AUDITORY GRAPHS: THE EFFECTS OF REDUNDANT DIMENSIONS AND DIVIDED ATTENTION

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ABSTRACT

An experiment is presented comparing the effectiveness of three parameters of sound for the auditory presentation of statistical data or auditory graphs. The dimensions of pitch, loudness, and time were used alone and redundantly to map the values of a box plot to an auditory graph. While previously, temporal mappings had resulted in better performance than mappings using pitch, panning, or loudness, these benefits were not consistently found in the current paradigm. Furthermore, to investigate possible benefits of mappings using two dimensions redundantly over mappings using one dimension, this experiment, compared mappings using integral and separable dimensions of sound - specifically, pitch and loudness (integral) and pitch and timing (separable). There was a benefit of a redundant design when the dimensions of sound used were integral whereas there was no benefit when they were separable. Finally, a task closer to a real-life application of auditory graphs was used where two sources of information were monitored simultaneously. The results support the argument that auditory graphs can be used effectively in “eyes busy” situations where more than one source of information is being monitoring.

1. INTRODUCTION

Statistical graphs are important for communicating parameters of a dataset and it is well documented that the visual presentation of graphs can be very effective [1, 2]. However, a visual presentation is not practical on devices without displays or with small displays (i.e., cell phones and PDAs), for individuals with visual disabilities [3, 4], and for divided attention tasks when the user’s eyes are otherwise occupied [5]. Sonification, or the representation of data through sound or non-speech audio, could be effective in these situations.

The designers of auditory graphs, however, face several challenges. The principles for designing effective auditory graphs are not as well documented as those for visual graphs. To this end, several researchers in the auditory display community have conducted investigations designed to identify and describe the elements of good design for auditory graphs. These elements include issues associated with appropriate tasks for auditory displays (e.g. trend analysis and point estimation [1, 2]), issues associated with the human user of these graphs (e.g. musical training, cognitive abilities [3, 4]) and effective methods of displaying the data (e.g. data dimensions, polarities and scaling of sound, adding context to auditory graphs, etc. [1, 5, 6]). This paper seeks to add to this body of knowledge and focuses on the effects of different dimensions of sound for one type of statistical graph: box plots. Box plots are widely used and important graphical displays. Moreover, their simplicity makes them well suited for testing the basic principles of design for auditory graphs.

Previous work on different elements of display has primarily investigated how sound dimensions could be “designed” to best display the information contained in a graph. While this body of work is important, there is a dearth of information regarding *which* dimensions of sound (e.g. pitch, loudness, tempo, timbre) should be used in these displays and what effects, if any, are there if the dimensions are used redundantly.

Peres and Lane [7, 8] conducted a series of studies specifically designed to investigate the effectiveness of pitch for auditory graphs as well as spatial location, loudness, and the temporal aspects of sound. While the latter three are not as frequently considered for use with the auditory graphs, there is some research suggesting that they may be effective dimensions for these displays [9, 10]. Furthermore, the Peres and Lane studies investigated the effects of using dimensions redundantly in auditory graphs. While there is reason to believe that in some contexts, using two sound dimensions together in a redundant fashion is a better representation of the data than could be achieved by the dimensions used individually [11], empirical evidence has not supported this [12, 13].

Essentially, the studies conducted by Peres and Lane had participants identify a visual box plot that matched an auditory box plot presented. The basic findings were that participants performed best when temporal aspects of sound were used to map the visual box plot to the auditory box plot. Moreover, there were no benefits of using dimensions of sound redundantly in this experimental paradigm. This pattern was consistent with the results of studies using a simple task in which participants map sounds to absolute numeric values [12, 13].

The experiment presented here was designed to continue the investigation on redundant dimensions and specifically compared auditory displays using integral and separable dimensions of sound. In speeded card sorting tasks, integral dimensions of sound result in better performance when two dimensions are used redundantly [14]. This experiment was designed to see if the benefit of integral dimensions of sound would generalize to the interpretation of auditory graphs and what impacts, if any, a divided-attention monitoring task would have on performance.

Previous research has found that frequency (or pitch) and loudness are integral [15, 16] whereas pitch and temporal are separable [17, 18], although the findings for the latter are not as consistent as those for the former. These dimension pairs (pitch and loudness, pitch and temporal) were used in the design of the auditory box plots for this experiment. Specifically, all of the participants had a condition in which redundant mappings are used for the sonified box plots. However, for one of the groups the redundant condition used the sound dimensions of pitch and loudness and for the other group pitch and time were the sound dimensions for the redundant condition. For each group, the dimensions were used both individually and redundantly to map the auditory box plots. For example, the participants in the pitch-loudness group performed the monitoring task in three different sound design conditions: pitch, loudness, and redundant (pitch and loudness).

One of the more valuable potential applications of data sonification is an "eyes busy" situation. These are situations requiring divided attention between a visual task and an auditory task simultaneously. Dual task performance generally places large demands on central capacity and results in decrements in task performance [19, 20, 21]. The investigation of these decrements is important to inform any application of sonification used concurrently with an eyes-busy task. One purpose of this experiment was to investigate whether the finding that participants are more accurate with temporal than with pitch mapping would generalize to situations in which there is little available processing capacity. It may be that the temporal dimension is more attention demanding than the pitch dimension and would therefore not be as effective in a dual-task situation. To investigate this, the participants in this experiment had a concurrent visual task for 50% of the trials. The visual task consisted of a target detection task in which the participant saw a series of visual images and had to indicate, as quickly as possible, when a visual target was been presented. A visual task with a reaction time requirement was chosen because it is thought to be attention demanding. This type of task is also, in an abstract way, similar to a real monitoring task where an individual is attending to information on visual display while simultaneously monitoring information from an auditory source.

2. METHOD

The task in the experiment was designed to roughly approximate a real-world task in which individuals had to monitor data and identify whether or not the data presented met certain criteria. The task used in this experiment required participants to listened to auditory box plots and identify whether or not the box plot was out of range. If it was out of range, the participants indicated which parameter was "off target" (i.e., it did not meet the target specifications for central tendency or skew). Successfully completion of this task required attention to the statistical parameters of the data.

2.1. Participants

All participants were undergraduate students between the ages of 18 and 24 from Rice University who received course credit and were randomly assigned to one of the two experimental groups—Integral or Separable. There were a total of 66 participants, 33 in the Integral group and 33 in the Separable group, all with normal hearing. There were 25 males and 41 females overall. Over half of the participants (35) had not had a statistics course before while 10 participants had 2 or more courses. Twenty-two of the participants who had taken at least one course in statistics reported doing better than average in the course. Half of the sample had three or more years of musical training while 33% had no musical training at all.

2.2. Procedure

Before the experiment, participants completed a 30-minute training session focused on familiarizing them with the sounds and the auditory task. After the training, they did the experiment and subsequently completed a survey asking them to provide demographic data as well as evaluate the sounds and the tasks. The experiment lasted approximately one and a half hours and consisted of 300 trials. The trials were completed in blocks of 25 with each block having one sound condition presented. The participants did four sets of three blocks and the order that the sound conditions were presented was counter-balanced. Thus the participants would have 25 trials with one type of sound, 25 trials with another type of sound and then 25 trials with the third type of sound. The sequence would then repeat three more times.

2.3. Equipment

For the experiment, eMac computers with a 17-inch flat screen monitor and Internet access were used and participants heard the auditory box plots through headphones. The training, experiment, and data collection were done using an interactive website with Java programming.

2.4. Task

The auditory task in this experiment was a monitoring task in which the participants listened to auditory box plots and identified when a box plot was "off target" for two different parameters (i.e., skew or location). The participants were instructed that the box plot could be off target for either skew or location but not both. For each trial of the auditory monitoring task, the auditory box plot was presented through headphones and once it finished playing, three buttons would appear on the screen. Participants would click on a button to categorize the auditory box plot as "In-Control," "Out-of-Control Location," or "Out-of-Control Skew" and were given feedback on their selection. If the participants incorrectly categorized the auditory box plot on the first attempts, they were told to try again until they got it correct. Participants clicked the "Next Trial" button to continue the experiment.

For the concurrent visual task, 10 images were presented while the auditory box plot was playing, thus the image changed every .82 seconds (the box plots were 8.2 seconds). The images were 215 pixels by 223 pixels and consisted of black circles with a diameter of 180 pixels on a gray background with a portion of the circle gone. Target images were those with 75% or more of the circle in black. Figure 1a shows an example of a target image and Figure 1b shows an example of a non-target image. When a target image appeared, the participant's task was to respond as quickly as possible by using the mouse to click the "Targe" button on the screen. The website provided feedback to the participants and when they clicked the "Target" button, the trial ended (regardless of whether they were correct). Targets appeared on 20% of the trials and only the trials without a target were used for data analysis. For the trials where participants only performed the auditory monitoring task, no images were presented.

Figure 1a *Example of a target image*

Figure 1b *Example of a non-target image (or a distracter)*

2.5. Stimuli

There were 75 different box plots used in the study and the values of these box plots were based on scale from –16.0 to 16.0. The box plots represented the "5 number summary" and were presented in the following order: minimum of the scale (as reference), minimum of the distribution, lower 25th, median, upper 75th, maximum of the distribution, and finally, maximum of the scale. They were built by combing different levels of skewness and location (both in-control and out-of-control). Skewness was varied by manipulating the proportions between the two inner quartiles and the two outer quartiles and location was varied by manipulating the median. The "out-of-control location" box plots had a median ranging from –4.0 to –6.0 while the "in-control" box plots had a median ranging from 1.0 to –1.0.

One-third of the box plots were "in control" (Normal) and were built by combining 5 levels of in-control skewness and in-control location. One-third of the box plots were out-of-control skew (Skewed) and were built using 5 levels of out-of-control skewness and in-control location. The last third of the box plots were out-of-control location (Location) and were built using 5 levels of out-of-control location and in-control skewness. The box plots were randomly selected for each trial from the set of 75 box plots.

For the separable dimensions, the pitch mapping was done by mapping the values from the box plots to a note on the equal tempered scale in the range of 16 notes below and 16 notes above 440 Hz. For the temporal mapping, the distances between the values of the box plot were represented by the time between the onsets of the sounds and the pitch of all the sounds remained constant at 440 Hz. The redundant condition was a combination of the pitch and temporal mapping.

For the integral dimensions, the pitch condition was identical to the one in the separable condition. The loudness condition used a range of 40 to 80 decibels and the values of the box plots were mapped to a decibel level in this range. For all conditions, an equal loudness adjustment was done to insure that the different pitches were perceived at the appropriate loudness for that pitch. In particular, for the redundant condition in the integral group, the pitch and the loudness mappings were used and both were adjusted so that the perceived pitch and loudness of each of the redundant sounds would be the same as the perceived pitch or loudness in either of the single dimension mappings. The algorithms used to make these adjustments were obtained from the International Organization for Standardization ISO 226 "Acoustics - Normal equal-loudness level contours" [22]. The decibel and Hz levels used were within the ranges used by Grau & Nelson in their work that documents the integrality of pitch and loudness in a speed sorting task [15], thus these ranges were assumed to be integral for the sake of stimuli here.

2.6. Measures

Performance on the visual task was measured by calculating the proportion of times the participants' accurately identified the target image. For the auditory task, Hit and False Alarm rates were used to calculate d' for the "out-of-control skew" (Skew) and the "out-of-control location" (Location) box plots. These values were calculated because they allowed investigation of the participants' ability to discriminate the targets from the distracters and whether this differed by the independent variables—integrality of dimensions (Integrality: Integral or Separable), auditory design (Design: Pitch, Loudness/Temporal, or Redundant), distribution type (Distribution: Skewed or Location) and task environment (Task: Single or Dual task). The measures were investigated in summary to look at overall performance as well as across the four blocks to investigate the changes in performance over time.

2.7. Design

The experiment was a factorial design with four independent variables—one between group variable (Integrality of dimension: 2 levels) and three within group variables (Auditory design—3 levels; Concurrent task—2 levels; Distribution type—2 levels). Table 1 outlines the design of the study and shows that for each of the Integrality of dimension groups, the participants monitored box plots with three different auditory designs: two single dimension auditory designs and one redundant design. Table 1 further shows that, for 50% of the trials, the participants were required to perform a visual monitoring task while they were conducting the auditory monitoring task. A visual target was presented in 20% of the visual monitoring trials. The participants were told that half of the trials would contain a visual task and, when present, it was the more important task thus to focus their efforts on it. The third within group variable was distribution type and participants were presented with all three distribution types in each level of the other variables.

Table 1 Outline of the four independent variables, both between and within.

Within Variables	Between Variable	
	Integral	Separable
Auditory design	Pitch Loudness Redundant	Pitch Temporal Redundant
Task	Single (auditory) Dual (+ visual)	Single (auditory) Dual (+ visual)
Distribution type	Location Skewed Normal	Location Skewed Normal

3. RESULTS

Results for both the visual task and the auditory task are presented for two independent variables, integrality (integral vs. separable) and auditory design (pitch, loudness/temporal, or redundant). Furthermore, for the auditory task, the results are also given as a function of task (single vs. dual) and distribution type (skewed vs. location).

3.1. Visual Task

As can be seen in Table 2, performance on the visual task was very high and did not differ by integrality (integral vs. separable) or auditory design (pitch, loudness/temporal, or redundant).

Table 2 Proportion of correct responses for the visual task as a function of Integrality and Design.

	Integral	Separable
Pitch	0.968	0.957
Loudness/Temporal	0.956	0.958
Redundant	0.958	0.965

3.2. Auditory Task

Before any analysis of the auditory task was conducted, the following trials were excluded: any trials with a visual target presented (~10% of the trials), trials where the participant incorrectly responded that a target was present (1% of the trials), and trials where there was no record of any response from the participant (~.002% of the trials).

Each participant had four blocks of the three types of auditory design. Overall, participants' performance increased over the four blocks (Table 3) and this increase did not differ by integrality, design, or task (see [8] for more details). The first block was considered training and all subsequent analysis were conducted on blocks 2 – 4.

Table 3 Hit and False Alarm Rates as a function of Integrality and Block.

	Block 1	Block 2	Block 3	Block 4
Hits				
Integral	0.42	0.51	0.56	0.54
Separable	0.39	0.40	0.40	0.41
False Alarms				
Integral	0.50	0.47	0.57	0.58
Separable	0.49	0.61	0.52	0.74

As mentioned previously, the hit and false alarm rates were used to calculate the d' scores for each subject. For both the skewed and location distributions, there were participants whose d' had to be estimated because it could not be calculated. For example, some participants had no false alarms and perfect hit rates for some conditions. A d' for these participants would be infinitely large and thus had to be approximated for the purposes of data analysis. Table 4 shows the types of situations where d' could not be calculated and the d' assigned to those participants for those conditions. There were 29 participants with a false alarm rate of zero, 21 with participants with a hit rate of 1 and 5 participants with a hit rate of 0.

Table 4 Criterion for assigning d' when it could not be calculated.

Hit Rate	False Alarm Rate	Assigned d'
0.00	--	0.0
> .05	0	3.5
1.00	> 0	3.5
1.00	0	4.0

Table 5 gives the mean d' for the Skewed and Location distributions. To investigate any benefit of a redundant design, the mean d' values of the better of the two single dimension were compared to the mean d' values for the redundant designs. As seen in Tables 5, this was primarily pitch for the integral conditions and temporal for the separable conditions.

Table 5 Mean d' for Skewed and Location distributions as a function of integrality and task condition.

Integral	Pitch	Loud	Redund
Location			
Single	0.85	0.97	1.14
Dual	0.88	0.74	1.17
Skewed			
Single	1.59	1.29	1.89
Dual	1.38	1.17	1.71
Separable	**Pitch**	**Temp**	**Redund**
Location			
Single	0.98	1.58	1.70
Dual	0.70	1.44	1.32
Skewed			
Single	1.45	1.92	1.95
Dual	1.17	2.10	1.99

To investigate the effects of the independent variables on the participants' ability to identify the Skewed and Location distributions a mixed design ANOVA was conducted for integrality (2: integral, separable), design (2:better, redundant), task (2: single task, dual task), and distribution type (2: Skew, Location). Integrality was the between subject variable and the within subject variables were design, task, and distribution type. Figure 2 shows the distributions of d' values for the integral and separable conditions. As seen in Figure 2a, for the integral conditions, the d' values are higher for the redundant design than the better design. However, in the separable conditions (Figure 2b) there is practically no difference between the better and the redundant designs. This design by integrality interaction was significant, $F(1,64) = 5.13$, $p = 0.027$, and did not differ as a function of distribution type or task, $F(1,64) = 0.09$, $p = 0.77$ and $F(1, 64) = 0.53$, $p = 0.470$ respectively. While the performance for the dual task conditions was lower overall, these differences are not significant nor were any of the interactions with stimuli, design, or integrality.

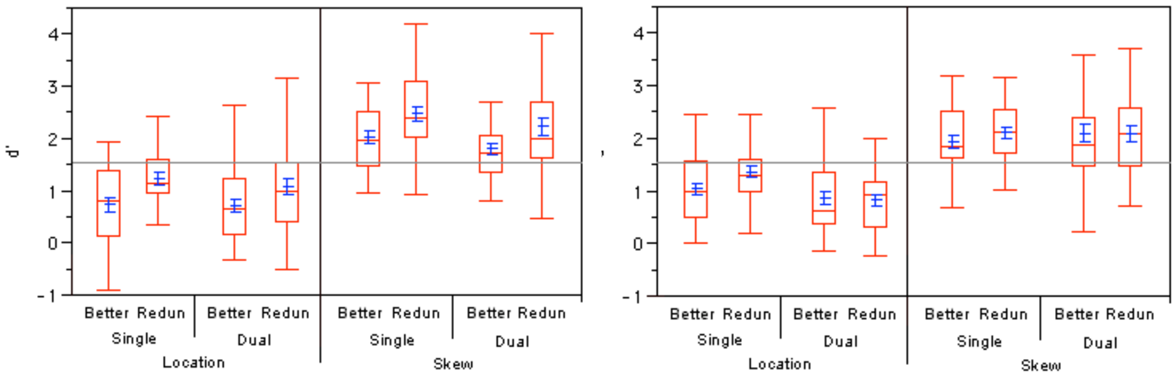

Figure 2a *Box plots for the Integral conditions.*

Figure 2b *Box plots for the Separable conditions.*

Figure 2 *Box plots for the Integral (2a) and Separable (2b) conditions as a function of distribution type, task, and design. In addition to the median, each box plot shows the mean ± 1 standard error. The horizontal lines traversing the graphs indicate the grand means.*

Although Block 1 was considered practice, it seemed worthwhile to investigate the effects of the independent variables on performance for this block. As seen in Table 6, participants had lower d' scores for the dual task than the single task, F(1, 64) = 5.61, p = 0.021. This difference was a substantial for the Location distributions and smaller for the Skew distributions. This interaction was significant, F(1, 64) = 14.35, $p<0.001$. Neither the effect of integrality, F(1, 64) = 0.25, p = 0.616, or any other interaction approached significance.

Table 6 Mean d' for the first Block as a function of Task, Integrality, and Distribution type.

	Single	Dual	Difference
Location			
Integral	0.80	0.54	0.27
Separable	0.93	0.75	0.18
Skewed			
Integral	1.17	1.02	0.15
Separable	1.18	1.08	0.09

4. SUMMARY

One of the motivations for this experiment was to address whether the previous findings of no benefit for using dimensions of sound redundantly would generalize to auditory designs using integral dimensions of sound. For this task and these stimuli, the redundant design using integral dimensions of sound resulted in better performance over the better of the two single dimension mappings whereas for the separable dimensions, the redundant design did not benefit performance. The approximate difference in d' (collapsing across task) between the better of the single dimensions and the redundant design for the Integral group was 0.25 for the Location distributions and 0.23 for the Skewed distributions. For the Separable group, these differences were not statistically significant and were only 0.01 for the Location distributions and 0.06 for the Skew distributions. These results suggest that for a task such as this, auditory displays using integral dimensions redundantly can improve the user's performance.

The task in this experiment was designed to very roughly approximate a real-life monitoring situation where people would be simultaneously monitoring two sources of information. While performance was degraded for the dual task environment for the first block of trials, this effect did not continue after the first block. Participants may have learned to interleave the two tasks into one after the first block. This suggests that the use of auditory displays of data in an "eyes busy" environment may be an appropriate application for sonified graphs.

5. DISCUSSION

The redundancy gains found in this experiment are consistent with the body of research on redundancy gains using a card-sorting task. However, it is not certain that the redundancy effects that occurred in the present experiment were because the dimensions were integral. It could be simply that there is a redundancy effect for some pairs of dimensions and not others and it just so happened the two dimensions used here showed a redundancy gain.

There was a lot of variability in participants' performance with d's varying from –1.47 to 4.00. Participants generally found the task difficult. However, their performance improved after training and asymptoted quickly. Although this experiment was not designed to compare participants' ability to identify skew or central tendency, it does seem that the skew was easier for the participants to identify. A possible explanation for this is that the number of values needed to identify a skewed box plots is fewer than the number needed to identify a location or control box plot. For these box plots, all of the skewed distributions had three values close together (minimum, 25th percentile and the median); thus, if three values were heard that were very similar, that display could easily be identified as skewed. For the "In-Control' and "Out-of-Control Location" stimuli, the participants had to listen to all seven sounds in the auditory display before determining anything about the distribution represented by those sounds.

One finding with implications for the use of sonification in divided attention tasks was participants' ability (after 75 trials of practice) to perform equally well in the auditory monitoring task for both single and dual task environments. While there are some who feel that dual-task deficits almost always disappear with practice [23], the fact that so little practice was needed for this task is noteworthy for those looking to incorporate auditory displays into complicated monitoring environments.

All of the experiments presented here used a fixed stimulus design and the different type of box plots were specifically designed to be distinguishable from each other. As with all designs of this type, it is possible that the results obtained here are limited to the specific stimuli used, thus caution must be used when generalizing these results.

The study of sonification often uses sound experimental methods to test the effects and uses of particular displays. Given that humans are the ultimate users of these displays, it is also important to have the designs and implementations of these displays guided by sound psychological theory. Appropriately applied, the theories of perception and information processing provide important information and allow for predictions regarding how people will perform when interpreting auditory graphs. Although these experiments were not designed to test a theoretical position, this paper presents results suggesting that the body of work on the perceptual effects of integral dimensions of sound (specifically, redundancy gains with integral dimensions) can meaningfully inform the ongoing research on appropriate design guidelines for auditory graphs.

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