Increasing Agency of Screen-Reader Users in Consuming Information From Online Data Visualizations

Ather Sharif
Paul G. Allen School of Computer Science and Engineering
University of Washington
Seattle, WA, USA
asharif@cs.washington.edu

Andrew M. Zhang
Paul G. Allen School of Computer Science and Engineering
University of Washington
Seattle, WA, USA
azhang26@cs.washington.edu

Jacob O. Wobbrock
The Information School
University of Washington
Seattle, WA, USA
wobbrock@uw.edu

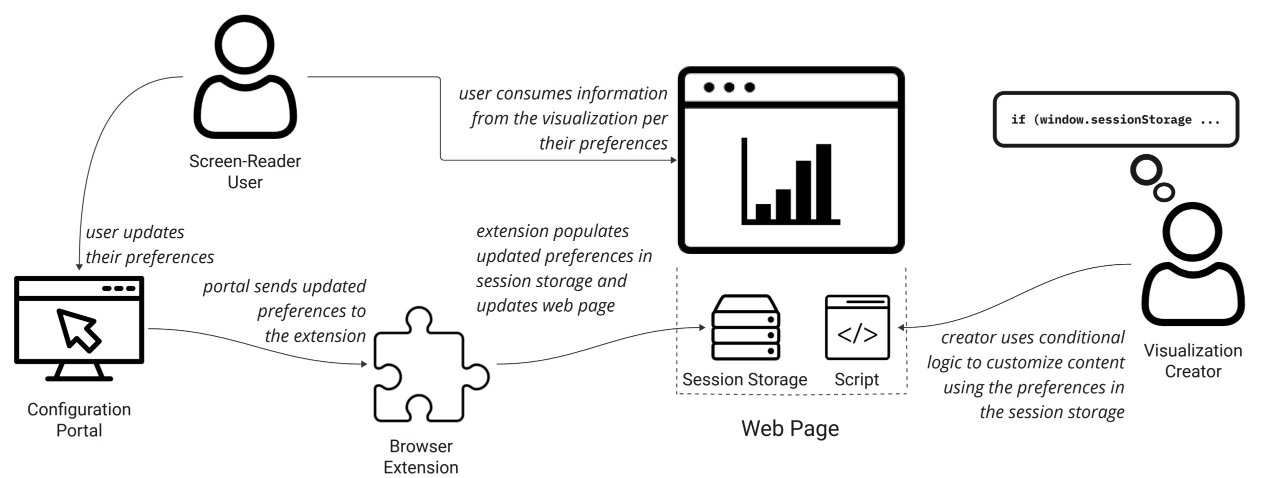

Figure 1: The system diagram of VoxEx, showing the interaction flow of a screen-reader user from specifying their preferences to obtaining customized information from an online data visualization. The implementation flow for creators is also shown.

Abstract

Screen-reader users are limited to the information that visualization creators choose for them to extract. Consequently, they cannot consume or produce information (e.g., for work) as they prefer. For example, the information in an alt-text, expected to meet the needs of *all* screen-reader users, may be either insufficient or excessive for some users. We present VoxEx, a system that enables users to customize the information they consume from online data visualizations. We conducted two formative studies that informed our design of VoxEx. To assess the utility of our system, we administered a field deployment of our system by integrating it with VoxLens (Sharif *et al.*, 2022), subsequently conducting two case studies with screen-reader users and creators. We present the findings from these studies, reporting that our system improves users' efficiency in information extraction and requires minimal effort from creators.

W4A '25, Sydney, NSW, Australia

ACM ISBN 979-8-4007-1882-3/25/04
https://doi.org/10.1145/3744257.3744262

CCS Concepts

• **Human-centered computing → Information visualization**; **Accessibility systems and tools**; • **Social and professional topics → People with disabilities**.

Keywords

agency, visualization, accessibility, screen-reader users, blind

ACM Reference Format:
Ather Sharif, Andrew M. Zhang, and Jacob O. Wobbrock. 2025. Increasing Agency of Screen-Reader Users in Consuming Information From Online Data Vi-sualizations. In *W4A '25: Proceedings of the 22nd International Web for All Conference (W4A '25), April 28–29, 2025, Sydney, NSW, Australia.* ACM, New York, NY, USA, 147-159.
https://doi.org/10.1145/3744257.3744262

1 Introduction

Inaccessible online data visualizations exacerbate the inequity and disenfranchisement screen-reader users[1] experience with access to digital content [37, 50]. Prior research shows that due to inaccessible visualizations, screen-reader users extract information 61% less accurately and spend 211% more interaction time than non-screen-reader users [66]. To make matters worse, even when accessibility

[1]People who use screen readers (*e.g.*, JAWS [65]) for permanent or temporary needs and may have complete or partial blindness, learning disabilities, or motion sensitivity [66].

measures are applied, the information provided to screen-reader users by visualization creators[2] is often either insufficient or excessive [36, 66, 93]. For example, alternative text ("alt-text") too often serves as the single source of accessible information with an expectation to satisfy the needs of over 2.2 billion[3] screen-reader users worldwide. Not having agency over the information screen-reader users consume can further aggravate the disenfranchisement these users experience with digital content, especially when performing their employment responsibilities.

Researchers have examined the utility of customization in their solutions to provide screen-reader users agency over the information they consume [32, 40, 80]. However, despite these efforts, how to best provide screen-reader users more agency over their own manner of information consumption from data visualizations, such that their agency isn't limited to a particular software, remains unclear. Our work addresses this timely issue by being the first to investigate and improve screen-reader users' agency in consuming information from online data visualizations through both empirical and artifact contributions.

Specifically, we developed `VoxEx`, a system that provides agency to screen-reader users to customize the information they consume from online data visualizations. To make informed design decisions while creating `VoxEx`, we conducted two formative studies: (1) a survey of 60 screen-reader users, and (2) a semi-structured interview with 12 screen-reader users. Through these studies, we collected participants' customization needs and preferences from various modalities, including alt-text, data tables, and sonification. We also gathered their thoughts on potential technology interventions. Based on our findings, we created three significant system components for `VoxEx`: (1) a backend server, (2) a browser extension, and (3) a configuration portal. Together these components enable screen-reader users to provide their preferences, and make these preferences available to visualization creators. Visualization creators can utilize these preferences to cater their content to the individual needs of screen-reader users using logical if-else conditions. Additionally, we administered a field deployment of `VoxEx` through integration with `VoxLens` [71], a multi-modal open-source JavaScript plug-in that makes online data visualizations accessible to screen-reader users.

To examine the utility of `VoxEx`, we conducted two case studies: (1) a five-day diary study with three screen-reader users, and (2) a single-session study with three visualization creators. Our findings show that `VoxEx` improves our participants' efficiency in extracting information from online data visualizations and requires minimal development effort from visualization creators. In addition, our participants did not name any privacy or security concerns with `VoxEx`, even when prompted. Our results also shed light on the importance of user agency for screen-reader users and identified areas of improvement `VoxEx`, including providing definitions for configuration options and modifying verbosity level by domains of interest. We enhanced our system by implementing solutions for these areas of improvement.

[2]People who create online data visualizations. These include people with all levels of expertise in creating visualizations, from beginners to experts. This term encompassed similar terms, including "developer" and "designer."

[3]https://www.who.int/news-room/fact-sheets/detail/blindness-and-visual-impairment

The main contributions of this work are:

(1) Empirical results from our formative studies with screen-reader users, including a survey of 60 users and interviews with 12 users.
(2) `VoxEx`, a system that provides agency to screen-reader users to customize the information they consume from online data visualizations.
(3) An integration of `VoxEx` with the open-source tool `VoxLens` [71], a multi-modal JavaScript plug-in that makes online data visualizations accessible to screen-reader users.
(4) Empirical findings from our case studies with three screen-reader users and three visualization creators that we conducted to assess the utility of `VoxEx`.

2 Related Work

We review prior work on techniques commonly used to make data visualizations accessible, enhancing user agency for screen-reader users, and the employment challenges these users experience.

2.1 Modalities for Visualization Accessibility

2.1.1 Alt-Text. Alternative text ("alt-text") is one of the most widely used techniques to provide screen-reader users with a description of visual content [48, 52, 54]. Researchers have made contributions by assisting developers in auto-generating alt-text [35, 47, 53, 67, 76, 91]. For example, Singh *et al.* [76] developed `FigurA11y`, an interactive system that supplies authors of scientific papers with draft alt-text and offers suggestions based on figure and paper metadata. Their findings from a study with 14 authors indicate that their system improved authors' effectiveness in producing descriptive alt-text in scientific papers. However, screen-reader users can only consume information chosen for them. In our work, we address this disenfranchisement by providing these users the agency to customize the information they consume from data visualizations.

2.1.2 Sonification. Sonification communicates information to screen-reader users using non-speech audio representations [3, 21, 82]. Prior research has explored sonification to improve the experiences of screen-reader users with data visualizations [2, 18, 29, 64, 77] and developed open-source solutions [20, 28, 44, 70, 78]. Hoque *et al.* [30] used natural sounds, such as waterfalls, to sonify data visualizations through their tool, `Susurrus`. Similarly, Sharif *et al.* [69] extended Wang *et al.*'s [83] work by investigating various oscillators and synthesizers and developing `Sonifier` [70], an open-source library that creates sonification using these oscillators and synthesizers. Our work enables screen-reader users to specify their preferences for sonification, including the sound type and speed.

2.1.3 Data Tables. In contrast to alt-text and sonification, data tables offer screen-reader users granular access to underlying data. Several prior works have discussed the utility of data tables as an accessibility technique [36, 41, 84]. For example, Ferres *et al.* [19] and Sharif *et al.* [66] reported that screen-reader users relied on raw data to extract information from data visualizations in their user studies. However, data tables require linear access to data points and can cause cognitive overload for users, especially when the data cardinality is high [43, 66]. To this end, in this work, we enable screen-reader users to specify their preferences to consume information from data tables. For example, data tables can be organized based on the sorting preferences of screen-reader users.

2.2 User Agency for Screen-Reader Users

Prior work in human-computer interaction has defined user agency as "a user's inherent capacity to form goals and intentionally take action to achieve those goals", and reported that it is "central in managing technostress". Researchers have widely discussed the importance of user agency for disabled people [12, 15, 42], including screen-reader users [4, 27, 33, 49]. For example, Barter [4] discussed the limitations of blind and low-vision users' agency in accessing information equitably compared to their sighted peers. Researchers have also explored user agency through customization in their solutions [32, 40, 80]. For example, Thompson *et al.* [80] developed a web-based accessibility engine called `ChartReader` and implemented customizations in its "filter" feature to minimize the auditory and processing loads on the user. However, these customizations are limited to the context of `ChartReader`. Similarly, Sharif *et al.* [71, 72] created `VoxLens`, a multi-modal JavaScript plugin that enables users to extract information through verbal queries. While their findings show a significant improvement in users' accuracy by 164% and interaction times by 50% to access data in visualizations, the modalities used in `VoxLens` do not offer the agency to customize the information users receive.

2.3 Employment Challenges

People with disabilities face several challenges at work, including inaccessible technologies [14, 57], negative stigma [11, 14, 57], and discrimination in hiring and promotion [11, 57]. Consequently, these challenges affect their performance, adversely affecting promotion opportunities and reinforcing employment barriers [11, 17, 34]. Such is particularly true for the increasing number of jobs that involve creating and consuming data from visualizations to perform essential job requirements, as the inherent nature of visualizations automatically puts screen-reader users at a disadvantage by default. For example, a participant from O'Donnell's [57] study said: "*You are taking someone with skills, and training ... and expecting them to research and learn along the way ... you cannot research something if the information you need is inaccessible, unclear, or unavailable.*"

Our work improves the accessibility and effectiveness of information consumption from data visualizations for screen-reader users by enabling them to access data based on their preferences. For example, a screen-reader user may be able to extract information from data tables more effectively by specifying their data sorting or summary preferences, consequently enhancing their job performance. To do so, first, we provide generalizable findings of the information screen-reader users customize from data visualizations. Then, we present `VoxEx`, a centralized interface that enables users to specify their preferences and can be integrated with other state-of-the-art solutions to make online data visualizations accessible. Additionally, adopting our system places a minimal development burden on visualization creators and does not demand additional installation. We created `VoxEx` using the generalizable findings from our formative studies, presented in detail below.

3 Formative Studies

To better understand opportunities for enhancing user agency for screen-reader users consuming information from online data visualizations, we administered two formative studies: (1) a survey of 60 screen-reader users and (2) semi-structured interviews with 12 screen-reader users. We conducted the interviews to solicit a more in-depth understanding of the survey results. Altogether, the results from these two studies provide complementary insights. We analyzed the data using a mixed-methods approach involving qualitative analysis and descriptive statistics.

3.1 Participants

We recruited our participants for both formative studies through collaboration with the National Federation of the Blind [56], social media platforms, and distribution lists for screen-reader users. Among our 60 respondents (M=49.1 years old, SD=14.9), 38 identified as women, 20 as men, and two as non-binary. Fifty-three had complete blindness, and seven were partially blind. Participation in the survey was voluntary and without financial compensation.

We also conducted semi-structured interviews with 12 screen-reader users (M=48.2 years old, SD=17.2). Among our interviewees, seven identified as women, three as men, one as non-binary, and one did not disclose. Ten had complete blindness, and two were partially blind. We compensated them with a $25 Amazon gift card. We ceased recruitment after reaching saturation of insights [16, 24].

3.2 Procedure

3.2.1 Online Survey. Our online survey included two steps. Participants filled out each step without supervision. In the first step, we displayed the purpose of our study, eligibility criteria, and data anonymity clause. Additionally, we collected participants' demographic information, including their gender [79], preferred pronouns, age, preferred screen reader, vision level, diagnosis, and education level. Next, we asked what they would customize in alt-text and sonification of data visualizations and tables. We also asked our participants to provide details of their choices via a use case and examples as free-form responses. Additionally, we inquired about any optional comments they have pertaining to user agency.

3.2.2 Semi-Structured Interviews. We conducted the 45-minites semi-structured interviews on Zoom. During the interview sessions, we gathered participants' thoughts about user agency in extracting information from data visualizations. Particularly, we asked about *what* they would customize in different modalities, and *how* they would do so (*i.e.*, technology interventions). We provided them with examples of various modalities to increase their engagement.

3.3 Analysis

We calculated descriptive statistics and qualitatively analyzed our participants' responses from both studies. Specifically, we conducted a theoretical thematic analysis [7]. We used a semantic approach [61] and an essentialist paradigm [62, 87] for our analysis, following guidelines from Braun and Clarke [8]. We calculated the inter-rater reliability (IRR) using pairwise percentage agreement, reaching a high agreement percentage of 97%. Our determination

Table 1: Modalities and their customizations identified by participants during our formative studies.

Modality		Customization
Alt-text	C1	*Adding more information (e.g., chart type)*
	C2	*Removing unwanted/excessive information*
	C3	*Controlling the verbosity of the text*
	C4	*Including the chart type (e.g., bar graph)*
Data Tables	C5	*Sorting data by ascending order*
	C6	*Sorting data by descending order*
Sonification	C7	*Change pitch type (continuous and discrete)*
	C8	*Toggle between traditional and musical*
	C9	*Adjust sound speed*

of calculating IRR in our analysis is based on recommendations on best practices put forward by McDonald *et al.* [51].

3.4 Results

Overall, many of our participants expressed the desire to customize alt-text (75%), data tables (73%), and sonification (48%). Additionally, 8% of our participants identified the necessity of having agency over information extraction using verbal question-and-answer modalities, such as provided by VoxLens [71]. Table 1 presents a summary of findings for each modality. In this work, we focused on the three most commonly identified modalities: (1) alt-text, (2) data tables, and (3) sonification.

3.4.1 Alt-Text. Our participants communicated their desire to customize the summary content of data visualizations. Some participants were interested in hearing a detailed summary, whereas others preferred succinct responses. To cater to the varying needs of users, P1 suggested providing more than the standard options in a summary. She said, "*For a graph I'm particularly interested in, I wanna know more than just the average, the maximum, the minimum. I would want that option [to know more].*" On the other hand, P4 highlighted the importance of removing excessive information she didn't want to know from the summary. She stated, "*For the description, the problem sometimes that we run into is there's excessive alt-text. I wanna be able to have the flexibility of invoking that because I may not want to know.*"

3.4.2 Data Tables. A common desire of all participants who stated a need for customizing data tables was a feature to sort data based on their preferences. This finding aligns with those from prior work [69, 80] on data visualization accessibility, particularly sonification. S21 shared his interaction and discussed the benefits of customizing sorting: "*I've encountered charts and graphs where the screen reader moves across each row first and then to the next row. This makes it difficult to navigate because sometimes it is hard to remember or keep track of column headings. It happens a lot with financial data. So, being able to customize sorting would be great.*" S21's statement resonates with prior work's [66, 93] recognition of the cognitive overload caused by screen readers' linear access of data in tables. S21 proposed sorting as the solution to this problem.

3.4.3 Sonification. Participants emphasized the need to customize the pitch, speed, and sound type of a sonified response to interpret data better. S22 expressed her need to customize the speed of the sound, saying, "*I would like to customize the speed of the sound or the length of the sound. Sometimes audio information moves very quickly, and it would be nice to be able to slow it down and get more details.*" Further, S33 discussed the need to customize the pitch, frequency, and sound type, finding it critical for people with multiple disabilities: "*Pitch, frequency, and sound type can be important to customize for people with intersectional disabilities that affect sensory processing so as not to trigger any discomfort, as well as to maximize clear understanding for those with hearing impairments. It is important that any sounds do not interfere with the screen readers.*" While our work did not explore the intersectionality of different disabilities, it provides avenues for future work to explore this further.

3.4.4 Technology Intervention. Our participants shared positive views about having a centralized system to enable them to specify their preferences that visualization creators could utilize to provide a customized response. P2 shared the benefits of a centralized system: "*I'm notorious for having, like, three, four, five different machines with different setups and doing the same thing on different machines to install something. And then all of a sudden, something needs to be updated, and all hell breaks loose, and then I have to change it everywhere.*" Furthermore, P5 considered browser extensions a potential technology intervention and shared her opinion of an authentication feature. She said, "*You could [develop a] Google extension; sometimes you install extensions and as soon as you launch them, it's ready to go. But for some extensions, you launch them, and then it asks you to sign in. So, I'd rather have it sign in because that way you know your data is somewhat protected.*"

From the formative studies, our goal was to understand *what* information screen-reader users prefer to customize in using the most common modalities to access data in visualizations and *how* they can accomplish this task without compromising their privacy and security. Based on these preferences of our participants, we considered four key elements to build our technology intervention: (1) a centralized system, (2) using users' existing preferences as default settings, (3) a browser extension, and (4) an authentication feature for privacy and security. In the next section, we provide our system, VoxEx, that incorporates these four elements.

4 VoxEx

VoxEx is a centralized system comprising a configuration portal, a browser extension, and a backend server. We created VoxEx based on the findings from our formative studies. Specifically, our goal was to enable screen-reader users to specify their information consumption preferences and provide creators with an interface to utilize these preferences to customize the accessibility of their data visualizations. By enabling screen-reader users to receive data visualizations customized to their preferences, VoxEx embodies the principles of ability-based design [88, 89].

4.1 System Overview

VoxEx is a system that assists two stakeholder groups: screen-reader users and visualization creators. Figure 1 shows the system overview of VoxEx. To enable screen-reader users to specify

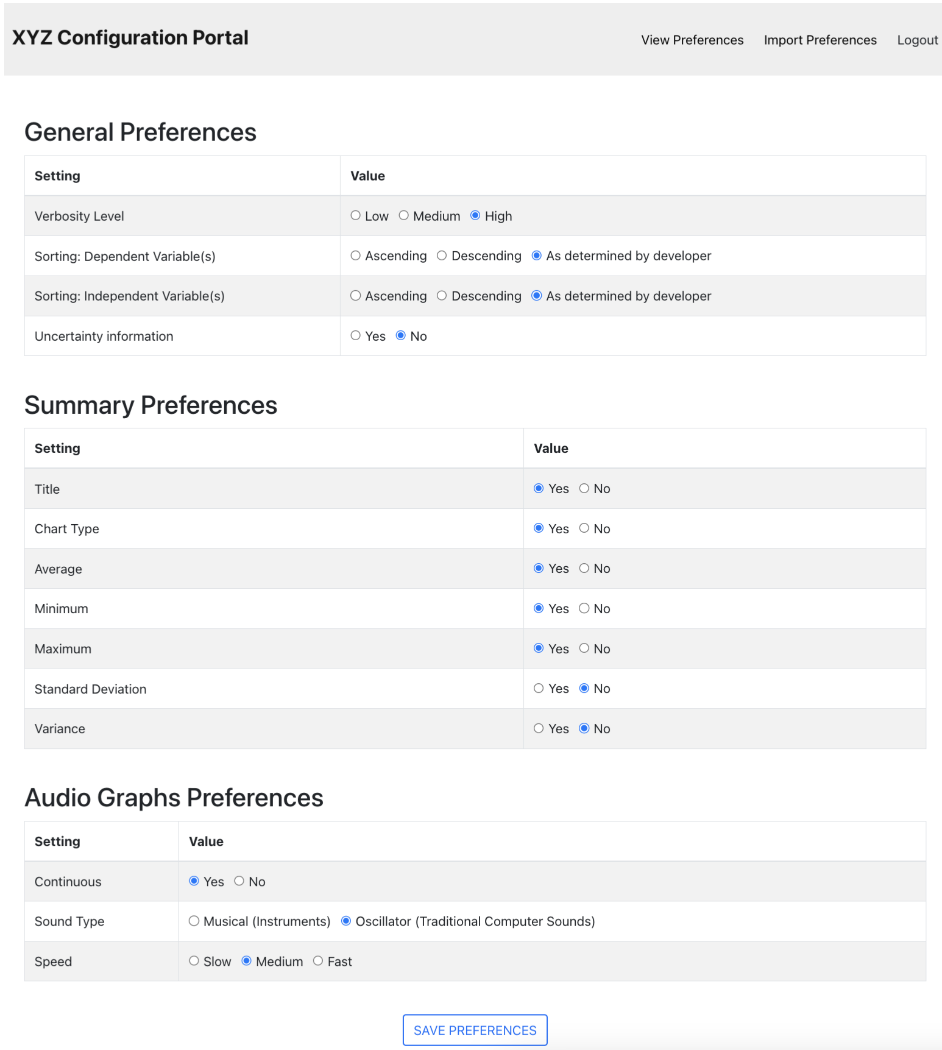

Figure 2: Screenshot of the configuration page of the `VoxEx` portal, displaying preferences categorized by modalities.

their preferences, we created a Chrome extension and an online configuration portal. Users can add our Chrome extension to their browser through the Chrome Web Store[4]. The online configuration portal is a website that enables these users to securely log in using their Google accounts and specify their information consumption preferences. These preferences are not limited to output modality and style, like verbosity. Users can also specify the content they prefer to hear as well. These preferences are stored in the session storage[5] of all the existing windows in the user's browser as well as new windows or tabs.

The session storage of any given web page is accessible to the visualization creators and web developers via the `sessionStorage`[6] property of the `Window` interface[7]. When a user specifies their preferences, our system populates these preferences in the session storage for creators to access them programmatically. For example, if the user states their preference to hear the standard deviation alongside means, the visualization creators can use if-else conditions to include this information in the alt-text of their visualizations. In doing so, our system facilitates visualization creators to provide users the agency to customize the information they wish to hear and not what is chosen for them by the creators. The visualization creators do not need to install the browser extension or visit the configuration portal to enable support for `VoxEx`. However, our open-source repository includes a "playground emulator" for non-screen-reader users to interact with the system as screen-reader user, and documentation for beginners and expert creators alike.

[4]https://chromewebstore.google.com/
[5]A separate storage area for each website, available for the duration of the page session.
[6]https://developer.mozilla.org/en-US/docs/Web/API/Window/sessionStorage
[7]https://developer.mozilla.org/en-US/docs/Web/API/Window

4.2 System Components

4.2.1 Configuration Portal. We created the configuration portal using `Apollo`[8] and `ReactJS`[9] and hosted it on our server. Our configuration portal comprises three components: (1) Google authentication, (2) configuration page, and (3) import preferences page.

4.2.1.1 Google Authentication. To store users' preferences, we require users to log in using their Google account to access our portal, using their email as the primary key in our database. We implemented the log-in feature using the `react-oauth`[10] library.

4.2.1.2 Configuration Page. We display the configuration page once the user has successfully logged in, which shows options for their information consumption preferences in a tabular format organized by different modalities. For example, under "Summary Preferences," users have the options of "Yes" and "No" for various information types, including title, chart type, and standard deviation, (Figure 2). We curated these options based on the findings from our formative studies (Table 1). Specifically, we organized the preferences in the portal into three categories: (1) *General Preferences*, (2) *Summary Preferences*, and (3) *Audio Graphs Preferences*.

The General Preferences category contains options for users to specify their preferences for the *verbosity level* (C3 in Table 1) [low, medium, high], *sorting of dependent and independent variables* (C5 and C6) [ascending, descending, as determined by developer], and *information on data uncertainty*. The data uncertainty information was not a strict finding from our formative studies and was included due to its significance identified by prior work [73]. The Summary Preferences category provides binary options (yes/no) for users to curate the alt-text (C1 and C2) by specifying their preferences for the title, chart type (C4), and descriptive statistics. The list of the descriptive statistical measures was obtained from the findings of prior work [66, 93]. Finally, the Audio Graphs Preferences category enables users to select their preferences for pitch type (C7), sound type (C8), and sound speed (C9).

The findings from our formative studies also suggest that our participants expressed a desire to customize their information extraction per data visualization. Successfully achieving this feature requires additional user studies to address the feature's complexities, such as providing users with an intelligent system and an easy-to-use interface to manage separate settings for each data visualization. As our scope was limited to exploring user agency and customized information extraction, we did not explore this granular feature. However, as a workaround, users can modify their preferences *while* viewing a particular data visualization. Our extension auto-updates the session storage of each browser tab on preference changes, allowing users to immediately hear catered information without any additional action, including refreshing their desired web page.

After selecting their preferences, users can click on the "Save Preferences" button, which updates their preferences in the database and dispatches these preferences to the browser extension via a `MessageEvent`.[11]

[8]https://www.apollographql.com/
[9]https://react.dev/
[10]https://www.npmjs.com/package/@react-oauth/google
[11]Events referencing a named message dispatched by a source object.

4.2.1.3 Import Preferences. In addition to the configuration page, we added the functionality for screen-reader users to import their preferences directly from their screen readers. Specifically, we extended the functionality of our system by enabling users to upload their screen reader settings in the configuration portal. Our system parses the uploaded file, matches the settings from the screen reader with those present in our system, and updates the preferences of the users based on their specified screen reader settings. (Users can obtain their screen reader settings using the export functionality in screen readers.) This feature is helpful to save time and reduce the burden on users to re-enter their preferences in the portal. Currently, this feature is limited to VoiceOver [31], and work is underway to extend this feature to JAWS [65] and NVDA [1].

We followed the WCAG 2.1 accessibility guidelines [9] in developing our portal. Specifically, we used Color Vision Deficiency (CVD) friendly palettes and checked the contrast ratio using the WebAIM Contrast Checker tool [85], ensuring it to be at least 3:1.

4.2.2 Browser Extension. We created a `VoxEx` browser extension and published it on the Chrome Web Store, following the Chrome extension development guidelines and complying with standard privacy and security policies. Our browser extension receives the preferences sent by the configuration portal via a `MessageEvent`, verifies the sender's source, and updates the session storage of each tab with these preferences. Our extension implements a background listener, which receives the updated preferences whenever a user modifies their preferences and dispatches these preferences to each browser window and tab to be stored in the session storage. In other words, our extension enables anonymous sharing of screen-reader users' preferences to visualization creators without requiring additional hardware or software, serving as the middle-tier connection between the two user groups.

4.2.3 Backend Server. To enable a secure transaction of preferences, we followed suggestions from prior work [38, 46] to implement a server-side approach. Our backend server receives users' information and preferences, and stores this data in our `Postgres`[12] database. We restricted access to our backend server by implementing strict cross-origin resource sharing (CORS) policies to only allow requests from our configuration portal host. We also used the `google-auth-library`[13] to verify the authorization token from the request headers as an additional security measure. We created our backend using `Node.js`[14] and `GraphQL`[15]. Specifically, we implemented a "getPreference" query and a "setPreferences" mutation to fetch and update data, respectively.[16] In summary, our server ensures secure access to a user's preferences, taking into account appropriate privacy and security measures.

4.3 Enhancements to VoxLens

We used `VoxLens` [71–73], a multi-modal open-source JavaScript plug-in that makes online data visualizations accessible to screen-reader users, to explore `VoxEx`'s utility and usability through a field

[12]https://www.postgresql.org/
[13]https://www.npmjs.com/package/google-auth-library
[14]https://nodejs.org/en
[15]https://graphql.org/
[16]In GraphQL, a "query" is a read-only operation, and a "mutation" represents a write operation.

deployment. It is worth reiterating that VoxLens is *not* a part of the VoxEx system, despite the similarity in their names. VoxEx and VoxLens are independent systems and our usage of VoxLens is limited to the purposes of conducting a field deployment of VoxEx. We chose VoxLens because it is (1) open-source, (2) multi-modal, and (3) suitable for online data visualizations. VoxEx is a generalizable solution, having no dependencies on VoxLens. Additionally, VoxLens caters to the individual needs of users by supporting holistic and drilled-down information extraction through three modalities: (1) Question-and-Answer mode (verbal queries), (2) Summary mode (alt-text), and (3) Sonification (audio graphs). However, without our integration, it does not cater to individual *preferences*, such as verbosity levels, summary content, and sound types.

We implemented conditional if-else logic in VoxLens to integrate it with VoxEx. As a preliminary matter, we checked if preferences were present in the session storage. We defaulted to the original VoxLens response in cases when these preferences were absent. When the preferences were present, we curated the appropriate response, excluding, including, and modifying information as needed. Given that VoxLens serves as a proxy for visualization creators to implement multi-modal accessibility in online data visualizations, our enhanced version of VoxLens automatically provides information customization and does not need additional development effort from creators. To shed further light into the usage of VoxEx with and without VoxLens, we provide two use-case scenarios below.

4.3.1 Background for the Scenarios. For the purpose of demonstrating the scenarios, we will consider *John* and *Jane* as two screen-reader users who have VoxEx system set up, and *Alex* as the creator. John has specified their preferences in our configuration portal, stating that they only wish to hear the average in the alt-text, whereas Jane has specified that they prefer to hear all statistical measures. Our browser extension received and populated the respective preferences in the session storage of John and Jane's browsers. Alex is tasked with writing the alt-text for a data visualization on their organization's web page. In writing the alt-text, Alex had originally included the average, minimum, and maximum, considering these measures the most commonly sought measures from data visualizations. However, Alex understands that their selection of measures does not satisfy the needs of *all* screen-reader users and wishes to make adjustments to support VoxEx users.

4.3.2 Scenario 1: Without VoxLens*.* Alex writes code to access users' preferences using the "getItem" function from the "sessionStorage" property. Then, Alex uses conditional if-else logic to programmatically determine which measures should be included or excluded from the alt-text. Specifically, the if-else condition checks to see if a given measure is specified in the users' preferences in the session storage and dynamically generates the alt-text based on these checks. This approach allows John to hear the average only and Jane to hear all the statistical measures and is effective for both JavaScript-based (*e.g.,* D3.js [6]) and image-based data visualizations (*e.g.,* screen captures and image exports).

4.3.3 Scenario 2: With VoxLens*.* Alex incorporates our enhanced version of VoxLens as the middle-tier layer in their JavaScript-based visualization to make visualizations accessible to screen-reader users. As our enhancements already include the if-else conditions, Alex does not need to make any code modifications. Since VoxLens is only functional for JavaScript-based visualizations, this approach does not support image-based data visualizations.

We used the integration of VoxEx with VoxLens for a field deployment that we used in our case studies to assess the utility and usefulness of our system, presented below.

5 Case Studies

VoxEx is the first system to provide screen-reader users the ability to customize their information consumption from online data visualizations. Therefore, we did not conduct a baseline comparison to avoid straw-man and performative comparisons. Rather, we reviewed the guidelines on system evaluation strategies [23, 45, 60, 90] and administered case studies to study the performance of our enhancements and their ability to help screen-reader users achieve their goals. Additionally, we followed the methodology from prior work in accessibility research [68, 92] to make epistemological choices for our case studies, including the sample size. Specifically, we conducted two case studies [74]: (1) a diary study with three screen-reader users lasting five days, and (2) a single-session study with three visualization creators.

5.1 Participants

We recruited three screen-reader users and three visualization creators through respective social media platforms and distribution lists for screen-reader users and visualization creators. The average age of screen-reader users was 51.0 years old (*SD*=14.7). Two were completely blind, and one had partial vision. Among the three visualization creators, the average age was 32.0 years (*SD*=5.2). None were screen-reader users. All participants had an industry affiliation. We compensated screen-reader users and creators with a $130 and $30 Amazon gift card, respectively.

5.2 Procedure

Prior to our studies, we performed a field deployment [10, 75] of VoxEx. We published our Chrome extension on the Chrome Web Store and hosted our configuration portal on our server. Additionally, we created a page containing a sample visualization using D3.js [6] integrated with our enhanced version of VoxLens [71].

5.2.1 Case Study with Screen-Reader Users. We conducted a diary study [5, 58, 63] with our screen-reader participants that lasted five days. First, we introduced our participants to VoxEx through a tutorial session. Specifically, we asked the participants to share their screens, assisted them in installing our Chrome extension, and guided them in setting various options for "Verbosity Level" (High, Medium, and Low) to extract information from the sample visualization. For example, participants selected the setting for verbosity level to "High," navigated to the sample visualization page, and extracted information using all three VoxLens modalities (Q&A, Summary, and Sonification). They repeated this task using the "Medium" and "Low" settings for verbosity level to experience the difference in responses for each setting. We finished our tutorial session once the participants expressed comfort in interacting with our system without supervision.

During the next three days, participants interacted with our system without supervision and logged a diary entry each day. Their task was to interact with a visualization using every setting for each option in the configuration portal. Each participant interacted with the same visualization during their case study. After their interaction each day, they submitted a diary entry log of their interactions with VoxEx for that respective day in a freeform manner, specifying their overall experiences and areas of improvement. For three participants over three days, a total of $3 \times 3 = 9$ log entries were recorded and subsequently analyzed. We conducted a semi-structured interview on the fifth day to ask questions about their interactions with our system. We also administered the NASA-TLX perceived workload questionnaire [25, 26].

5.2.2 Case Study with Visualization Creators. We interviewed visualization creators via Zoom in a semi-structured manner, which lasted an hour. We introduced our participants to VoxEx and shared use-case scenarios (Section 4.3). Specifically, we discussed the design of our system and guided them through the implementation process end-to-end, providing examples of using logical if-else conditions to enable VoxEx users to extract information using various modalities in a customized manner. At the end of this process, we showed them the "final product" using a screen reader, particularly highlighting how screen-reader users could customize their information consumption that they couldn't before. Our goal was to seek their thoughts on our system design and to identify their perceived utility of our system, development effort, and areas of improvement. Additionally, we sought their perception of user agency.

5.3 Analysis

We qualitatively analyzed our interviews and the diary entries from our screen-reader users. Similar to our formative studies, we used a semantic approach [61] and an essentialist paradigm [62, 87] to conduct a theoretical thematic analysis [7]. We followed guidelines from Braun and Clarke [8]. Additionally, we analyzed the subjective ratings collected from the NASA-TLX questionnaire [25, 26].

6 Results

We present the results from our two case studies with three screen-reader users and three creators. Additionally, we describe further enhancements to VoxEx based on participants' feedback.

6.1 Case Study with Screen-Reader Users

We conducted a five-day diary study with three screen-reader users, which involved a tutorial session, unsupervised interaction with VoxEx, and a follow-up interview. We studied participants' interactions and privacy and security concerns, asked them about areas for improvement, and sought their overall feedback. We also collected their subjective ratings using the NASA-TLX questionnaire.

6.1.1 Information Extraction Experience. A prevalent theme in our interviews was participants recognizing how VoxEx improved their efficiency in extracting information from online data visualizations, providing them the autonomy to control and choose the information they wanted to extract. C3 expressed their enthusiasm this way: "*It allows me to do things quickly and efficiently, get the information, glance at it like a sighted person. And then when I started to define what I wanted, I felt even better. It's a useful way of describing information in the format that I need. It's about damn time.*"

Similarly, C2 discussed the importance of autonomy and agency over information she wanted: "*Being able to choose the information felt really important and meaningful because I had more autonomy and control over the information I wanted; it would save time not having to listen to information I didn't need or care about. As a blind person, it takes about 50, maybe even a hundred percent longer than a sighted person to do anything. So, any way I can make things more efficient or kind of control how much time something takes is great.*"

6.1.2 Privacy and Security Concerns. During the follow-up interviews, we asked the participants if they had any privacy or security concerns with installing and using VoxEx. Our participants did not report any concerns, regarding the research study as trustworthy. Naturally, we inquired about participants' concerns if they had encountered VoxEx outside of a research study and what factors might contribute toward resolving any concerns. C2 stated that having a credible source resolves their concerns: "*So really, that's just kind of my standard practice when I download anything is to make sure it's [from] a reliable source based on my research and then ask people that I trust who understand these things a lot more.*"

6.1.3 Areas of Improvement. We inquired about areas of improvement for VoxEx from our screen-reader participants. All three participants highlighted the need to provide definitions of the configuration options. In addition to definitions, C2 specified mathematical and scientific concepts as particular use cases for definitions: "*Mathematical and scientific concepts I'm rusty [with], so [I] don't have a solid understanding of standard deviation and variance and stuff like that. Having the option to get more information about standard deviation in a graph takes the burden off.*"

C3 recognized the opportunity for VoxEx to be an educational tool: "*Describing standard deviation for someone who doesn't know could be a good thing. I think if a person hasn't had statistics in school, just a quick definition of what those are would help them a lot. It could be an educational tool as well.*"

6.1.4 Overall Comments and Feedback. Our participants provided additional feedback on the usefulness of VoxEx by highlighting our import preferences feature. For example, C2 shared: "*I think it's really helpful in time-saving because if I don't have that ability, then I'm using a lot of my time and mental load on getting the configurations exactly as I want them for general use. I think it's a very good call on having settings be able to be imported and stuff.*"

Furthermore, our participants discussed how VoxEx would be helpful for non-screen-reader users, including people with non-visual disabilities and those without disabilities. C3 discussed its benefits for people with learning disabilities: "*Not only would I use this with people that have visual or cognitive disabilities, I'd introduce it to people that have learning disabilities but show them how you can use them with other skill sets, and it would enhance it and also increase the ability and speed to process information.*"

6.1.5 Subjective Workload Assessment. We used the NASA Task Load Index questionnaire (NASA-TLX) [25, 26] to collect subjective workload ratings from our participants. The NASA-TLX questionnaire uses six 21-point scales to determine users' perceived task workload: *mental demand, physical demand, temporal demand, effort, frustration,* and *performance.* To characterize VoxEx's workload, we relied on a characterization from prior work [71], since a control condition for comparison does not exist. Our results indicated that VoxEx requires low mental demand (*M*=3.0, *SD*=1.0), low physical demand (*M*=1.3, *SD*=.6), low temporal demand (*M*=5.0, *SD*=3.0), low effort (*M*=5.3, *SD*=2.1), low frustration (*M*=3.7, *SD*=2.9), and has high perceived performance (*M*=17.3, *SD*=6.4).

6.2 Case Study with Visualization Creators

We interviewed three visualization creators in a semi-structured manner. We introduced them to VoxEx and sought their feedback on the utility of VoxEx and development effort. Additionally, we inquired about areas of improvement and overall comments.

6.2.1 Perceived Utility of VoxEx. We introduced our participants to VoxEx and demonstrated an example use case to aid them in forming an understanding of our system's features. Subsequently, we inquired about their perceived utility of VoxEx. Our participants showed enthusiasm for our system, finding it useful for all users, particularly screen-reader users. V2 classified VoxEx as "remarkable" and surmised that it provides equal access to data visualizations as noted in Section 508 of the Rehabilitation Act [13, 59]: "*I think it's really fantastic. I mean, thinking of laws in the United States, like Section 508 and providing comparable equal access, this [tool] does that. I can't stress enough this is truly remarkable, to be honest. I think it's incredibly useful. I do think this is huge in so many ways and many leaps in the right direction toward agency when it comes to screen reader users and data visualization.*"

V3 shared her experiences as a developer about our system's usefulness in catering the content to the preferences of target users: "*Every time I develop something, I think of my target users first. It's pretty useful because you get to know them more, what their preferences are, and how you can address those preferences in your design. Because without this [tool], you actually don't know what your user's preference is. You can only give them all of the information but then people feel impatient that you're reading a long paragraph that they are not even interested in. They can get the information straight like a short answer, you have a setting to control that and speed and stuff.*"

6.2.2 Development Effort. We asked participants their thoughts on the development effort needed to provide customized information from online data visualizations using VoxEx. Specifically, we asked them to rate their perceived difficulty of implementation on a Likert scale of 1 to 7, with "1" representing none-to-minimal difficulty and "7" representing extreme difficulty. All our participants rated the difficulty as "1". V1 elaborated on her choice: "*It doesn't seem like that much work. Like, you know the person doesn't want a title. So you then decide, okay, the user doesn't want the title, then I'm not going to include the title in it. It's pretty simple really.*"

This finding shows that the effort required to incorporate VoxEx in creators' workflows is none-to-minimal – a promising and encouraging result that could assist in the wide adoption of VoxEx.

6.2.3 Areas of Improvement. Similar to our screen-reader participants, visualization creators also emphasized the need to provide definitions of the configuration options. For example, V2 expressed her opinions as: "*If I have no idea what a standard deviation is, and especially [what] uncertainty [of] information [is], having a definition here to make this even more accessible would be fantastic.*"

Additionally, our participants noted that domain interest could be a potential factor in determining verbosity levels. V1 suggested to adjust the content based on the domains of interest: "*You might not have the same preferences if you're going through something you're invested in. So, if you asked users for their interests or the domains they're interested in and adjusted the content based on that, then I think that would probably increase the utility.*"

6.2.4 Overall Comments and Feedback. Our participants provided positive and encouraging feedback on VoxEx. In particular, they were excited about our system's central focus on user agency for screen-reader users. For example, V1 conveyed her enthusiasm for the importance of user agency: "*It's pretty important and critical to have agency over the information you consume. Giving users the option to specify what information they want and what information they don't want, and to control that is pretty important.*"

V2 agreed, saying: "*I think it's super important. Because it could frankly disenfranchise people sometimes from even attending higher education institutions to be able to then participate in a way that feels equal and comparable.*"

6.3 VoxEx Enhancements

We made enhancements to VoxEx to incorporate the feedback we received from our participants during the case studies. In particular, we focused on the areas of improvement they identified and addressed their concerns by: (1) adding definitions of configuration options, and (2) using domains of interest to determine verbosity levels. We present these enhancements below.

6.3.1 Definition of Configuration Options. A unanimous suggestion from our participants was to add a definition for each configuration option to support users in understanding these terms. Therefore, we added an accessible help tooltip icon next to each configuration option, enabling users to obtain the term's definition.

6.3.2 Domains of Interest. Our visualization-creator participants noted the need for an additional feature to determine verbosity levels based on domains of interest. We integrated the ChatGPT API[17] to implement this feature in VoxEx as Large-Language Models are a beneficial source of extracting categories from web content [39, 81, 86]. First, we issued ChatGPT the query "website categories" to obtain the list of broader website categories. We included this list on the configuration portal and provided users the option to select multiple categories of their interest. Then, on the client side, we queried ChatGPT with the text from the web page's meta tags, title, and body to determine its category. For example, on our sample visualization page, we queried "website category for 'Data visualization showing average class scores for each student"' and received the following response: "The appropriate website category for a 'Data visualization showing average class scores for each student' would likely fall under 'Education' or 'Academic Resources."' If the identified category of the web page was among the list of user's categories of interest, we set the user's verbosity setting to "High." More work is underway to improve the network latency of VoxEx.

[17] https://chat.openai.com/

7 Discussion

In this work, we surveyed 60 and interviewed 12 screen-reader users. We used the findings from these studies to create `VoxEx`, a system that provides screen-reader users the agency to customize the information they consume from online data visualizations. We performed a field deployment of `VoxEx` through its integration with `VoxLens` [71]. Specifically, we conducted two case studies to assess the utility and usefulness of our system: (1) a five-day diary study and interviews with three screen-reader users, and (2) a single-session interview with three visualization creators. We utilized the findings from our case studies to enhance our system.

7.1 User Agency for Screen-Reader Users

V1 expressed during her case study interview that "it's pretty important and critical to have agency over the information you consume." Similarly, C3 said, "It allows me to do things quickly and efficiently, get the information, glance at it like a sighted person." These results are aligned with those from prior work [71, 72, 93], which show that users desire the agency to customize their information consumption. Screen-reader users are limited to the content chosen by visualization creators, unlike non-screen-reader users, who have more freedom and options to interact with and consume information from online data visualizations. Even multi-modal tools, such as `VoxLens`, generate summaries of data visualizations based on the most commonly extracted information, which may not satisfy the needs of some screen-reader users. Our empirical findings show that giving users the agency to customize the information they consume can enhance their experiences with online data visualizations. Therefore, we urge researchers to explore and incorporate user agency in their solutions whenever possible.

7.2 Balance Between Providing Agency and Suggesting Critical Information

Providing screen-reader users agency to customize their information consumption is a vital step toward minimizing the digital divide. At the same time, it is crucial to relay the information creators intend to convey to the users in data visualizations. For example, depending on the data, creators may find it necessary to provide information on data uncertainty, which may or may not be the user's preference. Determining an acceptable balance between providing agency and suggesting critical information is a key consideration to equitable information consumption. While our effort contributes toward achieving the aforementioned balance, it is limited to the data sorting setting. Future work can explore how this balance can be effectively extended to other configuration options.

7.3 Usage of Large Vision Language Models

Large Vision Language Models (LVLMs) have recently gained popularity by enabling users to obtain information about images using computer vision together with large language models. While plausible, these features have not been tested for data visualization accessibility, particularly for complex and unconventional visualizations. As Namikoshi *et al.* [55] noted, "Modeling the beliefs, preferences, and behaviors of a specific population can be useful for a variety of different applications. Existing work has had mixed success using large language models to accurately model human behavior in different contexts." In addition, concerns exist about Generative AI's negative impact on inclusion, representation, and equity for people with disabilities, ableist biases, and association of disabilities with toxic content or harmful stereotypes [22]. Therefore, we did not employ LVLMs in this work. Once LVLMs are determined appropriate for data visualization accessibility, future work can incorporate these models into accessibility solutions, including `VoxEx`.

7.4 Utility Beyond Online Data Visualizations

We developed `VoxEx` with a central focus on screen-reader users. However, as our participants identified, our work can benefit non-screen-reader users, including those with non-visual disabilities. For example, our system can support people with color-vision-deficiency (CVD) by enabling them to specify preferences that creators can use to automatically modify color palettes in visualizations and graphics based on their CVD type and preferences. We aspire to extend the utility of our system for other demographics, additionally exploring its benefits for visualization literacy.

7.5 Limitations and Future Work

Based on our participants' suggestions, we enhanced `VoxEx` by enabling users to specify their domains of interest. However, we did not include subdomains in this exploration. For example, a user might only be interested in the "basketball" subdomain under the broader domain of "sports." Future work can utilize AI-powered tools to determine and incorporate these subdomains into our system. Another limitation is that we did not *quantify* the gains in information extraction speed, accuracy, or efficiency compared to prior work. Participants roundly supported `VoxEx` as an enhancement to efficiency, in particular, but a more formal lab-based experiment would be necessary to quantify these gains. For example, `VoxEx` could be compared to the *de facto* `VoxLens` without `VoxEx` to measure the specific gains represented by the former.

8 Conclusion

In this work, we sought to provide enhanced agency to screen-reader users to customize the information they consume from online data visualizations. To achieve our objective, we surveyed and interviewed screen-reader users and subsequently used the findings from these formative studies to develop `VoxEx`. Through integration with an open-source visualization accessibility tool, `VoxLens`, we conducted a field deployment of our system. We conducted a diary study with screen-reader users and a single-session interview with visualization creators to assess the utility and usability of `VoxEx`. We reported the findings from our studies showing that our system improves screen-reader users' efficiency of information extraction and requires minimal effort from visualization creators. Additionally, we incorporated the suggestions from our participants to improve `VoxEx`. We hope that by improving the efficiency of screen-reader users to extract information from data visualizations, our work will not only contribute toward increasing employment opportunities for these users but also toward enhancing their performance in their current roles.

Acknowledgments

This work was supported in part by the University of Washington Center for Research and Education on Accessible Technology and Experiences (CREATE). We also extend our warmest gratitude to Harry and Gemma for their *purr*vasive feline support and cuddles.

References

[1] NV Access. 2006. NV Access | Download. https://www.nvaccess.org/download/. (Accessed on 08/08/2021).

[2] David Austin and Volker Sorge. 2023. Authoring Web-Accessible Mathematical Diagrams. In *Proceedings of the 20th International Web for All Conference* (Austin, TX, USA) *(W4A '23)*. Association for Computing Machinery, New York, NY, USA, 148–152. https://doi.org/10.1145/3587281.3587297

[3] Stephen Barrass and Gregory Kramer. 1999. Using sonification. *Multimedia systems* 7, 1 (1999), 23–31.

[4] David Barter. 2023. Degrees of Freedom: Designing Information and Communication Technologies to Support Enhanced Agency for Blind and Partially Sighted Individuals Through Cross-Sensory Information Representation. (2023).

[5] Niall Bolger, Angelina Davis, and Eshkol Rafaeli. 2003. Diary methods: Capturing life as it is lived. *Annual review of psychology* 54, 1 (2003), 579–616.

[6] Michael Bostock, Vadim Ogievetsky, and Jeffrey Heer. 2011. D^3 data-driven documents. *IEEE transactions on visualization and computer graphics* 17, 12 (2011), 2301–2309.

[7] Richard E Boyatzis. 1998. *Transforming qualitative information: Thematic analysis and code development.* sage.

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

[9] Ben Caldwell, Loretta Guarino Reid, Gregg Vanderheiden, Wendy Chisholm, John Slatin, and Jason White. 2018. Web content accessibility guidelines (WCAG) 2.1.

[10] Albert Cherns. 1976. The principles of sociotechnical design. *Human relations* 29, 8 (1976), 783–792.

[11] Pramod Chundury, Urja Thakkar, Yasmin Reyazuddin, J Bern Jordan, Niklas Elmqvist, and Jonathan Lazar. 2024. Understanding the Visualization and Analytics Needs of Blind and Low-Vision Professionals. In *Proceedings of the 26th International ACM SIGACCESS Conference on Computers and Accessibility*. 1–5.

[12] Mary J Clinkenbeard. 2020. A posthuman approach to agency, disability, and technology in social interactions. *Technical Communication Quarterly* 29, 2 (2020), 115–135.

[13] Federal Communications Commission. 1998. Section 508 of the Rehabilitation Act | Federal Communications Commission. https://www.fcc.gov/general/section-508-rehabilitation-act. (Accessed on 03/07/2024).

[14] Adele Crudden, Lynn W McBroom, Amy L Skinner, and J Elton Moore. 1998. Comprehensive examination of barriers to employment among persons who are blind or visually impaired. (1998).

[15] Jiamin Dai, John Miedema, Sebastian Hernandez, Alexandra Sutton-Lalani, and Karyn Moffatt. 2023. Cognitive accessibility of digital payments: A literature review. In *Proceedings of the 20th International Web for All Conference*. 116–121.

[16] Tin Doan, Shelagh Mooney, and Peter B Kim. 2023. The moments of truth: A qualitative exploration of service interactions between employees with disabilities in the food service industry, and their customers. *International Journal of Hospitality Management* 115 (2023), 103602.

[17] W Erickson, C Lee, and S Von Schrader. 2013. Disability statistics from the 2011 American Community Survey. *Cornell University Employment and Disability Institute, Ithaca, NY. Retrieved from www disabilitystatis tics org* (2013).

[18] Danyang Fan, Alexa Fay Siu, Wing-Sum Adrienne Law, Raymond Ruihong Zhen, Sile O'Modhrain, and Sean Follmer. 2022. Slide-Tone and Tilt-Tone: 1-DOF Haptic Techniques for Conveying Shape Characteristics of Graphs to Blind Users. In *CHI Conference on Human Factors in Computing Systems*. 1–19.

[19] Leo Ferres, Gitte Lindgaard, Livia Sumegi, and Bruce Tsuji. 2013. Evaluating a tool for improving accessibility to charts and graphs. *ACM Transactions on Computer-Human Interaction (TOCHI)* 20, 5 (2013), 1–32.

[20] Center for Digital Music Queen Mary University of London. 2023. Sonic Visualiser. https://www.sonicvisualiser.org/. (Accessed on 07/04/2023).

[21] Perkins School for the Blind. 2023. Sonification Summary Page – Perkins School for the Blind. https://www.perkins.org/resource/sonification-summary-page. (Accessed on 07/03/2023).

[22] Kate S Glazko, Momona Yamagami, Aashaka Desai, Kelly Avery Mack, Venkatesh Potluri, Xuhai Xu, and Jennifer Mankoff. 2023. An Autoethnographic Case Study of Generative Artificial Intelligence's Utility for Accessibility. In *Proceedings of the 25th International ACM SIGACCESS Conference on Computers and Accessibility*. 1–8.

[23] Saul Greenberg and Bill Buxton. 2008. Usability Evaluation Considered Harmful (Some of the Time). In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (Florence, Italy) *(CHI '08)*. Association for Computing Machinery, New York, NY, USA, 111–120. https://doi.org/10.1145/1357054.1357074

[24] Greg Guest, Arwen Bunce, and Laura Johnson. 2006. How many interviews are enough? An experiment with data saturation and variability. *Field methods* 18, 1 (2006), 59–82.

[25] Sandra G Hart. 2006. NASA-task load index (NASA-TLX); 20 years later. In *Proceedings of the human factors and ergonomics society annual meeting*, Vol. 50. Sage publications Sage CA: Los Angeles, CA, 904–908.

[26] Sandra G. Hart and Lowell E. Staveland. 1988. Development of NASA-TLX (Task Load Index): Results of empirical and theoretical research. In *Advances in psychology*. Vol. 52. Elsevier, North-Holland, Netherlands, 139–183.

[27] Jaylin Herskovitz, Andi Xu, Rahaf Alharbi, and Anhong Guo. 2023. Hacking, Switching, Combining: Understanding and Supporting DIY Assistive Technology Design by Blind People. In *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems* (<conf-loc>, <city>Hamburg</city>, <country>Germany</country>, </conf-loc>) *(CHI '23)*. Association for Computing Machinery, New York, NY, USA, Article 57, 17 pages. https://doi.org/10.1145/3544548.3581249

[28] Highcharts. 2009. Sonification | Highcharts. https://www.highcharts.com/docs/accessibility/sonification. (Accessed on 08/01/2021).

[29] Leona M Holloway, Cagatay Goncu, Alon Ilsar, Matthew Butler, and Kim Marriott. 2022. Infosonics: Accessible infographics for people who are blind using sonification and voice. In *Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems*. 1–13.

[30] Md Naimul Hoque, Md Ehtesham-Ul-Haque, Niklas Elmqvist, and Syed Masum Billah. 2023. Accessible Data Representation with Natural Sound. In *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems* (Hamburg, Germany) *(CHI '23)*. Association for Computing Machinery, New York, NY, USA, Article 826, 19 pages. https://doi.org/10.1145/3544548.3581087

[31] Apple Inc. 2005. Accessibility - Vision - Apple. https://www.apple.com/accessibility/vision/.

[32] Chandrika Jayant, Hanjie Ji, Samuel White, and Jeffrey P Bigham. 2011. Supporting blind photography. In *The proceedings of the 13th international ACM SIGACCESS conference on Computers and accessibility*. 203–210.

[33] Shuli Jones, Isabella Pedraza Pineros, Daniel Hajas, Jonathan Zong, and Arvind Satyanarayan. 2023. "Customization is Key": Four Characteristics of Textual Affordances for Accessible Data Visualization. *arXiv preprint arXiv:2307.08773* (2023).

[34] Crescentia Jung, Shubham Mehta, Atharva Kulkarni, Yuhang Zhao, and Yea-Seul Kim. 2021. Communicating visualizations without visuals: Investigation of visualization alternative text for people with visual impairments. *IEEE transactions on visualization and computer graphics* 28, 1 (2021), 1095–1105.

[35] Edward Kim, Connor Onweller, and Kathleen F McCoy. 2021. Information Graphic Summarization using a Collection of Multimodal Deep Neural Networks. In *2020 25th International Conference on Pattern Recognition (ICPR)*. IEEE, Institute of Electrical and Electronics Engineers, New York, NY, USA, 10188–10195.

[36] Nam Wook Kim, Grace Ataguba, Shakila Cherise Joyner, Chuangdian Zhao, and Hyejin Im. 2023. Beyond Alternative Text and Tables: Comparative Analysis of Visualization Tools and Accessibility Methods. In *Computer Graphics Forum*, Vol. 42. Wiley Online Library, 323–335.

[37] Nam Wook Kim, Shakila Cherise Joyner, Amalia Riegelhuth, and Y Kim. 2021. Accessible visualization: Design space, opportunities, and challenges. In *Computer Graphics Forum*, Vol. 40. Wiley Online Library, 173–188.

[38] Engin Kirda, Nenad Jovanovic, Christopher Kruegel, and Giovanni Vigna. 2009. Client-side cross-site scripting protection. *computers & security* 28, 7 (2009), 592–604.

[39] Jan Kocoń, Igor Cichecki, Oliwier Kaszyca, Mateusz Kochanek, Dominika Szydło, Joanna Baran, Julita Bielaniewicz, Marcin Gruza, Arkadiusz Janz, Kamil Kanclerz, et al. 2023. ChatGPT: Jack of all trades, master of none. *Information Fusion* 99 (2023), 101861.

[40] Aditi Kulkarni, Allan Wang, Lynn Urbina, Aaron Steinfeld, and Bernardine Dias. 2016. Robotic assistance in indoor navigation for people who are blind. In *2016 11th ACM/IEEE International Conference on Human-Robot Interaction (HRI)*. IEEE, 461–462.

[41] Pauli PY Lai. 2013. Adapting data table to improve web accessibility. In *Proceedings of the 10th International Cross-Disciplinary Conference on Web Accessibility*. 1–4.

[42] Ali Lakhani, Donna McDonald, and Heidi Zeeman. 2018. Perspectives of self-direction: a systematic review of key areas contributing to service users' engagement and choice-making in self-directed disability services and supports. *Health & social care in the community* 26, 3 (2018), 295–313.

[43] CM Laney, KS Baker, DPC Peters, and KW Ramsey. 2013. Recommendations for data accessibility. *Long-term trends in ecological systems. a basis for understanding responses to global change. Technical Bulletin* 1931 (2013), 216–225.

[44] Julianna Langston. 2022. GitHub - julianna-langston/chart2music: Turns charts into music so the blind can hear data. https://github.com/julianna-langston/chart2music. (Accessed on 07/04/2023).

[45] David Ledo, Steven Houben, Jo Vermeulen, Nicolai Marquardt, Lora Oehlberg, and Saul Greenberg. 2018. Evaluation Strategies for HCI Toolkit Research. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems* (Montreal QC, Canada) *(CHI '18)*. Association for Computing Machinery, New

York, NY, USA, 1–17. https://doi.org/10.1145/3173574.3173610
[46] Xiaowei Li and Yuan Xue. 2014. A survey on server-side approaches to securing web applications. *ACM Computing Surveys (CSUR)* 46, 4 (2014), 1–29.
[47] Alan Lundgard and Arvind Satyanarayan. 2021. Accessible visualization via natural language descriptions: A four-level model of semantic content. *IEEE transactions on visualization and computer graphics* 28, 1 (2021), 1073–1083.
[48] Kelly Mack, Edward Cutrell, Bongshin Lee, and Meredith Ringel Morris. 2021. Designing tools for high-quality alt text authoring. In *Proceedings of the 23rd International ACM SIGACCESS Conference on Computers and Accessibility*. 1–14.
[49] Poukong Colin Manikoth. 2016. *Web-Enabled Technologies and Individual User Agency*. University of Idaho.
[50] Kim Marriott, Bongshin Lee, Matthew Butler, Ed Cutrell, Kirsten Ellis, Cagatay Goncu, Marti Hearst, Kathleen McCoy, and Danielle Albers Szafir. 2021. Inclusive data visualization for people with disabilities: a call to action. *Interactions* 28, 3 (2021), 47–51.
[51] Nora McDonald, Sarita Schoenebeck, and Andrea Forte. 2019. Reliability and inter-rater reliability in qualitative research: Norms and guidelines for CSCW and HCI practice. *Proceedings of the ACM on human-computer interaction* 3, CSCW (2019), 1–23.
[52] Tom McEwan and Ben Weerts. 2007. ALT text and basic accessibility. (2007).
[53] Silvia Mirri, Silvio Peroni, Paola Salomoni, Fabio Vitali, and Vincenzo Rubano. 2017. Towards accessible graphs in HTML-based scientific articles. In *2017 14th IEEE Annual Consumer Communications Networking Conference (CCNC)*. IEEE, Las Vegas, NV, USA, 1067–1072. https://doi.org/10.1109/CCNC.2017.7983287
[54] Martez E Mott, John Tang, and Edward Cutrell. 2023. Accessibility of Profile Pictures: Alt Text and Beyond to Express Identity Online. In *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems*. 1–13.
[55] Keiichi Namikoshi, Alex Filipowicz, David A Shamma, Rumen Iliev, Candice L Hogan, and Nikos Arechiga. 2024. Using LLMs to Model the Beliefs and Preferences of Targeted Populations. *arXiv preprint arXiv:2403.20252* (2024).
[56] National Federation of the Blind. n.d.. Homepage | National Federation of the Blind. https://nfb.org/. (Accessed on 03/12/2022).
[57] William O'Donnell. 2014. An analysis of employment barriers facing blind people. (2014).
[58] Sandra Ohly, Sabine Sonnentag, Cornelia Niessen, and Dieter Zapf. 2010. Diary studies in organizational research. *Journal of Personnel Psychology* (2010).
[59] Abiodun Olalere and Jonathan Lazar. 2011. Accessibility of US federal government home pages: Section 508 compliance and site accessibility statements. *Government Information Quarterly* 28, 3 (2011), 303–309.
[60] Dan R. Olsen. 2007. Evaluating User Interface Systems Research. In *Proceedings of the 20th Annual ACM Symposium on User Interface Software and Technology* (Newport, Rhode Island, USA) *(UIST '07)*. Association for Computing Machinery, New York, NY, USA, 251–258. https://doi.org/10.1145/1294211.1294256
[61] Michael Quinn Patton. 1990. *Qualitative evaluation and research methods*. SAGE Publications, inc.
[62] Jonathan Potter and Margaret Wetherell. 1987. *Discourse and social psychology: Beyond attitudes and behaviour*. Sage.
[63] Harry T Reis and Shelly L Gable. 2000. Event-sampling and other methods for studying everyday experience. (2000).
[64] Tanumon Roy and Lakshmi Boppana. 2022. Interactive web-based image and graph analysis using Sonification for the Blind. In *2022 IEEE Region 10 Symposium (TENSYMP)*. 1–6. https://doi.org/10.1109/TENSYMP54529.2022.9864411
[65] Freedom Scientific. n.d.. JAWS® – Freedom Scientific. https://www.freedomscientific.com/products/software/jaws/. (Accessed on 08/08/2021).
[66] Ather Sharif, Sanjana Shivani Chintalapati, Jacob O. Wobbrock, and Katharina Reinecke. 2021. Understanding Screen-Reader Users' Experiences with Online Data Visualizations. In *The 23rd International ACM SIGACCESS Conference on Computers and Accessibility* (Virtual Event, USA) *(ASSETS '21)*. Association for Computing Machinery, New York, NY, USA, Article 14, 16 pages. https://doi.org/10.1145/3441852.3471202
[67] Ather Sharif and Babak Forouraghi. 2018. evoGraphs — A jQuery plugin to create web accessible graphs. In *2018 15th IEEE Annual Consumer Communications Networking Conference (CCNC)*. IEEE, Las Vegas, NV, USA, 1–4. https://doi.org/10.1109/CCNC.2018.8319239
[68] Ather Sharif, Joo Gyoeng Kim, Jessie Z. Xu, and Jacob O. Wobbrock. 2024. UUnderstanding and Reducing the Challenges Faced by Creators of Accessible Online Data Visualizations. In *The 26th International ACM SIGACCESS Conference on Computers and Accessibility* (St. John's, NL, Canada) *(ASSETS '24)*. Association for Computing Machinery, New York, NY, USA. https://doi.org/10.1145/3663548.3675625
[69] Ather Sharif, Olivia H. Wang, and Alida T. Muongchan. 2022. "What Makes Sonification User-Friendly?" Exploring Usability and User-Friendliness of Sonified Responses. In *Proceedings of the 24th International ACM SIGACCESS Conference on Computers and Accessibility* (Athens, Greece) *(ASSETS '22)*. Association for Computing Machinery, New York, NY, USA, Article 45, 5 pages. https://doi.org/10.1145/3517428.3550360
[70] Ather Sharif, Olivia H. Wang, Alida T. Muongchan, Katharina Reinecke, and Jacob O. Wobbrock. 2022. Sonifier: JavaScript library that converts a two-dimensional data into a sonified response. https://github.com/athersharif/sonifier. (Accessed on 06/12/2022).
[71] Ather Sharif, Olivia H. Wang, Alida T. Muongchan, Katharina Reinecke, and Jacob O. Wobbrock. 2022. VoxLens: Making Online Data Visualizations Accessible with an Interactive JavaScript Plug-In. In *CHI Conference on Human Factors in Computing Systems* (New Orleans, LA, USA) *(CHI '22)*. Association for Computing Machinery, New York, NY, USA, Article 478, 19 pages. https://doi.org/10.1145/3491102.3517431
[72] Ather Sharif, Andrew M. Zhang, Katharina Reinecke, and Jacob O. Wobbrock. 2023. Understanding and Improving Drilled-Down Information Extraction from Online Data Visualizations for Screen-Reader Users. In *Proceedings of the 20th International Web for All Conference* (Austin, TX, USA) *(W4A '23)*. Association for Computing Machinery, New York, NY, USA, 18–31. https://doi.org/10.1145/3587281.3587284
[73] Ather Sharif, Ruican Zhong, and Yadi Wang. 2023. Conveying Uncertainty in Data Visualizations to Screen-Reader Users Through Non-Visual Means. In *Proceedings of the 25th International ACM SIGACCESS Conference on Computers and Accessibility* (<conf-loc>, <city>New York</city>, <state>NY</state>, <country>USA</country>, </conf-loc>) *(ASSETS '23)*. Association for Computing Machinery, New York, NY, USA, Article 67, 6 pages. https://doi.org/10.1145/3597638.3614502
[74] Kristen Shinohara and Josh Tenenberg. 2007. Observing Sara: a case study of a blind person's interactions with technology. In *Proceedings of the 9th international ACM SIGACCESS conference on Computers and accessibility*. 171–178.
[75] Katie A Siek, Gillian R Hayes, Mark W Newman, and John C Tang. 2014. Field deployments: Knowing from using in context. *Ways of Knowing in HCI* (2014), 119–142.
[76] Nikhil Singh, L. Lucy Wang, and Jonathan Bragg. 2024. FigurA11y: AI Assistance for Writing Scientific Alt Text. In *Proceedings of the 29th International Conference on Intelligent User Interfaces* (Greenville, SC, USA) *(IUI '24)*. Association for Computing Machinery, New York, NY, USA, To Appear.
[77] Alexa Siu, Gene SH Kim, Sile O'Modhrain, and Sean Follmer. 2022. Supporting accessible data visualization through audio data narratives. In *Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems*. 1–19.
[78] Statistical Analysis Software. 2023. SAS Graphics Accelerator - Chrome Web Store. https://chrome.google.com/webstore/detail/sas-graphics-accelerator/ockmipfaiiahknplinepcaogdillgoko. (Accessed on 07/04/2023).
[79] Katta Spiel, Oliver L Haimson, and Danielle Lottridge. 2019. How to do better with gender on surveys: a guide for HCI researchers. *Interactions* 26, 4 (2019), 62–65.
[80] John R Thompson, Jesse J Martinez, Alper Sarikaya, Edward Cutrell, and Bongshin Lee. 2023. Chart Reader: Accessible Visualization Experiences Designed with Screen Reader Users. In *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems*. 1–18.
[81] Tamás Vörös, Sean Paul Bergeron, and Konstantin Berlin. 2023. Web content filtering through knowledge distillation of large language models. In *2023 IEEE International Conference on Web Intelligence and Intelligent Agent Technology (WI-IAT)*. IEEE, 357–361.
[82] Bruce N Walker and Michael A Nees. 2011. Theory of sonification. *The sonification handbook* 1 (2011), 9–39.
[83] Ruobin Wang, Crescentia Jung, and Yea-Seul Kim. 2022. Seeing Through Sounds: Mapping Auditory Dimensions to Data and Charts for People with Visual Impairments. In *The 24th EG/VGTC Conference on Visualization (EuroVis' 22), Rome, Italy, 13-17 June, 2022*. Eurographics-European Association for Computer Graphics.
[84] Yanan Wang, Ruobin Wang, Crescentia Jung, and Yea-Seul Kim. 2022. What makes web data tables accessible? Insights and a tool for rendering accessible tables for people with visual impairments. In *Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems*. 1–20.
[85] Web Accessibility In Mind. n.d.. WebAIM: Contrast Checker. https://webaim.org/resources/contrastchecker/. (Accessed on 03/30/2022).
[86] Xiang Wei, Xingyu Cui, Ning Cheng, Xiaobin Wang, Xin Zhang, Shen Huang, Pengjun Xie, Jinan Xu, Yufeng Chen, Meishan Zhang, et al. 2023. Zero-shot information extraction via chatting with chatgpt. *arXiv preprint arXiv:2302.10205* (2023).
[87] Sue Widdicombe and Robin Wooffitt. 1995. *The language of youth subcultures: Social identity in action*. Harvester/Wheatsheaf.
[88] Jacob O Wobbrock, Krzysztof Z Gajos, Shaun K Kane, and Gregg C Vanderheiden. 2018. Ability-based design. *Commun. ACM* 61, 6 (2018), 62–71.
[89] Jacob O Wobbrock, Shaun K Kane, Krzysztof Z Gajos, Susumu Harada, and Jon Froehlich. 2011. Ability-based design: Concept, principles and examples. *ACM Transactions on Accessible Computing (TACCESS)* 3, 3 (2011), 1–27.
[90] Jacob O Wobbrock and Julie A Kientz. 2016. Research contributions in human-computer interaction. *interactions* 23, 3 (2016), 38–44.
[91] Shaomei Wu, Jeffrey Wieland, Omid Farivar, and Julie Schiller. 2017. Automatic alt-text: Computer-generated image descriptions for blind users on a social network service. In *proceedings of the 2017 ACM conference on computer supported*

cooperative work and social computing. 1180–1192.

[92] Zhuohao Zhang and Jacob O Wobbrock. 2023. A11yBoard: Making Digital Artboards Accessible to Blind and Low-Vision Users. In *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems*. 1–17.

[93] Jonathan Zong, Crystal Lee, Alan Lundgard, JiWoong Jang, Daniel Hajas, and Arvind Satyanarayan. 2022. Rich Screen Reader Experiences for Accessible Data Visualization. *Computer Graphics Forum* 41, 3 (2022), 15–27. https://doi.org/10.1111/cgf.14519 arXiv:https://onlinelibrary.wiley.com/doi/pdf/10.1111/cgf.14519