Infosonics: Accessible Infographics for People who are Blind using Sonification and Voice

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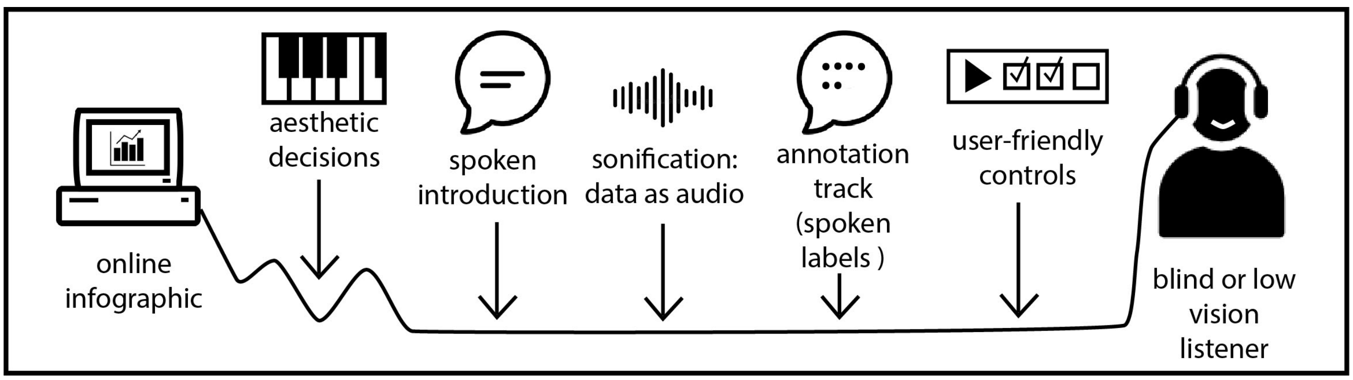

Figure 1: Key elements of infosonics for audio access to infographics by a general audience of people who are blind or have low vision

ABSTRACT

Data visualisations are increasingly used online to engage readers and enable independent analysis of the data underlying news stories. However, access to such infographics is problematic for readers who are blind or have low vision (BLV). Equitable access to information is a basic human right and essential for independence and inclusion. We introduce infosonics, the audio equivalent of infographics, as a new style of interactive sonification that uses a spoken introduction and annotation, non-speech audio and sound design elements to present data in an understandable and engaging way. A controlled user evaluation with 18 BLV adults found a COVID-19 infosonic enabled a clearer mental image than a traditional sonification. Further, infosonics prove complementary to text descriptions and facilitate independent understanding of the data. Based on our findings, we provide preliminary suggestions for infosonics design, which we hope will enable BLV people to gain equitable access to online news and information.

CCS CONCEPTS

• **Human-centered computing** → **Accessibility technologies**; **Empirical studies in accessibility**.

KEYWORDS

Blind, low vision, information access, accessible graphics, sonification

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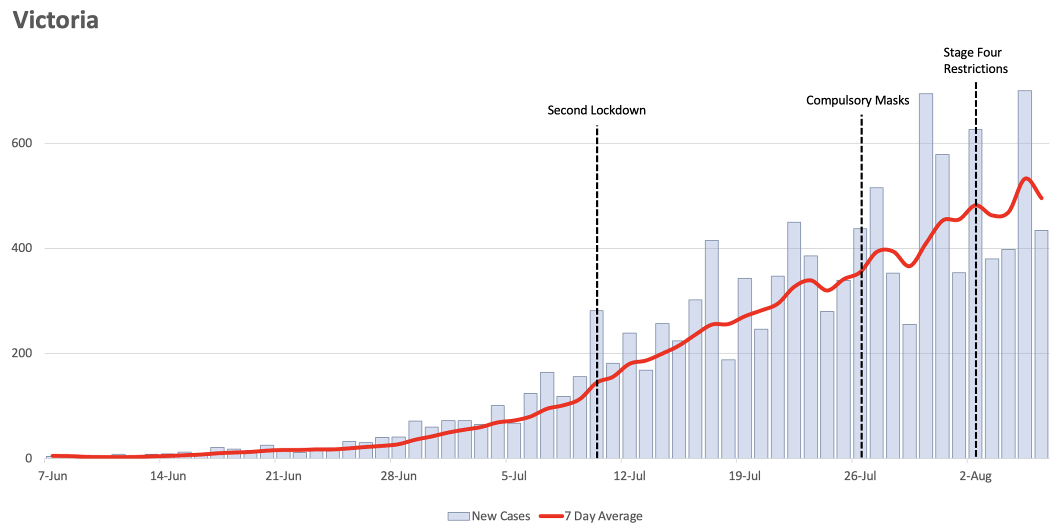

Figure 2: Example news infographic examining the impact of various health measures on COVID-19 case numbers. Note the text labels and strong design aesthetic.

1 INTRODUCTION

Data visualisations are increasingly used by journalists and others as an integral part of online stories about data [17, 68]. They allow readers to independently understand trends and patterns in the data and verify the journalist's message [12]. Sometimes called (news) infographics, such visualisations (e.g. Figure 2) are distinguished from the more traditional visualisations used for data exploration by an underlying narrative and a stronger design aesthetic. They are carefully crafted to be easily understood and to appeal to their intended audience – usually the general public. If you are blind or have low vision (BLV), however, access to online infographics is problematic [50]. For instance, the BLV community has identified a lack of access to online data visualisations about COVID-19 as a significant concern [19, 34].

Accessibility guidelines by W3C [64] recommend that online graphics include an alternative text description that BLV readers can access using a screen reader or braille display. However, this description necessarily summarises the underlying data, limiting the opportunity for independent analysis. Sonification, a non-speech audio presentation of data, could arguably provide a better approach to presenting online graphics. Audio is readily embedded in online web pages, presenting all of the data in a way that allows the listener to independently identify high-level patterns or anomalies [37]. This is the approach we investigate here.

Sonifications have, however, been criticised for being challenging to understand [63], aesthetically unappealing [3], and having interfaces that are difficult to use [44]. This is because most sonifications for BLV access to data are designed to support data exploration by expert users. They are purely utilitarian: they employ standard tones and aesthetic appeal and ease of use by non-expert users are not design considerations. Such utilitarian sonification is used in data exploration tools for BLV people such as the SAS Graphics Accelerator[1] or accessible graphing calculators, e.g. [1].

We explore how to present infographics to a general BLV audience using enhanced sonifications that are designed to be easy to access and understand as well as aesthetically pleasing. **We call these *infosonics*, as they are the audio analogue of an infographic**.[2] As illustrated in Figure 1, infosonics are distinguished from traditional utilitarian sonifications by their attention to aesthetics, an introduction that uses speech and non-speech audio to explain how to interpret the sonifications, an annotation track that can be played in parallel with the sonifications and uses speech to provide more information and potentially highlight points of interest (equivalent to the text labels in Figure 2) as well as a simple and easy to use interface that is accessed with standard web browsers. **Our primary contribution is to investigate the effectiveness of infosonics as a method for presenting online infographics to BLV readers**. We conducted a controlled user study with 18 BLV participants evaluating an infosonic of COVID-19 daily data compared with a more traditional sonification and a text description, i.e. written text that gives the title, type of chart, axes, overall trend, annotations and key data points. Our main contributions are:

- Introduction of infosonics as a new and distinct style of sonification for BLV listeners that employs a mix of non-speech and speech audio, and aesthetically pleasing sound design to present an engaging data-driven narrative;
- Empirical evidence that BLV people prefer infosonics to more traditional utilitarian sonifications, and find that they are more understandable and lead to a clearer mental image;

[1] https://support.sas.com/software/products/graphics-accelerator
[2] We note that Twedt [58, 59] uses the term infosonic in a slightly different sense to refer to her musical compositions inspired by climate change data. Unlike our infosonics, these are designed for sighted listeners and are augmented with visual images and text rather than speech.

- First comparison of sonification based presentations with text descriptions. This has clarified the complementary benefits of infosonics and text descriptions.

Our research suggests that infosonics have the potential to significantly improve access by BLV people to online infographics and that they provide complementary benefits to text descriptions. More broadly, we believe our work addresses barriers that currently restrict the wider use of sonification by BLV people by introducing a new style of sonification that is more engaging as well as easier to use and understand than traditional more utilitarian sonifications.

2 RELATED WORK

2.1 Data Visualisation

Online news articles increasingly use a mix of text, information graphics and video to create a multimodal, often interactive, reading experience [17, 61, 68]. A new subclass of journalism, data journalism or data storytelling, has emerged. Data journalists build stories based on data, using a mix of text and graphics (often called news infographics [17]) to explain their findings and to engage the reader [62]. A textual annotation layer with explanations and descriptions is often included to ensure that the graphic can be easily understood by a broad audience [18]. Text and other annotations are also used to clarify and emphasise the intended message. The most common infographics in data journalism are maps, charts and graphs (bar, line, and pie charts) and pictures with numbers and pictograms. If they provide interaction, it is mainly for inspecting a data value, navigation on a map, or for filtering data [36, 54, 70].

The use of visualisations in data storytelling contrasts to their use in more traditional data visualisation. Traditional data visualisation supports data exploration. Here the graphics do not come with a message: it is up to the viewer to analyse and explore the data and come to their own conclusions. Furthermore, in visual data storytelling there is a strong focus on aesthetics: the graphics are designed to be "beautiful in the sense of being attractive, intriguing and even aesthetically pleasing" [12].

To date there has been little consideration of how online data stories and, in particular, news infographics can be accessed by BLV readers.

2.2 Information Access by BLV People

Accessibility guidelines by W3C [64] recommend that online graphics should be accompanied by an alternative (alt) text description that BLV readers can access using a screen reader or braille display. In addition to alt text, longer text descriptions are used to provide information about graphics in textbooks [51], to supplement tactile graphics in textbooks [48], and in the theater [33], movies or television [46], galleries [4] and museums [2]. There is often a tension between providing an objective description versus a more subjective description that may be more engaging but less trustworthy. Moreover, for larger data sets a text description must necessarily summarise, leaving out potentially important information. As such, alt text descriptions of graphs are often inadequate for readers to gain a full understanding [20] or independently draw their own conclusions. Consequently, we believe that while descriptions providing an introduction and overview are a necessary component for accessibility, they should be complemented by accessible formats that provide equivalent information to the graphic whenever possible [49].

Raised line drawings called tactile graphics are recommended for the presentation of spatial and graphical information [8]. Active haptic exploration of a tactile graphic allows a touch reader to understand its spatial layout and draw their own conclusions. However, tactile graphics can be expensive to print and require special equipment, making them impractical for the presentation of ephemeral online graphics.

Sonification presents a third approach. Sonification uses non-speech audio to convey data for the purposes of communication or interpretation [37]. We believe that sonification in conjunction with speech provides a better approach than either a stand alone text description or a tactile graphic for providing access to online infographics. Unlike tactile graphics, sonifications can be readily accessed by providing an audio file on the web page as a graphic alternative and do not require special purpose hardware for viewing. Unlike a text description, they can present the complete data set and so allow for independent interpretation.

2.3 Sonification

There has been considerable research into sonification. Sonifications such as heart-rate monitors are used to present data in environments when the user needs to focus their visual attention on their surroundings [23]. Sonification can also be used as a data exploration tool by scientists as an alternative to, or in conjunction with, data visualisation [37]. It has the power to uncover patterns and anomalies that are masked in visual displays [37]. For example, we are very sensitive to a sound's temporal characteristics and can readily detect small changes in the temporal characteristics of audio signals [37], which is why the Geiger counter is so effective [60]. We are able to monitor and process multiple auditory data sets in parallel and sounds can incite high engagement and an emotional response [37]. However, sound must be presented sequentially, with processing relying on memory and its constraints [37].

An early study found that sonification of a line chart using a continuous pitch scale had similar performance to tactile line charts [42]. This study used a mix of sighted and BLV participants. In a series of studies with sighted participants, Flowers and colleagues [25–27] found that sonifications of data distributions, time-series plots and scatter plots give comparable information to the corresponding visual graphic, including the ability to see overall trends.

Further research has confirmed that BLV participants can understand sonified line graphs of one [9] and two data series [10] and that adding sonification to a speech interface for a data table improves performance [9, 35]. Based on these studies, Brown et al. [11] presented guidelines for sonification of line graphs and tables for BLV readers. These include: map the y-axis of graphs to the pitch of musical notes and the x-axis to time; use musical sounds rather than pure sine waves; place data points between 50-70ms apart; only use MIDI notes within the range 35-100; and use stereo panning to separate data series.

Early sonifications present only the data. More recently there has been investigation of how to add contextual information such as the scale data along one axis, e.g. [43, 52]. However, the presentation of more complex contextual information has received much less attention.

The main application of sonification for BLV people has been for mathematics education, including its use as an output for accessible graphing calculators, e.g. [1, 14, 29, 30, 55]. Other research on data sonification for BLV people includes sonification of infrared spectrographic data for BLV chemists [41], sonification of spatial data [71, 72] including weather maps [13, 39] and the use of 3D sonification to show a virtual map for orientation and mobility training [32]. All of these specialised applications require significant investment on behalf of the BLV user: they must download the software, learn a complex software interface and then learn how to interpret that particular sonification.

A number of researchers have investigated perceptual congruence between sonification encodings such as pitch, tempo, volume and roughness and the data values they represent, e.g. [21, 22]. In particular, Walker and colleagues [65, 66] investigated BLV listeners' perception of scale and polarity for audio line graphs using pitch (frequency) and tempo. While generally similar to those of sighted listeners, the differences demonstrated the need to evaluate sonifications with BLV participants when they are the intended audience.

A general pattern of the research into BLV people's use of sonification has been a focus on functionality, e.g. does it allow the listener to understand the data? While this is clearly important, there has been little consideration of user engagement or pleasure. For instance, BLV participants criticised the sonifications used in vOICe [3] as not engaging, aesthetically pleasing or easy to understand [31].

In contrast, Ben-tal and Berger [6] argue for more "musical sonification" when discussing sonifications designed for a general audience, and Bonet et al. [7] warn that sonifications risk being unpleasant or unintelligible if not aesthetically sound. Studies have found that people find music less fatiguing than test tones and more aesthetic sonifications have been shown to deepen engagement [69]. As a consequence, the sonification community has begun to investigate the aesthetics of sonification [5], 'aesthetic' data sonifications [40, 63] and 'musifications' [7, 69] in which data forms the inspiration for a musical piece, e.g. [47].

Thus, while sonification is used by the BLV community as an audio analogue to data visualisations, the focus has been on data exploration by subject matter experts or students, not on providing access to infographics by the general BLV community. As a consequence, the BLV community has focused on utilitarian sonifications. However, for a general BLV audience, this may not be the best choice. There seems considerable scope to increase understandability and engagement by incorporating speech and using more aesthetic sonifications. We also agree with Nees [44] that many current sonification tools have complex interfaces designed for expert users. Furthermore they may require installation of software. Thus they are not suited to casual users seeking entertainment or news and so there also seems considerable scope to explore simpler, easier to use interfaces.

3 INFOSONICS

Our research was motivated by preliminary findings that sonification is of interest to BLV adults but that most have not encountered it [34]. We wished to provide an audio equivalent to a news infographic: a sonification that could be readily understood and accessed by the general BLV community and which was aesthetically appealing. The considerations detailed above led us to devise what we call an *infosonic*. This has the following components:

- **Sonification** of data sets, each in its own track. Aesthetics should be considered so as to increase listener engagement.
- An **introduction track** using speech synthesis and short samples from the sonification to describe the data and provide the listener with an understanding of the audio encoding and scale. This is designed to improve understandability by a general audience.
- An **annotation track** using speech synthesis to indicate points of interest in the data sets, intended to be heard in parallel with the sonification tracks. This is the audio equivalent of the text annotations in Figure 2.
- A **simple interface** to enable casual use by a general BLV audience. Infosonics should be accessible with a standard web browser and have basic, easy to understand user interactions. These should allow the listener to start, pause or stop playback, choose which tracks (information layers) to play (similar to filtering in an infographics), and control the speed of playback without affecting pitch.

3.1 Example Infosonic: COVID-19

As an example we created an infosonic using COVID-19 data. This data was chosen because it was of immediate relevance to participants, it is an example of a prevalent visualisation with data that changes daily, and BLV access to COVID-19 visualisations has been limited [34]. Furthermore, the data's real world significance potentially makes representations more engaging and allows exploration of design aesthetics for emotional impact. Data for COVID-19 cases was obtained from 'COVID-19 in Australia Real-Time Report' web site at https://covid-19-au.com/. We used daily cases confirmed, recovered and deaths from March 4 to September 6 2020. This data and associated events are illustrated as an infographic in Figure 3.

Musical Instrument Digital Interface (MIDI) files for each data set were generated – a standard protocol that allows data to be used to trigger virtual musical instruments – with values scaled to fit within the MIDI note range of 33-96, in accordance with [11]. These MIDI files were imported into Ableton Live – a professional Digital Audio Workstation – where the MIDI files were assigned to different virtual instruments, pitch ranges and musical scales.

The sonification was created by one of the researchers who is an accomplished composer and sound designer. The following aesthetic decisions were made:

- For new confirmed cases and recoveries, each MIDI note was assigned a pitch correlated to the number per day, with the MIDI note length of one beat for each day, sustained for the entire beat. Higher notes indicate more cases. This use of pitch to indicate data value is the most common approach used in sonification [45].

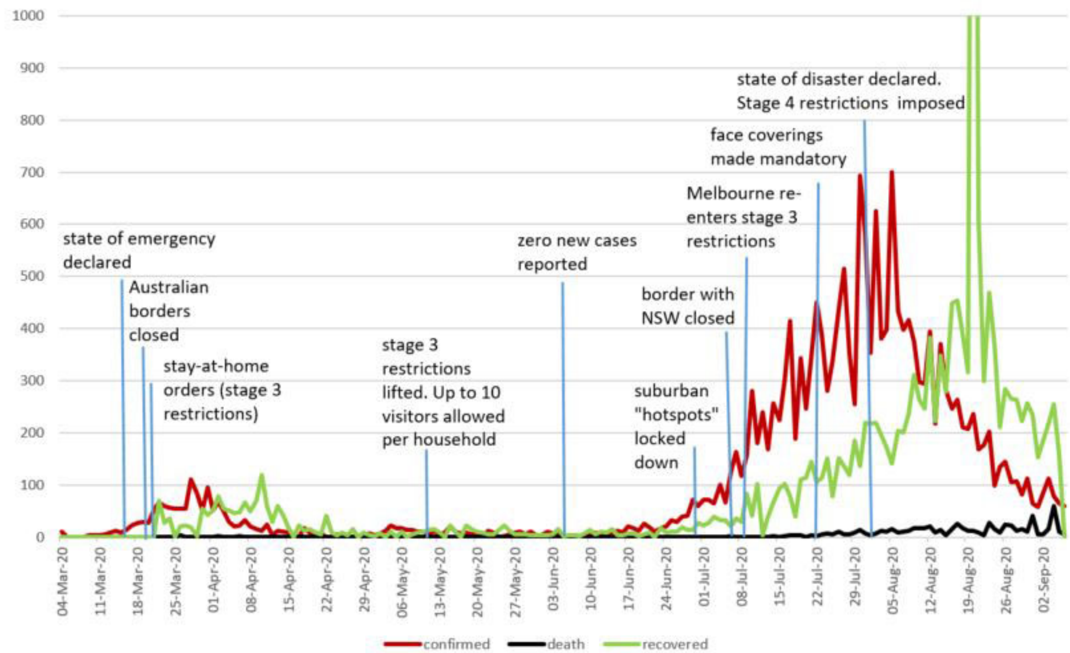

Figure 3: Infographic corresponding to the COVID-19 infosonic

- Confirmed cases were assigned to an ominous synth sound, panned hard left, and the recovered cases were assigned to a synthesised harp sound, panned hard right. This panning was chosen to give a clear separation when listening with headphones and accords with Brown et al.'s guidelines [11];
- A 'C' Dorian scale was chosen to make the ascending and descending passages more pleasant, compromising some of the finer data points to avoid a more dissonant chromatic mapping [11];
- A number of tempos were trialled. Brown et al.'s recommendation [11] of one beat per 50-70ms brought chaotic results. While it communicated a sense of urgency, clarity was lost at the time of peak deaths. A slower tempo was also required for the sonification to align with the annotation track. We settled on a much slower tempo, with data points 333ms apart.
- The slower tempo allowed us to experiment with ways of sonifying daily deaths, which were far fewer in number than confirmed cases and recoveries. Each death was represented by a a short C sine tone reminiscent of the flat-lining of a ECG monitor, with the number of tones in a given day correlating to the amount of deaths, turning this data set into a rhythm. This allowed us to present three different data sets at once.

The introduction track gives the graph title and explains the sounds, positions and their meaning, with audio samples to illustrate different values:

> COVID-19 in Victoria. In the left ear, each beat is a day and the pitch goes up in proportion to the total confirmed daily cases of COVID-19. For example: Zero cases [low beat in left speaker]. First peak, 111 cases [higher beat in left speaker]. Second peak, 700 cases [high beat in left speaker.] In the right ear, same mapping is used for recovered cases of COVID-19. In both ears, each bleep [bleep] represents a death from COVID-19. We start from March 4th, 2020.

It uses a synthetic voice that moves to the left, right or centre speaker according to the audio track being described. The annotation track speaks the date and event at the relevant point in the audio, beginning with 'March 16th state of emergency declared'.

The infosonic was embedded in a web page. The simple, accessible controls are shown in Figure 4, with keyboard shortcuts indicated in brackets. The controls provided buttons to play the infosonic with or without the introduction track, skip forward or backwards, adjust the playback rate, and select the information layers (tracks).

We strongly encourage the reader to listen to the infosonic in the supplementary materials.

4 USER STUDY METHODOLOGY

A user study was conducted to evaluate the value of infosonics. The study was designed to provide a controlled comparison of an infosonic with a text description and with a more utilitarian sonification based on existing guidelines. In particular, we were interested in evaluating: (1) whether adding audio labels in an annotation track and making aesthetics driven sound design decisions would increase engagement and understandability of sonifications; and (2) how infosonics/sonifications compare with a text description in terms of providing access to an infographic.

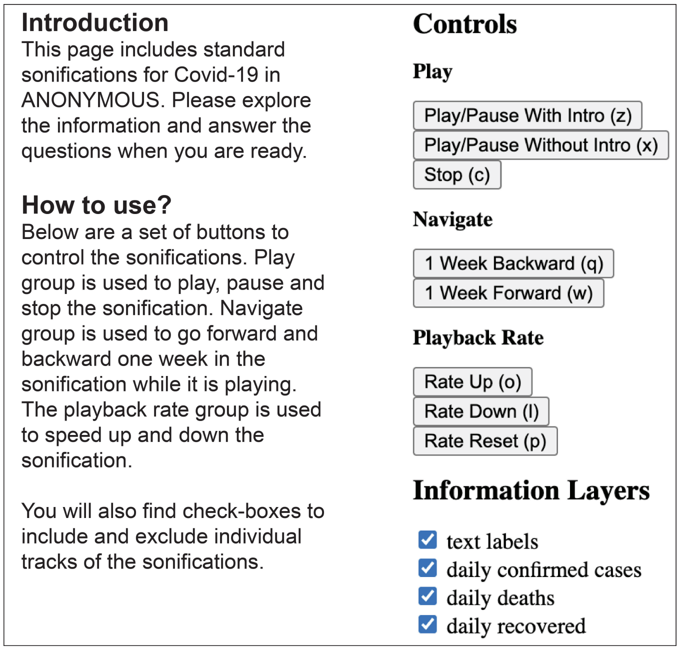

Figure 4: Introductory text and controls given on the web page to present the COVID-19 infosonic

4.1 Materials

We used the COVID-19 infosonic described in the previous section. For comparison with the infosonic, we created a text description and a more utilitarian sonification based on existing guidelines. All materials are available for inspection as supplementary material with this paper.

The text description was written by an experienced accessible formats transcriber. It was designed to give the same information as the infosonic and the infographic shown in Figure 3. The text began with a description of the topic then a description of the trends and key turning point figures for confirmed cases, deaths and recoveries. This was followed by a list of the key events with exact dates. The description of trends was the main way in which the text description differed from the audio's spoken introduction and annotation track. The text description was presented on the web page as text with structured headings so that it could be easily read and navigated using screen reading software or a refreshable braille display.

Distinct from the infosonic described in 3.1, a more standard sonification was created from the same MIDI files. Its design was based on Brown et al.'s guidelines [11]. The only recommendation we did not adopt was that of having only two sounds, one in each ear. We instead allowed the listener to have all three elements playing, i.e. confirmed cases on the left, recovered cases on the right, and deaths (as a pitch, not rhythm) in the middle. We did this to allow a fairer comparison with the infosonic.

Although not part of sonification guidelines, an audio introduction explaining the data set and sounds used was also given at the beginning of the sonification to ensure a fair comparison with the infosonic, as we were primarily interested in understanding the impact of the sound design decisions and speech annotation track.

All materials were presented on an online web site with one page per presentation format. The pages were designed for accessibility and ease of use by non-experts, with structured headings for navigation and labelled controls with keyboard shortcuts for the sonification and infosonic. These had identical controls as shown in Figure 4. Both audio pages included a short text description about the use of controls.

4.2 Participants

Recruitment was conducted through a BLV research study pool and social media. Eighteen people took part – 14 women and four men aged from 26 to 76 years ($\overline{x} = 49$, sd=16). Fourteen were totally blind and the remaining four were legally blind, including three who were able to access print at a very enlarged font at close distance. The onset of vision loss was birth for 11 of the participants, childhood for four, and adulthood for three. Three of the participants also suffered from mild hearing loss in one ear, corrected with hearing aids. All confirmed they were able to adequately hear the samples. Participant profiles are given in Appendix A.

In general, the participants had a good level of computer literacy. Three considered themselves early adopters of new technology, ten were up-to-date and five said that they needed support or encouragement to learn new technology. The participants all reside in Australia.

Fifteen participants took part in the study in September 2020 when the data was current, followed by a further three participants to increase the sample size in August 2021. The majority already knew 'a lot' (n=8) or 'a moderate amount' (n=9) about COVID-19 infections in Victoria before the commencement of the study. They mentioned high press coverage, daily government press conferences and a popular podcast as common sources of information. Only four of the 18 participants had a medium or high level of prior exposure to sonifications.

4.3 Procedure

Participants were randomly assigned to one of three groups, each with a different order for presentation of the three formats. This counterbalancing was designed to combat effects of learning and/or fatigue. Additionally, the three participants with enough vision to access enlarged print were placed in separate groups.

Sessions were conducted remotely via video conferencing over a 30-90 minute session that was recorded. As illustrated in Figure 5, participants explored the material on each web page freely, sharing their screens and audio so that the researchers could observe their use of the controls, choice of settings and time spent.

Participants were asked to confirm that they could adequately hear the audio samples in the introduction tracks before proceeding. Immediately after listening to the first format, participants were asked to describe the information and overall trends to encourage them to interrogate the samples for this information. After each each format had been explored they were also asked: Did you learn anything new? How engaging was the presentation? How easy was it to understand? and How easy was it to picture the flow of data in your mind?

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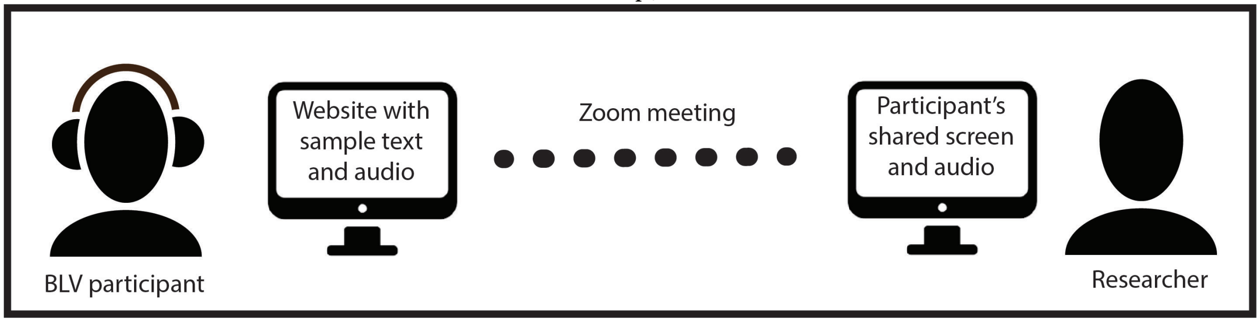

Figure 5: Experimental setup, with the participant accessing the materials online while the researcher observes their screen and audio over Zoom.

After exploring all three presentations, participants were asked to rank them in order of preference. Finally, they were asked further detailed questions about the infosonic: Was the infosonic easy to use? What controls would you like to use when listening to infosonics? Was the introduction useful? Were the text labels useful (the annotation track)? Do you have any suggestions about how the infosonic could be made easier to understand or more pleasant to listen to? Would you like to access the individual data values and if so, how? Would you like to use infosonics to access other information and if so, what? Where and how would you like to access infosonics? Would you recommend infosonics to a friend who is BLV? and Do you have any further comments?

4.4 Analysis

We present p-values in our statistical analysis but, as advocated by the American Statistical Association [67] and others [56], we do not use this as evidence for significance. Instead, we describe the trends.

Dialogue and emotional reactions (smiles and laughs) were transcribed in full, coded under the categories of engagement, aesthetics, understanding and mental imagery, and rated as positive, neutral or negative. Two researchers each coded the full set of comments then discussed and resolved any differences.

5 RESULTS

5.1 Exploration Time

Participants were instructed to play each format as many times as they wanted. This differed markedly according to format (Friedman test $\chi^2(2) = 19.69$, p<.001). Participants chose to play the sonification the most times ($\overline{x} = 3.72$, sd=2.78), followed by the infosonic ($\overline{x} = 2.56$, sd=1.29) and then the text description ($\overline{x} = 1.44$, sd=0.62). This may be an indicator of ease of understanding but is also likely to reflect other factors such as engagement (a more interesting presentation will be accessed more times) and time required to access (a shorter presentation requires less investment to play again).

Accessing audio was much more time consuming than the text description (Friedman test $\chi^2(2) = 18.03$, p<.001). Time spent exploring the web page, controls and audio was longest for the infosonic ($\overline{x} = 7.33$ min, sd=3.61) and sonification ($\overline{x} = 5.64$ min, sd=3.37). Reading the text description, usually with a screen reader on high speed, was much faster ($\overline{x} = 2.28$ min, sd=1.49).

5.2 Engagement

As shown in Figure 6(a) there was no clear pattern in terms of self-rated engagement, apart from the sonification being the only format given a 'low' rating (Friedman test $\chi^2(2) = 2.23, p = .328$). This surprised us as we believed that participants would find the infosonic to be more engaging than the other formats because of the deliberate sound design decisions.

However, the level of engagement was also revealed through comments and emotional reactions, as shown in Table 1. Engagement statements were most common for the infosonic (53 comments) and generally more positive (94%), with comments such as "I nearly got up and danced" [P15], "It sounds/sounded like a horror movie" [P13, P18], "theatrical" [P1] and "dramatic" [P12].

Engagement comments relating to the sonification (25 comments) were either positive (68%) or reflected difficulty in understanding, for example it was described as "cool" [P13, P18], "interesting" [P7, P12, P16] and "weird" [P6, P11].

Far fewer emotional responses were elicited by the text description (12 comments), including statements such as "it's just text" [P10], "not really entertaining" [P18] and "there's no emotion to it" [P12].

Similarly, comments relating to aesthetics were more positive for the infosonic (72%) than the sonification (40%) and there was no discussion of the text description in terms of aesthetics (Table 1).

Furthermore, seven participants drew parallels between the infosonics or sonifications and other media or tools they had used, mainly relating to entertainment. They spoke about listening to: Disney's Fantasia with audio narration, in which each character is represented by a different instrument; the Virtual Barber Shop [38]; 3D audio games; Travelear app with binaural recordings of travel experiences [57]; and SoundScape, a GPS app with binaural audio directions [15]. Again, these hint at a higher level of engagement with the audio formats than the text.

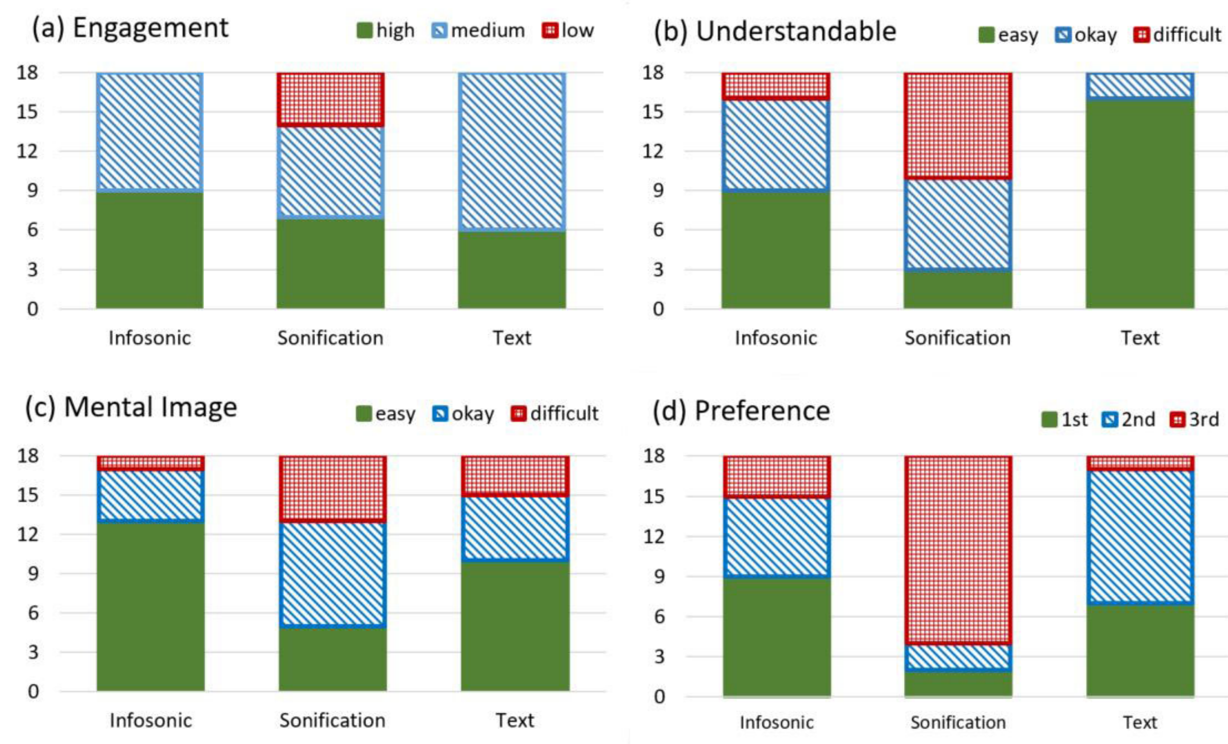

Figure 6: Responses to the questions (a) 'how engaging was the presentation?', (b) 'how easy was it to understand?', (c) 'how easy was it to picture the flow of data in your mind?' and (d) preference rankings ratings for the three formats (n=15)

Table 1: Positive comments as a proportion of all comments relating to engagement, aesthetics, understanding and mental imagery for the three formats.

Format	Engagement	Aesthetics	Understanding	Mental Imagery
Infosonic	50/53 = 94%	13/18 = 72%	37/74 = 50%	16/16 = 100%
Sonification	17/25 = 68%	4/10 = 40%	9/53 = 17%	9/9 = 100%
Description	3/12 = 25%	0/0	24/36 = 67%	4/8 = 50%

5.3 Understanding the Data and Building a Mental Image

Responses to the question 'how easy was it to understand?' were most positive for the text description, followed by the infosonic and sonification, as seen in Figure 6(b). Beyond an overall difference between groups (Friedman test $\chi^2(2) = 17.76, p < .001$), there was clearly a better understanding gained using the text description compared with the infosonic (Wilcoxon signed ranks $z = 2.310, p = .021$), and the infosonic in turn was more understandable than the sonification ($z = 2.66, p = .030$). Similarly, as seen in Table 1, participant comments relating to understanding were most positive for the text description (67%), followed by the infosonic (50%), and were poor for the sonification (17%). It was suggested that the infosonic was easier to understand than the sonification thanks to the text annotation track and because the beats for deaths were very distinct. Participants who struggled to gain an understanding from the infosonic reported feeling overwhelmed by too much information at once. Accordingly, seven of the participants used the controls to turn some tracks off after their first hearing of the infosonic.

Answers to the questions 'did you learn anything new?' gave further insight into understanding. Nine participants agreed that they had learnt something new after reading the text description, compared with only four for the sonification and three for the infosonic. This perhaps reflects the level of detail provided by each format, with precise numbers given in the text description but not in the sonification or infosonic.

However, we also found that participants were overly trusting in the accuracy and objectivity of the text description, which they described as 'factual'.

> " I trust what I read more than what I am hearing or imagining. Words have a higher truth." [P6]

In fact, the text description is a subjective interpretation by a transcriber or an automated process. The writer must choose what to focus on. In our example, the description uses the term 'erratic', which is open to interpretation, and generalises dates such as 'mid April'. By contrast, a sonification that directly relays all of the data allows a skilled listener to draw their own conclusions.

Mental imagery (as evidenced by the answer to 'how easy was it to picture the flow of data in your mind?') provides some evidence for the value of infosonics. Participants were most easily able to build a mental image of the data using the infosonic, as seen in Figure 6(c). There was an overall difference between formats (Friedman test $\chi^2 = 8.318, p = .016$) with the infosonic providing a mental image much better than the sonification (Wilcoxon signed ranks $z = 2.652, p = .008$) but not much better than text ($z = 1.155, p = .248$). Again, participant comments (Table 1) provide further support for this finding. All comments relating to mental imagery for the infosonic and sonification were positive, while only 50% of comments were positive for the text description.

> "I think the sounds gave it more of a picture as if I was looking at a graph" [P2]

5.4 Learning Effect

The order of presentation was counterbalanced across groups to mediate any learning effects, particularly given that the majority of participants had low or no prior experience with sonifications. Indeed, we did find that participants who listened to the infosonic last were more likely to rank the infosonic as their favourite format (n=4.5) than those who listened to the infosonic first (n=2), however the effect was mild (Mann-Whitney U=12.00, p=0.297). Some participants who listened to the infosonic first reported feeling overwhelmed by it, but were more confident about what they were listening for by the time they were exposed to the sonification.

5.5 Preferred Format Overall

After listening to all three formats, participants were asked to rank them in order of preference. Two people ranked both the infosonic and text description as equal first; their responses were entered as equal first for one person and equal second for the other. As seen in Figure 6(d), the text description and infosonic were more favoured overall, while the sonification was most often ranked third. There was an overall difference in rankings (Friedman test $\chi^2(2) = 12.343, p = .002$), with negligible difference between the infosonic and text description (Wilcoxon signed ranks $z = .000, p = 1.00$) but a preference for the infosonic over the sonification ($z = 2.424, p = .015$).

Examination of the data failed to reveal any factors, such as age or prior experience with sonification, related to preference or performance with the infosonic.

Sixteen of the 18 participants stated that they would recommend infosonics to a friend who is blind or has low vision. Most participants were also able to give examples of when they would like to use infosonics themselves, such as accessing news-related graphics, statistics, workplace metrics and study materials.

5.6 Interface

The audio controls were generally easy to use and considered useful. All participants agreed that the play/pause buttons and the tracks on/off controls were needed. Thirteen used the 'play without intro' button after listening to the introduction at least once, and ten of the participants turned audio tracks off and on.

> "I really liked that you could isolate. Doing that did help. I was looking at different combinations." [P3]

The speed controls were also wanted by 12 participants and skip forward/back controls were wanted by 11. However, the four people who used the skip control only did so once and said that an audio announcement is needed to identify the new position. Six people used 'rate down' to decrease the speed of the audio, compared with only person who used the 'rate up' control.

5.7 Introduction and Annotation Track

All participants agreed that both the introductory text and the annotation track were useful when listening to the infosonic.

> "You have to have that [introduction]" [P14];

Of interest is that the annotation track was not only important for providing context and detail of the data, but also for supporting the listener in understanding where they were in the infosonic.

> "I need that anchor point [provided by the text labels]" [P13];
> "It gave me a sense of where we were" [P3].

On average, they listened to the introductory text 1.6 times and only one person turned off the annotation track.

6 DISCUSSION

6.1 The Value of Sonifications and Infosonics

Our results show that the infosonic is preferred to the traditional sonification, that it is easier to build a mental image from it and also suggest that it is more understandable. However, there is no clear advantage of the infosonic over the text apart from comments revealing more engagement with the infosonic. In terms of preferences, the two had similar rankings and text was found to be more understandable.

We conjecture that this pattern of responses reveals a difference between the listener being given an interpretation of the data in the text description, which is easier to understand, and the listener needing to build their own high-level understanding of the data based on a mental model with the sonification and infosonic, which is more demanding. However, it is only with the sonification or infosonic that it is possible for the listener to independently look for patterns or anomalies in the data. This suggests that a text description may be best for an initial or cursory understanding while sonification allows a deeper more independent understanding and is better for building a mental image of the data trends.

This conjecture is supported by participant comments. The two participants who ranked infosonic and text equal first, explained that they considered the two formats to be best for different purposes: the text for accessing the information and the infosonic for gaining an equivalent to a visual impression of the graph. Another participant stated that the different formats served different purposes:

> "If you just want an overall picture, the sonic is really good but ... having some text was helpful" [P3]

And some participants reported having used the information from the previous format to assist in their understanding of the next.

> "The different kinds of information [formats] are coming together to help me understand a bit more about the graph." [P3]

Our results therefore strongly suggest providing both a text description and a infosonic as these provide complementary benefits. It is not the case that one accessible format is best, but rather that a range of formats provide choices for optimal access depending on context and preference or learning style. Indeed, four participants (P1, P2, P4, P18) mentioned tactile graphics as a preferred or accompanying format if available.

6.2 Infosonic Design Reflection

The infosonic incorporated a number of design features intended to allow a general BLV audience to better understand and explore sonifications. We now refine this design based on the results and participant suggestions for improvement.

6.2.1 Interface. Although not used by all participants, the controls were wanted by the great majority. Our interface was deliberately designed for simplicity and ease of use, and we were pleased to find that usability issues did not prevent our BLV participants from fully accessing or exploring our infosonics. The option to turn tracks on and off was the main strategy that participants used to interrogate the data and improve their understanding. The interface could be improved in a number of regards:

- Participants requested that after skipping forward or back they be given the date of the new position. Give specific data when the track is paused and give the date after skipping forward or back.
- They also requested the ability to adjust the synthetic speech rate separately to the speed of the playback. The default speech rate was very slow for most synthetic speech users and when the audio was slowed down, the slower speech was distracting.
- The interface did not allow the user to interactively inspect the value of a specific data point (an interaction frequently provided in online infographics). We suggest that the value of the current data point be read out when playback is paused.
- If there are multiple tracks, turn off the least important tracks by default so that the listener is not overwhelmed (as some of our participants were) when they first listen to the infosonic.

6.2.2 Introduction and Annotation. The use of a spoken introduction with audio key and an audio annotation track received universal approval, with some participants saying that the audio would not make any sense without them.

A text-based introduction to a sonification is analogous to an audio introduction to describe theatre [28] or static state descriptions for interactives [53]. The introduction can be provided in writing, however audio allows the various sounds and aural positions to be demonstrated for greater clarity. If a key has been provided for a print graphic, then it is likely that an introduction will be required for the corresponding sonification.

Some participants suggested announcing the start of every week or month in the annotation track to give a regular indicator of time. More investigation is required to see if speech or non-speech indicators are better [43].

6.2.3 Sonifications. We did not explicitly ask participants their opinion of the aesthetic design choices made in the infosonic. Our study found some evidence that more aesthetic sonifications lead to increased engagement but further studies are required to investigate this.

Some participants found it was too difficult to tell the difference between new cases in the left ear and recoveries in the right ear because they used similar sounds. On reflection, it is important to design for people with some hearing loss and so each track or type of information should be represented by a very different sound.

6.3 Limitations and Future Work

As this study was the first introduction of infosonics, it was exploratory in nature with an emphasis on self-reported data to allow unexpected observations to raised by the BLV participants. There is now potential for future studies that could measure engagement and understanding using more standard rubrics and focus on specific issues, as suggested below.

There was a tendency for our participants, who had little prior exposure to sonifications, to better prefer the infosonic if they had already listened to the sonification. It would be useful to know how easily people are able to learn to interpret infosonics and to compare the performance of novices with experts.

While our infosonic was designed in collaboration with a musician to enhance both audio clarity and aesthetics, much more could be done in this realm. The use of harmonious notes, played on pleasant instruments, and sampling of musical scores or audio snippets, can all potentially increase enjoyment and engagement for listeners of sonification. More research is required to seek a ideal balance between musification, engagement and understandability. Similarly, further work is required to determine whether more than tracks can be added without compromising understanding and overwhelming the listener.

Arguably, the most important direction for future research is to investigate how to automate or semi-automate the production of infosonics. Clearly, if infosonics are to be used for news infographics that are updated regularly, such as COVID-19 data, then they must be able to be generated automatically. Descriptions may be the most difficult task for automation of infosonics, as the audio can be generated easily once the parameters for sonification are determined. Prior research has been conducted on automatically generating text descriptions of simple online statistical graphics such as bar or line charts [16, 24]. In order to make the sonifications aesthetically pleasing and as easy as possible to understand, it may be necessary to have a human first create an infosonic 'template' that can then be used to automatically generate the infosonic from a known data stream.

7 CONCLUSION

We introduced the infosonic, a new style of sonification that is the audio equivalent of an infographic. It augments aesthetic sonifications with an introductory text and a speech annotation track, and supports simple, user-friendly interaction.

We compared an infosonic of COVID-19 infections with a traditional more utilitarian sonification and text description in a controlled study with 18 blind participants. The infosonic was easier to understand and better for forming a mental image than the sonification and while self-reported engagement did not differ, a higher level was demonstrated through their comments and reactions to the infosonic. Participants ranked the infosonic and textual descriptions equally. Our results indicated that they provided complementary benefits: text was easier to understand while the infosonic allowed independent judgement and tended to be more engaging.

We are confident that, when paired with text descriptions, infosonics can significantly improve access by BLV people to online infographics such as those employed to chart COVID-19 infections. More broadly, we believe our work addresses barriers that currently restrict the use of sonification by the broader BLV community by providing a model for sonification that is more engaging as well as easier to understand and use than the traditional utilitarian sonifications that are currently employed in tools designed for BLV users such as accessible calculators.

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A PARTICIPANT PROFILES

Table 2: Participant profiles

Particpant	Infosonic order	Mild hearing loss	Exposure to sonification	Onset of vision loss	Uses enlarged print
P1	1	none	medium	birth	no
P2	1	right ear	low or no	child	no
P3	1	none	low or no	birth	no
P4	1	none	medium	birth	no
P5	1	none	low or no	birth	yes
P6	1	none	low or no	birth	no
P7	2	none	low or no	birth	yes
P8	2	none	low or no	birth	no
P9	2	none	high	birth	no
P10	2	none	low or no	birth	no
P11	2	none	low or no	birth	no
P12	2	none	medium	child	no
P13	3	right ear	low or no	child	no
P14	3	none	low or no	birth	no
P15	3	none	low or no	adult	no
P16	3	none	low or no	adult	yes
P17	3	left ear	low or no	adult	no
P18	3	none	low or no	child	no