarify trends provided in alt text summaries (P3, P6, P12), and summaries to understand the sonified range (P8).

Several participants used tables to explore the progression of the trend by first sorting the table by date, then moving down a parameter column to track how that parameter changed over time (P1, P3–P5, P9–P12). Two participants also sorted by the parameter of interest, such as number of COVID-19 cases, to understand how their state ranked compared to other states (P1, P10).

When using sonification, participants described focusing on the pitch (P1, P5, P8, P11), rate of pitch change (P5), and when pitch features occur (P1, P11). Two participants used stereo panning to spatially anchor sonification features (P1, P4).

For dense summary descriptions, several participants revisited information line-by-line to internalize the information they heard (P6–P8). One participant described how they looked out for important or extreme words, such as "exponential," to target their focus (P5).

5.7.3 Making Comparisons for Completing the Task. The open-ended task asked participants to compare COVID-19 severity between two states. On a high level, we observed two types of strategies used for making the comparison. Both strategies involved getting an overview of how the data was presented first, then deciding what parameters were important for the task. In one strategy, participants synthesized and summarized information from one state, synthesized and summarized information from another, and compared between the summaries (P1–P6, P8–P11). This process of exploring, focusing, and synthesizing might repeat several times, especially if they felt overwhelmed by the amount of information they needed to interpret.

In the other strategy, participants made individual comparisons across parameters and synthesized these comparisons (P1, P3, P7, P10–P12). This required convenient access to information across both states. Tables that contain information about both states tend to facilitate these interactions. For a website that separated states by web pages, two participants (P9, P12) opened multiple tabs to quickly navigate between the states.

5.8 Impact of Data Literacy on Understanding

We report on how participant's data literacy and experience impact the takeaways gained from data representations.

5.8.1 Using Domain-specific Knowledge to Broaden Insights. Prior work shows that readers with higher levels of graphical understanding use particular language and make more aggregate observations [45, 69]. Similarly, we observed how participants leveraged these characteristics to accomplish data tasks in several ways. Participants devoted attention to domain-specific *"words that would indicate sharp rises"* like *"exponential"* (P5), grouped spatial features into data-visualization concepts such as local and global extrema (P11), and connected spatial features to prior *"experience of touching tactile graphics"* (P5). By applying their prior data literacy knowledge and experience, participants focused on key areas of the representations, abstracted information pertinent to the task, and constructed spatial models to navigate and understand the data.

5.8.2 Knowledge Gaps Lead to Gaps in Insights. Gaps in knowledge caused participants to misinterpret the data or limited their ability to gain insights altogether. One example is with the case of sonified plots. Participants without prior knowledge of sonification drew false comparisons by directly comparing pitch values across different plots. Other participants did not know how to interpret sound features altogether. P2 remarked *"This is interesting. The daily one is not a steady tone. So those wavy sounds probably mean something."* While users may identify sound characteristics such as trend, frequency, interval, from the sonification, how accurately they map those characteristics to data graphics insights depends heavily on domain-specific knowledge and websites providing sufficient context to easily make those associations.

5.9 Sources of Tension between Accessible vs. Useful Data Representations

While participants were able to access the data and information in different ways across all the websites visited, accessible data representations often did not provide all the utility participants were looking for.

5.9.1 No One Representation Is Best for All Tasks. Unlike visual and tactile graphs, where broad patterns can be readily retrieved and contextualized, gaining the same information is more difficult through audio-based representations [134]. With tactile graphics, participants described being able to quickly explore both detailed and overall trends and explore different data series in parallel. However, for web audio-based methods, participants described how the amount of information presented made comparisons difficult (P1–P4, P6, P8–P12). Choi et al. found that long and complicated descriptions impose a greater cognitive load to the reader [36]. We observed how the cognitive load of comparing sonifications sequentially can also be difficult. Furthermore, while participants described how tables made retrieval of values easier, tables did not facilitate understanding of the broader picture, echoing observations made from prior works that explored providing overviews of tabular data using audio [31, 116]. The usefulness of each representation was much more dependent on the task, emphasizing that just having access to a data representation does not mean users will find the specific representations useful for their intended tasks.

5.9.2 Supporting Screen Reader Interactions. While a data representation may offer the utility that users need, usability issues in screen reader navigation can make search and retrieval difficult. For example, screen reader users often use heading levels or link lists to skim through web content. However, tables and alt text are not designed to provide similar functionality and users have to resort to sequential navigation, which becomes increasingly cumbersome when wanting to focus on specific regions of the data or make comparisons. Participants adopted coping strategies or workarounds [77] by using link lists to jump between table values tagged as links or opening multiple tabs and leaving their screen reader focus at different parts of the same dataset so they could easily resume exploration (P3, P9, P12).

5.10 Factors that Affect Confidence

Confidence played a role in participants' exploration and use of data in their decision-making. We detail several of these factors.

5.10.1 Unfamiliar Representations and Tools. Unfamiliar representations such as sonification reduced participants' confidence in their interpretation (P1, P2, P8, P9, P10). As P10 described it, *"I like hearing graphs through sonification it's just something I'm not all that used to, so it may take me awhile to be a more discriminate listener."* However, familiar structures provided a way for participants to confirm their interpretations and increase their confidence. Participants new to sonification (P6, P9, P12) often used the tabular data to check assumptions. Other participants (P1, P5) wanted to download the data and explore it using more familiar tools (e.g., Excel). These tools provided an environment where participants knew what to expect and how to apply known operations, making screen reader navigation faster and interpretation easier.

5.10.2 Relying on Others' Accuracy and Quality of Interpretation. Participants were less confident using representations where they relied on somebody else's subjective interpretations, such as alt text of data graphics (P3, P5, P10, P12). As P3 described it, *"I'm a little cautious about the description because people who provide the description have to be skilled enough doing it…it needs to be done well."* Participants also recognized how descriptions may only capture what the author chose to include and thus also limit their interpretation, *"somebody had to input that and somebody had to decide which data points were worth mentioning"* (P10). Participants appreciated representations where they were able to make their own interpretations, *"sonified leaves all the language out of it so I can make my own interpretation"* (P5), or provide a method to validate others' interpretations such as through access to the raw data.

5.10.3 Discrepancies in Data. Data discrepancies within the websites made participants question the reliability of the information or their own interpretations of the data. For example, when users listened to the sonification and wanted to associate the sounds to numerical values, they would check the graph's alt text that described the graph's axis range (P3–P5, P7, P8, P10, P11). In one of the websites, the graph sonification was updated daily, but the alt text had not yet been updated. P3 described how they could not tell whether this was a mistake in *"my perception of the sonification"* or whether *"that's just an error."* Reflecting on this, P3 said, *"I'm not being able to trust what's right. Did they just make a mistake in not updating the dates or why is it that there is a discrepancy...?"*

5.11 Diversity of Preferences for Consumption

Participants had diverse preferences for representations, modalities, and levels of abstraction to understand the information and make a decision. Though many of these preferences were influenced by participants' prior knowledge, experiences, skills, and confidence discussed in prior themes, in this section, we focus directly on these diverse needs and preferences as considerations for broadening data engagement on the web.

5.11.1 Varied Preferences in the Level of Data Abstraction Needed to Complete Data Tasks. While some participants expressed that key takeaways were sufficient (P5, P7), others expressed the need to investigate the progression of specific data values over time (P1, P10, P11). P10 stated that *"the nice thing about looking through the table is that I can see the actual numbers, and somehow that makes it more concrete for me."* Participants, many of whom wanted access to specific values, recommended broadening the level of data abstraction available through sonified graphs by adding the ability to zoom in on sections, retrieve values, and add speech annotations.

5.11.2 Varied Preferences in the Modality Used to Interact with the Data. Some participants preferred hearing descriptions of the graphs (P2, P3, P7), while others appreciated being able to gain an overview of the trends through sonification without the cognitive load of associating words to graphical concepts (P1, P4, P9, P12). P2 contextualized their preferences to their prior experiences, stating *"To me, I don't have a lot of experience [with] graphs so I always go by verbal description."* In contrast, P12 described having to *"be very cognitively engaged"* to comprehend the data, and a benefit of sonification is that they *"wouldn't need to know English."* Sonification, unlike alt text, provides a more direct perceptual mapping. While certain modalities such as speech require higher cognitive loads to interpret and remember, factors such as prior experience and familiarity discussed in Section 5.8 also contribute to user preferences and are important to consider.

5.11.3 Leveraging Insights from Multiple Representations to Fill Gaps in Understanding. A number of participants used representations of broader-level information, such as sonification and alt text, to contextualize and inform more detailed explorations of the table (P3, P6, P7, P9–P11). As P11 put it, *"the description really paints a picture of the graph in my mind and the table actually gives the real values."* Most participants also used textual descriptions to gather contextual information missing from the sonification (P2–P8, P11, P12) in two ways: by retrieving both trends and snapshot summaries of current statistics and by contextualizing what they heard using the alt text description of axes ranges. Enabled by the fact that the representations convey data on different levels of abstraction, we observed how participants complement their understanding of the data by making use of multiple representations.

5.12 Contextual Inquiry Takeaways

Our observations contribute to what other studies in times of crisis have found: that PWD are often impacted early and disproportionately [117, 127], including with regards to access to vital data-driven information. Participants described broad inaccessibility particularly early on in the pandemic when most were keen on accessing daily information. As a result, participants discussed their ongoing participation in advocacy efforts that only then led to change. Other participants described their low expectations for accessing spatial information, how they resorted to piecing together information from different sources, and how they relied more on community and advocacy groups, which was observed by Holloway et al. as well [62].

We also observed that not all access is equal access [21, 74, 118]. Websites sometimes default to the provision of alt text and tables that are considered best practice. Even as the websites participants explored met many of the audit criteria and were on average rated highly, these representations can lack the necessary affordances for data-oriented tasks, suggesting the need to consider the variety of data-related goals in addition to the accessibility of different data representations. Card et al. described how visualizations can amplify cognition by offloading information from working memory into organized external representations that can be retrieved and processed perceptually [33]. However, for comparison tasks observed in the study, these benefits are undermined if screen reader users are required to keep in their working memory large quantities of information just to navigate between graphs, especially when compounded with the cognitive load of retaining data and descriptions. In specific cases, participants were able to use *find* and *navigation* options, multiple tabs, and sorting to reduce the number of navigation steps and make direct comparisons between parameters. Data representations could take advantage of inherent HTML header tags or links to facilitate jumping between points in the data and across different plots to help screen readers navigate and compare with greater ease.

Individual preferences for different modalities and levels of data abstraction affected how participants interacted with the various data representations available. While much research progress has been made investigating more compelling methods for users to interact with data, many challenges such as the lack of standardization, authoring support, and awareness hinder their quick dissemination to the public. During times of crisis when providing immediate access is important, our findings show that participants can integrate information from more standard representations with existing web-support to form deeper understandings of data. We found that almost all participants leveraged insights from multiple representations to complement information gaps of each individual representation (P3–P12).

Participants leveraged their prior data literacy knowledge and experience to effectively navigate and understand data representations. However, gaps in knowledge and unfamiliar domain-specific terminology caused participants to misinterpret or limit their understanding of the data. Public service websites, especially during times of crisis, should provide content that is accessible to general audiences without assuming domain expertise. Participants often found summaries of key metrics and main takeaways to be the most accessible and digestible (P2, P5–P7), which we recommend public service websites to prioritize at the top of pages populated with data content. Additionally, participants uncertain about terms and features often explored their immediate surroundings to seek clarification of those features (P4, P5–P7, P10, P11). We recommend all domain-specific phrases be accompanied with references or simple definitions next to the phrase rather than in dedicated sections, as screen-reader's navigation features may lead users to easily skip past those sections.

Users need ways to increase their confidence and confirm their interpretation. Factors that reduce users' confidence include relying on others' data interpretations, data discrepancies, and unfamiliar representations and tools. These barriers compound with challenges finding and accessing information about data source and uncertainty identified in the accessibility audit (Section 3). Particularly during times of crisis, building user trust and confidence in accurate information is critical. Several participants were keenly aware of the subjectivity of certain types of information, and recent work by Lundgard et al. found that in contrast with sighted users, blind users preferred descriptions that described the data itself, rather than author's subjective interpretations [76]. One way to build confidence is to provide data tables and downloadable files per accessibility guidelines [7, 56] that enable people to interpret data through familiar methods and tools directly. More generally, as social media and news sources struggle to contain widespread misinformation [47, 65, 131], broadening data literacy can empower individuals to explore, interpret, and evaluate data-driven sources on their own. Several participants indicated that new technologies, such as sonification, can help people understand data in new ways. Leveraging accessible websites to teach data concepts can empower users to more confidently evaluate their data-driven sources and access new types of information.

5.13 Contextual Inquiry Limitations

First, as with the survey, participants that opted to participate might have a particular interest in data accessibility, which could affect the range of perspectives captured by our study. Second, participants were randomly sampled from survey respondents in Section 4, which may inherit potential biases from the survey sample. Purposive sampling may have been used to capture more diverse or balanced samples. Third, the contextual inquiry investigated how participants might gain insights from three *Born Accessible* websites, which the audit showed to have higher accessibility ratings and criteria pass rates than visualizations that appear in the top results of Google Searches. Therefore, our observations may not capture how users might experience visualizations from more prominent websites that are less accessible. Fourth, we used a think-aloud protocol and two of the experimenters were present for conducting the study and note-taking, both of which may affect users actions. Expanding on the methods used to investigate this topic (e.g., case studies, diary studies, instrumented websites for automated data collection, critical incident analysis) could add to the dimension of findings and perspectives reported. Moreover since we focused on data representations that were available based on standards and survey responses, the contextual inquiry findings may be under-representing the range of interactions BVI users may come across on the web.

6 GENERAL DISCUSSION

We observed several common themes across the three studies, highlighting ways in which implementation choices affect users' experiences. We discuss several of these themes in the following sections and synthesize recommendations that could improve current practices as well as guide further research in data accessibility on the web.

6.1 Data Access as a Holistic Experience, Implementations of Visualizations on the Web

Our systematic review shows that only a few of the audited top-ranked Google search results visualizations on the web (in the *Top Results* group) provide screen reader access to content, context, effective navigation, and interactive features [RQ1]. Several of our results reflect findings from other studies conducted during this time, which also report how visualizations were not discoverable to screen readers [102] and did not provide adequate textual summaries [62]. We also found that data value, trends, and tabular alternatives were typically not provided, important contextual information was often inaccessible, and navigation controls were often inadequate.

Additionally, both the audit and contextual inquiry results highlight how the accessibility of web visualizations should be examined in the context of the entire web page and not just in isolation. On one hand, both auditors and contextual inquiry respondents appreciated the proper use of headers to delineate between individual groups of visualizations; this helped auditors perceive individual representations and contextual inquiry participants navigate between multiple representations to synthesize information from each representation. On the other hand, webpages and dashboards with poor semantic structure were a barrier for discovering information related to the visualization, such as source, update frequency, and download links, and potentially the visualization itself, especially when navigation through the entire page can take hundreds of commands. Chartability provides visualization guidelines for *"data experiences,"* which is defined as *"a data visualization such as a chart, graph, or plot, a 'bespoke' (highly customized) graphic based on data, a model, or an algorithm, or a data driven interface or system"* [40]. For visualizations on the web, we advocate for practitioners to consider data experiences both in isolation and in the context of the entire web page. Furthermore, we believe that for pages with multiple visualizations, each visualization experience should be complete, meaning that the update frequency, data source, download features, and alternative representations that are often provided separately should be easily accessible through each visualization, especially as navigating through the entire page may require hundreds of screen reader commands. Additionally, the web page structure should enable quick and clear navigation between representations to promote comparisons, cross-contextualization, and broader synthesis of information, which was performed by many contextual inquiry participants in *Born Accessible* web pages.

Screen readers are the prevailing method for consuming information on the web, and consuming content through screen readers is largely sequential [72]. Considering the importance of navigation order, screen reader experiences of web-based visualizations can be conceptualized as narratives in which effective structures and techniques can improve users' experiences and understandings. Scheneiderman first proposed the "Visual Information Seeking Mantra" (overview first, zoom and filter, then details-on-demand) [104]. Zhao et al. identified several insight-seeking actions that are utilized by audio-based methods for consuming data visualizations, which provide a contextual overview or *"gist"* before the data and supporting methods to *"situate"* data exploration within the surrounding context [134]. Similarly, BANA guidelines for the construction of tactile graphics recommend providing all relevant contextual information before the data content [6]. In this study, we observed how contextual inquiry participants made use of the *overview then explore* process to understand information presented in *Born Accessible* websites, and how auditors described ways in which poor reading order, scattered contextual information, and lack of information to *"situate"* interactions were barriers towards understanding. Like previous studies exploring HTML-based screen reader accessible charts, we observe the importance of page structure when situating a visualization and simplifying navigation between visualization and supporting information [123]. Based on these observations and echoing recommendations from several recent works, we suggest that the reading order of a visualization should provide contextual overviews before specific data points and details [67], and coordinate data points with corresponding details [137] as users interact with the visualization.

Additionally, many visualizations make use of visual design themes and spatial patterns to implicitly convey information. Examples include using empty space to delineate between content, font sizes to convey hierarchical relationships, and colored themes to form across-the-page connections. This implicit information must also be explicitly stated or embedded in the hierarchical and navigation structure of the screen reader to be accessible to screen reader users.

6.1.1 Data Access Recommendations.

- **Consider** the accessibility of data experiences both in isolation and in the context of the entire web page.
- **Implement** visualization experiences that are complete. Specifically, the update frequency, data source, download features, and alternative representations should be easily accessible through each visualization experience.
- **Implement** web structures that provide quick and clear navigation between representations to promote comparisons, cross-contextualization, and broader synthesis of information.

- **Consider** screen reader experiences as narratives. Provide contextual overviews before specific data points and details. Situate the data points and details contextually as users interact with the visualization.
- **Provide**, explicitly or through hierarchical and navigation structures, implicit details conveyed through visual design themes and spatial patterns.

6.2 Towards Data Insights, Practically Useful vs. Technically Accessible Visualizations

Throughout the study, users described several challenges with inaccessible data presented on the web. Some of these issues are well documented in prior work [25, 72] and can be addressed by following guidelines [7, 56]. However, our findings emphasize how simply providing access is not sufficient. For example, *Born Accessible* websites received significantly higher accessibility ratings and typically had better organization, labeling, and more frequently adopted data interaction techniques investigated through accessibility research, such as sonification. Yet, *Born Accessible* visualizations typically did not contain many of the interactive features (55%, 42/76) *Top Results* visualizations (89%, 68/76) supported for visual consumption. Many of the *Top Results* visualizations used visual cues to highlight broader patterns, drill down on specific regions, make comparisons, or gain additional details through click and hover-over actions, which can help users gain broader levels of insight [20, 68]. Without ready access to these types of interactions for screen reader users even in *Born Accessible* visualizations, we observed several contextual inquiry participants resorting to external workarounds such as frequently using "find" queries and opening multiple tabs to focus on and compare between data points and patterns. Limitations to the types of interactions *Born Accessible* visualizations support for screen reader users highlight the importance of providing more effective interaction methods and bring into consideration the intricate relationship between accessibility and usability as identified by prior work in other web-accessibility areas [21, 74, 118].

The need to improve support for interactive features through screen readers is important for providing access to insight-seeking actions using existing tools. We observed how users leveraged other representations to fill in the gaps inherent in one, altogether gaining a more holistic understanding. Thus, we recommend using representations in tandem to complement their respective strengths and shortcomings in addition to fulfilling users' diverse preferences for data abstraction, which was observed in our survey results. However, using existing technologies to support this process often requires users to retain multiple pieces of information in their working memory as they navigate between the different representations. Providing more tightly coordinated views between multiple complementary representations, such as coupling overview summaries with sonified patterns, specific data values, and interactive search and filter operations, could accommodate users' diverse needs and preferences for learning [107, 116].

To help facilitate coordinated views, we encourage researchers and practitioners to consider deconstructing visually derived categories of representations and redefining representations with an audio-first approach. For example, although tables and line plots visually appear to be two distinctly different representations as the data is organized and mapped to distinctly different spatial features, auditory methods of accessing these visually different representations could be quite similar. Stockman et al.'s work [115], which enables tabular exploration with sonified tones, is an example of a design that takes two visually different representations (tables and line plots) and expresses them in a familiar and unified way that conveys data in speech and tonal modalities across multiple levels of data abstraction. However, the ways in which visual metaphors should still be considered is relatively unknown, as recent work by Wang et al. found that BVI participants considered the visual look of charts when evaluating audio-to-data mappings for effectiveness [124].

Text summaries provided through screen readers are inherently sequential in nature and several contextual inquiry participants described how interpreting data through them requires additional cognitive load. Investigating methods that include other modalities in the web infrastructure could provide more flexible and direct access to the data and support the diversity of data-related tasks and goals. The majority of respondents from our survey ($\geq$ 77%) agreed that tactile and audio-based methods are helpful for exploring data-driven graphics. Visual perception supports flexible navigation, direct access to data attributes, pattern recognition through gestalt properties, interactive feedback, and expressive communication. Haptic perception shares similar advantages [83] and is also naturally suited for exploring spatial relationships [91]. Audio interactions can also be powerfully expressive [42], spatially situated [88], help users understand semantic content [76], and complement the spatial limitations inherent to haptic interfaces. Multiple modality channels can be used to delineate between the different levels of abstraction.

6.2.1 *Data Insight Recommendations.*

- **Consider** the diversity of user backgrounds, data-related tasks, and goals that visualizations may serve.
- **Provide** multiple representations in tandem to complement their respective strengths and shortcomings in addition to fulfilling users' diverse preferences for data abstraction.
- **Consider** deconstructing visual-derived categories of representations and redefining representations with an audio-first approach.
- **Research** how to make more explicit the connections between multiple complementary accessible representations to provide more tightly coordinated views.
- **Research** methods for embracing other modalities in web-infrastructure to support flexible navigation, gestalt understandings, interactive feedback, expressive communication, and multiple levels of data abstraction.

6.3 The Importance of Access, an Evolving Need

Data and visualization literacy is traditionally framed as a means of participating in an increasingly technical and quantitative workforce. However, as governments, industries, and individuals increasingly rely on data to track, synthesize, communicate, and decision-make, the ability to understand data is becoming not only an applied skill, but also as a means and metric of greater social inclusion in a data-driven age [22]. Survey results showed that screen reader users wanted access not only for accomplishing work and education related tasks, but also for understanding data-driven media, supporting orientation and mobility, tracking personal finance and health, and engaging in art and music.

The COVID-19 pandemic highlights the need for improving data visualization access for BVI people. Our survey respondents and study participants noted a broad lack of accessibility to sources of reliable data in publicly available websites at the early onset of the pandemic when it was most important, echoing findings of earlier COVID-19 work [50, 62], and expressed widespread concern for timely and accurate COVID-19 data graphics. Contextual inquiry participants described their efforts to engage in advocacy, synthesize information from disparate sources, and rely on community groups to gain access, further emphasizing the importance placed by the community on information access. Audit results highlight the onus still placed on screen reader users to install add-ons or learn specific sets of screen reader commands to gain access to visualizations. Historically, PWD have had to widely advocate for their needs to affect change [100]. In times of crisis when social services and needs are rapidly changing, an even larger burden is placed on the BVI community to assert their need to make informed decisions and maintain their safety [16].

The spread of data visualizations into non-technical domains also challenges assumptions practitioners make about data literacy when communicating to broader audiences. While data visualization has traditionally been used in STEM-specific fields, where a certain degree of data literacy is assumed, data journalism and web-based representations can reach wider audiences with varying levels of data literacy [101]. Data storytelling, progressive detail, and summary descriptions are increasingly used in journalistic spheres to communicate visualization concepts [101] and improve data literacy as users consume the content. However, our audit reveals that interactive features that enable *learning through consumption* are currently not accessible through screen readers. Morris et al. introduced a taxonomy of relevant properties for augmenting non-visual representations [85]. While that work did not focus on data representations, some of the proposed interactions such as "progressive detail" and "question & answer" could be suitable for enhancing screen reader interactions with both alt text and tabular data; this echoed recommendations made by several of the participants in our contextual inquiry. These techniques could provide users better access to different levels of abstractions and regions of interest in the data, address the cognitive burden of filtering through dense representations, and make data visualization more approachable to broader audiences.

Audio-driven narratives also offer an opportunity to make data concepts even more approachable. Data-driven stories have been increasingly used in journalism to communicate data insights in a way that is engaging to both novices (through context) and experts (through the data) [97]. Several recent works found that users gain more insights and clearer mental images through audio data narratives that combine textual descriptions and sonification than sonification alone [63, 106]. Interactive and multimodal audio narratives that provide context through speech and data through sonification could broaden access to data on the web while supporting data literacy skills.

Additionally, both the audit and contextual inquiry reveal that even *Born Accessible* visualizations make assumptions about users' level of data literacy and show that these assumptions can cause confusion and reduce confidence, especially with less familiar modes of presentation such as sonification. These observations complement McGookin & Brewster's observations that prior experience using a specific type of graph and the "ability to extract information from a graph" (i.e., graph literacy) are among the critical factors affecting a BVI participant's performance on tasks using an accessible data representation [81]. Providing definitions and instructions can not only help reduce confusion and improve confidence, but could also reinforce data literacy concepts to users as they access data-driven information on the web. We believe there are opportunities to research effective methods for assessing and building data literacy through web-based visualizations.

6.3.1 Data Approachability Recommendations.

- **Consider** people with disabilities from the beginning of web development to reduce the burden on marginalized communities to advocate for access, especially during times of crisis.
- **Research** methods and interactions to build data literacy as screen reader users consume data visualizations on the web. For example, progressive detail can provide scaffolding for digesting and understanding information, while question & answer can strengthen associations between visualizations parameters and what they represent.
- **Research** how audio narratives may help make data concepts more approachable to people of diverse data literacy skills.
- **Provide** instructions for how to interpret visualization content for audiences with diverse backgrounds, especially with less familiar representations such as sonification.

6.4 An Ecosystem for Now and in Crisis, Structural Barriers to Access

The extreme demand for information and the rapid pace at which it was being disseminated also placed a burden on content creators. During the COVID-19 pandemic, government, news, and research organizations were mobilized to provide up-to-date visualizations tracking the progression of the pandemic. Many of these visualizations are provided through dashboards that rely on data-tracking tools, libraries, and services that automatically update from back-end datasets. While these tools, libraries, and services provide convenient ways to organize and convey large quantities of data and visualizations, both our audit and other recent work [102] found that they are mostly inaccessible to screen reader users, even two years after the beginning of the pandemic. As many organizations rely on these common services to disseminate information quickly during times of crises, there is a great public need for making them accessible.

Several of the websites we examined were created by independent organizations and individuals offering their time and effort as a public service while also being impacted by the health crisis. While accessible, non-visual techniques to present a variety of data graphics have largely been investigated in research [43, 92, 93, 130, 134], few have been translated to standard web tools for use in practice. The lack of web guidelines and public websites using multimodal representations and supporting data-driven tasks for screen reader users leaves content creators with a lack of guidance or precedent to rely on. Chartability is an ongoing effort to develop visualization standards for the web [40]. We advocate for greater efforts to integrate accessible data features into everyday web tools in a way that web-developers can easily incorporate into their workflows rather than having to bootstrap resources together from disparate tools and guidelines. Voxlens is a library that makes JavaScript-based visualizations more accessible through only one line of code [103]. Tools and extensions that automatically provide well-labeled table or charts from poorly formatted visualizations also show great promise in expanding data access, particularly when developers are not providing visualizations accessibly [82, 125].

Prior studies conducted during other times of crisis have concluded that proper infrastructure had not been in place to ensure PWD had access to essential information [117, 127]. Our survey found that while tactile methods for exploring data visualizations are preferred, they were rarely available for consumption. We also observed from both the survey and contextual inquiry ways in which community groups, allies, and blindness organizations strove to fill important information access gaps for BVI users. When BVI users encountered inaccessible graphics in news articles, many complemented their understanding with information and data from community and blindness organizations. A closer examination into how these groups incorporate accessibility throughout their community-facing services and amplify their work can provide a model for practitioners. Understanding how local blindness groups effectively interact to disseminate information would be critical in the event of future global and local crises.

6.4.1 *Structural Recommendations.*

- **Ensure** the accessibility of data dashboards that agencies and services use to quickly communicate up-to-date information, especially during times of crisis.
- **Integrate** accessible data features and considerations into everyday web tools in a way that web-developers can easily incorporate into their workflows.
- **Research** how community and blindness organizations incorporate accessibility throughout their community-facing services as a model for disseminating information.

7 CONCLUSION

The COVID-19 crisis has highlighted the importance of information access and the use of data visualization in everyday life. However, the results from our audit and survey confirm that data visualization remains largely inaccessible to BVI users. Beyond this, our three empirical studies have shown: (1) widespread accessibility issues across *Top Results* websites and visualizations, (2) the impact that information access inequities have on the BVI community when exacerbated by a time of crisis, (3) ways screen reader users sought access to data-driven information and made use of online visualizations to form insights, (4) and the important need to make larger strides towards improving data literacy, building confidence, and enriching methods of access for BVI users. Based on our findings, we have provided recommendations for researchers and practitioners to broaden data accessibility on the web. As implementing these improvements is a multifaceted challenge that involves many stakeholders including researchers, standard setters, library developers, content creators, organizations, and end-users, understanding the role and workflow of each stakeholder in the overall process is an important avenue for future work.

APPENDICES

A AUDITOR DEMOGRAPHICS

Table 4. Auditor Demographics

Auditor Number	Level of Vision	Title	Certification	Years of Web Accessibility Experience	Screen Reader	Browser
A1	Sighted	Senior Accessibility Consultant	CPWA	15	NVDA	Firefox
A2	BVI	Accessibility Lead	CPWA	25	JAWS	MS Edge
A3	Sighted	Senior Accessibility Trainer	CPWA	3.5	Mac Voiceover, then NVDA	Firefox, Chrome, Safari

B AUDIT VISUALIZATIONS

Table 5. Breakdown of Audited Websites and Visualizations by Organization Type

Organization Type	Number of Websites (Top Results)	Number of Visualizations (Top Results)	Number of Websites (Born Accessible)	Number of Visualizations (Born Accessible)
Inter-government/ Federal Govt.	4	11	1	3
State/ Count/ District/ City Govt.	13	38	0	0
News/ Media Organizations	3	8	0	0
Research/ Health Institutions	4	10	2	5
Data Companies	2	6	1	2
Non-Profit/ Independent	1	3	1	1

Table 6. Breakdown of Audited Visualizations by Visualization Type

Visualization Type	Number of Visualizations (Top Results Group)	Number of Visualizations (Born Accessible Group)
Area	0	2
Bar	17	3
Line	14	2
Bar and Line	6	0
Bubble	1	0
Pictoral Fraction	1	0
Pie	1	0
Summary	8	0
Table	13	3
Map	15	1

Table 7. Breakdown of Visualization Services Used by Audited Visualizations

Visualization Service	Number of Visualization (Top Results)	Number of Visualizations (Born Accessible)
Arcgis	11	0
Chartjs	2	0
Datawrapper	3	0
Highcharts	4	0
Mapbox	3	0
Plotly	1	0
SAS	0	5
Tableau	10	0
None/ Other	42	6

Table 8. Table of Audited Visualizations

Vis. Code	Vis. Group	Vis. Type	Org. Type	Web page Link
AD1	Born Accessible	Bar	Research Institution	https://accessiblegraphs.github.io/montana.html
AD2	Born Accessible	Line	Research Institution	https://accessiblegraphs.github.io/montana.html
AD3	Born Accessible	Table	Research Institution	https://accessiblegraphs.github.io/montana.html
CACT1	Statement	Map	Non-Profit	https://covidactnow.org/?s=25461459
CACT2	Statement	Table	Non-Profit	https://covidactnow.org/?s=25461459
CACT3	Statement	Line	Non-Profit	https://covidactnow.org/?s=25461459
CDC1	Statement	Summary	Government (Federal)	https://covid.cdc.gov/covid-data-tracker/#datatracker-home
CDC2	Statement	Map	Government (Federal)	https://covid.cdc.gov/covid-data-tracker/#datatracker-home
CDC3	Statement	Table	Government (Federal)	https://covid.cdc.gov/covid-data-tracker/#datatracker-home
CENSUS1	Statement	Summary	Government (Federal)	https://covid19.census.gov/
CENSUS2	Statement	Bar	Government (Federal)	https://covid19.census.gov/
CHI1	Statement	Bar and Line	Government (City)	https://covid19.census.gov/
CHI2	Statement	Table	Government (City)	https://www.chicago.gov/city/en/sites/covid-19/home/latest-data.html
CHI3	Statement	Summary	Government (City)	https://www.chicago.gov/city/en/sites/covid-19/home/latest-data.html
CMS1	Statement	Map	Government (Federal)	https://www.chicago.gov/city/en/sites/covid-19/home/latest-data.html
CMS2	Statement	Bar	Government (Federal)	https://data.cms.gov/covid-19/covid-19-nursing-home-data
CMS3	Statement	Line	Government (Federal)	https://data.cms.gov/covid-19/covid-19-nursing-home-data
CNN1	Statement	Map	News Organization	https://data.cms.gov/covid-19/covid-19-nursing-home-data
CNN2	Statement	Table	News Organization	https://www.cnn.com/interactive/2020/health/coronavirus-us-maps-and-cases/
CNN3	Statement	Bar and Line	News Organization	https://www.cnn.com/interactive/2020/health/coronavirus-us-maps-and-cases/

CT1	Statement	Map	Government (State)	https://www.cnn.com/interactive/2020/health/coronavirus-us-maps-and-cases/
CT2	Statement	Table	Government (State)	https://portal.ct.gov/coronavirus/covid-19-data-tracker
CT3	Statement	Bar	Government (State)	https://portal.ct.gov/coronavirus/covid-19-data-tracker
CTRACK1	Statement	Summary	News Organization	https://portal.ct.gov/coronavirus/covid-19-data-tracker
CTRACK2	Statement	Bar and Line	News Organization	https://covidtracking.com/data
CVSTATS1	Born Accessible	Table	Independent	https://covidtracking.com/data
DC1	Statement	Line	Government (District)	https://coronavirus.dc.gov/data
DC2	Statement	Map	Government (District)	https://coronavirus.dc.gov/data
DC3	Statement	Bar	Government (District)	https://coronavirus.dc.gov/data
HD1	None	Line	Research Institution	https://covid19.healthdata.org/global?view=cumulative-deathstab=trend
HD2	None	Map	Research Institution	https://covid19.healthdata.org/global?view=cumulative-deathstab=trend
JHU1	Statement	Summary	Research Institution	https://coronavirus.jhu.edu/map.html
JHU2	Statement	Map	Research Institution	https://coronavirus.jhu.edu/map.html
JHU3	Statement	Bar	Research Institution	https://coronavirus.jhu.edu/map.html
LA1	Overlay	Summary	Government (State)	https://ldh.la.gov/coronavirus/
LA2	Overlay	Map	Government (State)	https://ldh.la.gov/coronavirus/
LA3	Overlay	Table	Government (State)	https://ldh.la.gov/coronavirus/
LAC1	Statement	Line	Government (County)	http://publichealth.lacounty.gov/media/coronavirus/data/
LAC2	Statement	Table	Government (County)	http://publichealth.lacounty.gov/media/coronavirus/data/
MA1	Statement	Summary	Government (State)	https://www.mass.gov/info-details/covid-19-response-reporting
MA2	Statement	Line	Government (State)	https://www.mass.gov/info-details/covid-19-response-reporting
MA3	Statement	Bar	Government (State)	https://www.mass.gov/info-details/covid-19-response-reporting
MAYO1	Statement	Map	Medical Center	https://www.mayoclinic.org/coronavirus-covid-19/map
MAYO2	Statement	Line	Medical Center	https://www.mayoclinic.org/coronavirus-covid-19/map
MD1	Statement	Map	Government (State)	https://coronavirus.maryland.gov/
MD2	Statement	Line	Government (State)	https://coronavirus.maryland.gov/
MD3	Statement	Bar	Government (State)	https://coronavirus.maryland.gov/

MDC1	Statement	Table	Government (County)	https://publichealthmdc.com/coronavirus/dashboard
MDC2	Statement	Bar and Line	Government (County)	https://publichealthmdc.com/coronavirus/dashboard
MDC3	Statement	Pie	Government (County)	https://publichealthmdc.com/coronavirus/dashboard
MN1	Statement	Table	Government (State)	https://www.health.state.mn.us/diseases/coronavirus/situation
MN2	Statement	Bar and Line	Government (State)	https://www.health.state.mn.us/diseases/coronavirus/situation
MN3	Statement	Bar	Government (State)	https://www.health.state.mn.us/diseases/coronavirus/situation
MTG1	Statement	Summary	Government (County)	https://www.montgomerycountymd.gov/covid19/data/
MTG2	Statement	Line	Government (County)	https://www.montgomerycountymd.gov/covid19/data/
MTG3	Statement	Pictoral fraction	Government (County)	https://www.montgomerycountymd.gov/covid19/data/
NNELS1	Born Accessible	Area	Government (Federal)	https://nnels.ca/covid-19-accessible-information#ConfirmedCases
NNELS2	Born Accessible	Bar	Government (Federal)	https://nnels.ca/covid-19-accessible-information#ConfirmedCases
NNELS3	Born Accessible	Map	Government (Federal)	https://nnels.ca/covid-19-accessible-information#ConfirmedCases
NYC1	Statement	Table	Government (City)	https://www1.nyc.gov/site/doh/covid/covid-19-data.page
NYC2	Statement	Line	Government (City)	https://www1.nyc.gov/site/doh/covid/covid-19-data.page
NYC3	Statement	Bar	Government (City)	https://www1.nyc.gov/site/doh/covid/covid-19-data.page
NYT1	Statement	Line	News Organization	https://www.nytimes.com/interactive/2021/us/covid-cases.html
NYT2	Statement	Table	News Organization	https://www.nytimes.com/interactive/2021/us/covid-cases.html
NYT3	Statement	Map	News Organization	https://www.nytimes.com/interactive/2021/us/covid-cases.html
OW1	None	Line	Research Institution	https://ourworldindata.org/coronavirus
OW2	None	Map	Research Institution	https://ourworldindata.org/coronavirus
OW3	None	Table	Research Institution	https://ourworldindata.org/coronavirus
SAS1	Born Accessible	Bar	Data Company	https://support.sas.com/accessibility/Samples/COVID-19/hotspots/
SAS2	Born Accessible	Line	Data Company	https://support.sas.com/accessibility/Samples/COVID-19/hotspots/
SCLARA1	Statement	Bar	Government (County)	https://covid19.sccgov.org/dashboards
SCLARA2	Statement	Line	Government (County)	https://covid19.sccgov.org/dashboards
SCLARA3	Statement	Bar	Government (County)	https://covid19.sccgov.org/dashboards
SKI1	Born Accessible	Area	Research Institution	https://covid.ski.org/#

SKI2	Born Accessible	Table	Research Institution	https://covid.ski.org/#
TAB1	Statement	Bar	Data Company	https://www.tableau.com/covid-19-coronavirus-data-resources
TAB2	Statement	Bubble	Data Company	https://www.tableau.com/covid-19-coronavirus-data-resources
TAB3	Statement	Bar	Data Company	https://www.tableau.com/covid-19-coronavirus-data-resources
WA1	None	Map	Government (State)	https://www.doh.wa.gov/Emergencies/COVID19/DataDashboard
WA2	None	Bar and Line	Government (State)	https://www.doh.wa.gov/Emergencies/COVID19/DataDashboard
WA3	None	Bar	Government (State)	https://www.doh.wa.gov/Emergencies/COVID19/DataDashboard
WHO1	Statement	Map	Inter-Gov. Agency	https://covid19.who.int/
WHO2	Statement	Bar	Inter-Gov. Agency	https://covid19.who.int/
WHO3	Statement	Bar	Inter-Gov. Agency	https://covid19.who.int/
WM1	None	Line	Data Company	https://www.worldometers.info/coronavirus/
WM2	None	Bar	Data Company	https://www.worldometers.info/coronavirus/
WM3	None	Table	Data Company	https://www.worldometers.info/coronavirus/

C AUDIT CRITERIA

Table 9. A List of Criteria Used for the Accessibility Audit

Criteria Category	**Criteria Code**	**Criteria Description**	**Evaluation Notes**
Content	VisDetectable	Is the visualization detectable through your screen reader?	Partial indicates that the visualization is perceivable but is difficult to find
Content	TrendConveyed	If the visualization is conveying a trend or a pattern, is that trend or pattern described or sonified in a way that is accessible through the screen reader?	NA indicates that no trends are being explicitly communicated through the visualizations, such as with tables
Content	VisualAlternative	Do visual features (i.e., trendlines, markers, colors, shapes) in the visualization have alternative forms of access for the screen reader? (You may need to look outside of the visualization).	Researchers provided alt text descriptions of visual features for auditors to reference. NA indicates that visualization does not rely on visual features to convey semantic information
Content	DataConveyed	Are specific data points conveyed in a way that is accessible through screen reader or sonification?	
Content	GroupsAccessible	If the visualization is depicting multiple groups of information, is information about each group accessible through the screen reader?	Multiple groups is defined as if data for multiple categorical variables are shown. Examples include if a graph shows multiples series of information, or if a table shows multiple categorical variables. NA indicates that only single groups of data are depicted

Content	TableAccessible	Does the visualization consist of or is supported by a table that can be accessed?	NA indicates that visualization only contains summary statistics that does not need alternative tables. Partial indicates that alternative tables are difficult to find
Content	TableSortDownload	Does the visualization consist of or is supported by a table that can be downloaded or sorted through your screen reader?	NA indicates that visualization only contains summary statistics that does not need alternative tables. Pass indicates that either columns can be sorted, or that an accessible version of the table can be downloaded
Content	TableHeaders	Does the visualization consist of or is supported by a table in which row and column headers are articulated when navigating through the table?	NA indicates that visualization only contains summary statistics that does not need alternative tables. Partial indicates either row or column headers are provided but not both
Content	FormatUnderstan dable	Is information formatted in a way that can be reasonably understood through your screen reader?	For example, six five zero zero zero zero zero zero zero zero should be described as six point five billion
Content	HTMLSemantics	Are semantic HTML elements used correctly?	Headers, tables, buttons should be properly used
Content	ComplexityAdequate	Is the complexity of information appropriate for tasks users may want to do with the visualization through screen reader access?	Information complexity is inappropriate if there is too much distracting information, or if the accessible information is oversimplified to which the goal of the visualization is not being met
Context	TitleAccessible	Is the title of the visualization accessible through your screen reader?	
Context	TypeIndicated	Is the type of visualization indicated (i.e., table, bar graph, line graph, map) through screen reader?	NA indicates that visualization only contains summary statistics
Context	SummaryAdequate	Is an adequate summary or caption of the visualization provided that is accessible through your screen reader?	NA indicates that visualization only contains summary statistics or is a table
Context	UpdateIndicated	Is there any indication through your screen reader of when the data has been last updated, either within or outside the visualization?	
Context	SourceProvided	Is information about the source of the data or potential uncertainty or inaccuracy pertaining to the data provided through your screen reader?	Partial indicates that either the source or information about update frequency is provided
Navigation	TellInVis	Is it difficult to tell if you are in the visualization of interest using your screen reader?	Visualizations that contain only summary statistics are indicated as NA as they do not need additional summaries
Navigation	DesignApproachable	Is the design of the visualization familiar, follows best practices, and consistent through screen reader access, or is an adequate explanation of the visualization design provided that is accessible through your screen reader?	Pass indicates that the visualization is either familiar, follow best practices, and consistent through screen reader access, or an adequate explanation of the visualization design is provided
Navigation	KeyboardOverride	Are there any custom keyboard controls that override screen reader settings?	

Navigation	ControlsAdequate	Are the controls provided appropriate for tasks users may want to do with the visualization through screen reader access?	Tables should be navigable both along rows and columns; line graphs show navigable over the data; graphs with connections should be navigable along connections
Interactivity	InteractivityExposed	Is the presence of animation exposed to screen reader users?	Interactive features include buttons, dropdown lists, keyboard commands that change the information conveyed, such as filtering, sorting, zooming, changing the type of information plotted, accessing more specific details, changing sound parameters, and so on. To auditors, criteria was provided as: "Can you tell through your screen reader if the visualization has any interactive features?" Researchers cross-referenced auditor responses to if animated features are visually perceivable to determine if all interactions are perceivable. NA indicates that the visualization does not contain interactive features
Interactivity	FollowChanges	Is it easy to follow changes that are made to the visualization using your screen reader?	NA indicates that the visualization does not contain interactive features.
Interactivity	ConfigurationsReturn	Are different configurations of the visualization easy to return to using your screen reader?	A visualization is in a different configuration if the provided information or view of the information has changed. NA indicates that the visualization does not contain interactive features.
Interactivity	AnimationExposed	Is the presence of animation exposed to screen reader users?	To auditors, criteria was provided as: "Does the visualization contain any animations, videos, or audio clips?" Researchers cross-referenced auditor responses to if animated features are visually perceivable to determine if animations are perceivable. NA indicates that the visualization does not contain animated features
Interactivity	AnimationPausable	If there are animations, videos, or audio clips longer than 2s length, can they be paused or stopped using your screen reader?	NA indicates that the visualization does not contain animated features
Interactivity	AccessiblyReproduce	Is the visualization easy to share or reproduce in a way that is accessible?	

D AUDIT DATA

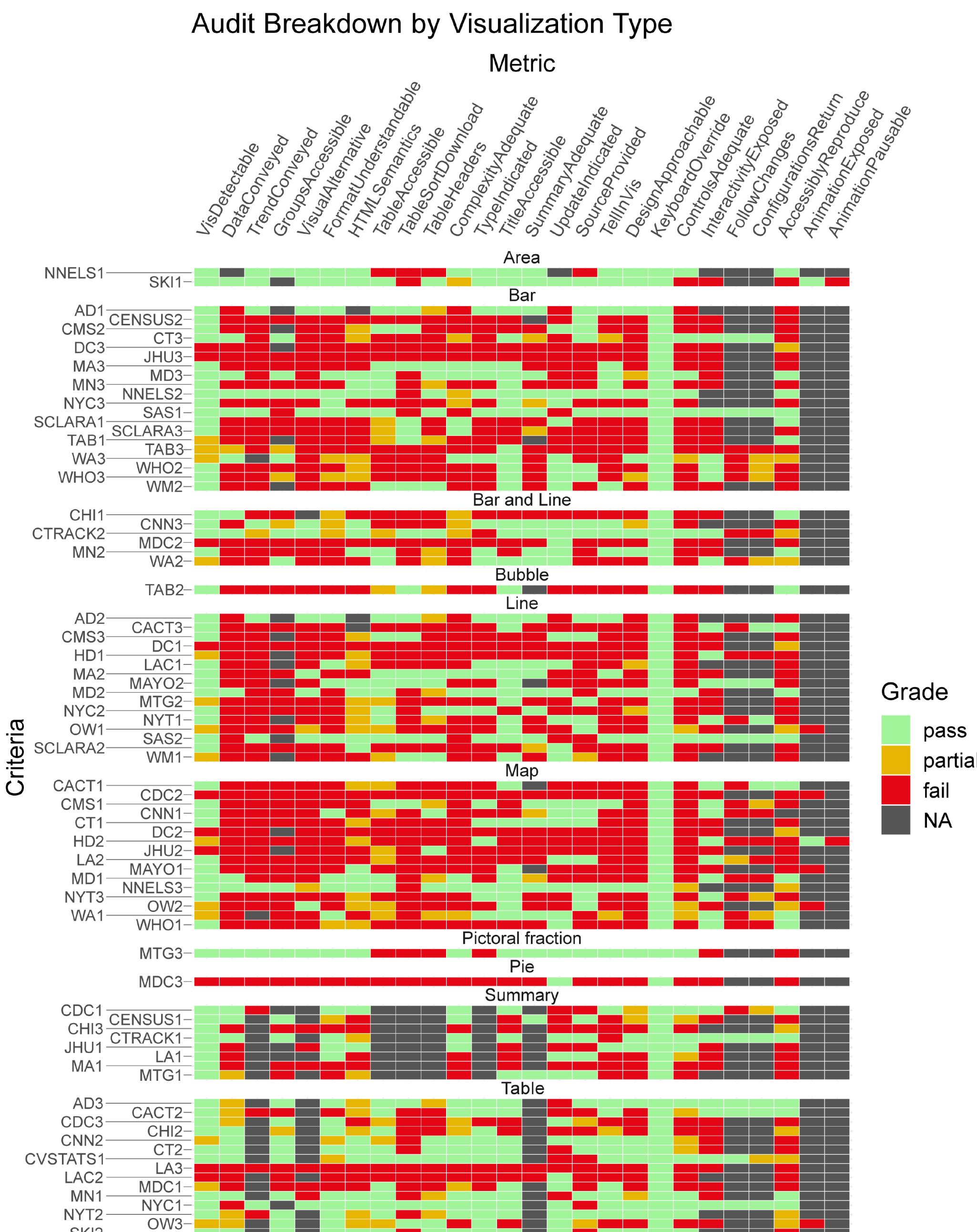

Fig. 12. Criteria grades for all audited visualizations, grouped by visualization type.

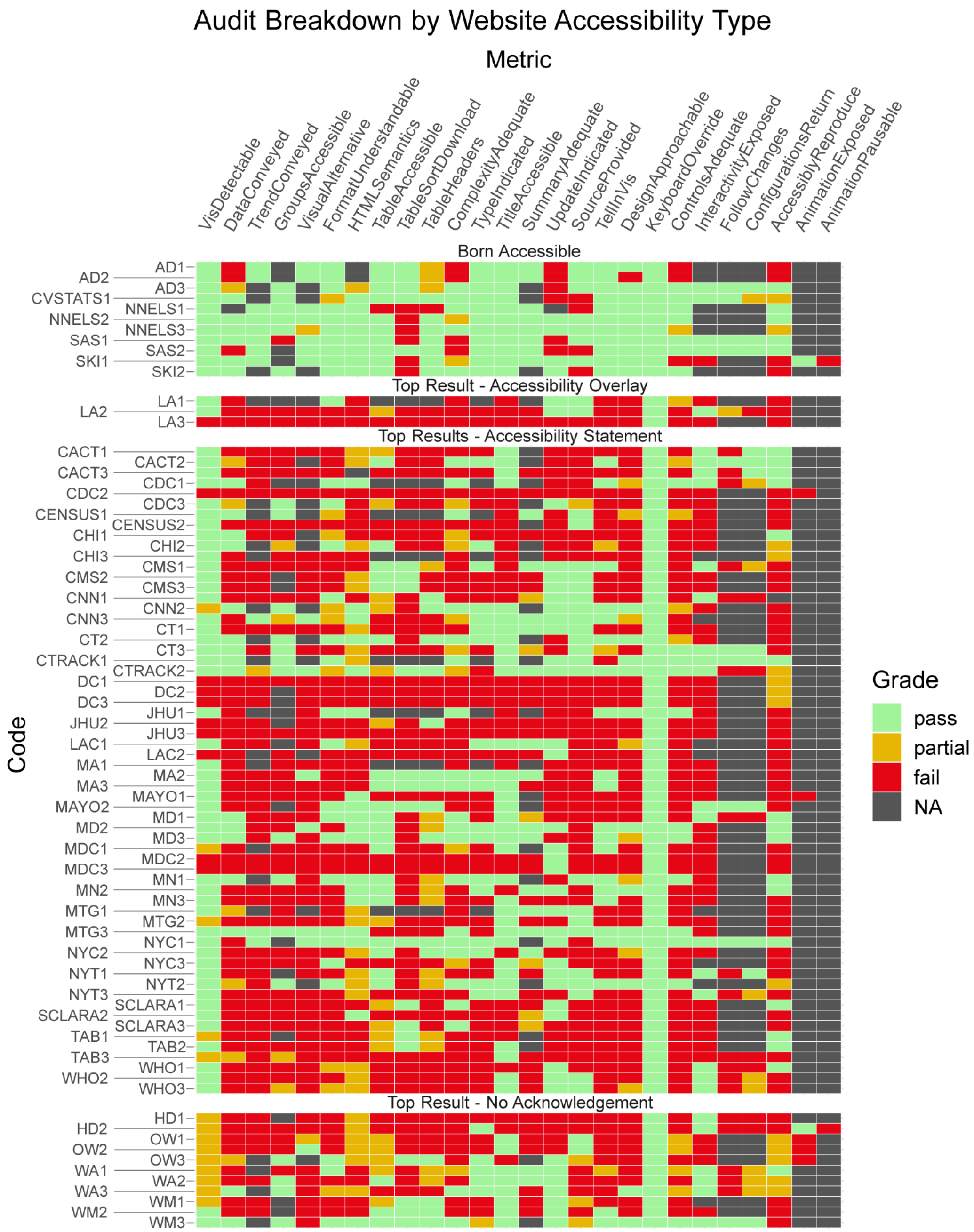

Fig. 13. Criteria grades for all audited visualizations, grouped by whether the host website was *Born Accessible*, made accessibility statements, used accessibility overlays, or did not acknowledge accessibility.

Table 10. Criteria Grade Breakdown between the *Top Results* ("TR") and *Born Accessible* ("BA") Visualization Groups

Category	**Criteria**	**Pass Percent (TR)**	**Partial Percent (TR)**	**Fail Percent (TR)**	**NA Percent (TR)**	**Pass Percent (BA)**	**Partial Percent (BA)**	**Fail Percent (BA)**	**NA Percent (BA)**
Content	VisDetectable	68.42	18.42	13.16	0	100	0	0	0
Content	TrendConveyed	3.95	1.32	71.05	23.68	72.73	0	0	27.27
Content	VisualAlternative	9.21	1.32	71.05	18.42	63.64	9.09	0	27.27
Content	DataConveyed	21.05	7.89	71.05	0	54.55	9.09	27.27	9.09
Content	GroupsAccessible	19.74	5.26	53.95	21.05	54.55	0	9.09	36.36
Content	TableAccessible	30.26	22.37	36.84	10.53	90.91	0	9.09	0
Content	TableSortDownload	21.05	0	68.42	10.53	45.45	0	54.55	0
Content	TableHeaders	19.74	15.79	53.95	10.53	63.64	27.27	9.09	0
Content	FormatUnderstandable	26.32	10.53	63.16	0	90.91	9.09	0	0
Content	HTMLSemantics	23.68	31.58	43.42	1.32	72.73	9.09	0	18.18
Content	ComplexityAdequate	27.63	11.84	60.53	0	45.45	18.18	36.36	0
Context	TitleAccessible	55.26	0	44.74	0	100	0	0	0
Context	TypeIndicated	30.26	1.32	57.89	10.53	100	0	0	0
Context	SummaryAdequate	19.74	7.89	42.11	30.26	72.73	0	0	27.27
Context	UpdateIndicated	48.68	0	51.32	0	36.36	0	54.55	9.09
Context	SourceProvided	34.21	5.26	60.53	0	63.64	0	36.36	0
Nav	TellInVis	27.63	3.95	68.42	0	100	0	0	0
Nav	DesignApproachable	15.79	10.53	73.68	0	90.91	0	9.09	0
Nav	KeyboardOverride	100	0	0	0	100	0	0	0
Nav	ControlsAdequate	15.79	11.84	72.37	0	63.64	9.09	27.27	0
Int	InteractivityExposed	31.58	0	57.89	10.53	36.36	0	9.09	54.55
Int	FollowChanges	7.89	1.32	23.68	67.11	36.36	0	0	63.64
Int	ConfigurationsReturn	11.84	10.53	10.53	67.11	27.27	9.09	0	63.64
Int	AnimationExposed	1.32	0	6.58	92.11	9.09	0	0	90.91
Int	AnimationPausable	0	0	1.32	98.68	0	0	9.09	90.91
Int	AccessiblyReproduce	22.37	15.79	60.53	1.32	45.45	18.18	36.36	0

E CONTEXTUAL INQUIRY PARTICIPANT DEMOGRAPHICS

Table 11. Demographics for Participants of the Contextual Inquiry

P#	Described Level of Vision	Gender	Age Group	Braille display	Screen reader	Tactile Graphics Expertise	Audio Graphics Expertise	SGL Avg (1-6)	Additional Websites Used
1	totally blind	Male	65–74	Y	JAWS	Expert	Advanced beginner	5.4	CVStates
2	totally blind	Female	65–74	Y	JAWS	Advanced beginner	No experience	1.8	N/A
3	totally blind	Female	25–34	Y	JAWS	Expert	Proficient	4.6	N/A
4	Optic Nerve Hypoplasia	Male	25–34	N	NVDA	Proficient	Advanced beginner	4.2	N/A
5	totally blind	Female	45–54	N	JAWS	Advanced beginner	No experience	4.6	N/A
6	totally blind	Male	18–24	N	VoiceOver	Competent	Advanced beginner	4.4	N/A
7	totally blind	Female	35–44	N	JAWS	Proficient	Competent	4.2	COVID Act Now
8	totally blind	Female	55–64	N	JAWS	Advanced beginner	Advanced beginner	3.6	Chicago Tracker
9	light perception only	Female	35–44	N	JAWS	Expert	Proficient	4.2	who.int
10	totally blind	Female	55–64	Y	JAWS	Proficient	Competent	3.8	CVStats, MN Tracker
11	totally blind	Male	25–34	Y	JAWS	Expert	Expert	5.4	CVStats
12	Extremely low vision, right above light perception	Male	25–34	N	NVDA	Proficient	Expert	4.6	CVStats, covid.ski, Canada Covid Tracker

F CONTEXTUAL INQUIRY WEBSITES

Table 12. Websites Visited During the Contextual Inquiry and the Accessibility Features Each Provided at the Time of Access

Website	Mention	Accessibility Branded	Table: historical data	Table: sortable	Table: filterable	Table: csv download	Sonification: interactive	Sonification: panning	Sonification: retrievable values	Sonification: time indicator	Graphics: svg	Graphics: alt text	Graphics: graphic title	Graphics: plot type	Graphics: labels/units/ranges	Graphics: axes increments	Graphics: colors/patterns	Summaries: snapshot	Summaries: interpretations
CVStats	Task	Y	N	Y	N	N	-	-	-	-	-	-	-	-	-	-	-	-	-
Accessible Data	Task	Y	Y	N	N	Y	-	-	-	-	N	Y	Y	Y	Y	Y	Y	Y	-
covid.ski	Task	Y	N	N	N	N	N	Y	N	Y	N	Y	Y	Y	Y	N	N	Y	N
COVID Act Now	Interview	N	N	Y	N	N	-	-	-	-	Y	N	Y+	N	N	N	N	Y	Y
who.int	Interview	N	N	Y	N	Y	-	-	-	-	Y	N	Y+	N	N	N	N	Y	N
CDC Data Tracker	Interview	N	Y	Y	N	Y	-	-	-	-	Y	N	Y+	N	N	N	N	Y	N
Chicago Latest	Interview	N	N	N	N	N	-	-	-	-	Y	N	N	N	N	N	N	Y	N
MN Health Tracker	Interview	N	Y	N	N	N	-	-	-	-	N	Y	Y	N	N	N	N	Y	N

* Requires plugin installation + Outside of alt text - Not Applicable.

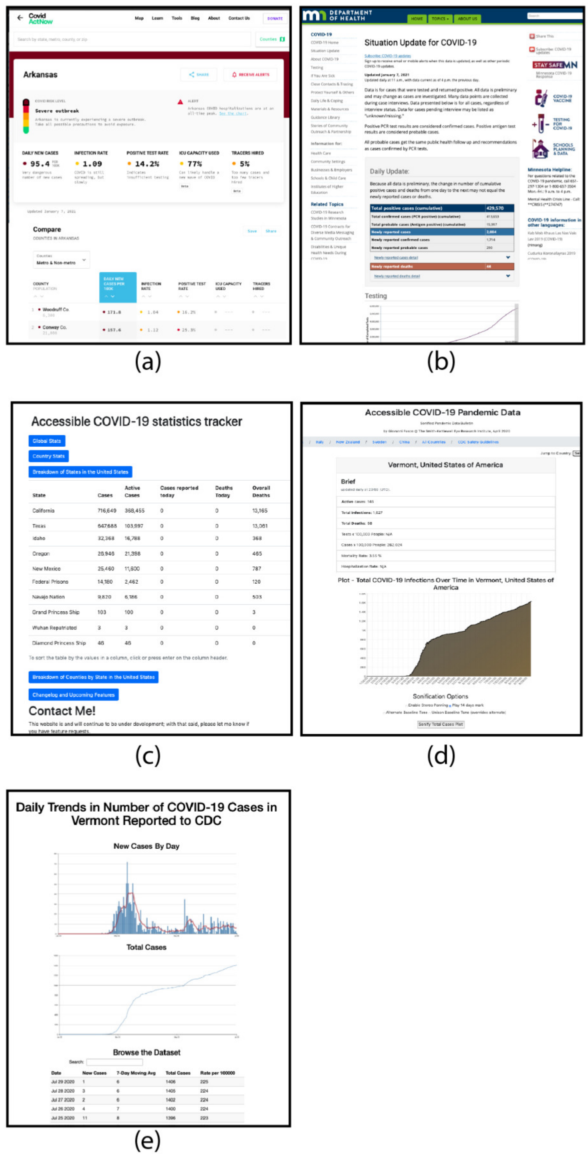

Fig. 14. Sample of websites visited during the contextual inquiry. (a) COVID ACT NOW presented data primarily through tables and provided a brief summary. (b) MN Department of Health Situation Update provided a summary in the form of text and key statistics. (c) CV Stats provided tabular data. (d) COVID SKI provided access to sonification of different data charts as well as summarized tabular data. (e) Accessible Data provided access to image descriptions and tabular data. (a) and (b) were examples of sites that individual participants used frequently (COVID Tracking Project, MN Department of Health Situation Update). (c), (d), and (e) were branded as accessible and explored by all participants for the contextual inquiry (CVStats, covid.ski, AccessibleData).

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