A Screen reader and Sonification Approach for non-sighted Users to explore Data Visualizations on the Internet

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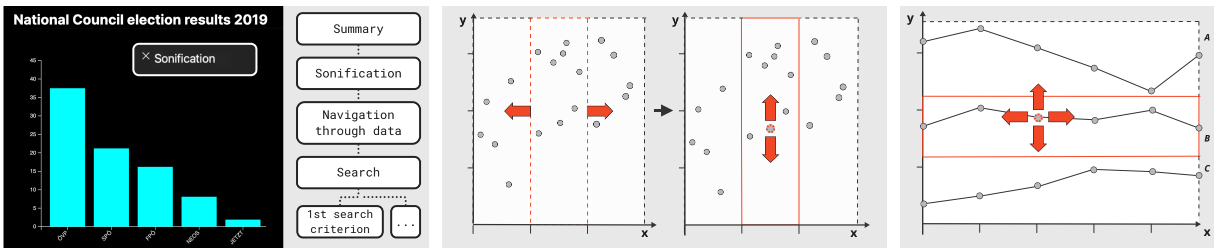

Figure 1: A screenshot of the prototype is presented along with a schematic representation of the interaction menu (left); Navigation concept for scatter plots that includes navigating through sections and data points (middle); Navigation concept for line charts (right)

Abstract

Content on the internet is often not accessible to all users. In particular with data visualizations, blind and visually impaired people face the problem that the presented data is either impossible or very difficult to access with the help of a screen reader. The aim of this paper is to develop a concept that enables screen reader users to explore online data visualizations. The concept should enable users to gain a comprehensive overview of the data and search for specific data items. In addition, sonification is integrated to help users understand the data. A user study with five non-sighted participants provides insight into how data visualizations can be explored with the help of the prototype.

Index Terms: accessibility, data visualization, sonifcation, screen reader, non-sighted users.

1 Introduction

Data visualizations are widely spread on the Internet and are increasingly used, both by domain experts and by general audiences, to communicate important information from complex data [16, 15]. They help people extract information efficiently and effectively, taking advantage of the ability of the human visual system to quickly recognize and interpret visual patterns [12]. However, due to their visual nature, extracting information from visualizations can be difficult or impossible for users who rely on a screen reader [14, 17]. Therefore, many visualizations are inaccessible to blind and visually impaired (BVI) readers [5, 18].

Screen readers are the most common assistive technology used by BVI users to access web-based content [9]. They read the information and meta-information of websites in a linear way. Therefore, websites must be carefully designed to ensure proper access with screen readers [7]. The Web Accessibility Initiative (WAI) of the World Wide Web Consortium (W3C) defined the Web Content Accessibility Guidelines (WCAG) to help developers to make web content more accessible to all, including screen reader users [3, 7]. However, Power et al. found that only 50% of problems were addressed by these guidelines, showing that meeting the accessibility criteria does not ensure that screen reader users have access to the information [13]. Consequently, there is a gap between what is considered technically accessible and what is practically usable [7].

Therefore, the aim of this paper is to develop a screen reader and sonification concept that enables BVI users to explore online data visualizations. The concept will be developed with a user-centric approach that includes interviews to understand how BVI users interact with data visualizations. Based on these findings, a prototype is developed that enables the exploration and sonification of the data. A user study will then be conducted to evaluate the extent to which the prototype supports the exploration of the data in an understandable way.

2 Background

There are various efforts to make data visualizations accessible, such as comprehensive alternative text (alt text), and access to tabular data [7]. However, alternative texts and data tables make it difficult or even impossible for the user to carry out analytical activities [10]. Alt text can just provide a high-level overview and does not allow readers to develop their own independent interpretation [11], and data tables negate the benefits of abstraction that visualizations provide [19]. Moreover, many interaction methods that are available to sighted users are not accessible to BVI users. Beyond that, during the Covid 19 pandemic, Holloway et al. observed that many visualizations lack sufficient textual descriptions [8]. Even when online data visualizations include basic accessibility functions, screen reader users still spend 211% more time interacting with them and extract information 61% less accurately, compared to non-screen reader users [14]. However, many BVI people want access to the rich, expressive communication made possible by visualization that goes beyond text or audio representations [12].

Sharif et al. suggest that online data visualization libraries need to offer screen reader users both a holistic view of the data and support for a drilled-down exploration [14]. In this context, Kim et al. describe three different levels of information granularity that relate to the amount of detail conveyed in a visualization: *existence*, which includes information that a chart is present; *overview* that includes a summary information about data; and *detail* that includes information about precise data values [10]. Zong et al. address these levels in their screen reader concept and propose three different ways of navigating through the data: *structural navigation* refers to ways users move within an accessible structure, e.g. a tree structure; *spatial navigation* refers to the navigation through the visualization according to directions in the screen coordinate system; and *targeted*

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navigation refers to methods that require the user to specify a target location [19]. Another screen reader approach is *VoxLens*, an interactive JavaScript plug-in that enables screen reader users to extract information using a multimodal approach [15]. The authors offer three different modes for accessing a data visualization: a question-and-answer mode, a summary mode, and a sonifcation mode.

Data sonifcation is an alternative representation of data that exploits the ability of the human auditory system to recognize temporal changes and patterns [16, 5]. It can be an effective medium for BVI users to understand the data in a visualization [18]. However, there are no established design principles that apply to various charts with different data types. In a user study with BVI users, Fan et al. discovered that sonification could make it easier to recognize trends in the data, but that a lack of experience in using sonification could also lead to the misinterpretation of the data presented [7]. To better understand users' mental models, Engeln and Keck analyzed various sketch-based associations of sounds to derive insights for sonification [6]. And Wang et al. investigated the intuitiveness and effectiveness of different sound encodings for BIV users. They found out that pitch is most intuitive to encode data and that visual metaphors such as line charts being "continuous" and scatter plots being "scattered" influence perception [18]. Based on these findings, we aim to develop a concept that supports navigation in the data with the help of a screen reader, but also the summarization of data through textual descriptions and sonification.

3 Interviews with BVI users

To understand how BVI users deal with data visualizations and screen readers, four interviews were conducted with blind people who rely on a screen reader in their everyday lives. The participants were recruited with the support of the Austrian Federation of the Blind and Partially Sighted, and the conversations took place in the form of semi-structured interviews. The focus of the interviews was to find out which terms and concepts related to data visualization are clear to BVI users.

Experience with data visualization: Regarding their experience with data visualizations, two participants stated that they were familiar with line and bar charts from working with tactile diagrams as part of their school education. One participant became blind later in life, so she was familiar with common terms and concepts from data visualizations. The fourth participant was not familiar with terms such as line and bar charts. However, when the participant was presented with descriptions of data visualizations, such as the temperature curve in a city using lines, this person was able to imagine them better. One participant emphasized during the interview that it is not important how the data is displayed for sighted users (e.g. as areas in a pie chart or as bars in a bar chart), but that he would like to be able to perceive the content and the data shown in the visualization just like sighted users.

Dealing with data-related tasks: The participants were also asked how they currently solve various data analysis tasks. As part of this, they were asked how they would solve the problem of finding the cheapest car in a table of car prices. All interviewees stated that the first thing they would try whether it is possible to sort the data set so that the car with the lowest price is at the top and can be found easily. However, if this function is not available, they have no choice but to navigate through the data manually and memorize the current lowest price until they have gone through the entire list. Although this would be possible with small amounts of data, it would be very time-consuming. However, if the dataset becomes too large, the task can only be completed with great effort or not at all. One interviewee noted that he weighs up very carefully whether it is really worth processing the information provided. The cognitive effort involved is very high, and if the available information does not provide much added value, he would rather not try to analyze the data. One participant also pointed out that it is important that the screen reader indicates to the user that interaction with the data is possible, but that it should not immediately start reading out the individual data points.

4 Screen reader concept

The visual structure of data visualizations enables sighted users to perceive and compare a lot of information in parallel, while screen reader users can only process the data sequentially. To ensure that BVI screen reader users can also benefit from online data visualizations, the concept should enable them to capture and freely explore the desired information without much additional effort. Our concept focuses on basic chart types, such as line chart, bar charts and scatter plots and follows the different levels of information granularity according to Kim et al. [10] (see section 2).

Existence of the visualization: To enable navigation for screen reader users, they should first be informed about the existence of the visualization. There is no information provided about the presented data itself, but the user is only informed that the screen reader is currently in a data visualization. In the interviews it was stated that some tools specifically designed for use with screen readers are intrusive and almost force screen reader users to use them. However, when using data visualizations, sighted users are also free to decide whether and how intensively they want to engage with the presented data. Therefore, users should be able to browse the rest of the website content without having to navigate through all the data.

Overview: There are various ways to provide an overview of the data: One is through a textual description of the presented data visualization that explains the essential elements and relationships of the data. Another option is to use sonification to communicate the data auditorily. Both forms of presentation offer users different advantages: The textual description allows insight into predominant patterns and an interpretation of the data visualization. In contrast, the auditory representation provides an overview of how the data is distributed. In our concept, we decided to offer both options. Although a textual description only reflects the author's interpretation of the data [19], we have decided to provide a text **summary** to describe general information about the data and predominant patterns. The overview itself should not be too detailed, as an overload of information makes it difficult for users to fully grasp and memorize it. The interviews with blind users revealed that not all of them have knowledge of data visualization. Therefore, the summary should not contain information that requires specific prior knowledge in order to be understood.

In addition, a **sonification** is offered for each chart type, which provides a quick overview of the distribution of the data points. Based on the findings of Wang et al. [18], the pitch is used to encode the data values on the y-axis in the Cartesian coordinate system. The values on the x-axis determine the time at which the data point is played in the sonification. The calculation by Brown et al. [2] is used to transform the data points into musical notes. In bar charts and scatter plots, the sounds of the individual data points are played one after the other in a discrete manner, as they should be interpreted individually and not as a continuous sequence. In contrast, the data points in line charts form a continuous sound and thus reflect the relationship between the individual data points.

Detail: A navigation concept for exploring the data visualization is provided to obtain information on precise data values on demand. It includes both undirected navigation through the data and a targeted search. The **navigation** concept is based on the work of Zong et al. [19] and enables movement through the data using the keyboard. *Structural navigation* is suitable for complex visualizations and is used for navigation in scatter plots, as the amount of data presented is difficult for screen reader users to process. Figure 1 (middle) shows the navigation through the scatter plot: the data is divided into sections based on the ranges on the x-axis. Initially, the focus is on the section with the lowest values on the x-axis. The user can then navigate left and right through this sections using the arrow keys. A brief summary of the value range of the data in each section is represented. If users want to explore the data in more detail, they can select a section and then navigate up and down through the individual data points. When a data point is selected, the label and the quantitative values of the x- and y-axis are provided by the screen reader.

With line charts, the continuity of the data can be lost with structural navigation. Bar charts are also simple that structural navigation could overwhelm users rather than support them. For this reason, *spatial navigation* is used for these chart types, which makes it possible to effortlessly navigate through the data using the underlying coordinate system. In line charts, the focus is on the first line, and the arrow keys can be used to navigate up and down between the lines (see Figure 1 - right), with the name of the currently focused line being provided by the screen reader. After selecting a line, the focus is placed on the first data point, and the arrow keys can be used to move left and right. The same spatial navigation is used in bar charts, and the bar label, the quantitative value on the y-axis and the position of the bar within the bar chart are provided by the screen reader when navigating through the individual bars.

Furthermore, a **targeted search** is provided to search for specific data points. It can be compared to the third option in the classification by Zong et al. - the *targeted navigation*, which allows the user to jump directly to data points in the visualization based on a predefined list of possible targets [19].

5 Prototype

The concept was implemented using Angular, TypeScript and D3.js. When developing the prototype, care was taken to ensure that it could be used on different systems. For this reason, regular tests were carried out with a Windows PC and the NVDA screen reader in the Google Chrome browser as well as with a macOS system and the VoiceOver screen reader in the Google Chrome browser.

As various functionalities should be made available to the screen reader user, these were encapsulated in an interaction menu in the order defined in section 4. The menu is embedded in the data visualization so that screen reader users can quickly reach and select the individual desired functionalities. As soon as screen reader users reach the position of the data visualization on the website, the title of the visualization is represented and the corresponding menu can be selected. If users do not wish to explore the data visualization any further, they can continue to navigate through the content of the website and are therefore not forced to immerse themselves in the data presented. A screenshot of the prototype can be seen in Figure 1 (left), which shows a focused visualization and the currently selected interaction feature that triggers the sonification of the bar chart. As the prototype only focuses on interaction via the screen reader, the individual menu items are shown schematically to the right of the screenshot to provide an overview.

6 Evaluation

The aim was to develop a concept that enables BVI users to explore simple data visualizations such as line charts, bar charts and scatter plots with the help of screen readers. In addition, the extent to which sonification can support the understanding of the data will be investigated. To answer these questions, the prototype was tested with five blind screen reader users.

6.1 Participants

The five participants were recruited via the Upper Austrian Federation of the Blind and Partially Sighted and all identified themselves as male (age: M = 52,2, SD = 11.5). All participants were blind and rely on screen readers as assistive technology in everyday life to interact with computers and smartphones. Four participants used the prototype on Windows with NDVA. The other one used VoiceOver with MacOS together with Google Chrome. All participants had extensive experience in using screen readers, with the exception of the latter participant, who had about 1.5 years of experience.

6.2 Procedure

The evaluation was divided into four phases and lasted around 1.5 hours on average.

Exploration phase: In the first phase, the participants were each presented the prototype with a line chart, a bar chart and a scatter plot. The task was to freely explore the visualizations and the available interaction features and to communicate their thoughts using the Thinking Aloud method.

Interaction phase: In the next phase, each participant was presented with an example of each available chart type, showing data on the election in Austria [1]. For each chart type, they were given several tasks to solve using the available and previously explored interaction options. The participants could freely choose the interaction features or combine several of them to solve the respective task. Some of these tasks were only set for certain chart types (see Table 1). The following list contains an example for each task type:

- **Data:** *What kind of data is presented?*
- **Axes:** *What information is represented on the axes?*
- **Sorting:** *Is the data sorted in a recognizable way?*
- **Extreme values:** e.g. *Which party achieved the highest election result and how high was it?*
- **Identification:** e.g. *What were the election results of the [PARTY] in 1999?*
- **Trends:** *Describe the trend of the election results of [PARTY].*
- **Sonification:** *Play a sonification of the four parties with the highest election results.*
- **Correlation:** *Can you see a connection between campaign costs and election results?*

Error detection phase: In the third phase, the participants were presented with data visualizations together with a statement about the data, such as *"The following visualization shows that new registrations of electric cars in Austria have increased continuously since 2008"*. They then had to verify or falsify this statement.

Feedback phase: Finally, the participants were asked to describe their general experience of using the prototype.

6.3 Results

Thinking Aloud: During the exploration phase, the participants gave feedback on the features of the prototype.

All participants were able to use the **interaction menu** independently from the beginning without having to ask for additional explanations. Participants P1, P2 and P4 noted that the consistent structure of the menu across the different chart types meant that it was easier to use each time it was utilized.

Participants were first familiarized with **sonification** in the context of bar charts during the exploration phase. With the exception of P1, all participants were immediately able to correctly interpret the auditory representation of the data and gain an overview of the data. In contrast, P1 stated that sonification was completely new to him and initially difficult to interpret. However, after listening to it several times, he was able to interpret the sonification correctly. None of the participants had problems correctly interpreting the sonification with the line charts. The participants stated that they were able to get an overview of the distribution of the data and outliers quickly and without major problems. However, most participants had more difficulty with scatter plots, as some of them could not immediately assign the meaning of the playback time and pitch. P3 then suggested that the sonification of scatter plots should not play the individual data points themselves, but the density of points in relation to the axes.

Table 1: Results of the tasks by participant (P1-P5) and tasks per chart type for bar charts (B1-6), line charts (L1-4) and scatter plots (S1-5). Features used to solve the task are indicated as: T – Title, SM – Summary, N – Navigation, Targeted Search – TS, S – Sonification

Task	P1	P2	P3	P4	P5
B1: Data	✓(T)	✓(SM)	✓(T)	✓(T)	✓(T)
B2: Axes	✓(N)	✓(SM)	✓(N)	✓(N)	✓(N)
B3: Sorting	✓(N+S)	✓(N)	✓(N)	✓(N)	✓(N)
B4: Extreme values	✓(SM)	✓(N)	✓(N)	✓(N)	✓(N)
B5: Identification	✓(N)	✓(N)	✓(N)	✓(N)	✓(N)
B6: Sonification	✗	✓(S)	✓(S)	✓(S)	✓(S)
L1: Data	✓(T)	✓(N)	✓(T)	✓(T)	✓(T)
L2: Axes	✓(SM)	✓(N)	✗	✓(N)	✓(SM)
L3: Trends	✓(SM)	✓(S)	✓(S)	✓(S)	✓(N)
L4: Identification	✓(N)	✓(TS)	✓(N)	✓(N)	✓(N)
S1: Data	✓(T)	✓(T)	✓(T)	✓(T)	✓(T)
S2: Axes	✓(SM)	✓(N)	✓(N)	✓(N)	✓(N)
S3: Correlation	✓(N)	✓(N)	✓(N)	✓(N)	✓(N)
S4: Extreme values	✓(N)	✓(N)	✓(N)	✓(N)	✓(TS)
S5: Identification	✓(N)	✗	✓(N)	✓(N)	✗

Navigating through the bar chart proved to be easy for all participants and required no additional assistance. After selecting the menu item *"Navigate through data"*, participants immediately recognized that they could navigate through the data using the left and right arrow keys. All participants were also immediately able to interpret the data presented in a bar chart and recognized that these were individual data points whose values were compared with each other and did not form a common trend. P5 pointed out that the output of the current index is helpful to keep the orientation in the bar chart, but the information that this is represented by a bar is unnecessary and becomes redundant over time.

When **navigating through the line charts**, participants had no major difficulties and were able to recognize that the line chart is used to represent a sequence of data. P5 suggested that it would be useful to indicate the slope of the currently focused data point to compare data points between different lines. He also noted that with the current implementation of the prototype, it is difficult for users to recognize if they are at the end of a line and suggested playing a beep or the index of the current data point for that.

When **navigating through the scatter plot**, most participants except P1 and P4 were overwhelmed with the functionality and needed additional help to navigate through the data points. P2 commented that the navigation seemed reasonable but overwhelming. P3 suggested that one should be able to choose whether they want to move along the x-axis or the y-axis first.

Results of the interaction phase: To evaluate the interaction phase, the responses of the participants are analyzed to determine whether they were able to answer the questions. The results are broken down in Table 1 into the tasks that each participant had to solve per chart type with the correct and incorrect results. In addition, the interaction feature used to solve the task is indicated in brackets after each result. Almost all participants were able to solve the tasks correctly, with a few exceptions for tasks B6, L2 and S5. The most common strategy used to characterize the data was to have the screen reader read the title of the visualization, followed by the *"Summary"* function with the textual description. Navigation in the data was mainly used to identify axes, extreme values, identification of values, sorting and correlation. Sonification was used mainly to identify trends in the line charts. The targeted search was only used by 2 participants in one task each.

Results of the error detection phase: All participants were able to correctly verify or falsify this statements. Only P5 was not able to recognize errors in the statement about the scatter plot.

Results of the feedback phase: Overall, the prototype was rated positively and all participants indicated that they would like to use a finalized version on websites to explore data visualizations. The interaction menu was rated as easy to use by all participants except P5. All participants also found it easy to navigate through the data visualizations. Only P5 differentiated here between navigation in bar and line charts, which he found easy, and navigation in scatter plots, which he found more difficult. Sonification was also noted by all participants as helpful for getting an overview of the data. P5 stated that there was again a difference between bar and line charts (easy) and scatter plots (more difficult).

6.4 Discussion

The evaluation provided valuable information on how participants gained an understanding of the data presented with the help of the prototype. In addition, conclusions could be drawn about how comprehensible the interaction features were for the users and how they used them to solve specific tasks. It turned out that the participants learned the functionality of the interaction menu quickly and were able to navigate through the individual menu items without any problems. With the interaction features provided, they were able to solve most of the tasks and find the data they were looking for. This indicates that the combination of functionalities offered provides users with an effective tool to independently explore the data presented according to their information needs. For bar charts and scatter plots, sonification was not used by any participant to solve the tasks (except for task B6), but it was emphasized as a very helpful feature to gain an overview of trends in line charts.

However, the results also showed that the features provided for bar and line charts are easier to understand than for scatter plots. For scatter plots, participants had more difficulty navigating through the data points or interpreting the sonification. For this reason, the navigation and search in more complex data visualizations such as scatter plots should be revised in future work. The participants were also overwhelmed with too many individual data points when sonifying the scatter plot. One participant suggested that it would be sufficient to sonify the point density rather than each individual point. A promising approach for this is presented by Chundury et al., who sonified the data density in scatterplots and combined touch and sound to provide a more scalable data exploration method for blind users [4].

Furthermore, some participants stated that there are many redundancies when reading out the individual data points and that it is not necessary to constantly repeat that this data point is a bar, line or point. Such redundancies should be removed in the revision of the prototype.

7 Conclusion

In this paper, we presented a screen reader and sonification concept that aimed to enable screen reader users to explore online data visualizations. Through a user study involving five blind participants, we gained valuable insight into how the features of our prototype were used and perceived. The results of the evaluation suggest that the developed concept, including interaction features such as interaction menus, sonification, and navigation, effectively supports BVI users in analyzing data visualizations and exploring different levels of detail. Most of the tasks were successfully completed, demonstrating the potential of the prototype to facilitate independent exploration of data visualizations.

The user study revealed that while features were generally well-received and effective for bar and line charts, there were challenges with more complex visualizations such as scatter plots. The participants found sonification and navigation in scatter plots to be more difficult, suggesting the need for further revision of these features. Reducing redundancies in the output of individual data points and exploring alternatives for more complex chart types are part of our future work.

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