Data Sonification for Screen-Reader Users: When and When Not to Use

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Abstract

Visualization creators often use data sonification to make online data visualizations accessible to screen-reader users. However, the effectiveness of sonification for screen-reader users remains unclear. Therefore, in this work, we assessed the experiences of screen-reader users with data sonification to illuminate the use cases in which sonification offers the most value in interpreting data from visualizations, such as in performing employment responsibilities. Specifically, we conducted a need-finding survey of 106 screen-reader users, reporting that only half of respondents found sonification to be at least "somewhat beneficial." We also conducted in-depth interviews with 12 screen-reader users, with results showing that sonification is an underutilized technology that can help obtain data overviews and trends but has limited value in comprehending complex visualizations and exploring data granularly. Utilizing our findings, we offer recommendations from screen-reader users to enhance the utility of data sonification. Additionally, we offer a decision tree for visualization creators to assist them in appropriately using sonification to make data visualizations accessible.

CCS Concepts

• **Human-centered computing → Empirical studies in accessibility**; **Empirical studies in visualization**; *Visualization design and evaluation methods.*

Keywords

sonification, audio graphs, blind, accessibility, visualizations

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1 Introduction

Screen-reader users face significant disenfranchisement due to the inaccessibility of online data visualizations [47, 60]. Sonifications[1] are the non-speech audio representations of data visualizations and used to make data visualizations accessible to screen-reader users [7, 23, 71]. In the past five years (2018 – 2023), at least 518 and 347 papers[2] on ACM Digital Library and IEEE Xplore, respectively, utilized, created, or improved data sonification tools across varying domains. Additionally, commercial products are increasingly and ubiquitously using sonification as an accessibility technique [66, 69, 72]. For example, Apple added sonification as a standard feature across all their devices in their 2021 operating system releases [5].

Despite sonification's first usage to represent graphs dating back to 1974 [15] and recent wide and plausible adoption in research [6, 21, 32, 33, 63], the use cases where sonification is—and is not—beneficial for screen-reader users remain unclear. In particular, given the wide usage of data visualizations in today's world, screen-reader-user employees, who are already disenfranchised due to the inaccessibility of digital content [47, 60], may not be able to effectively, or at all, perform their job responsibilities in cases where sonification does not offer meaningful benefits to these users.

Therefore, our goal was to assess the experiences of screen-reader users with sonification when interpreting data from visualizations, and to explore the factors that make sonification beneficial for them. For consistency, we follow prior work's definition of "screen-reader users" [60, 63], not limiting our intended demographic to only blind and low-vision users but also including people who use screen readers for temporary or situational needs (for example, motion sickness or light sensitivity).

To achieve our goal, we conducted and analyzed the responses from a need-finding survey with 106 screen-reader users. Our findings show that 48% (N=51) of respondents were unfamiliar with

[1]In this paper, we use "sonification" synonymously with "audio graphs," limiting its domain of usage to data visualizations.
[2]We combined the search results for "sonification" and "audio graph," accounting for plural terms, too.

sonification before taking our survey. Additionally, 63% (N=67) of respondents had never encountered sonification in online data visualizations. We also found that 75% (N=41) of respondents who had prior familiarity with sonification rated it to be at least "somewhat useful." In contrast, this percentage was only 27% (N=14) for respondents unfamiliar with sonification before taking our survey.

These results motivated us to gather additional insights into the experiences of screen-reader users with sonification. Therefore, we conducted in-depth semi-structured interviews with 12 screen-reader users. Results from the interviews show that our participants rarely encounter sonification online and that their experiences with sonification are often limited to only research studies; these results comport with our survey findings. Specifically, we report three themes from our qualitative analysis: (1) "Needle in a Haystack," (2) "Keep it Simple, Sonifier," and (3) "Suggestions to Improve Sonification's Effectiveness." Our participants found sonification helpful for obtaining an overview of data, particularly data trends. Conversely, they did not find it useful for understanding the data at a more granular level, especially for complex visualizations (e.g., multi-dimensional datasets, multi-series visualizations, or geospatial maps). Furthermore, they shared suggestions and techniques that could improve the effectiveness of sonification for screen-reader users, including customizations, learnability, and combining sonification with other modalities. We utilized these findings to generate a decision tree for visualization creators to aid them in using sonification appropriately for making online data visualizations accessible to screen-reader users.

The main contributions of our work are as follows:

(1) Empirical results from a survey of 106 screen-reader users.
(2) Empirical results from our semi-structured interviews with 12 screen-reader users.
(3) Decision tree for visualization creators to assist them in making informed decisions about using sonification to make data visualizations accessible to screen-reader users.

2 Related Work

We review prior work that has utilized sonification in practice and research. Additionally, we highlight research on the assessment of sonification as a technique to make data visualizations accessible for screen-reader users.

2.1 Sonification in Practice

Developers and researchers have created several sonification solutions for screen-reader users; some of these solutions are open-source [22, 31, 41, 43, 51, 62], whereas some are proprietary [5, 66, 69, 72]. However, only a few are suitable for *online* data visualizations. For example, Statistical Analysis Software (SAS) Graphing Calculator [66] is a browser extension that enables screen-reader users to interact with online data visualizations using sonification but is limited to graphs created using the SAS software. Highcharts [31] is a proprietary JavaScript library that aids visualization creators in developing online data visualizations and offers free and open-source built-in sonification. Similarly, Sonifier [62] and Chart2Music [43] are open-source JavaScript libraries that make online data visualizations accessible to screen-reader users by generating sonified responses using various oscillator waveforms and synthesizers. However, these libraries do not aid in determining when sonification may not be suitable for use.

2.2 Sonification in Research

Several research projects have explored sonification to improve the experiences of screen-reader users with data visualizations [3, 6, 21, 32, 49, 57, 63, 65, 76]. Most recently, Hoque *et al.* [33] developed Susurrus, which sonifies visualizations using natural sounds, such as birds singing in a forest. Their findings show that natural sounds can benefit screen-reader users in interpreting data from visualizations, especially charts representing multiple categories. Similarly, Fan *et al.* [21] built two audio-haptic interfaces that provide shape feedback to blind and low-vision people using sonification, reporting an increased appreciation for shape information from their users due to the addition of sonification. Likewise, Sharif *et al.* [63, 64] introduced `VoxLens`, an open-source library that makes online data visualizations accessible by offering screen-reader users multiple modalities for information extraction, including sonification. Their results indicate a "closure of the gap" between screen-reader- and non-screen-reader users in the accuracy of information extraction and interaction times. Specifically, they reported `VoxLens` providing a 164% increase in accuracy and a 50% reduction in interaction times.

2.3 Assessment of Sonification

Prior research has assessed the usability of sonified responses [2, 27, 56, 61, 73]. Most recently, Wang *et al.* [73] examined the impact of various auditory channels (e.g., pitch and volume) on users' perception of data visualizations. Sharif *et al.* [61] extended their work by investigating the effects of various oscillator waveforms and synthesizers on the pleasantness and confidence of users in interpreting simple and complex sonified responses. In addition to assessing the usability of sonification, researchers have also used sonification as a baseline to examine the utility of multi-modal solutions. For example, Siu *et al.* [65] investigated the usefulness of audio data narratives compared to a standard sonification representation. Their results suggest that audio data narratives help users gain a more complete gist of the data. Similarly, Chundury *et al.* [16] reported that their blind and low-vision participants preferred a combination of sound and touch to interpret data visualizations compared to using only auditory feedback.

2.4 Employment Challenges

The ubiquitous use of data visualizations in work environments necessitates making content equitably accessible to all users, regardless of their ability levels[47]. When these visualizations are not accessible to screen-reader-user employees, they may be unable to perform their job responsibilities, which can adversely affect their career growth [17, 20, 35]. Given sonification's wide adoption in commercial products (e.g., Apple products, SAS Graphing Calculator), it is critical to assess when—and when not—sonification can be a helpful technique to interact with data visualizations.

Therefore, in contrast to prior work, our work contributes to the existing accessibility and visualization literature by investigating the experiences of screen-reader users with sonification as a

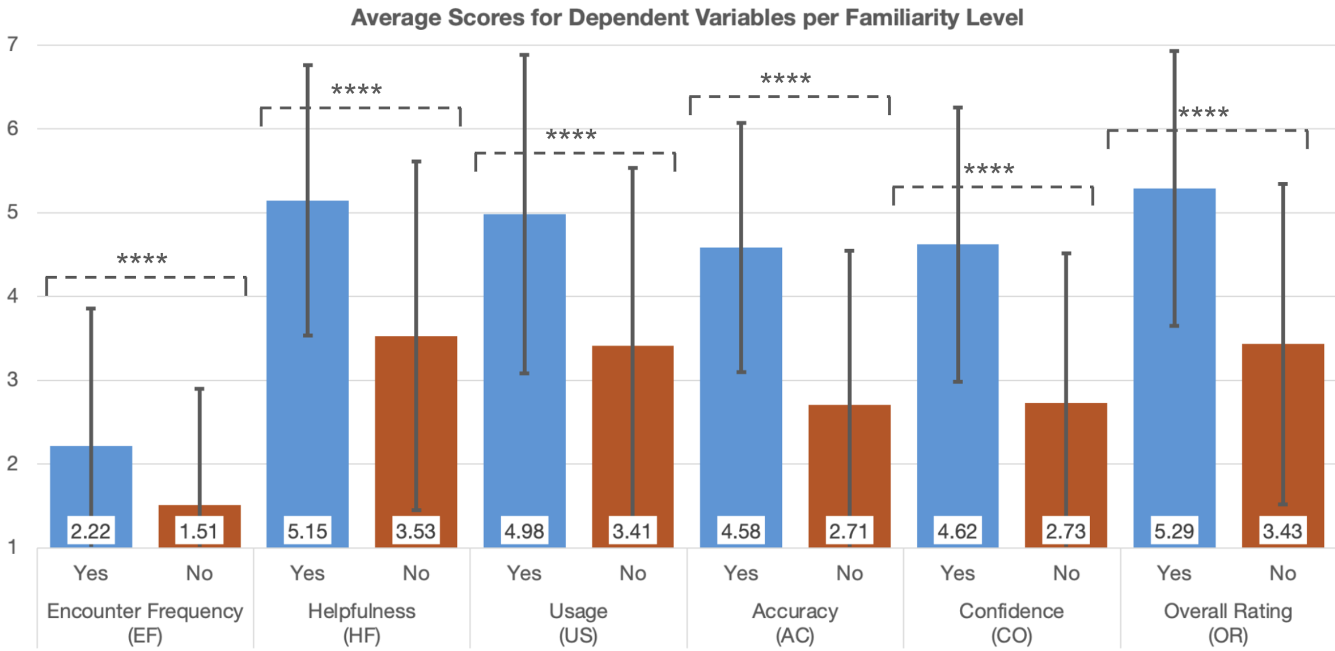

Figure 1: Average ratings for *EF*, *HF*, *US*, *AC*, *CO*, and *OR* per each familiarity level (*PF*) ["Yes" or "No"]. We recognize these are ordinal values; means and SDs are shown for illustrative purposes only, and inferential statistics were performed appropriately using ordinal logistic regression, non-parametric ANOVA. Error bars represent mean ± standard deviation. All results are statistically significant ($p < .05$).

standalone technique to interpret data from visualizations. Our research provides empirical findings from a large-scale need-finding survey and an interview study with 106 and 12 screen-reader users, respectively. Furthermore, our work utilizes these findings to build a decision tree as a recommendation aid to assist visualization creators in using sonification to make data visualizations accessible to screen-reader users.

3 Need-Finding Survey

As an initial step, we surveyed 106 screen-reader users. We examined their responses with multiple methods, handling Likert responses with quantitative methods [48, 50] and open-ended responses with qualitative [9, 10, 53].

3.1 Participants

Our survey respondents ("participants") were 106 screen-reader users (M=49.8 years, SD=16.1). We advertised our survey through the National Federation of the Blind [52]. Sixty-one identified as women, 38 as men, five as non-binary, and two did not disclose their gender identity. Sixty participants used JAWS screen reader [59], 25 used VoiceOver [34], 17 used NVDA [1], and the remaining four used a combination of multiple readers. Fifty-nine participants were blind since birth and 47 had lost vision gradually; 84 participants had complete blindness. The highest level of education was a doctoral degree for 10 participants, a master's degree for 34, a bachelor's degree for 34, an associate's degree for eight, a high school diploma for 18, and pre-high-school for the remaining two participants.

3.2 The Survey

Participants filled out our three-step survey online without supervision that we created using Google Forms[3]. The first step included the purpose of our study, eligibility criteria, data anonymity clause, the definition of sonification, and an example of sonified output. In step two, we collected demographic information from our participants. We recorded their gender identity, pronouns, age, screen reader usage, vision level, diagnosis, age of diagnosis, and education status. We followed guidelines from Spiel *et al.* [68] to inquire about their gender identities appropriately. Lastly, we asked about their familiarity with sonification as a binary response ("yes" or "no") and used a Likert scale ranging from 1 (lowest; e.g., "not at all") to 7 (highest; e.g., "extremely helpful") to get the answers to the following questions on sonification:

(1) How often do you encounter sonification? (*EF*)
(2) How helpful do/would you find sonification to extract information from data visualizations? (*HF*)
(3) How often do/would you use sonification in practice? (*US*)
(4) How do/would you perceive the accuracy of information extracted using sonification? (*AC*)
(5) How confident do/would you feel in their overall understanding of the data from sonification? (*CO*)
(6) What is your overall rating for sonification's usefulness? (*OR*)

[3]https://forms.google.com

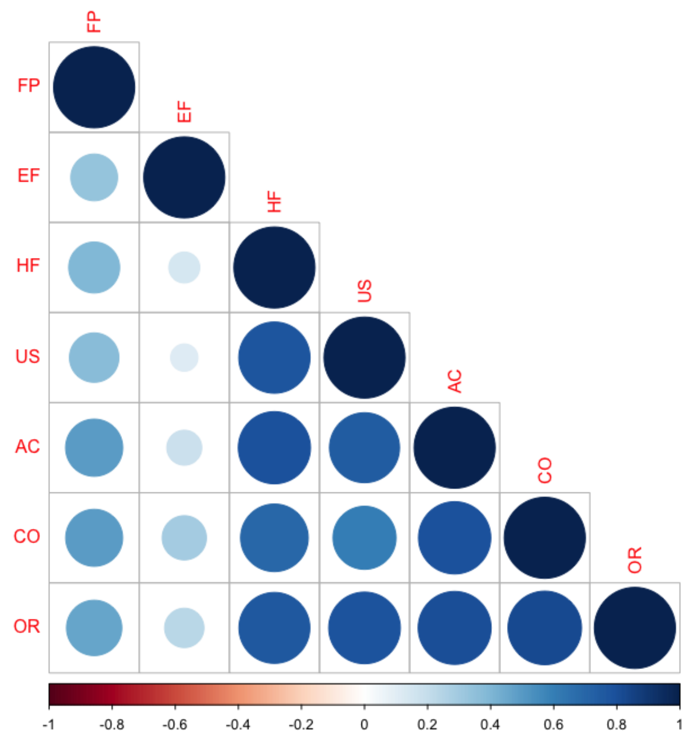

Figure 2: Correlogram showing correlations between each pair of *EF*, *HF*, *US*, *AC*, *CO*, and *OR*.

Finally, we asked our participants open-ended questions about situations in which they do/would find sonification helpful and in which they do/would not. We also asked about their opinion on sonification and their interest in a follow-up interview.

3.3 Quantitative Evaluation

We investigated the effect of their prior familiarity with sonification on their Likert responses. Our goal was to distinguish between ratings from participants who had experienced sonification before and those from participants who had either never experienced it or only encountered it via examples. We note that responses from both these groups are vital to provide insights into the utility of sonification. Therefore, prior familiarity was of particular interest to us in our exploration. Our independent variable was *Prior Familiarity* (PF), having dichotomous levels ("yes" and "no"). We used the questions identified in the subsection above as our dependent variables (*EF*, *HF*, *US*, *AC*, *CO*, and *OR*), each having an ordinal representation (1-7). To analyze the effect of each of these variables on *PF*, we used ordinal logistic regression [48, 50], a standard technique used for analyzing ordinal response data.

Prior familiarity (*PF*) had a significant effect on all dependent variables, *i.e.*, the Likert responses (1-7) named above, indicating that each response differs significantly between the two familiarity groups (see Figure 1 for average scores for each dependent variable per each familiarity level).

Overall, 74.6% (N=41) of the participants with prior familiarity rated sonification at least "somewhat useful" (5 to 7 on the Likert scale). For participants unfamiliar with sonification, this percentage was only 27.4% (N=14), constituting 47 percentage points (%pt) for *OR*. Using the same scale for comparison, *pp* was identically high for *HF* (32 %pt), *AC* (33 %pt), *CO* (41 %pt), and *US* (30 %pt). For *EF*, it was 5 %pt (12.7% *vs.* 7.8%), indicating an agreement between the two groups on the low presence of sonification in data visualizations.

In addition to examining the effect of prior familiarity, as a secondary exploration, we performed Spearman's rank correlation analysis [67] between all our variables to gather further insights. We found a statistically significant and positive correlation between all variables *except* for *EF* and *HF* (p=.139), *EF* and *US* (p=.249), and *EF* and *AC* (p=.057) (see Table 1 and Figure 2). We note that correlation does not imply causality but helps determine the linear relationship between the variables. The fact that many of these responses are correlated suggests an interdependent relationship among these variables that future work can explore further. For example, taken together, our results show that with an increase in encountering frequency (*EF*), participants' confidence in understanding the data in visualizations also increased.

3.4 Qualitative Evaluation

We qualitatively analyzed the open-ended responses from 106 screen-reader users. Specifically, we conducted a theoretical thematic analysis [9] using a semantic approach [53] and an essentialist

Table 1: Statistical results from our Spearman's rank correlation analysis of all our variables. "V1" means Variable 1 and "V2" means Variable 2. ρ is the Spearman's rank correlation coefficient. All results with p <.05 are statistically significant.

V1	V2	ρ	p
PF	*EF*	.33	< .001
PF	*HF*	.40	< .001
PF	*US*	.37	< .001
PF	*AC*	.50	< .001
PF	*CO*	.49	< .001
PF	*OR*	.47	< .001
EF	*HF*	.15	.139
EF	*US*	.11	.249
EF	*AC*	.19	.057
EF	*CO*	.30	< .05
EF	*OR*	.24	< .05
HF	*US*	.77	< .001
HF	*AC*	.79	< .001
HF	*CO*	.70	< .001
HF	*OR*	.77	< .001
US	*AC*	.75	< .001
US	*CO*	.61	< .001
US	*OR*	.78	< .001
AC	*CO*	.80	< .001
AC	*OR*	.81	< .001
CO	*OR*	.82	< .001

paradigm [55, 75], following guidelines from Braun and Clarke [10]. Three co-authors coded each response, reaching a high agreement percentage of 95%. Our final analysis converged to a single prominent theme of *"useful but only in the right context."* Overall, our participants accentuated its limited usefulness. For example, P51 and P70, both of whom had experienced sonification before, found it helpful for a high-level overview and unhelpful for identifying granular details, respectively:

> `Better to keep sonification for high-level overview and not to over-complicate them. The audio equivalent of a first glance. In general, I think this is their best use.` (P51)

> `Where I would need a very specific information, sonification would not be helpful. I see it more for a general overview and less for specific data.` (P70)

On the other hand, P25 and P26, who had only encountered sonification in examples, classified it as "a tool with great potential" and a solution that "needs refinement," respectively.

The findings from our need-finding survey motivated our need to delve further into the use cases in which screen-reader users do and might find sonification useful. We present the details of our in-depth semi-structured interviews below.

4 In-Depth Interviews

To gather further insight into the experiences of screen-reader users with data sonification, we conducted in-depth semi-structured interviews with 12 screen-reader users. We present our methodology and results from our qualitative analysis. Additionally, these interviews form the basis for our decision tree.

4.1 Participants

Using the list of respondents interested in participating in a follow-up interview from our survey, we created two participant pools based on their prior familiarity (*PF*) with sonification. We excluded participants who did not provide meaningful responses to our open-ended questions in the survey (e.g., "none" or "n/a"). We randomly chose six participants from each *PF* pool, totaling 12 screen-reader users (see Table 2; S1–S6 are participants with prior familiarity with sonification and S7–S12 are participants without). Among participants with prior familiarity, four identified as women and two as men. Their average age was 53.7 years (*SD*=19.5). Four had complete blindness, whereas two were partially blind. Four had attained a master's degree, and the remaining two participants had bachelor's and associate's degrees, respectively.

For participants unfamiliar with sonification, three identified as women, one as a man, one as gender-fluid, and one preferred not to disclose. All participants were blind, and their average age was 42.7 years (*SD*=14.0). The highest level of education was a doctoral degree for two participants, an associate's degree for three participants, and a high school diploma for the remaining participant.

We ceased recruitment of participants once we reached saturation of insights and compensated them with a $25 Amazon gift card for 45 minutes of their time.

4.2 Procedure

We conducted the semi-structured interviews via Zoom using its built-in features to record and transcribe our 45-minute-long sessions. At least three authors partook in each interview, with at least one author taking detailed notes during the session. During the interviews, we inquired about the usefulness of data sonification and future efforts to improve the information extraction experiences of screen-reader users with sonification. Specifically, we explored the nuances and intricacies of when sonification is, or might be, helpful in extracting information from online data visualizations for screen-reader users.

4.3 Analysis

We used inductive thematic analysis[10], following a semantic approach [53], guided by an essentialist paradigm [55, 75]. Using the first two interviews, we developed an initial set of codes [10, 58]. Three co-authors coded each interview transcript independently, resolving disagreements through mutual discussions. Following Braun and Clarke's guidelines on thematic analysis [10], we combined our 41 open codes into 11 axial codes. Our final analysis revealed three prominent themes, which we discuss below. Following the suggestion by Landis *et al.* [42], we calculated inter-rater reliability (IRR) using pairwise percentage agreement as well as Krippendorff's α [39]. The pairwise percentage agreement was 82%, showing a high agreement between raters [28, 29]. Krippendorff's α

Table 2: Gender, age, prior familiarity ("PF"), vision level, and diagnosis of our participants. Under the "G" (*Gender*) column, M = *Man*, W = *Woman*, NB = *Non-binary*, and "-" means preferred not to disclose.

	G	Age	PF	Vision-Loss Level	Diagnosis
S1	W	41	No	Complete blindness	Functional Neurological Disorder
S2	M	76	No	Complete blindness	Retinitis Pigmentosa
S3	M	55	Yes	Complete blindness	Leber Congenital Amaurosis
S4	W	50	Yes	Complete blindness	Retinitis Pigmentosa
S5	W	36	No	Complete blindness	Retinopathy of Prematurity
S6	W	24	Yes	Complete blindness	Astrocytoma
S7	NB	28	Yes	Complete blindness	Leber Congenital Amaurosis
S8	W	65	No	Partial blindness	Retinitis Pigmentosa
S9	W	72	No	Partial blindness	Retinitis Pigmentosa
S10	W	42	Yes	Complete blindness	Glaucoma
S11	-	57	Yes	Complete blindness	Retinopathy of Prematurity
S12	M	32	No	Complete blindness	Retinal Detachment

was 0.81, indicating a high level of reliability [40], computed using ReCal 3.0 [25].

4.4 Results

We present the findings from the qualitative analysis of our semi-structured interviews with 12 screen-reader users. We identified three themes: (1) "Needle in a Haystack," (2) "Keep it Simple, Sonifier," and (3) "Suggestions to Improve Sonification's Effectiveness." We discuss each of the these themes in turn. Additionally, we append "+" and "-" to the participants' identifiers for ease in recognizing which participants had prior familiarity with sonification and which did not, respectively.

4.4.1 Needle in a Haystack. In our survey, 63% of participants answered "never" when asked about how often they encounter sonification in online data visualizations. This finding was also a prevalent theme in our interviews. Our findings show that the participants had seldom encountered sonification before, mostly only in research studies. S3+ and S4+ expressed that they have not experienced sonification often in online data visualizations, attributing to it being a "newer technology" (S3+) and not "mainstream" (S4+):

> It seems like it's a newer technology, so it's not in practice quite yet. Because I think the first time I heard of sonification was through a podcast. (S3+)

> I don't really think sonification is at all mainstream. Like, you know, data visualizations are super common, super used, but sonification, I find not very often. (S4+)

On the other hand, S5+ and S2+ shared that their familiarity with sonification was only through participating in research studies:

> Actually, a few years ago when the pandemic was starting, I did participate in a focus group where sonification was used in a chart for COVID-19, and I found that really helpful and interesting. So I guess the last time I interacted with was maybe three years ago. (S5+)

> I encounter it maybe once every few months in a couple of studies that were investigating sonification for different purposes. (S2+)

4.4.2 Keep it Simple, Sonifier. The title of our second theme is inspired by the KISS principle ("keep it simple, stupid") [4]. In our in-depth interviews with participants, we found that sonification helps interpret the data in online visualizations when used to provide an *overview* of the data, particularly data trends. For example, S4+ and S12- expressed the usefulness of sonification to obtain an overview of the data and the data trend, respectively:

> I think it has to stick to, like, if you're just trying to give somebody an overview. And that's it, that's kind of all you can do with sound. If you try to really explain lots and lots and lots and then it just becomes too hard and too complicated to understand. (S4+)

> It would be generally useful if you could hear a trend. Like if, for example, work gave me income breakdowns for every single week, and instead of me having to look through all of it, if I could sonify that, and it played a sound of where the income's going up or when it's going down, that would be helpful for me. (S12-)

On the other hand, our participants expressed concerns regarding using sonification for complex[4] data and visualizations. For example, S7- and S4+ did not find sonification helpful for understanding the data at a granular level, especially when extracting specific data points:

[4]We use the term "complex" based on the complexity factors mentioned in prior work [38, 46, 54, 70], including data dimensionality, series, cardinality, and users' cognitive load.

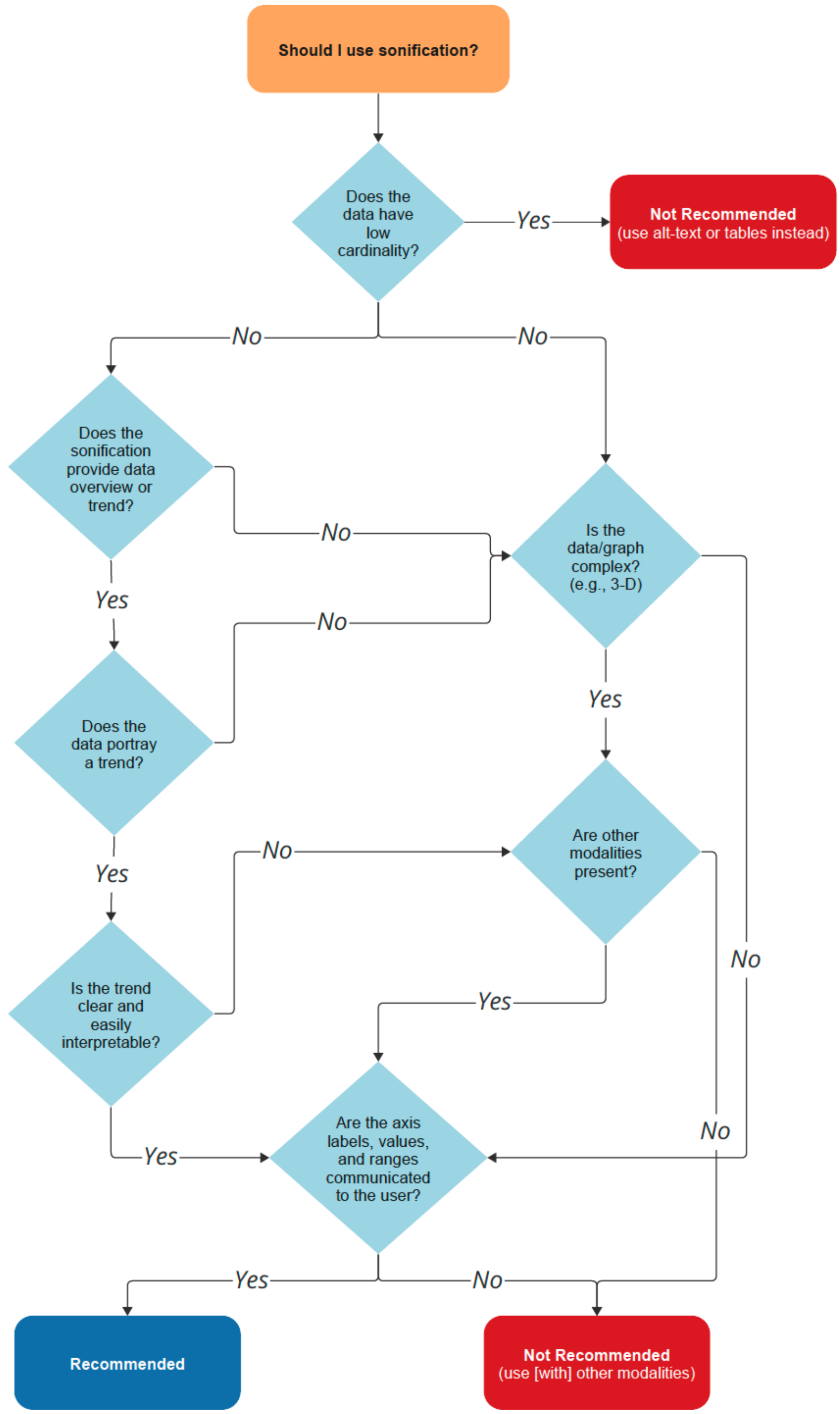

Figure 3: Decision tree to assist visualization creators for using sonification for accessibility.

> Basically, sometimes it's the visualization that's difficult to understand, and sometimes it's the data. So a lot of things come into play. Sometimes even a simple scatter plot might have data that is really complex to interpret a simple summary out of it. So, I think if anything is going to be super complex, that would make it very challenging to understand sonification. (S7-)

> But say you wanna know more than just the general trend, you wanna actually know where all the data points are. But just something that gets harder to just represent with, like, one beam of sound. It's more so how much you personally wanna delve into that data that dictates whether sonification is going to be useful or not. (S4+)

Interestingly, while our participants considered sonification beneficial for "simple" data (easily interpretable via sound), they did not find it helpful for data that was "too simple" (*e.g.*, of low cardinality). For example, S5+ preferred data to be relayed via text or tables when data points were very few.

> Probably a really simple chart that only had a few points, then that's not very helpful. Because if the alternative text was already there or the table and there wasn't too much to the chart, then there's really no need to have the sonification. I think that information could be relayed through other means. (S5+)

4.4.3 Suggestions to Improve Sonification's Effectiveness. Despite the low encounter frequency of sonification solutions online, our participants overall felt positive about it as a technique to make online data visualizations accessible for screen-reader users. Additionally, they identified avenues to enhance the utility of sonification. For example, several participants indicated that sonification would have increased usefulness when combined with other modalities, such as alternative text or data tables. S9- emphasized the need for other modalities, and S3+ suggested providing a summary of the data and an explanation of the response through other modalities (such as alt-text):

> So, just as a blind person, you would want to have multiple modalities so you can use sonification when you think it's appropriate and then turn it off and just use something else like alt-text. (S9-)

> Basically, you're given a little bit of a summary about the graph and then explained what the sonification would mean, such as the higher pitches mean the higher data, or lower pitches mean the lower values. It gives users a better understanding of the graphs that they're looking at. (S3+)

Additionally, similar to prior work [61], our participants identified the need to make sonification customizable to cater to screen-reader users' individual preferences and discussed the benefits of customization. For example, S9- considered customization important for her interaction needs:

> Customization's so important to me. I don't know if a sighted interface is like that, but I'd like sonification to be like that, where you can customize it however you want. Like, sounds, speed, all that. (S9-)

Specifically, our participants identified the need to have the ability to turn the sound on or off and pause it when needed. In addition, they deemed it essential to select the pitch, frequency, and speed of the sound. S11-, S1+, and S7- all discussed the necessity of these features:

> So, if there were some kind of well-labeled and easy-to-find buttons on the screen that the blind person could either hit or touch on the phone screen, they could pause the sonification and then hit the button to give, maybe the specific data point number or more information or whatever, you know. (S11-)

> We would like to set the pitch to whatever we want. Like a variable frequency oscillator, right? I tune the dials a bit different than my sighted colleagues. But every man is different, right? Every guy has a different ear tolerance. (S1+)

> I think it would be really cool because like even with VoiceOver and JAWS, we have ways that we can do different voices and we can make it all at different speeds and stuff, and we can speed it up or slow it down or change it in between. I think that would be really neat to be able to make sonification customizable. (S7-)

Finally, our participants accentuated the importance of learnability, highlighting that learning sonification can sometimes have a big learning curve and may need practice. S8- shared his thoughts:

> This is the kind of thing that takes practice. See, two things have to change here. The computer has to change, but the human has to change also. So I have to learn a different way of understanding data. I could do it well with practice. (S8-)

Overall, our findings show that sonification has a limited presence in online data visualizations, would be more helpful in providing overviews of data than granular explorations, and could be improved with customization features and resources to help learnability.

5 Decision Tree

Utilizing the findings from our need-finding survey and semi-structured interviews with screen-reader users, we developed a decision tree for visualization creators to assist them in appropriately selecting sonification to make online data visualizations accessible. Specifically, our decision tree considers the nuances discovered in our studies, serving as a *recommendation* tool for visualization creators. Figure 3 shows our decision tree.

5.1 Accessibility Measures

Following WCAG 2.1 [14], we chose a CVD-friendly (Color Vision Deficiency) color palette using ColorBrewer 2.0 [11] and ensured the color contrast ratio was at least 4.5:1 using the WebAIM Contrast Checker [74]. We also present a textual description of our decision tree below as an effort to make our visual content accessible for screen-reader users.

5.2 Usage

Visualization creators can use our decision tree to decide if providing data sonification would be helpful for screen-reader users. For example, for a stock market data visualization, a visualization creator would first determine the data cardinality to decide using sonification. For low cardinality, they can use alternative text or tables instead. Otherwise, they can move to the next step in the decision tree to determine if the visualization shows a trend. If the trend is easily interpretable, and the creator has communicated axis labels, values, and ranges to the user, they can use sonification as a standalone accessibility technique. Otherwise, they can use sonification in conjunction with other modalities.

5.3 Textual Description of Our Decision Tree

Our decision tree begins with the Start Terminator symbol containing the text: "Should I use sonification?" A single arrow originates from it, connecting it with the Decision symbol $D1$ containing the text: "Does the data have low cardinality?" The "yes" arrow from $D1$ points to an End Terminator symbol that reads, "Not Recommended (use alt-text or tables instead)." Two "no" arrows originate from $D1$, connecting it with the Decision symbols $D2$ and $D3$, which read, "Does the sonification provide data overview or trend?" and "Is the data/graph complex? (e.g., 3-D)," respectively. The "yes" arrow from $D2$ connects it with the Decision symbol $D4$ that reads, "Does the data portray a trend?" The "no" arrows from $D2$ and $D4$ connect them to $D3$. The "yes" arrow from $D4$ connects it with Decision symbol $D5$, which reads, "Is the trend clear and easily interpretable?" The "no" arrow from $D5$ and "yes" arrow from $D3$ both lead to Decision symbol $D6$, which contains the text "Are other modalities present?" The "yes" arrows from $D5$ and $D6$ and the "no" arrow from $D2$ all connect to the final Decision symbol $D7$, which reads, "Are the axis labels, values, and ranges communicated to the user?" The "yes" arrow from $D7$ leads to the End Terminator that reads "Recommended." The "no" arrows from $D6$ and $D7$ both connect them with the End Terminator that contains the text "Not Recommended (use [with] other modalities)."

6 Discussion

In this work, we assessed the experiences of screen-reader users with sonification to shed light on when sonification is beneficial in interpreting data from online visualizations and when it is not. Specifically, we conducted a need-finding survey of 106 screen-reader users and delved further into the findings through in-depth semi-structured interviews with 12 screen-reader users. Utilizing the findings from these studies, we created a decision tree for visualization creators to aid them in making informed decisions about using sonification as an accessibility measure in online data visualizations. Our findings show that sonification remains underutilized in online data visualizations but can be a helpful tool for gathering an overview of data by screen-reader users.

6.1 Underutilization of Sonification

Almost half (48%, N=51) of screen-reader users who participated in our survey did not have prior familiarity with sonification, and among the 52% (N=55) who did, 80% rated their encounter frequency at "3" or below on a Likert scale ranging from 1- to 7 (1 representing "never" and 7 being "very often"). In addition, S3+ considered sonification a "newer technology" and "not in practice quite yet." However, scientists, researchers, and practitioners have used data sonification in graphs for decades [7, 18, 26, 30], with its first usage reporting back to 1974 [15]. Altogether, these findings accentuate the underutilization of sonification in making online data visualizations accessible to screen-reader users. We urge future work to incorporate their sonification solutions with mainstream platforms (such as D3 [8]) and to explore ways of sustainable translation [19, 37] of sonification solutions from research to practice. We encourage researchers and future work to seek iterative feedback from screen-reader users whenever possible.

6.2 "Realism" versus "Imagination"

In our survey and in-depth semi-structured interviews, we inquired about the prior familiarity of our participants with sonification. We used this information to accentuate the distinction between responses based on real experiences and responses based on imagination and speculation. Our findings showed that 75% of screen-reader users who were *familiar* with sonification rated it to be at least "somewhat useful." On the other hand, only 27% of screen-reader users who were *unfamiliar* with sonification communicated the same ratings. Hence, their familiarity with sonification may have influenced their perception of sonification's usefulness. Our results also showed that sonification is an underutilized accessibility technique for data visualizations. Together, these findings suggest that increased utilization of sonification could improve screen-reader users' perception of its usefulness, consequently improving their experiences with data visualizations.

6.3 Sonification as a Standalone Technique

As the findings from our studies show, sonification is beneficial for comprehending a high-level overview of the data, similar to results from prior work [30, 36, 44, 61]. For a granular understanding of the data, sonification as a standalone technique might be ineffective and induce undue cognitive load on users. Even when used for simple data trends, without axis values communicated to users in the order of appearance, users could experience confusion and potentially misinterpret the sonified responses. For example, sonification for time-series data in ascending order would sound the opposite in descending order, leading to different conclusions.

S3+ recommended explicitly stating that "higher pitches mean the higher data and lower pitches mean lower values," as that is not always the case [12, 24]. Therefore, we suggest using sonification with other modalities and providing screen-reader users with metadata for contextual understanding. Additional modalities can also provide screen-reader users the agency to choose their preferred techniques in extracting information from online data visualizations. Additionally, visualization creators and researchers can use our decision tree to make determinations about using sonification appropriately.

6.4 One Size Does Not Fit All

Similar to the findings from prior work [61], a prevalent and frequent observation from our studies was the emphasis on having customization options for sonification. Some participants mentioned familiar screen reader settings (different voices, speed controls, etc.) to convey the significance of customization. Of course, several technical design considerations are critical in effectively implementing customizability features [13, 45], including minimizing the burden of repeatedly specifying preferences across different platforms and identifying default values. Visualization creators can utilize the "export preferences" feature of screen readers to use the default settings from a user's screen reader and provide them with a centralized interface to set their preferences. Future work can also incorporate personalization, building appropriate models of predictors to deliver screen-reader users an enhanced experience with sonification.

6.5 Limitations and Future Work

Our goal was to perform an *overall* assessment of screen-reader users' experiences with sonification in interpreting data from online visualizations. Therefore, we did not explore its domain-specific usage for expert users (*e.g.*, for screen-reader user brokers who interact with financial data visualizations extensively). We encourage future work to investigate the experiences of screen-reader users with sonification in different disciplines, domains, and professions. Our findings highlighted the unfamiliarity of screen-reader users with sonification and their emphasis on learning how to interpret sonified responses. Therefore, we did not conduct task-based usability studies to evaluate the use and usefulness of sonification, as subject matter knowledge could have been a significant confound in the analyses. Future work can explore efficient learning methods for screen-reader users to minimize this confound. *In situ* think-aloud usability studies would also allow us to understand how sonification is used in practice by screen reader users, undoubtedly revealing additional insights to what we have presented in this work. Additionally, future work can utilize our findings to build customization and personalization tools for screen-reader users to enhance their experiences with sonification.

7 Conclusion

We assessed the experiences of screen-reader users with sonification through a survey of 106 screen-reader users and semi-structured interviews with 12 screen-reader users. Our findings show that sonification is a helpful technique for obtaining an overview of the data but not for exploring data granularly. Our results also show that screen-reader users seldom encounter sonification in online data visualizations and usually only encounter it during research studies. Our findings also show that participants who *have* encountered sonification are generally positive and optimistic about its usefulness and potential, suggesting it is underutilized and should be more widely incorporated into online data visualizations of the appropriate type. To aid in understanding what visualization types are appropriate, we presented a decision tree to assist visualization creators in using sonification to make data visualizations accessible to screen-reader users. We hope our findings and recommendations will guide visualization creators and researchers to improve screen-reader users' experiences of data visualizations with sonification.

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