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GRAPH REPRODUCTION TASK ON MOBILE AUDITORY GRAPH (MAG): AN EXPLORATORY STUDY

ZICO P. PUTRA[1,2,*], AUDITYA P. SUTARTO[3], MILA D. ANASANTI[2,4]

[1]School of Electrical Engineering and Computer Science, Queen Mary University of London, London, United Kingdom
[2]Faculty of Information Technology, University of Nusa Mandiri, Jakarta, Indonesia
[3]Department of Industrial Engineering, University of Qomaruddin Gresik, Gresik, Indonesia
[4]Department of Medicine, Imperial College London, London, United Kingdom
*Corresponding Author: z.putra@qmul.ac.uk

Abstract

Accessibility to visual information graphics is still a major obstacle for visually impaired people due to their restricted access to many graphics in STEM (Science, Technology, Engineering, and Mathematics) areas. We developed a mobile auditory graph (MAG) application and studied the performance using point estimation and graph reproduction tasks among 12 sighted users. This study evaluates the feasibility of the MAG by determining how accurate users' mental models matched the actual plot. The study explores point estimation errors, the relationship between the number of points estimated and errors, length of the pause, and the possibility of learning effects. The results show that the accuracy of point estimation and graph reproduction decreases when data notes are growing, indicated by increasing the number of errors. This work has not only demonstrated the ability of sighted users' to perform point estimation and graph reproduction tasks. but has also provided important findings on the auditory graph design process in the context of interaction design. These findings show the potential use of MAG among visually impaired users to understand graphs better, allowing them to collaborate with their peers in education and employment settings.

Keywords: Auditory Graph, Audiograph, Sonification, Mobile Application, Visually Impaired.

1. Introduction

Many mathematical and statistical graphs are so prevalent in STEM (Science, Technology, Engineering, and Mathematics) areas, social sciences, and business and economics. Nevertheless, their visual nature presents a major challenge for visually impaired or blind [1]. Auditory graphs are a potential solution for them to present non-visual access to data using non-speech sound [2].

Studies have shown that blind and visually impaired (BVI) people can read line diagrams that were sonified with a musical note by rendering each data point [3, 4]. Walker [5] has also demonstrated that sighted people can draw the mental model trend of graphs while listening. The auditory display allows both blind and sighted users to understand the non-speech sound displayed without the need for their vision. Quick recognition of acoustic signals and the overall perception of hearing can contribute to an auditory display's effectiveness even when vision is present. Nonetheless, the audio display designer must consider the end user's perceptual and cognitive expectations to verify that sonification and auditory graphs are practical and useful.

Meanwhile, the rapid development of more portable devices and smaller screens leads to the more importance of using audio to convey information [6]. Still, not much work has been undertaken to explore the auditory graphs' functionality embedded into a mobile device. Unlike visual graph, the technology to support mobile auditory graph was only available not so long ago. For example, we have a better touch screen interaction widely available only just the last decade. Previously, the touch screen input was slower in response to such a gesture. Thus, there is a need to develop a user-friendly Mobile Auditory Graphs application (MAG app) that can assist BVI to interpret the graphs better than if using the traditional embossed graphs. Therefore, this study aimed to explore the feasibility of MAG on graph reproduction tasks among sighted users. The findings are expected to provide a solid foundation for further implementation among BVI users.

The rest of this study is divided into following categories: In the next section, a literature review is presented for some methods. Section 3 describes the development of MAG App. Section 4 describes the proposed methodology in detail. The results are illustrated in section 5 according to the research questions for point estimation and graph reproduction tasks. Finally, Section 6 discusses conclusions and recommendations for future work.

2. Literature Review

This section describes auditory graphs and sonification and its related issues on mobile device implementation. The development of our first mobile application prototype was also discussed.

2.1. Auditory graph and its implementation on mobile device

Designing a useful and practical auditory graph requires some knowledge and experience, following conventions, and including enough contextual cues to support interpretation and meaning. As the visual graph properties (i.e., colour, spatial, trend, and size) need to be adjusted regularly, the audio properties in sonification such as frequency (pitch), amplitude (loudness), timbre, or tempo may be modified to represent the data values [5, 7]. Brown et al. [8] formulated guidelines for auditory graphs and the sonification of diagrams containing two or three data series.

The creation of auditory graphs requires a specific type of auditory display, i.e., sonification, a non-speech sound used to intentionally and systematically represent information, enabling users to understand data patterns by listening [9]. Data sonification offers benefits that can be perceived more broadly than speech, requiring precision and more focus efforts [10]. Moreover, speech-based descriptions have a shortcoming in their ability to deliver complex layouts briefly [11]. The predominant technique for representing sonification is parameter mapping, i.e., displaying changes in data values via an acoustic parameter. For example, adjusting temperature by changes in the pitch or representing speed using tempo [12]; Geiger counter to detect and measure radioactivity; and also, stock market data [7]. It has also been widely used in STEM simulation, medical data monitoring, weather monitoring, and control room sense-making to maintain awareness [13, 14].

Nevertheless, designing useful auditory graphs raises more concerns than merely deals with the issues of data-to-sound mappings. Tasks for reading graphs, such as point estimation, which focuses on this work, can be severely affected by the lack of context and reference information. For example, Nees and Walker [15] found that the user performance in point estimation tasks decreased in parallel with increases in data density (i.e., the number of discrete data points presented per second) and trend reversal. While presenting quantitative data on a visual display, additional information such as axes, labels, and tick marks improve such data's readability and comprehension by enabling more effective top-down processing [16-19]. Typically, a way to add the context of the x-axis or y-axis to a sonification is to use multiple clicks or create percussive sounds to improve the interpretation of auditory graphs [16, 20]. Research on sonification has been done since 1990 [21], and there has been growing in recent years due to the extensive use of mobile computing [22-24]. Accessibility features (i.e., screen readers and voice commands) have been widely exploited for communication purpose such as to create, record, send and receive emails; to access to webpages; use GPS navigation system; edit and listen to music; and modify a document [24-26]. Considering screen space limit to convey information, numerous studies have been conducted to solve this problem.

On the other hand, the utilisation of auditory graphs has received much attention in recent years in a wide range of application scenarios. Auditory graphs can facilitate the understanding of information for blind and sighted students and scientists [27]. AudioGraf was an early trial to make graphics readable using a tap panel and an auditory display [28]. TeDUB project made significant efforts to achieve existing Unified Modelling Language (UML) to make graphs accessible to the BVI individuals [29]. Furthermore Cohen et al. [30] have developed a system called exPLoring graphs at UMB (PLUMB) that presents a drawn graph on a tablet PC to help blind users understand graph and data structures auditory cues. The Georgia Institute of Technology Sonification Lab developed Graph and Number line Input and Exploration software (GNIE) which was embedded with sonification and installed in desktop for helping visually impaired middle school students to work independently [31]. For two years observation, the software was considered successful to be an appropriate supplement for traditional tactile techniques for teaching graphs and assist students to navigate around graphs particularly during the standardized testing. To improve interaction with auditory graphs, [32] assessed three pitch-based sonification mappings on point estimation task and found sighted users made more point errors when using the pitch-only sonification mapping compared to the one-reference and the multiple-references mappings. More recently, Sakhardande et al. [33] compared four different auditory graphs modes using simultaneous-note, simultaneous-speech, serial-note, and serial-speech. Based on the time completion assessment, they found that the simultaneous mode was faster than serial mode. Kim et al. [34] studied further the implementation of auditory graph in math using axes, quadrants, and differentiability.

The Graph Sketching tool (GSK) has been designed to facilitate visually impaired users to create and access graphs as node-link diagrams and share them with sighted people in real-time [35]. This tool helps BVI in computing and other STEM disciplines in which graphs are essential. Moreover, an accessible graphing calculator, GraCALC, has been developed by Goncu and Marriott [36] to provide numerical and statistical graphics to blind and severely visually impaired users. Their system creates a sonification-based graphic from a mathematical function as line graphs displayed on a web-based service. Despite having a standard code across multiple mobile platforms, their web-based design is not designed for collaborative work due to its limitation to access mobile-specific functions such as Bluetooth, SMS, and GPS. This study's motivation is to overcome this shortcoming and investigate user interaction with the auditory graph by utilising mobile devices' advanced features, such as multimodal gesture, which was never explored before in this graph study.

3. The Development of Mobile Auditory Graph Application

Our Mobile Auditory Graph (MAG) was built on the Android Operating System version 6.0.1 due to the convenience of programming in its open-source platform. It was presented on Google Nexus 7 tablet with a 7.02-inch (180 mm) display. The tablet form factor provided an excellent trade-off between portability and sufficient surface area for BVI users to comprehend a graph's layout.

Table 1. Reference mapping of note frequency values to y-axis values

Y	Frequency (Hz)	*Y*	Frequency (Hz)
0	0	**60**	982.8
10	163.8	**70**	1146.6
20	327.6	**80**	1310.4
30	491.4	**90**	1474.2
40	655.2	**100**	1638
50	819		

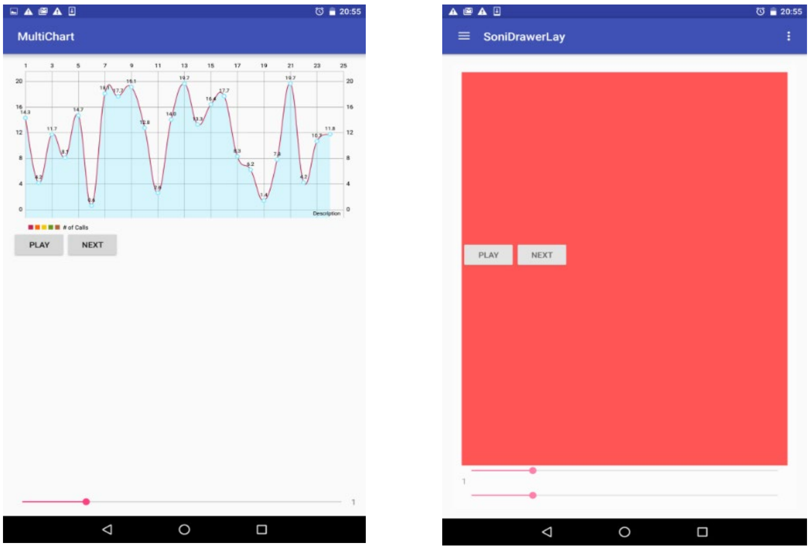
The dataset originally sampled intuitively at MIDI note G#6 (1638 Hz), mapped to 100 and decrease linearly to 0, as shown in Table 1. The musical note represented the corresponding Y value and the sound of the line graph. These notes were mapped to the maximum notes, as shown in Table 1.

The first MAG app interface structure has been developed according to the navigation menu, map area, button area, and scroll bar. The navigation menu had a window on the left side, which displayed the MAG app's primary navigation options. It was hidden by default, but it would be displayed when the users swiped their fingers from the left side of the screen or touch the program icons on the menu bar. The app had three menu lists: simple, medium, and complex, which were built based on the complexity of the graphs.

Our first MAG design had two different interfaces to present the graphs: the uncovered or normal graphs and the covered graphs, as illustrated in Fig. 1. The application would show a normal view graph with multiple data on the X-axis and Y-axis created based on the number of notes. Whereas on the blindfolded or covered view, these numbers were covered with a red layer over the graphs in the covered interface so that the sighted participants could not see these numbers. This scenario was intended to hide the numbers from users. The buttons "Play" and "Next" were located directly below the graphs. Since the red layer did not obscure the Playback button, the users could only locate the graph area above the Playback button.

The "drawer menu" has been set up for navigating to other task menus allowing users to switch to the other category of graph's complexity, i.e., between simple, medium, and complex graphs. The number of data points for the following auditory graphs was gradually increased to build up the complexity and was arranged as four simple graphs (6 to 9 points), six medium graphs (10 to 25 points), and six complex graphs (25 to 40 points).

All of the 16 graphs sets can be opened in sequence tasks by pressing the "next" button before proceeding to the next task, as shown in Fig. 1(a). In this mode, users need to press the Playback button to hear the entire data sounds. Furthermore, a speed control SeekBar was added to change the time interval between the data points. The speed was divided into five steps, starting from step one for the interval 0.5 s; step two for the interval 1.0 s; then up to step five for the interval of 2.5 s for each point.



(a) **(b)**

Fig. 1. MAG presentation view on (a) Normal view; and (b) Blind view.

4. Methods

The performance of our first version MAG was tested with sighted participants to examined whether audio graphs' complexity influenced sighted users' ability to perform point estimation and graph reproduction tasks. These tasks were aimed to gain a better knowledge of how closely their mental model matched the actual plot with the addition of the number of points. Further, it was expected to identify the challenges during the interaction, the pattern of behaviour, and the effect of speed setting on the data notes on the basic stages. Therefore, using an experimental design to meet the objective, this study aimed to resolve three specific research questions:

- How well can sighted users estimate points on the Y-axis in a graph along the X-axis?
- How well is the correlation between true and estimated points on graph reproduction task?
- How long be the pause (i.e., time interval) taken between the notes?

4.1. Participants

Participants were recruited from undergraduate and post-graduate students of the Queen Mary University of London. A total of 12 participants (9 males, 3 females) ranging from 18 to 44 years old. All participants reported having familiarity with touch screen features on mobile devices but did not have any auditory graph experience on a mobile device. A questionnaire related to the demographic information was handed to each participant before starting the experiment.

4.2. Apparatus

We tested the MAG app on Google Nexus 7 running on the Android 6.0.1 operating system. The graphs were presented in ascending order of complexity, starting from the graph that has the smallest number of points (simple 1). The study was recorded as points on the XY-axis on grid papers. A seek bar was also provided to allow the users to easily set the pause length between the played MIDI notes to display the notes' positions along the Y-axis. The duration of playback could be adjusted by changing the pause length between the notes.

4.3. Procedures

Before starting the tests, we conducted an initial training period to get familiar with the MAG app and clearly understand the experiment tasks. Participants were taught how to perform graph reproduction tasks using both blind and normal views on the MAG app. They were allowed to explore the application to get familiar with the playback modality and the frequency ranges used to represent points on each graph's Y-axis. We trained all the participants with all series of graphs for 10 minutes, followed by an explanation of all possible options to create the auditory graphs' sound on the device. The tests for this exploratory study were conducted in a quiet room at the Queen Mary University of London with a well-controlled environment. The experiment's duration lasted 45-90 minutes for each participant to complete the tasks sequentially from the simple, medium, and complex series. To avoid exhaustion, we decided to remove the last two complex series. Thus, the final tasks consisted of a total of 14 series. To evaluate the degree to what extent the mental model generated by the sonification procedures matched the actual plot, participants followed the experimental task as suggested by Walker and Nees [9] for performing a point estimation task. The participants were given a sheet of paper containing several empty X-Y axes to mark the estimated points using a pen. After playing and listening to the audio graph, they were asked to draw the perceived plot by selecting the grid positions corresponding to Y values' points along the X-axis. They could listen to the audio graphs as often as possible and change their prediction of point locations on the Y-axis while repeating the audio.

Participants could move to the next graph test by tapping the "next" button. They could continue to the other tasks by navigating the menu button then select the series of graphs presented in order. The participants could use the touch screen by tapping the "Play" button so that the system would playback the default of graphs with intervals of 500 milliseconds for each point. For example, assuming the user run the first task of simple graphs consisted of 6 data points, the entire audio playback graphs would playback for 3 seconds each time they tapped the button. They could also change the length of the pause between notes with the "seek bar" provided on the application. The tick position marked on the grid is based on the interpretation of sound from the audio graphs. The X-point represents its time series and the Y-point is the pitch values between 0 and 100 scales. Their estimation was then compared with the actual values for further analysis.

A different set of tasks were assigned in the experiment. The participants performed four tasks with simple graphs and were offered a five-minute break before the six-medium complexity graphs. After having another five-minute break, they moved to the last four complex graphs. The participants collected the data by completing the empty XY graph on a sheet according to the perceived pitch as they did in training. The sheet was filled out by marking the points from the beginning to the end of the line curve. At the end of the experiment, each participant was interviewed to get feedback and discuss the problems encountered while carrying out the tasks.

4.4. Statistical analysis

We used the unbiased root-mean-square error (RMSE) to measure the point estimation error. The RMSE was calculated by taking the differences between values predicted (estimated values = *f*) and the values observed from actual plot (true values = *o*) as shown in Barnston's formula [37]:

$$RMSE_{fo} = \left[\sum_{i-1}^{N} \left(z_{f_i} - z_{f_0} \right)^2 \Big/ N \right]^{1/2} \tag{1}$$

where: Σ = summation, $(z_{fi} - z_{fo})^2$ = differences, squared, and N = sample size.

Further statistical analysis was also performed to determine any significant differences across all tasks' complexity (i.e., simple, medium, and complex graphs series). To answer the second research question, we conducted a correlation test between the estimated and true values to determine the sighted users' accuracy in performed the graph reproduction tasks. Moreover, the third research question was addressed by examining the length of pauses between notes, which the users set to predict point estimation better. All of the statistical analyses were performed using Microsoft Excel and R Programming at a significance level of 0.05.

5. Results and Discussion

The results and discussion of this study were organized according to the research questions.

5.1. Point estimation task

To address the first questions, we evaluated the effect of adding pitch to a line curve along the X-axis on the obtained error between actual plot and estimated values by calculating its respective RMSE. The means plot of RMSE was visualized in Fig. 2. Before analysing inferential statistics, we presented descriptive statistics to summarize the central tendency (means, median) and variability (standard deviation, inter-quartile range) of RMSE [38]. Table 2 displayed the relevant descriptive statistics of RMSE from 12 sighted participants. To compare 14 independent task groups' outcomes, a non-parametric Kruskall-Wallis test was conducted as RMSE means data violated normality assumption. The Kruskall-Wallis statistic showed statistically significant difference ($\chi2= 33.9836$, $df = 13$, $p < 0.001$). Further posthoc analysis using the Dunn test was also performed to determine which specific RMSE means are significant from the others. To control the expected proportion of "discoveries" (rejected null hypotheses) that are false (incorrect rejections), Benjamini and Hochberg's (BH) stepwise-adjustment procedure was applied [39]. The entire Dunn test adjusted (BH) p-values from total 91 pairs revealed that the differences were found between six pairs: simple 1 vs simple 3 (p=0.007), simple 1 vs simple 4 (p<0.001), simple 4 vs medium 1(p=0.013), simple 4 vs medium 2 (p=0.007), simple 4 vs complex 2 (p=0.007), and simple 4 vs complex 3 (p=0.007).

These results are inconsistent with the initial assumption and previous work [15] that raising the number of data points will increase the number of errors in the point estimation task. Our findings show that the increase in point estimation errors was in line with the addition of data points up to a certain threshold before they decreased and remained constant.

Table 2. Mean, standard deviation (SD), median, and interquartile range (IQR) of root mean squared error (RMSE) of 12 participants across 14 conditions (Simple-1-4, Medium-1-6, Complex-1-4).

Conditions	Mean RMSE	SD	Median	IQR
Simple 1	8.55	4.66	8.16	6.80
Simple 2	14.91	4.45	14.88	3.38
Simple 3	18.65	5.95	19.68	6.60
Simple 4	21.85	7.04	21.46	6.90
Medium 1	12.13	4.91	13.42	4.92
Medium 2	12.65	6.19	11.34	5.48
Medium 3	12.94	5.20	12.10	4.02
Medium 4	14.00	6.57	12.04	7.48
Medium 5	13.30	4.81	11.98	4.00
Medium 6	15.07	5.44	14.97	9.06
Complex 1	14.27	6.81	12.96	4.38
Complex 2	12.94	5.20	12.16	4.36
Complex 3	12.33	9.14	12.06	4.45
Complex 4	15.12	5.37	14.30	6.29

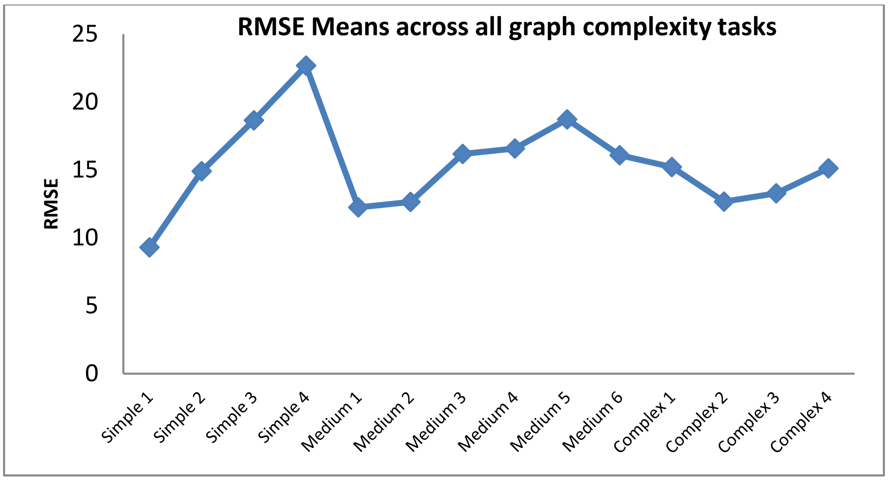


Fig. 2. Plot of the RMSE means of 12 participants across 14 conditions (Simple-1-4, Medium-1-6, Complex-1-4).

This result indicated that the point estimation task's difficulty level became stable after achieving some points (medium 1). These results somewhat contradicted our initial assumption that increasing the number of data points would increase the number of errors in graph reproduction tasks. During the experiment, a possible learning effect might be attributed to this finding as the listener could play the graph as often as needed. It was challenging to estimate points accurately as the complexity increases without multiple playback repetitions because auditory memory can only retain information for a short period [40]. It is needed to limit the trial of playback to a maximum of three times, as suggested by Metatla [32], who found that when many notes were played, people lost track of them and became less useful.

Furthermore, it was apparent that data points' addition will not increase error linearly at the value ranges from 10 and 25, suggesting a certain threshold. Despite the training to distinguish the minimum and maximum data points, the mapping perception and its scale comparison to the actual data can be relative to each listener's perception. Therefore, further studies should employ randomization of the task order.

5.2. Graph reproduction task

We performed Kendall tau's test to find the correlation between actual plot and estimated values for each participant across all complexity graph categories. Kendall's tau is the non-parametric equivalent of Pearson correlation, which provides a more robust technique to outliers and normality assumption. The means of Kendall's tau correlation for all participants are presented in Table 3 and depicted in Fig. 3.

The Kendall tau's correlation between true and observed values for all graph reproduction tasks ranged from 0.640 (simple 1) to 0.849 (complex 2), indicating a medium to a strong positive relationship. As shown in Fig. 3, the correlation means tended to decline with small fluctuations by adding number points. It started to increase at Medium 4 (20 data points and become marginally steady from task

Medium 6 (25 data points) to Complex 4 (36 data points) with correlation values ranging from 0.64 to 0.66. This result supports the assumption that the complexity may contribute to less ability to reproduce graphs up to a certain number of points. It appears that steadily decreased correlation values occurred at the Medium 2 task (14 data points). This finding is somewhat following RMSE analysis results where the transition point presents in Medium 1 task (10 data points). However, the boundary points to categorize the graph complexity into simple, medium and complex series were chosen arbitrarily. We had intended to do that to simplify the usability test in our first version of MAG. This approach implied a threshold value between 10-14 data points in the transition between simple and medium graphs before the performance of graph reproduction tasks decreases and became steady. Participants' feedback supported these findings after the experiment on the difficulty of the tests. They agreed that the estimation was easier in the simple category, and the difficulty was being moderate in the medium task and was very difficult in complex categories.

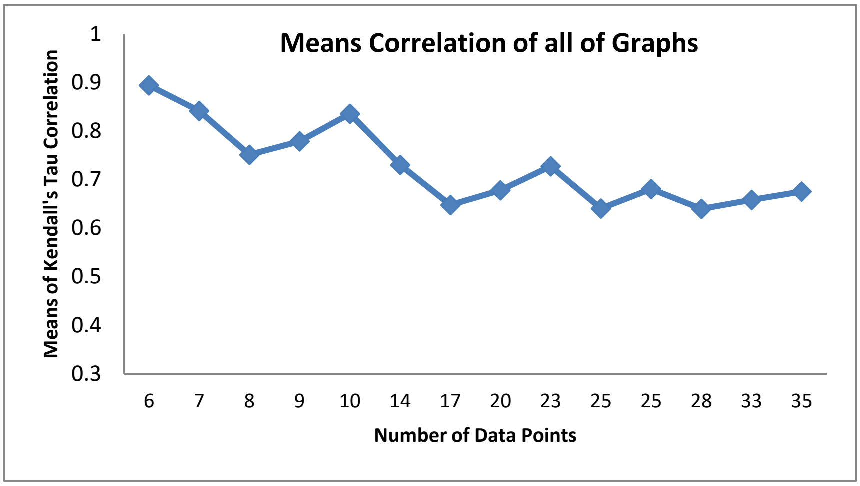


Fig. 3. Mean values of Kendall's Tau coefficient across all participants and number of data point complexity tasks.

Table 3. Means of Kendall Tau's Correlation Coefficient (CC).

Task	data points	CC	Task	data points	CC
Simple 1	6	0.894	**Medium 4**	20	0.678
Simple 2	7	0.842	**Medium 5**	23	0.727
Simple 3	8	0.752	**Medium 6**	25	0.641
Simple 4	9	0.779	**Complex 1**	25	0.681
Medium 1	10	0.836	**Complex 2**	28	0.640
Medium 2	14	0.731	**Complex 3**	33	0.658
Medium 3	17	0.648	**Complex 4**	35	0.676

5.3. Time interval between notes

To answer research question three, we recorded users' behaviour on the interval duration between data points while using the MAG app. The addition of the speed option allowed the participants to change the tempo of note playback. We monitored their choice of pause length by noting the setting of the search bar they were controlling whenever this changed. Each speed level from 1 to 5 represents 500 milliseconds (level 1) to a maximum of 2500 milliseconds (level 5). Figure 4 shows the summary of speed level selection to listen to the audio graph data from participant *Y*1 to *Y*12. It illustrates that the pause has increased slightly, from 0.82 s in the simple graphs to 1.09 s in the complex graphs. Further analysis using non-parametric statistics Kruskal-Wallis showed no significant differences in the time interval (χ^2= 3.169, *df*=2, *p* = 0.205).

Despite this insignificant result, listeners, however, took longer pauses to assess more complex graphs better. The majority of users selected the speed level of each data series with a single number or number of neighbours to each other (i.e., 1 (500 ms) to 2 (1000 ms) and 3 (1500 ms) to 4 (2000 ms). There are small indications that this may improve performance for identifying the shape based on their listening experience; thus, Brewster [41] suggested that pitch should be kept within a narrow.

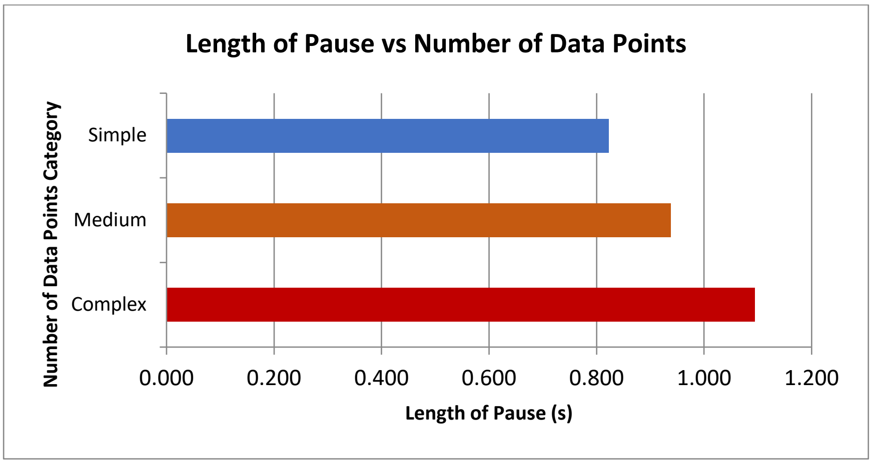


Fig. 4. Summary of user's length of pauses (in seconds) between data points compared to the task where the number of data points was varied.

6. Conclusions

This study aimed to explore our first design mobile auditory graph application feasibility for visually impaired users to better identify graph numbers and patterns. This exploratory study showed that sighted participants demonstrated the ability to create an approximately accurate mental model of the plots. We found the error increased in line with the increase of data points and remained stable after a certain number of points. While this finding is not entirely aligned with our initial assumption - increasing the number of data points would increase the number of errors-, this might be due to the learning effect because the listener could play the graph as often as needed. Further studies need to address this drawback by randomization on the order of tasks complexity and limit the trial of playback to three times. Despite the study limitation, these findings suggest that the design and analysis of mobile auditory devices have demonstrated the ability of sighted participants' to perform point estimation and graph reproduction tasks and provided important findings on the auditory graph design process in the context of interaction design.

The studies described here could be extended, for example, to apply to different types of plots other than line graphs such as pie charts and bar charts. It is likely that entirely new, or at least substantially revised sonification approaches than those reported here may be required to render these effectively. We plan to further refine MAG development by adding multi-touch gestures (i.e., swipe modality) to the presentation of auditory graphs. This feature can be an alternative tool for mental visualization and comprehension of data compared to passive listening (playback modality). Furthermore, given that most of the sighted participants could complete the graphical reproduction tasks, further studies with visually impaired users would be critical to get real users' feedback. In order for the BVI community to follow the future experiment, they should be familiar with the accessibility feature of the screen reader, have a basic understanding of musical notes, and have basic knowledge of graphical XY coordinates. The screen reader transmits any text or content shown on the display to a form that can be accessed by a BVI user by touch or auditory.

Nomenclatures

f	Forecasted values
o	True values

Abbreviations

BVI	Blind and Visually Impaired
MAG	Mobile Auditory Graphs
RMSE	Root-Mean-Square Error

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