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Sonification of numerical data for education

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ABSTRACT
Sonification is the use of non-speech audio to convey information. In the context of this article, sonifications are non-speech, audio representations of plots or graphs which may be used to improve accessibility of teaching materials. The electronic nature of sonification files means that they can be deployed to users (students) via websites and teaching interfaces such as virtual learning environments. In this paper we describe a two-phase study that explores sonifications of data plots as a teaching tool in the context of distance learning in STEM. The overall objective of the combination of these two phases was to begin to assess the suitability of audio versions of graphs as a teaching tool for non-sighted and sighted students. The first phase acted as 'proof-of-concept'; the effectiveness of sonifications within a small group of participants who took part in study-like activities similar to those that might be encountered in a distance learning setting was explored. Here we found that even though sonifications were new to them, the participants were able to use them to gain impressions of the corresponding plots. The second phase deployed sonifications to all students enrolled on an Open University module. Although many of the students who chose to respond did so in a negative way, some found the sonifications were an interesting augmentation of the plot. Overall, we demonstrate that for a subset of students, information in a plot can be communicated using sonifications.

KEYWORDS
Accessibility; sonifications; mathematics; audio graphs

1. Introduction

The depiction of numerical data using graphs and charts play a vital part in many STEM courses. As Tufte (Tufte, 1983) says in a key text about the design of plots and charts "at their best graphics are instruments for reasoning about quantitative measurement". Visually displayed (often printed) graphs engage users – in the context of education, *students* – by inviting them to *look* at data and process the information visually. One of the underlying questions of our study is: can students engage with such plots by *listening* to 'sonifications' of them?

Sonifications of graphs are non-verbal, audio, representations of plots or graphs.

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They provide a method for users to *listen* to data, and to process the information within the graph *aurally*. The processing of sound into information can be witnessed in several aspects of science; for example, Morse code and Geiger counters both provide audio signals to the user, which are *translated into context-specific information*. Engineers, mechanics and technicians can often diagnose faults by *listening to the sound* of the equipment. In nature, we know that both bats and dolphins, for example, use echolocation to *translate sounds into information* about their surroundings and prey.

Sonifying data dates back to at least the 1980s (Bly, 1982; Yeung, 1980); Bly suggested using sound to represent data to allow the listener to try to distinguish differences between datasets. Sonifications of more traditional plots and graphs have been proposed; for example, scatterplots (Edwards, 2011; Flowers, Buhman, & Turnage, 1997; Zhao, Plaisant, Shneiderman, & Lazar, 2008); box plots (Edwards, 2011; Flowers & Hauer, 1993); histograms (Flowers & Hauer, 1992); pie charts (Franklin & Roberts, 2003); spatial data (Nasir & Roberts, 2007); graphs (Brown, Brewster, Ramloll, Burton, & Riedel, 2003); plots of mathematical functions (Grond, Drossard, & Hermann, 2010).

A sonification matches the different dimensions of the data displayed in a graph with different aspects of sound. These aspects include:

- when the note is sounded;
- the pitch of the note;
- the loudness of note;
- the timbre of the note; for example, whether it sounds like a plain note, or like an instrument such as a piano or a violin.

See, for example Frysinger (2005); Walker and Kramer (2005). It is important that the chosen options enable the listener to distinguish different values; to help with perception it is possible to map more than one aspect of sound to a dimension of the data.

The principles of sonification creation have been implemented by others. For example MathTrax (National Aeronautics and Space Administration, 2008), Sonification Sandbox (Georgia Institute of Technology, 2002), FLOE (Inclusive Design Research Centre, 2016) and SAS (SAS, 2017). In some cases the sonification has been designed to work well with data arising in one particular context or even just one dataset.

The implementation used in this project was written by one of the project team members, and takes the form of a suite of functions designed to work in the statistical package, R (The R Foundation, 2018). In these functions, positions along the horizontal (x) axis are generally translated into when the note is sounded; a point further along the horizontal axis has its corresponding note sounded later. Positions along the vertical (y) axis are generally translated into the pitch of the note: the higher a point a point is up the vertical axis, the higher the pitch. For the purposes of the study, all sonifications of graphs were produced in advance and presented to participants as MP3 files ('Human Computer Interaction' (Hunt & Hermann, 2004)). Users were not able to customise the sonifications (for example, change the duration) to meet their own preferences.

Although the motivation for sonification given by Bly was to simultaneously represent more dimensions of the data than can generally be represented visually, the application of this approach to accessibility for disabled people has been noted by others (for example, Edwards (2011); Lunney and Morrison (1990)). So sonifications of graphs can be viewed as an alternative format, and as assistive learning technology that can augment existing teaching materials, in a way that may also benefit learners who have no problem viewing plots and graphs.

1.1. Accessibility of graphs

In order to meet the The Open University's mission of being open to [*all*] people, its teaching materials need to be accessible to *all* students. The UK Equality Act 2010 (Equality and Human Rights Commission, 2010) requires universities to avoid discrimination against people with protected characteristics, including disability, and to do so by making reasonable adjustments. The Equality and Human Rights Commission offers guidance for Higher Education providers (Equality and Human Rights Commission, 2016b). The Act created the Public Sector Equality Duty (Equality and Human Rights Commission, 2016a), which requires universities to promote equality of opportunity by removing disadvantage and meet the needs of protected groups.

In the context of the The Open University (OU), this means that the authors of module materials should ensure that plots and charts (or alternative versions of them) are accessible to all students including those students with visual impairments and those with no vision at all.

Desirable features of an accessible graph include the following (Summers, Langston, Allison, & Cowley, 2012):

- Perceptual precision: the representation allows the user to interpret the plot with an appropriate amount of detail.
- First-hand access: the representation allows the user to directly interpret the data and is not reliant on subject interpretation by others (bias).
- Works on affordable, mainstream hardware.
- Born-accessible: the creator of the plot would not have to put extra effort into creating the accessible version.

The first two of these features aim to provide the user of an accessible graph with an *equally effective* alternative to a visually displayed graph. The representation should give the user a "true" visualisation of the data depicted, and the user should be able to form their own opinion about the data without it being mediated through another's (possibly subjective) view. The remaining two criteria are about the practicality of the solution: it does not require the user to have access to specialist equipment and that, as far as possible, it does not require the creator of the original plot to do any additional tasks to create the accessible alternate version.

Another important desirable feature, not given by Summers et al. (2012) is as follows.

- Is timely: it is available as and when the user needs it, and the representation allows the user to extract the information required on a time scale similar to users of the original graph.

The time required for an average sighted student to digest plots and figures is factored into the estimation of the student workload when teaching materials are designed. If the accessible alternative slows down the rate at which the information in a plot or graph can be assimilated, this could have a significant impact on the workload for students who rely upon them. It could also distort the flow of the material presented, thereby impeding learning.

Methods commonly used to accommodate learners who are blind or have low vision include:

(1) use of sighted assistants who can describe graphics verbally;
(2) provision of figure descriptions, which are text-based descriptions that can be read with text-to-speech applications (for example JAWS (Freedom Scientific Inc, 2018), Dolphin (Dolphin Computer Access Ltd., 2018), Chromevox Google (2017), NVDA NV Access (2018)); accessed as Braille, either as hard copy or via refreshable display;
(3) provision of tactile graphics for visual representations.

Some online graphing tools such as Desmos (Desmos Inc., 2018) can interact with screen readers such as, for example, ChromeVox to produce audio versions of graphs.

Figure descriptions mediate information through the author of the description; the creation of the description may be subjective, as 'important' features may be ambiguous. For example, whether a line connecting data sufficiently conforms to a mathematical shape and if so which one, or whether particular data points appear to be sufficiently different to the rest so as to be noteworthy. Care must be taken not to disrupt learning objectives; for example, an exercise which asks students to determine if points in a scatterplot appear to have a positive correlation must not reveal any correlation in the figure description.

To be effective, tactile graphics cannot simply be given to a person who is blind with the expectation that meaning-making will commence; rather, there tends to be a need to verify their existing knowledge and describe the tactile in a way that leverages existing understanding of the information being depicted (Parks, Dietrich, & Wadors, 2015). At that point the tactile graphics can increase understanding. Producing tactile graphics and making them available for the person who is meant to access them takes time; this means, in the case of a distance learning student, the tactile graphics potentially need to be created at one location, then sent by mail to another location, with communication throughout.

Tactile graphics, assuming that the user has the ability to sense through touch, allow both first-hand access and perceptual precision. Assuming that the *institution* is responsible for the financial investment of the embosser, then from the *user*'s perspective, tactile graphs work on mainstream hardware.

Sonifications, like figure descriptions, can be delivered electronically, and once produced do not require specialised equipment to access. Furthermore, as a representation of the graph, in principle they provide first-hand access to the data; as detailed in Hermann and Ritter (1999), 'an auditory stream can be "consumed" with comparable little effort'. The extent to which sonifications can deliver perceptual precision as a teaching resource is the focal point of the two-phase study underpinning this paper.

1.2. Outline of the two phases

The first phase (Section 2) presents a 'proof of concept' and explores the effectiveness of sonifications within a small group of participants who took part in study-like activities similar to those that might be encountered in a distance learning setting. These participants, all with an interest in mathematics and/or science included some sighted users, and some with visual impairments. This phase of the study was qualitative and exploratory in nature.

The second phase (Section 3) deployed sonifications to all students enrolled on an Open University module; this phase of the study was quantitative. The motivation for opening the study to all students was two-fold:

(1) the delivery of the sonification was via the module website, and it is standard

practice to make all formats available to all enrolled students;
(2) it was of interest whether sonifications could be valued by *all* students.

The second phase focuses on the *augmentation* part of the Substitution, Augmentation, Modification and Redefinition (SAMR) model of assistive learning technology detailed by Ahmed and Chao (2018):

> technology that uses sonification for [students with visual impairments] to hear graphs augments the teaching and learning, so that *all* students can utilize the auditory characteristics of a graph in their emerging understanding.

Furthermore, as detailed in Hermann and Ritter (1999), 'Data can thus be experienced in a new way, which bears the advantage of a deeper and possibly richer understanding of data structures'.

The intention of this paper is to summarise the results of this two-phase study and hence to begin to assess the suitability of audio versions of graphs as a teaching tool for non-sighted and sighted students.

2. Phase 1: 'proof of concept'

This phase of the study was designed to investigate first year undergraduates' perceptual precision and first-hand access of sonifications of plots and line graphs from STEM modules. In particular, we focused on materials in first-year undergraduate courses in mathematics or science – areas that make significant use of plots and line graphs in their teaching.

2.1. Methodology

Materials from four first-year undergraduate mathematics and science OU modules were examined for suitable plots; of particular interest were plots where it was felt that written descriptions of the plots might struggle to provide an adequate alternative for visually impaired students. A total of six such plots were identified and were developed into examples to be presented to the participants.

The general structure of each example was designed to mimic learning activities that include graphs or plots as an integral part; each example started by giving some context in which the plot or plots arose. Each plot already had a figure description and for the purposes of this study a tactile version was created.

A facilitator went through each of the six examples with each participant. The methodology used in each example followed the same general pattern:

(1) Introduction and context of the plot.
(2) Listening to the sonification. Participants were free to listen to these as many times as they wished. We asked each participant 'engagement questions' at this point to check they understood the context of the example.
(3) Participants were asked to draw or otherwise describe/recreate what they thought the plot looked like based on the sonification.

    Throughout our examples, we asked our participants to 'sketch' an interpretation of the graph that the sonification represented. In the case of our sighted participants this meant sketching on paper using a pen or pencil; for our visually impaired or blind participants, we used Wikki Stix Omnicolor Inc. (2018) for the UK-based participants, and a Draftsman Tactile Drawing Board American

Printing House for the Blind Inc. (2009–2014) for the US-based participants.

(4) Reading the figure description; participants were then asked whether their impression of the plot had changed based on the extra information contained within the figure description.

(5) The 'big reveal', in which participants engaged with the plot using either the visual or the tactile version. For the VI participants, tactile versions of the plot were made available instead of the visual version.

For more details about the examples used, including the plots and the scripts, see Vines et al. (2016). The same ordering of the examples was used for all the participants; it was felt that the later examples demanded more skill in the interpretation of sonifications than those that were earlier. The first few examples were necessary to help participants calibrate themselves both to the sonification, and to the nature of the activities. It was clear to us that some (if not *most*) of our participants exhibited the signs of nervousness common to research participants, and the first example helped to put them more at ease. Each session was video recorded.

General background about each participant was gathered, which included: the participant's experience in studying maths and/or science, and the extent to which they enjoyed listening to music; we speculated that the importance that each participant placed upon music might be an indicator of how successfully they would be able to engage with the sonifications. At the end of each session, each participant was also asked to provide general feedback about the usability of the sonifications.

2.2. Participants

A total of 12 participants were included: 5 sighted OU students currently studying a first-year undergraduate Maths or Science module; 5 UK based adults, who were either blind or severely visually impaired, with an interest in mathematics and/or science (but not necessarily OU students); 2 further blind or visually impaired people studying mathematics at Portland Community College, Oregon, USA.

The VI adults were included to investigate whether there are any differences in the effectiveness of sonifications in this key group – the group whom it is hoped that sonifications would most benefit. Ideally the UK-based participants would have also been current OU students, however the pool of students from which to recruit to the project was limited.

In what follows, we will use S1,...,S5 to represent our five sighted participants, and VI1,...,VI7 to represent our seven visually impaired or blind participants.

2.3. Results

The results for each of the six examples highlighted different points of interest; we will detail results for three of the six examples. The quotes and visualisations we have chosen to present focus on participants' perceptual precision, their first-hand access to the medium, and the understanding (or not) that they were able to gain; we have tried to provide a balanced account.

2.3.1. Example 1: Graph of a sine function

Example 1 focused on modelling the height above the ground of a passenger on board a Ferris wheel over time, a quantity that is given by a sine function. Each participant answered the 'engagement' questions in the introduction section correctly, which helped them to gain confidence, both in the methodology of the study, and in their ability to process the information given within the sonification. The discussion surrounding these questions also meant that the participants had at least some intuition about the shape of the graph before engaging with any representation of it.

When first presented with the sonification, only half of the participants said that it sounded as they would expect; participants reported that the sonification was shorter than they expected or that they expected separate notes rather than a continuous tone.

When asked to describe the sonification, we received responses such as:

> *Sounds like my little boy going down the slide ... I can follow it along in my mind. I can visualise a wavy line ... it goes up and down 3 times*
>
> (S4)

and,

> *Rises from the base 0 line, rise, reach peak, come down ... sweeping series of arcs ... going between the 100 on the y-axis and 0*
>
> (VI3)

Overall, by the time the participants had listened to the sonification, most, if not all, appeared to have a good idea of the shape of the graph. An example of our participants' sketches is given in Figure 1.

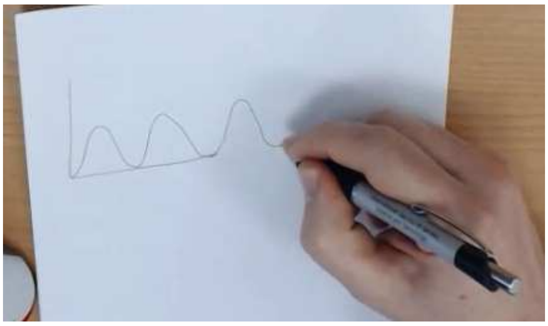


Figure 1. Visualisation of the sonification from S4.

Each participant was asked for feedback about the figure description. Overall the participants felt that the figure description did not essentially change their impressions of the graph. One participant said:

> *my initial reaction is that feels like a good figure description... but I wouldn't easily or very confidently be able to draw that as a result of hearing that*
>
> (VI4)

Finally, each participant was shown the graph, either in visual or tactile form; see Figure 2. Generally the participants noted that the graph did match the impression that they had built.

> *Hey, look at that! [positive response, counts cycles]. That is exactly what I was expecting from the sound*
>
> (S4)

> *That's kind of what I expected. I'm not sure of a better description of it, so I think the sound actually made me see that better than description*
>
> (S3)

> *Basically what I described I think.*

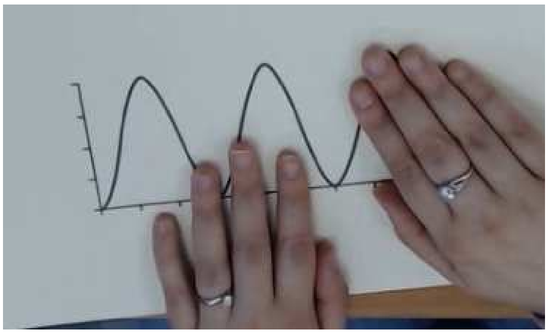


Figure 2. VI5 examining the tactile version of the graph for Example 1.

(VI6)

However when asked to describe which medium (sonification, description or visual graph/tactile version) is more helpful, it was notable that the VI participants really appreciated the autonomy the tactile graph gave them to interrogate the graph in the way they wanted to. For example

> *...the beauty of a physical graph is that I can stop it at any point and interrogate the points... whereas this [sonification] I can't really interrogate either of these*
>
> (VI4)

Nevertheless our participants, particularly the sighted ones, could see a role for sonifications:

> *I feel, for me personally, the [tactile] graph gives more information; if I'd had the description and just need an idea of the graph, the sound is much easier to interpret*
>
> (VI3)

> *I actually really like the sonification. Listening to the sound, I could actually see it in my mind what it was going to look like.*
>
> (S4)

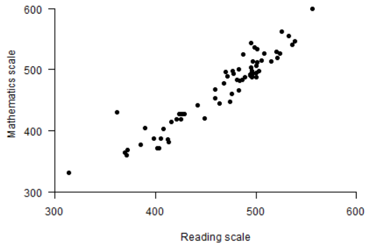
Thus although not representing a panacea, it was clear that the participants, including the sighted ones, were generally gaining something from the sonifications.

2.3.2. Example 5: Interpreting a scatterplot

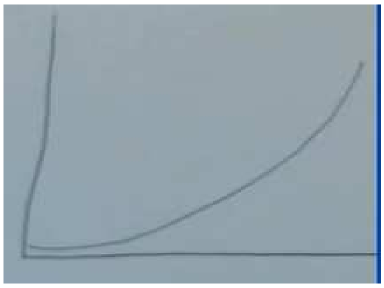
The focus of the teaching point associated with this example was to *interpret* the information from a scatterplot, and examine the relationship between two variables.

The specific scenario concerned average performance on mathematics and reading scales for 15-year-old students from different countries. In this case the expected answer is that the relationship appears to be positive, linear and relatively strong. There is one outlier and two extreme points, one corresponding to particularly low scores for reading and mathematics, and the other to one corresponding to particularly high scores for reading and mathematics, see Figure 3(a).

The participants were asked to decide whether the relationship is positive or negative, whether it is linear, how strong the relationship is (in an informal way) and whether there are any outliers. Sonification appeared to emphasise discrete groupings in the data; not only were the two extreme points in Figure 3 identified, but other clustering of points too. For example VI5 and S3 (Figures 3(c) and Figures 3(d)) appeared to visualise the scatterplot as discrete data points, whereas S2 drew a curve



(a) The original figure


(b) S2's representation


(c) V5's representation


(d) S3's representation

Figure 3. The scatterplot used in Example 5, together with some representations reproduced by participants

(Figure 3(b)); furthermore, it was said:

> *OK, so we've got correlation . . . so maths on one axis and reading on the other, it won't matter which way round, will it. Felt like there was one odd country that was down there all on its own. Bit of a bunch up here. An odd little . . . one up there. Sounded fairly positive because it was going up.*
>
> (S3)

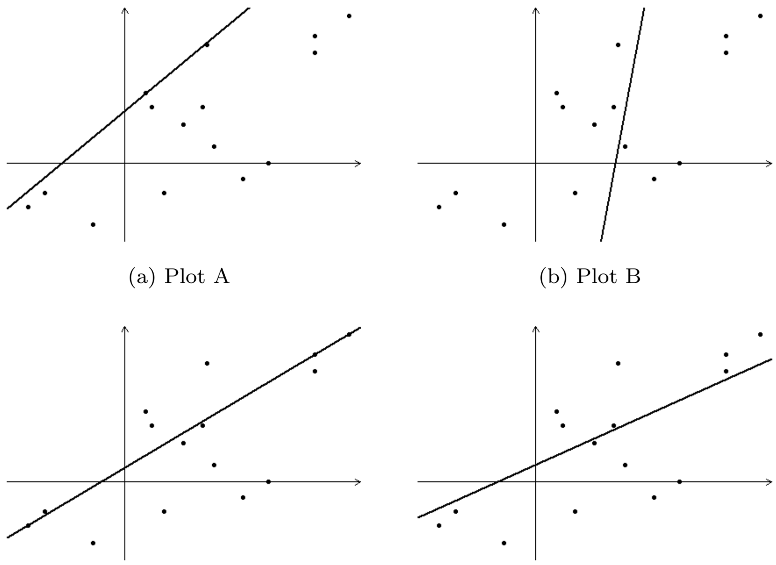
> *Well, I notice that there's one country that's probably really, really low– the lowest. There's one that's close. And then there's a little bit of a cluster. Then there's a bigger cluster as you're going. All this is as you're going higher, percentages of math and reading getting closer together – clustered in the high range. And then there's one that's really at the top.*
>
> (VI7)

However despite perceiving the clustering of points, the outlier was *not* generally interpreted by our participants. Even having listened to the sonifications many more times, and with the benefit of knowing what the scatterplot looked like, listeners could not pick this out. This suggests that a point which may appear as obviously different on the visual version of the plot, can becomes less so in the sonification.

2.3.3. Example 6: Assessing the fit of lines

The final example focused on how well a line (fitted 'by eye') was a good representation of the underlying scatterplot. In this example a total of five sonifications were played to participants: one just of the points on the scatterplot, and one each of four candidate lines along with the points on the scatterplot (Figure 4).

From the outset we felt that this example was likely to push the boundaries of the usefulness of sonifications because of the 'dual track' nature of the sonification



(a) Plot A (b) Plot B

(c) Plot C (d) Plot D

Figure 4. Plots A to D used in Example 6 – assessing the fit of lines

representation of a line along with the underlying points. This example was deliberately placed last so that participants could build their experience and confidence with the earlier, easier sonifications. It became clear that it was helpful to show the participants the 'points only' graph so as to help them calibrate; the protocol changed and evolved as we worked through our participants, to show the later participants the 'points only' graphic before moving on to any 'points and line' sonifications.

Nevertheless some participants seemed to grasp the idea quite well; with reference to Figure 4:

> *OK I have a good idea of what I think is being represented. (listens to the others twice each) OK I think I've got a good grasp of those. A was easy to grasp. It's a positive, relatively steady gradient, quite positive; (listened to B again) B quite low, very neutral gradient, then it suddenly peaked and a real strong trend and went off the scale as such; (listened to C again) Again more positive start than B, and then again really peaked towards the end and went up quite steep; (listened to D again) Plot D found it very similar to C, pretty much the same, about the same as C*

(S2)

while for others, it seemed to cause confusion:

> *Interesting. To me, you need to have your points clearly defined to start. Then, put your line through it. Its confusing things to have the line going through and you have the line going through but you haven't finished defining some of the points.*

(VI2)

> *OK, those three long lines sound the same to me. They sound - I don't know, I can't distinguish any difference. OK, maybe I have to hear them side-by-side. [listens to them all again in reverse order.] Well that one ended faster. I still can't tell the difference between the last two. the last two do a better job.*

(VI7)

The impression that participants had of the plots from just the sonifications did not always match that given by the figure descriptions:

> *I'd leave B as it is, obviously there's more points, but I'd say the line is roughly what I think... Wow. I must have gone totally off the rails here [referring to D]. D I totally thought was really steep but reading this I would change it and it would be [redraws] and the points are more even. .... I didn't get that from the sonification.*
>
> (S2)

or what the graphs/tactile versions were telling them

> *So I didn't quite get that (implies A). I didn't really. It's difficult to know what is positive and what is negative. C matched quite well. B doesn't fit well. C and D fit quite well. A doesn't fit - it's way on the outside - it's not in the middle of the points.*
>
> (S1)

This confirmed our view that these sonifications were at the limit of complexity with which students could be expected to engage. This suggests that sonifications of graphs involving more than two lines, or a set lines and points, would need to be broken down into a series of simpler sonifications.

3. Phase 2: pilot implementation on an OU module

The results from Phase 1 were sufficiently encouraging that it was felt appropriate to investigate the impact of sonifications as a teaching tool in a real distance learning environment. Explicitly, our goal was to measure the extent to which sonifications can deliver perceptual precision as a teaching resource in the context of distance learning.

3.1. Methodology

For this phase, sonifications were made available on a live module website for a first-year undergraduate course in statistics, and was one of those which was examined for suitable plots in phase 1. The sonifications corresponded to all the scatterplots in one unit of this module. The learning outcomes for this unit include: interpreting a scatterplot, fitting lines to scatterplots and recognising patterns in residual plots (see Hilliam and Calvert (2017)). The unit included about 75 sonifications.

The sonifications were placed on the module website in such a way that all those with access to the module website could access the sonifications. For each sonified graph, a visual version of the plot was displayed, with a link to the sonification included below to augment the visual plot. A link to the associated figure description was also provided. Listening to the sonifications was voluntary; in particular it was made clear to students that listening to the sonifications and answering the associated questionnaire was *not* part of their assessment. When communicating with the students we used the phrases 'audio versions of graphs' and 'audio graphs' rather than 'sonifications' to avoid introducing additional unnecessary terminology. The questionnaire consisted of the following questions, together with the option for students to specify their personal identifier (which would enable us to link their responses with their demographic data if needed):

(1) How many audio versions of graphs did you listen to?
(2) Please tell us roughly how important music is to you — tick all boxes that apply.

(3) How often could you imagine the shape of a scatterplot from its audio version?
(4) Did the audio versions help you understand what the scatterplots in the unit were showing? Please tell us briefly why or why not.
(5) If there were audio versions for graphs in other units would you listen to them?
(6) Do you have any other comments?

3.2. Participants

All enrolled students were invited to engage with the sonifications, and were encouraged to provide feedback, even if that feedback was that they did not listen to any. A total of 83 students provided responses, which represented approximately 9% of the total students enrolled; a range of views were expressed from this group of students.

3.3. Results

3.3.1. Engagement with the sonifications (Question 1)

The number of sonifications to which each respondent said they listened is given in Table 1. We have categorised the respondents as 'Few', 'Some', or 'Most' and will refer to these categories in what follows.

Table 1. The number of audio versions to which participants listened (Question 1)

Category	Response	Percentage	Total
Few	None	16%	13
	One or two	10%	8
Some	Between three and ten	33%	27
	I am not sure but not many	5%	4
Most	I am not sure but most of them	25%	21
	All of them	12%	10
Total		100%	83/83

3.3.2. Importance of music (Question 2)

We were keen to attempt to quantify the relationship (if any) between students' attachment to music and their response to sonifications. Table 2 details results that suggest those who listened to 'Some' sonifications attach less importance to music than those who listened to 'Few' or 'Most'.

All of the percentages relating to the 'Some' group, except for that in the final column, are lower than their equivalent percentages in the other rows. That is, all the columns in which a positive response indicates a greater importance of music, the percentage is lower for the 'Some' group and the one column in which a positive response indicates less importance of music, the percentage is higher.

So our expectation that students who attached more importance to music would be more likely to engage with the sonifications is not borne out by these data. If there is

Table 2. Percentages of listening groups who answered positively to Question 2 concerning music

Number of audio graphs listened to	Play music/sing in a choir	Can read music	Enjoy listening to music	Prefer to study with music in the background	Rarely have background music on
Few	24%	24%	76%	24%	38%
Some	6%	19%	55%	16%	48%
Most	29%	45%	81%	29%	29%

a relationship, it is not a straightforward one.

3.3.3. Imagining a scatterplot from its sonification (Question 3)

The question 'How often could you imagine the shape of a scatterplot from its audio version?' allowed us to assess the extent to which the students felt the sonification provided them with a similar view of the data as the scatterplot itself.

As Table 3 shows, those who listened to 'Few' audio graphs were more likely to have felt they could imagine them 'Rarely' or 'Not at all'. However the proportion who felt they could imagine them 'Always' or 'Most of the time' was about the same regardless of whether they listened to 'Few', 'Some' or 'Most' of the audio graphs.

Table 3. Imagining of the scatterplot (Question 3)

Number of audio graphs listened to	'Always' or 'Most of the time'	'Sometimes'	'Rarely' or 'Not at all'
Few	38%	12%	50%
Some	32%	32%	35%
Most	42%	42%	16%

More importantly overall most respondents felt that they could imagine the scatterplot at least some of the time. This is despite not having been given any training or guidance about how to interpret sonifications.

3.3.4. Interest in more scatterplots (Question 5)

We only made sonifications of plots available to students in one unit of the module, despite other units also containing graphs that were suitable for the creation of sonifications. We were therefore interested to know if students would listen to sonifications were they available in other units.

Overall about 20% expressed an interest in this; the respondents who had listened to 'Most' of the sonifications were the majority of the respondents. These results included one respondent who was interested in having more sonifications despite reporting that they had not listened to any of the available ones.

3.3.5. Free text responses (Questions 4 and 6)

Questions 4 and 6 allowed the students to provide free text responses, in which we invited their feedback about their understanding of the sonifications and then their general comments respectively; we repeat the questions here for clarity:

(4) Did the audio versions help you understand what the scatterplots in the unit were showing? Please tell us briefly why or why not.
(6) Do you have any other comments?

We gauged the overall tone, or sentiment, of each response by categorising them as *positive*, *neutral*, *mixed* and *negative*. The categorisation of responses to the 'understanding' question (Q4) and the 'general' question (Q6) are shown in Table 4.

Table 4. Tone of response to Questions 4 and 6

Number of audio graphs listened to	Positive		Neutral		Mixed		Negative	
	Q4	Q6	Q4	Q6	Q4	Q6	Q4	Q6
Few	10%	0%	20%	33%	0%	0%	70%	67%
Some	13%	25%	10%	6%	16%	31%	61%	38%
Most	29%	27%	14%	5%	18%	41%	39%	27%

The respondents who listened to 'Few' sonifications mostly provided negative comments; however even those who listened to 'Most' of the sonifications quite often gave negative responses.

Some of these negative responses arose because using the sonifications did not fit with the way they liked to study:

- *I prefer it silent to aid my concentration so it is not something I would actively look for to aid my learning.*
- *didn't use them, study from the books unless stuck*

For a few respondents the sonifications were actively disliked or inappropriate:

- *I'm afraid for me this reminded me too much of the many hearing tests that I endured as a child.*
- *I'm partially deaf...*

For others the negativity related to the difficulty that they had when interpreting the sonifications. Although many reported being able to obtain some information about the graph from the sound, the lack of detail and precision was seen as a problem:

- *No I did not get it only followed up and down*

In particular this difficulty was juxtaposed with the ease that many had with interpreting graphs visually. Many of the students did not feel that the audio graphs added anything:

- *am very comfortable with interpreting graphs in the traditional way and did not find this a useful addition*
- *They didn't add any insight to the visual*

It was noted by some respondents that this difficulty could have been ameliorated by training. After all, the skill to interpret graphs visually is something that students have learned and have probably been doing for years. In contrast attempting to interpret audio graphs was something new:

- *It'd perhaps be a good idea to provide a few examples with explanations as to what the sounds represent to make it clearer what the listener should look out for.*

However despite a lack of training some did feel that listening to the graph helped them interpret the graphs:

- *Listening to them required me to think more about the shape of the graph than simply looking at it.*
- *They didn't ADD understanding, but corroborated it*
- *With the graph next to it to look at I guess it forces you to really look at the points and the line to track what you're listening and perhaps that exercise in examining the points is useful to prompt slightly deeper thoughts/analysis of a graph*

Furthermore, even when students felt that the audio graphs were not helpful to them personally, some felt that they could be useful for other users:

- *I think these graphs are great for the visually impaired*
- *I think that these may be more useful for some individuals than others, depending on their learning style and development needs.*

The respondents did highlight areas in which further technical developments could be helpful. Currently the "stitching together" of the audio graph via a sequence of sound points led to some crackle in the audio; eliminating or reducing this would be desirable. Also the length of each graph (6 seconds) was not always seen as appropriate; it was felt to be too long when there were few points of the graph, but too short when there were many points. Furthermore one respondent suggested linking the sonification and visual plot in such a way that each point of the visual plot is highlighted as its note was sounded on the audio graph. In particular such a development would help with the training sighted people about how to interpret audio graphs.

Finally it should be noted that some students in were extremely positive; for example:

- *The audio was helpful if i had a pen and paper in hand. Listening to them required me to think more about the shape of the graph than simply looking at it. It helped me pay more attention to the spread and "timing" of the data entries.*
- *This was great! I've never 'looked' at data this way. You can really hear the shape of some of the graphs, and hear their positive or negative slope. This was fascinating, loved it! :)*

4. Overall conclusions from both phases of the study

The results from Phase 1 of the study validated that offering sonifications to augment visual teaching materials is appropriate. Each of the formats (sonifications, figure descriptions and tactile diagrams) provide a different, but complementary, aspect of the original (visual) plot/graph, and furthermore, a different way to engage and process the information within; we aim to represent this graphically in Figure 5.

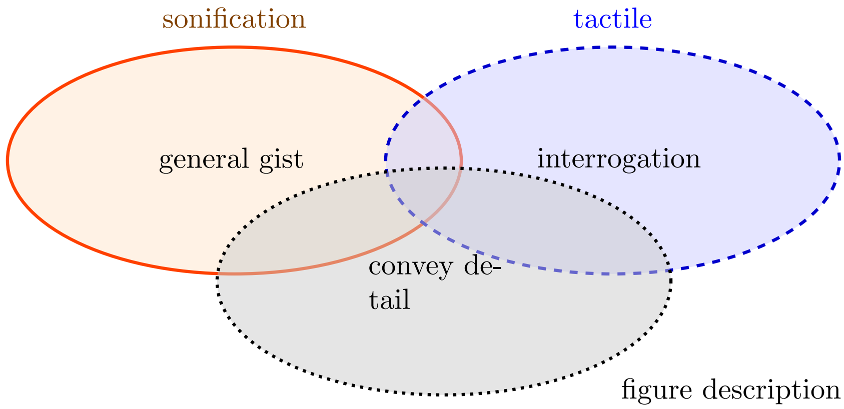


Figure 5. A blended, augmented approach to the provision of alternatives formats of graphs

The sonification provides the gist of a plot, giving the general sense of the shapes that form the plot in a *timely* fashion. Not only is this important for getting an overview of the relationships that are depicted in the graph, but it also allows the user of a tactile version to know where to look when interrogating the patterns in the plot.

The tactile diagram allows *interrogation* of the plot; for example reading of the position of points or lines against the scales, or against other points/lines. Perhaps more importantly, tactile diagrams give the user the freedom to explore the plot in the way that they want to, rather than having the information presented in a fixed order.

Figure descriptions *convey detail* such as axis labels and scales – information that is not available in sonifications. This information can be included on tactile diagrams, but that presupposes that all users can read Braille, which may not always be the case.

Phase 2 of this study showed that it is possible to offer sonifications to students via a module website, thus enabling students to access them as and when required. Furthermore making these sonifications available to all students is a reasonable thing to do. Many might choose not to make use of them, but a few found that they provide a fresh view of the scatterplots.

4.1. Discussion

The aim of this study was to see how effective sonifications can be as alternative versions of plots and graphs in module materials. The results show that the first-hand access these sonifications gave participants did enable most of them to get the gist of the plot; as in Zhao et al. (2008) a gist is 'the overall data trend presented via a short auditory message'. This was despite not being familiar with graphs in this format. In particular those participants who enjoyed listening to music seemed to more easily work with the sonifications. Greater experience with sonifications should only increase participants' ability to interpret plots and graphs given in this format.

The sonifications mostly enabled the participants to gain an impression of the plot or graphs in a timely fashion, as each of the sonifications was only 6 seconds long. We noticed in Phase 1, although participants generally listened to sonifications more than once, using them did not add significantly to the time taken to engage with the activity. Also in Phase 1 participants indicated that listening to sonifications was not an unpleasant experience so asking participants to engage with multiple sonifications in a single study session did not appear to be unreasonable.

In Phase 2 although only a minority of students appeared to get a benefit from the audio graphs, the instances in which it appeared to detract from the study of others were very rare. So its appears to be something that can be offered to students in the distance learning context. Furthermore the audio graphs exposed the students to important concepts in accessibility as they saw graphs of data points represented in an alternative format: audio. For example, the following feedback was among the responses we received from Question 6 in Phase 2:

- *I can see benefits for students with specialised learning requirements.*
- *I have some minor eyesight issues also, so this would make the files accessible to many students.*
- *There is far more detail and many nuances than can be perceived in audio versions*

Some further technical development of the method by which the audio graphs are produced is desirable. This may improve the acceptability of individual sonifications, for example by removing unnecessary crackle. Consideration of the usability of the software by which the sonifications are generated is desirable. All the sonifications used in the study were generated by just one of the authors. The process was not overly time-consuming, but user-friendly aspects had not been specifically built-in. The aspiration of 'born-accessible' graphs means that ideally such graphs should be no more difficult to produce than the standard graph. Also in this study the users of the sonifications were given no option to modify the sonifications. For example to make them longer or shorter. Technical development to enable this would be desirable to allow users to be able to customise the sonifications to suit their own preferences.

Where audio graphs are to be used, guidance about how to interpret them should be offered. In particular, reassurance about what is and is not reasonable to pick up from them.

4.2. Limitations and next steps

The results from Phase 2 indicate that sonifications can be safely delivered to student via module websites. So a logical next step is to create sonifications for a whole module and make them available to all registered students. This has implications for workload management. Can suitable sonifications be created for all plots? Moreover can this be done in an automated or at least semi-automated way?

Most of the plots considered in the two phases were scatterplots. For some other types of plot it may not be so clear how best to sonify them. For example, how should we sonify a plot that contains vertical asymptotes? So further user testing with different types of graph is desirable. Smoothing the creation of these sonifications into standard production systems (allowing sonifications to be 'born accessible') would help with working at scale.

In this study the users were not able to customise the sonifications in any way; as such because one only one implementation was used to generate the sonifications we cannot assess the impact of factors such as the duration, range of notes or timbre of the notes would have had. It is not clear how much benefit such customisation would bring.

4.3. *Final remarks*

We process information in a variety of different formats. As educators, one of our main objectives is to ensure that the information we present to our students is as accessible as possible to a diverse range of learners. We consistently embrace the different learning styles and different abilities of our students.

Integrating the three aspects (Figure 5) is beneficial, and certainly exploring the link between visual and auditory exploration of a graph is an interesting area for further research.

Our two studies have shown that, for some users, the use of sonifications can be an effective way to communicate information from a graph. The strength of the two studies has been in *augmenting* existing strategies with new innovations of assistive learning technology. We continue to strive to make our teaching materials as accessible as possible to all.

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