Journal of Experimental Psychology: Applied
2009, Vol. 15, No. 3, 183–198

1076-898X/09/$12.00 DOI: 10.1037/a0016329

Sonification Design for Complex Work Domains: Dimensions and Distractors

Janet E. Anderson
The University of Queensland

Penelope Sanderson
The University of Queensland

Sonification—representing data in sound—is a potential method for supporting human operators who have to monitor dynamic processes. Previous research has investigated a limited number of sound dimensions and has not systematically investigated the impact of dimensional interactions on sonification effectiveness. In three experiments the authors investigated accuracy for identifying changes in six target auditory dimensions of a continuous pulse stream under three conditions: no distractor, one distractor, and five distractors. In Experiment 1 amplitude, frequency, harmonics, speed, tremolo (cycles per pulse), and width were tested. Accuracy and patterns of interaction between the dimensions were mapped. In Experiment 2 the same dimensions were tested but tremolo was operationalized as cycles per second (Hz). The patterns of interaction between the temporal dimensions differed from Experiment 1. In Experiment 3 the amplitude contour of the pulse stream was changed. The dimensions tested were amplitude, frequency, formants, speed, tremolo (cycles per period), and width. Results showed low accuracy for formants and many interactions, both positive and negative between the dimensions. The authors interpret the results in terms of theories of perceptual interference in auditory dimensions.

Keywords: sonification, perceptual interaction, auditory perception, auditory attention, auditory display

In this paper, we explore the potential of six auditory dimensions for conveying information in a sonification. Our research was originally stimulated by the challenge of representing six patient vital signs in sonified form for use by anesthetists, but the experiments reported here handle the problem at a much higher level of generality. In the remainder of the introduction we introduce the case for sonification during patient monitoring in anesthesia. Then we address the problem of how to satisfy constraints relating to the discriminability between levels and the range of levels needed in a sonification, and the problem of interactions between acoustic dimensions. Finally, we introduce the three studies to be reported here.

Sonification in a Complex Domain

In complex work domains, such as anesthesia, attention must be drawn quickly to important information because any delay could compromise safety (Manser, Howard, & Gaba, 2008; Phipps, Meakin, Beatty, Nsoedo, & Parker, 2008). Auditory alarms are often used to draw attention to vital signs that move outside the normal range. Although alarms can be designed to convey the degree of urgency of a departure from normality (Hellier & Edworthy, 1999), they typically do not communicate the nature of the problem or distinguish between expected and unexpected problems (Seagull & Sanderson, 2001) or degrees of urgency (Haas & Edworthy, 1996; Stanton & Edworthy, 1999; Woods, 1995).

An alternative approach is to develop auditory displays that allow operators to monitor processes continuously and preattentively without significantly interrupting current tasks and without shifting visual attention (Woods, 1995). Several researchers have suggested that sonification could meet the need for displays that can be processed preattentively or outside of conscious awareness (Loeb & Fitch, 2002; Watson & Sanderson, 2004; Woods, 1995; Xiao, Mackenzie, Seagull, & Jaberi, 2000). Sonification—also called data auralization by Gaver (1997) and parameter mapping by Barrass and Kramer (1999)—is a type of auditory display in which data variables are mapped onto auditory dimensions. Changes in the data are reflected in changes in the sound parameters. Sonification allows several data variables to be represented by different dimensions of the sound.

In anesthesia, the pulse oximetry sonification is almost universally used for monitoring heart rate and oxygen saturation (Stoelting & Miller, 1994). Heart rate is mapped to the speed of a series of beeps and oxygen saturation is mapped to their pitch. Researchers have recently created complex multivariable sonifications that extend the pulse oximetry sonification.

Pioneering work carried out by Fitch and Kramer (1994) resulted in a sonification of eight physiological variables over two auditory streams. Two variables were mapped to one stream and six variables were mapped to the second stream. Fitch and Kramer

Janet E. Anderson, School of Psychology, The University of Queensland; Penelope Sanderson, School of Psychology, School of Information Technology and Electrical Engineering, School of Medicine, The University of Queensland.

Anderson is now at NIHR King's Patient Safety and Service Quality Research Centre, King's College London.

Sanderson is coinventor with Marcus Watson of a sonification design to support auditory monitoring of respiration, outlined in U.S. patent 7070570 (Sanderson and Watson).

We thank Tim Barrass and Mike Norris for their assistance with creating the stimuli for these experiments and Matthew Thompson for helping with the arrangements for Experiment 2. Some of the results of Experiment 1 were presented in Anderson and Sanderson (2002) and some of the results of Experiment 3 were presented in Anderson, Sanderson, and Norris (2002). The present report contains further analyses.

Correspondence concerning this article should be addressed to Janet Anderson, NIHR King's PSSQRC, King's College London, Strand Bridge House, 138-142 Strand, London, WC2R 1HH. E-mail: janet.anderson@kcl.ac.uk

(1994) showed that participants identified patient condition more accurately and more quickly with sonification than with either visually displayed data or a combination of sonified and visually displayed data. More recently, Loeb and Fitch (2002) created a two-stream sonification of six variables with speed, pitch, and timbre carrying information on each of the two streams (a repeated mapping of dimensions to streams). In a further study, Watson and Sanderson (2004, 2007) used the existing pulse oximetry display of heart rate and oxygen saturation as one stream and added a second stream for respiration, in which pitch, relative pitch, speed, and amplitude represented different respiratory parameters.

Higher-dimensional sonifications such as the ones described have been created by mapping dimensions to more than one auditory stream. Both Loeb and Fitch (2002) and Watson and Sanderson (2004) used repeated mappings of pitch and speed across two streams, and Loeb and Fitch (2002) also used repeated mappings of timbre across the two streams. To design an effective single stream sonification of more than a few dimensions, designers need to know how many dimensions can be usefully varied on one stream and which auditory dimensions are best suited to carrying information.

The three experiments reported in this paper operationalized and tested the effectiveness of six auditory dimensions that could be used for a potential single-stream sonification of data with the level of complexity required for anesthesia monitoring (although the results are not intended to be used for anesthesia monitoring). The choice of auditory dimensions for carrying information depends both on the ability of users to perceive changes in the dimensions and on users' expectations of the meaning of changes in the dimensions and the data represented (Guillaume, Pellieux, Chastres, & Drake, 2003; Walker, 2007). The present studies examined the perceptual aspects of the dimensions.

The three experiments were designed to provide empirical data in three areas. First, the intention was to investigate the discriminability and relative sensitivity of six auditory dimensions and so provide data about their potential usefulness for sonifying complex data. Second, the interaction between simultaneously changing auditory dimensions was explored. If performance is degraded when there are simultaneous changes, we wanted to know how much it is degraded and in which areas. Third, the studies explored how the design configuration of the sonification affected discriminability.

Discriminability of Dimensions

Sonification designers require information about the discriminability and range of the dimensions that might be used to convey information. The psychoacoustic literature provides basic guidance about the sensitivity of the auditory system to changes in specific auditory dimensions (e.g., Drake, Botte, & Baruch, 1992; Handel, 1989; Hirsh, Monahan, Grant, & Singh, 1990; Moore, 1997). These data may be of limited relevance, however, to the problems of sonification design (Anderson & Sanderson, 2004; Walker & Kramer, 2004) for several reasons.

First, the relevance of much psychoacoustic research to the design of sonification is typically low (Walker & Kramer, 2004). The test sounds used are unlike those that would be heard by a user interacting with an auditory display and psychoacoustic studies usually employ static stimuli composed of tones that are less harmonically complex than those used in sonification (Walker & Kramer, 2004). Furthermore, studies are usually conducted in ideal laboratory listening conditions, whereas a sonification will often be heard in a noisy environment with competing sounds.

Second, psychoacoustic studies typically examine the smallest differences between stimuli that can be perceived (D'Amato, 1970). Such discriminations will not be effective in applied domains, where changes in the sound must attract attention even when the listener is engaged in other tasks. Differences should be well away from threshold levels.

Third, not all dimensions offer the same range of discriminable steps (Barrass & Kramer, 1999; Kramer, 1994a, 1994b). It may not be possible to map certain data variables onto auditory dimensions when those auditory dimensions cannot be divided into enough discriminable steps.

In a paper on design principles for auditory displays, Kramer (1994b) recommended that overall loudness, pitch, and brightness could carry information and could be manipulated or "nested" to produce many more dimensions. Designers need to know the number of steps that can be reliably discriminated for these and other dimensions. Experiments are needed which test the discriminability of dimensions within the constraints of a domain of application so that the number of values required and the differences between adjacent values are realistic.

Interactions Between Dimensions

To support different forms of monitoring, changes in auditory dimensions need to be clearly perceptible even when several auditory dimensions change at once, otherwise the effectiveness of the sonification will be reduced (Barrass & Kramer, 1999; Neuhoff, Kramer, & Wayand, 2002; Walker & Ehrenstein, 2000). If the changes are not perceptible the operator may need to refer to visual displays, so obviating the benefits of sonifying the data.

Perceptual interactions between the tonal properties of sound, such as pitch, timbre, and loudness, have been found with static stimuli (Grau & Kemler Nelson, 1988; Kemler Nelson, 1993; Krumhansl & Iverson, 1992; Melara & Marks, 1990a, 1990b) and with dynamic stimuli (Neuhoff, Kramer, & Wayand, 2002; Neuhoff & McBeath, 1996; Neuhoff, McBeath, & Wanzie, 1999).

Temporal dimensions have not received as much attention in the research literature as tonal dimensions. However, some studies suggest that interactions between temporal dimensions and tonal dimensions occur. For example, interactions have been found between timing and intensity (Tekman, 1997), inter-onset interval and intensity (Tekman, 2002), and pitch and tempo (Collier & Hubbard, 2001). Rhythm has also been shown to interact perceptually with pitch (Boltz, 1998; Jones, Boltz, & Kidd, 1982). Temporal dimensions such as pulse speed and pulse width might also interact, and there might also be more extensive interactions between tonal and temporal dimensions. Empirical data are needed on how much performance is degraded when two or more auditory dimensions change, but designing experiments to investigate this is challenging. It is difficult to examine all potential interactions that might affect the intelligibility of a sonification because the range of one dimension can limit the range of another. Changes in some tonal dimensions can be difficult to hear when pulse width is very short. The size of the experiment quickly increases when there are a number of dimensions, a number of distractors and a range of values for each. Nevertheless, it is important to investigate the nature and extent of this problem for sonification designers.

Design Configuration

Perceptual interactions between auditory dimensions can reduce the perceptibility and therefore the usefulness of a sonification, but such interactions can possibly be overcome through innovative sonification design. Although a more principled approach to auditory display design is needed (Barrass, 1998; Kramer et al., 1999) and extensions of techniques such as Ecological Interface Design have been proposed (Anderson, 2005; Sanderson, Anderson, & Watson, 2000; Watson & Sanderson, 2004, 2007) very few reports address problems encountered when designing sonifications with many dimensions.

The Present Studies

The purpose of the three experiments was to explore discrimination performance with six auditory dimensions and hence to provide guidance on their usefulness for sonification. Although neither real nor simulated physiological data were used, the aim was to conduct the research within the constraints imposed by the anesthesia domain—the number of dimensions typically monitored and the approximate grain of discriminations needed. A change identification task was used to assess whether participants could detect when a particular dimension changed and in which direction it changed. A sonification user may also have to identify the absolute value and interpret the meaning of the change, but this was not assessed in the present studies.

In Experiment 1 we investigated people's ability to identify changes accurately in six auditory dimensions: amplitude, frequency, timbre (harmonics), pulse speed, tremolo, and pulse width. We tested discriminability for each dimension with no distraction from changes in other dimensions, with distraction from a change in one other dimension, and with distraction from changes in all five other dimensions. Timbre was operationalized as harmonics. Preliminary work on scaling the dimensions resulted in tremolo being operationalized as cycles per pulse. In Experiment 2, the stimuli were as in Experiment 1, except that tremolo was operationalized as cycles per second (or Hz) so that it varied independently of pulse width. In Experiment 3 the pulses were heard against a quieter background sound that allowed more information to be extracted when pulse width was short. Timbre was operationalized using formant frequencies and tremolo was operationalized as cycles per period.

In all experiments participants had to judge whether a specified dimension increased, decreased or stayed the same. Chance responding would therefore result in 33% accuracy. Determining the precise level of accuracy required for safe operation in a domain was beyond the scope of the present studies and would require complex analysis of the tasks and other information support available in the domain. Therefore, we evaluated whether accuracy was higher than the level of chance responding. Although responding more accurately than a 33% accuracy rate might not be considered very high performance, we argue that testing against this chance level is a stringent test of the discriminability of the dimensions.

These studies were conceived as incremental design studies, intended to explore people's ability to discriminate changes in a coherent stimulus set, rather than to test theories of auditory perception or attention. Although we could not with propriety use statistical techniques to test differences between the results found in each experiment, we applied practical knowledge to judge, where necessary, whether differences observed between the experiments would have a noticeable impact in an applied domain.

Experiment 1

The aim of Experiment 1 was to assess discrimination performance with six auditory dimensions when participants used selective attention to listen for a single change in a target dimension. The dimensions were amplitude, frequency, timbre (harmonics), speed, tremolo, and width. These dimensions were chosen following a pilot study of discrimination accuracy for changes in amplitude, frequency, timbre (harmonics), speed, vibrato frequency, and width (Anderson, 2004; Experiment 1). The stimuli were two successive sequences of pulses. Participants stated whether the nominated target dimension had the same value in both sequences or whether its value increased or decreased in the second sequence. Pilot results showed that discrimination with no distractors was only 64% for vibrato (Anderson, 2004), so vibrato was replaced with tremolo for Experiment 1.

We also assessed whether listeners could accurately report changes in the target dimension independently of changes in other dimensions. Discrimination was tested in three conditions: with no changes in other auditory dimensions (no distraction), with a change in one other auditory dimension (one distractor), and with a change in all the other five dimensions simultaneously (five distractors).

There were two hypotheses for Experiment 1. First, we hypothesized that the relative effectiveness of the dimensions would vary. We expected discrimination performance for all dimensions to be above the 33% level of chance responding. Second, we hypothesized that distractors would reduce discrimination accuracy.

Method

Participants

The participants were 12 undergraduate psychology students who received course credit for their participation. They all reported having normal hearing and were between 17 and 32 years old ($M = 20.64$, $SD = 4.93$). For the seven participants who had received musical training, the average length of training was 3.21 years ($SD = 1.99$).

Stimuli

Apparatus and presentation. The stimuli were generated using Csound software version 4 (Boulanger, 2000). Each sound sequence was stored in a .wav file. A Dell workstation with an external Extigy sound card and Phillips speakers was used to present stimuli to participants and to collect responses.

Mapping of streams and dimensions. Representative mappings of physiological variables to acoustic dimensions were made to establish ranges for the acoustic dimensions used in this experiment. In contrast to previous studies (Loeb & Fitch, 2002; Watson & Sanderson, 2004) the six dimensions were mapped to a single stream rather than to two streams. Oxygen saturation was mapped to frequency and heart rate was mapped to speed. This configuration is already used for the pulse oximetry sonification (Bradrakumar, Ball, Jefferson, & Lindhoff, 2001; Stoelting & Miller, 1994). It is appropriate for a rate variable such as heart rate to be mapped to the speed of the pulses. Similarly, respiration rate was mapped to a speed variable—here, tremolo frequency. Increasing blood pressure was mapped to pulse width. Carbon dioxide was mapped to harmonics and tidal volume to amplitude. With these mappings established, it was possible to determine the number of values that should be represented for each of the physiological variables, taking into account the range of the acoustic dimension. Again, these mappings are not design recommendations.

Construction of timbre and tremolo. Table 1 shows how each of the six auditory dimensions was operationalized. The implementation of timbre and tremolo is described here in more detail. To produce changes in timbre, the harmonic composition of the sound was manipulated. A sound with 16 equal-strength harmonic partials was filtered using a 500 Hz-wide bandpass filter to produce a linear dimension. Timbre was manipulated by changing the center frequency of the filter so that different frequency harmonics were selected. The sound was full and round at one end of the range, and thin and sharp sound at the other end. A spectrographic analysis of the nine timbre levels chosen was carried out to ensure that the power envelopes for the levels were comparable.

Tremolo was operationalized by creating a series of rapid rises and gradual decays of amplitude within each pulse (see Figure 1),

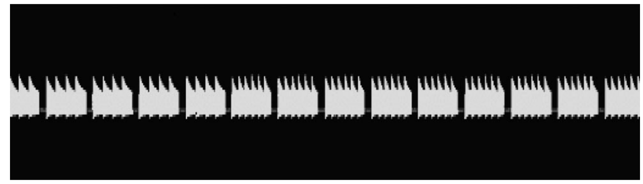

Figure 1. Temporal trace for tremolo. The waveform is shown with tremolo evident as distinctive rises and decays in amplitude within each pulse. The example shows a change in the number of tremolo cycles from four per pulse to six per pulse.

which created the perception of corrugations within the pulse. Preliminary work showed that when tremolo was operationalized as cycles per second, changes in tremolo were not discernible for many tremolo values and pulse width values. Only when pulse width was greater than .35 seconds was tremolo (cycles per second) audible through its full range. When tremolo was operationalized as cycles per pulse, however, tremolo was audible for all pulse width values except for the shortest pulse width, .03. Therefore, tremolo was operationalized in Experiment 1 as the number of tremolo cycles per pulse.

Stimulus changes and ranges. Participants made discrimination judgments with and without distraction. In the no distractor condition, only the target auditory dimension changed. In the

Table 1
Stimuli Description and Values Used for All Experiments

Auditory dimension	Implementation	Low range values	Middle range values	High range values	Value when not the target dimension (i.e., held constant)
Amplitude	Csound amplitude values. Experiments 1 and 3.	5,000	40,000	80,000	10,000
		10,000	50,000	90,000	
		20,000	60,000	100,000	
	Csound dB. Experiment 2.	56	68	76	72
		62	72	82	
		68	76	86	
Frequency	Hertz. Experiments 1 and 3.	174	354	606	440
		192	372	624	
		210	390	642	
	Mels. Experiment 2.	250	450	730	490
		270	470	750	
		290	490	770	
Timbre	Harmonic changes induced by filtering with a 500 Hz wide band pass filter. Experiments 1 and 3.	50	3,000	6,000	250
		1,100	4,000	7,000	
		2,000	5,000	8,000	
	Formant frequencies. Experiment 2.	1	4	7	5
		2	5	8	
		3	6	9	
Pulse speed	Pulses per second.	.60	1.02	1.95	1.2
		.76	1.19	2.12	
		.93	1.36	2.29	
Tremolo	Cycles per pulse (Experiment 1) and Cycles per period (Experiment 3)	2	8	18	10
		4	10	22	
		6	12	30	
	Cycles per second. Experiment 2.	2	8	20	10
		4	10	40	
		6	15	80	
Pulse width	Duration of the pulse in seconds	.03	.15	.3	.7
		.06	.2	.35	
		.1	.25	.4	

one-distractor condition, at the same time as the change in the target dimension, a change also occurred in a distractor dimension. Each target dimension was tested with simultaneous changes in every other dimension as a distractor. In the five distractor condition, changes occurred in all dimensions simultaneously and participants listened to a particular target dimension.

The values of each of the six dimensions in low, middle, and high ranges (see below for an explanation of ranges), and the change in the stimulus values for each increment are also shown in Table 1. Each dimension was scaled so that there were at least nine steps. Preliminary tests established that all steps were discriminable (Anderson, 2004).

Because it was not practical to test discrimination between all adjacent values in each auditory dimension, three values were chosen from each of the low, middle, and high parts of the range for testing. For pulse speed, values that were 10 increments per minute apart were chosen but for the other parameters adjacent values were used. The number of trials in which the target dimension increased, decreased, and stayed the same was determined by the number of comparisons that were possible. With three values in each part of the range, only the lower two values could increase and the upper two decrease and still stay within their part of the range, whereas all three values could remain the same.

Distractor dimension changes could be either an increase or decrease in the value of the dimension. For each target dimension in each distraction condition, there were four trials out of seven in which the dimension changed. The stimuli were constructed so that across different trials, increases and decreases in the target dimension were accompanied by an equal number of increases and decreases in the distractor dimension. Of the three trials in which the target dimension did not change, one of the trials had the distractor dimension increase, one had the distractor dimension decrease, and the third trial was randomly assigned to either an increase or decrease in the distractor dimension. In the five distractor conditions, for a given trial there was one target and five distractor dimensions and seven trials for each target dimension. Therefore, the number of times a distractor dimension increased or decreased could not be precisely controlled. However, the direction of the changes in the distractor dimensions was not as important as the fact that all the dimensions changed at once.

Stimulus sequences. The stimuli were sequences of pulses that were approximately 10 seconds long. When speed was varied the length of the sequences also varied slightly to ensure that whole pulses were heard instead of a pulse being truncated. Participants attended to a target auditory dimension, such as frequency, and indicated whether the target dimension increased, decreased, or stayed the same. The position of the change in the sequence of pulses varied but there were always at least two pulses before the change and at least two after. The stimulus sequences were long enough that expectancy effects could be avoided by varying the position of the change in the sequence, but not so long as to induce vigilance problems as participants listened for a single change. The times at which the changes could occur were 4.2, 5.8, 6.7, and 7.5 seconds after the start of the sequence, except for trials in which speed changed. As speed changed these times varied slightly to ensure that whole pulses were heard before the start of the change.

In the no distractor condition and the five distractor condition there were 21 trials per dimension. For the one-distractor trials, each target dimension was tested with every distractor (five combinations per dimension), so only the middle part of the range was tested to ensure that the experiment was not too long. This created 35 one distractor trials per dimension. There were 462 trials in the experiment and testing took approximately 2 hours per participant, including rest breaks.

Procedure

The independent variables were manipulated within subjects. Trials were blocked according to the auditory dimension serving as the target and were randomized within the dimension. The presentation order of the dimensions was also randomized. All participants first received the no-distractor trials for all dimensions, then the one-distractor trials for all dimensions, and finally, the five-distractor trials for all dimensions. Although presenting the distractor conditions in this order potentially introduced either fatigue or practice as confounds, it ensured that participants were exposed to the sound of the target dimension changing on its own before distraction was introduced.

Before the trials for each dimension, participants read an explanation of the target acoustic dimension named on the screen and heard two examples of changes in that dimension. For timbre, for example, the participants were told that timbre produces a change in the quality of the sound, and that in the present study the sound changes from a full, round sound at one end of the range to a thin squeaky sound at the other end of the range. They then heard two repetitions of a sequence in which the sound progressed through the range of variation of the target dimension.

In the distractor conditions, participants were informed that other dimensions would change in addition to the target dimension and that their task was to concentrate on the target dimension only. Participants were not informed of the underlying mapping of physiological measures to acoustic dimensions. On completion of the trials for each dimension, participants were asked to rate on a seven-point scale how easy or difficult it was to identify the changes.

Results

The results were analyzed using two-way within-subjects ANOVA. Where appropriate, post hoc comparisons were carried out with two-tailed *t* tests with a Bonferroni correction applied to the significance level. Where Mauchly's Test of Sphericity was significant the Greenhouse Geisser correction was used and the adjusted degrees of freedom are reported. Cohen's *f* was calculated to indicate the effect size and interpreted according to Cohen's (1988) classification: an *F* value of .10 is a small effect, .25 is a medium effect, and .40 is a large effect. *t* tests were used for specific comparisons and effect sizes for significant results were calculated using Cohen's *d*. For Cohen's *d* .2 indicates a small effect, .5 a medium effect, and .8 a large effect (Cohen, 1988).

Accuracy

The main findings were that accuracy differed according to which dimension was the target dimension, and that changes in distractor dimensions affected participants' ability to identify changes accurately (see Figure 2). Data were analyzed using a repeated-measures ANOVA with the factors of target dimension and number of distractors. There was a significant main effect for dimension, $F(5, 55) = 21.772$, $MSE = .016$, $p < .001$, $f = .55$ and

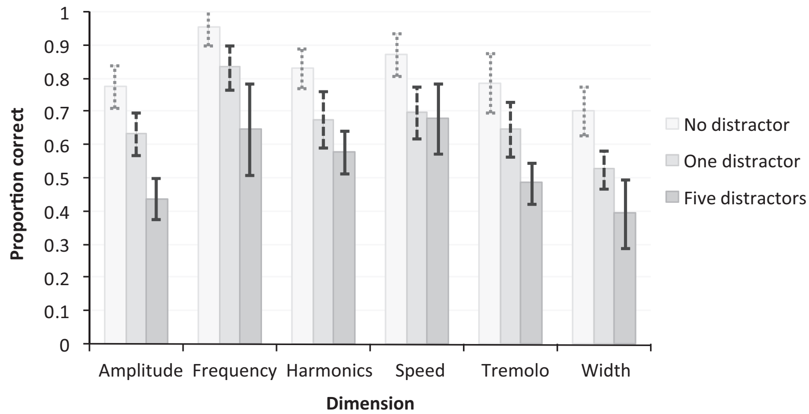

Figure 2. Mean accuracy (proportion correct) for dimensions in Experiment 1, across no, one, and five distractors. Error bars show the 95% confidence interval.

for number of distractors, $F(2, 22) = 71.774$, $MSE = .020$, $p < .001$, $f = .81$. The interaction was not significant, $F(4.11,45.20) = 1.378$, $MSE = .027$, *ns*.

Post hoc analysis of the dimension main effect was carried out with the *p* value required for significance adjusted to account for the 15 comparisons conducted. The adjusted *p* value was .003. Accuracy for frequency ($M = .81$) was significantly higher than for amplitude ($M = .61$), $t(11) = 4.80$, $p < .001$, $d = 2.28$, tremolo ($M = .64$), $t(11) = 3.86$, $p < .001$, $d = 1.88$, and width ($M = .54$), $t(11) = 6.08$, $p < .001$, $d = 3.45$. Accuracy for speed ($M = .75$) was significantly higher than for amplitude $t(11) = .4.85$, $p < .001$, $d = 3.02$ and width $t(11) = 2.43$, $p < .001$, $d = 3.08$. Accuracy for harmonics ($M = .69$) was significantly higher than for width $t(11) = 7.46$, $p < .001$, $d = 2.74$ and accuracy for tremolo was significantly higher than for width $t(11) = 4.01$, $p < .002$, $d = 1.66$.

Post hoc analysis of the distractor main effect with the adjusted *p* value of .016 found that accuracy was significantly worse for one distractor ($M = .67$) than for none ($M = .82$), $t(11) = 5.61$, $p < .001$, $d = 2.07$ and significantly worse for five distractors ($M = .54$) than for none, $t(11) = 12.62$, $p < .001$, $d = 4.56$ and one, $t(11) = 6.23$, $p < .001$, $d = 1.70$.

The 95% confidence intervals were examined to determine for which dimensions the lower limit of the confidence interval was above the level of 33% accuracy. In the no distractor and one distractor conditions all confidence intervals were above 33% accuracy and in the five distractor condition all except width were above this level.

Patterns of Interference

t tests were performed to see which distractor dimensions significantly worsened the discrimination of change in each target dimension. For each target dimension, the *t* tests were performed on the difference scores between accuracy in the no distractor condition and in the one distractor condition for each of the five distracting dimensions. All *t* tests were two-tailed because some distractor dimensions might facilitate discrimination of a target dimension. To minimize the chances of making Type I errors, the *p* value required for significance was adjusted for the five *t* tests performed for each target dimension. The adjusted *p* value was $p = .01$. This is a conservative test and because results that are marginally significant might still have important design implications we also report results that are significant at the unadjusted .05 level. The *t* test results are shown in Table 2 and mean accuracy for each target-distractor combination is shown in Figure 3.

Changes in frequency and harmonics reduced accuracy for amplitude. There was mutual interference between harmonics and frequency and detection of harmonics changes was worsened by concurrent amplitude and width changes. Discrimination of changes in speed was worse with simultaneous changes in tremolo and width, and discrimination of changes in tremolo was worse with simultaneous changes in speed and width. Detection of width changes was worsened by frequency, harmonics, and tremolo changes.

An influence diagram summarizes the patterns of interaction between the dimensions (see Figure 4a). Arrows are shown for each of

Table 2
Experiment 1 Results of t Tests Showing a Significant Effect on Detection of a Target Dimension by a Distractor Dimension

Target dimension	Distractor dimension	*t*	*df*	*p* value	*d*
Amplitude	Frequency	3.48	11	<.005	1.32
Amplitude	Harmonics	5.20	11	<.001	1.77
Frequency	Harmonics	4.55	11	<.001	1.78
Harmonics	Amplitude	2.54	11	<.028*	.22
Harmonics	Frequency	5.46	11	<.001	2.05
Harmonics	Width	2.43	11	<.033*	.85
Speed	Tremolo	6.26	11	<.001	2.35
Speed	Width	4.32	11	<.001	1.79
Tremolo	Speed	3.88	11	<.003	1.35
Tremolo	Width	7.22	11	<.001	2.63
Width	Frequency	2.47	11	<.031*	1.32
Width	Harmonics	4.14	11	<.002	1.52
Width	Tremolo	5.07	11	<.001	1.75

Note. Unless otherwise indicated, all cases are significant at the Bonferroni adjusted rate of $p < .01$.
* Significant at unadjusted rate of $p < .05$.

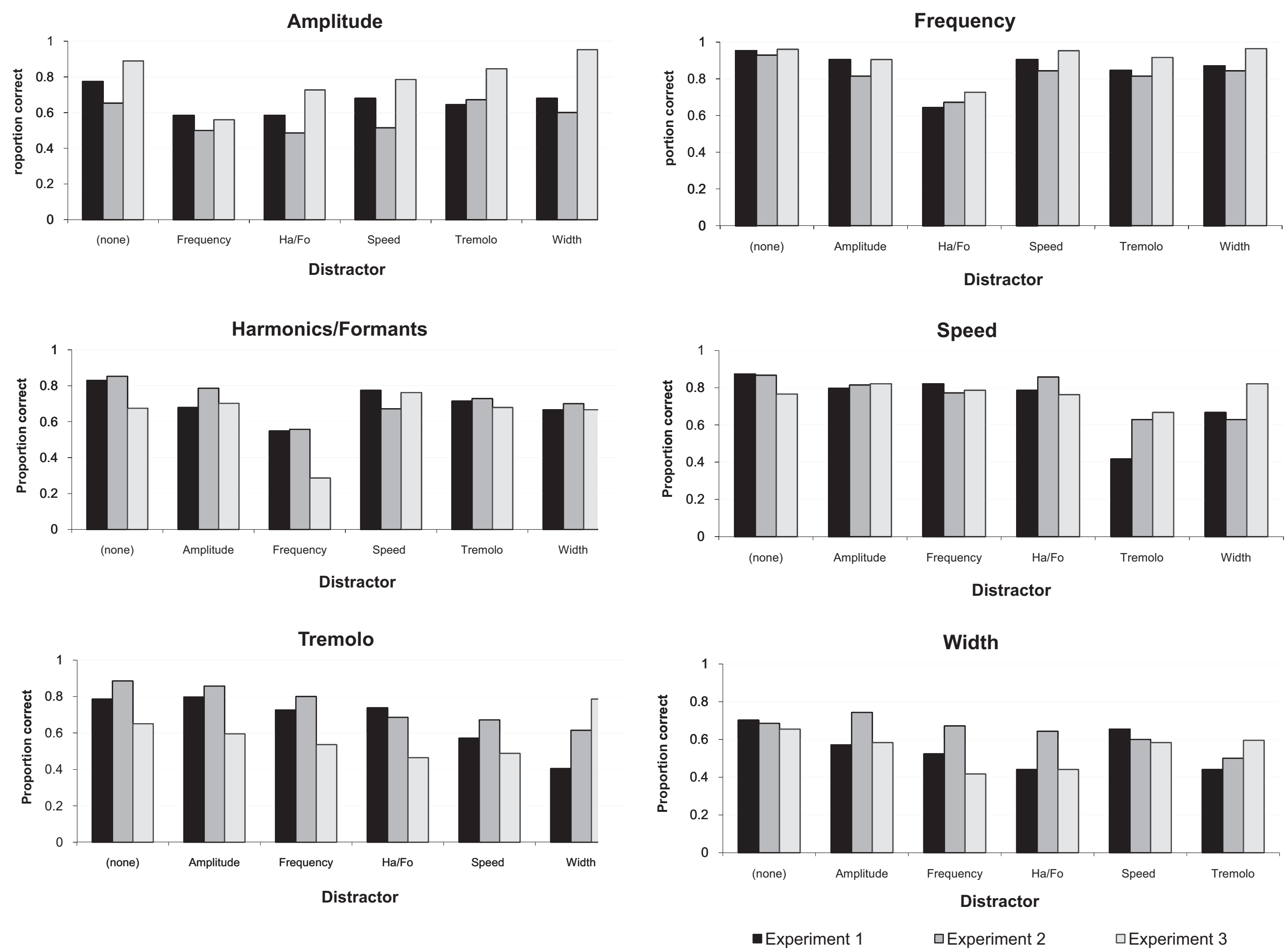

Figure 3. Mean accuracy (proportion correct) for target-distractor combinations in Experiments 1, 2, and 3. Ha/Fo = Harmonics/Formants, Tr = Tremolo in cycles per pulse (Experiment 1), cycles per second (Hz) (Experiment 2), or cycles per period (Experiment 3). Each graph is labeled with the target dimension at top. Distractors are identified along the *y*-axis. The bars labeled "(NONE)" at left of each graph indicate performance for the target dimension with no distractors.

the target-distractor combinations for which there was a significant *t* test result. Arrows are drawn from the distractor dimension to the target dimension; solid arrows indicate that the distractor had a negative effect on identifying changes in the target and dotted arrows indicate a positive effect. Interactions significant at the unadjusted .05 level are indicated by gray arrows. In this experiment all significant effects of distractor changes on target dimensions were negative—changes in the distractor dimension always worsened discrimination of changes in the target dimension.

Subjective Ratings

Participants rated how difficult it was to identify a change in each dimension. A repeated-measures ANOVA on the results revealed a main effect of dimension, $F(5, 55) = 3.66$, $MSE = 1.44$, $p < .006$, $f = .28$ but not for distractors $F(2, 22) = 2.04$, $MSE = 3.13$, *ns*. Post hoc tests with the adjusted significance value of $p = .003$ showed that frequency was rated as easier than harmonics $t(11) = 4.08$, $p < .002$, $d = .66$ and width $t(11) = 4.02$, $p < .002$, $d = .95$. Results also showed a significant interaction between distractors and dimension, $F(4.51,49.63) = 3.06$, $MSE = 2.50$, $p < .021$, $f = .33$.

Discussion

The discrimination task used in this study required participants to monitor a stream of pulses for a single change in a dimension in an unknown direction happening at an unknown time. Although the dimension being monitored had a large effect on discrimination accuracy, performance was acceptable for all dimensions when there was no distractor or one distractor. In the five distractor condition, discrimination accuracy was significantly above 33% for amplitude, frequency, harmonics, speed, and tremolo, but not width. As expected, distractor changes reduced discrimination accuracy overall, but the relative accuracy for the dimensions found in the no distractor condition was preserved for one and five distractors.

There were many interactions between the auditory dimensions. Although the interference between frequency and harmonics, and

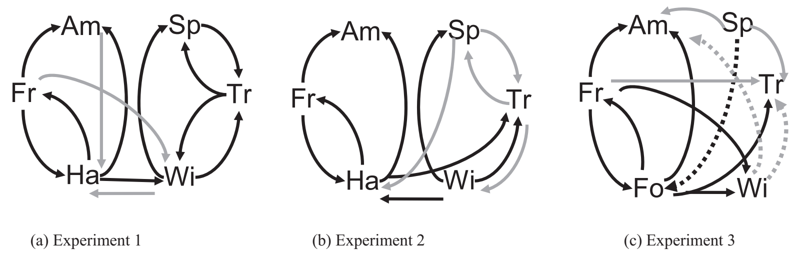

Figure 4. Pattern of distractor influences for Experiments 1, 2, and 3. Direction of arrows shows that dimension at origin affects perception of target dimension at destination. A black arrow indicates significance < .01, a gray arrow indicates significance <.05, a solid arrow indicates distractor had a negative effect on perception of target, a dotted arrow indicates distractor had a positive effect on perception of target. Am = Amplitude, Fr = Frequency, Ha = Harmonics, Fo = Formants, Sp = Speed, Tr = Tremolo in cycles per pulse (Experiment 1), cycles per second (Hz) (Experiment 2), or cycles per period (Experiment 3), Wi = Width.

amplitude and harmonics was expected from previous research (Krumhansl & Iverson, 1992; Melara & Marks, 1990a, 1990b), a novel finding was the pattern of interference between the temporal dimensions, and between the temporal and tonal dimensions. Some temporal interactions might have arisen because of the difficulty of distinguishing the different temporal dimensions of the sound. For example, faster and slower tremolo may have given the illusion of faster and slower pulse speed. Kramer (1994b) identified a potential similar confusion when discussing the use of clusters of pulses in which the speed of the pulses and the speed of the clusters can be varied.

Kramer (1994b) also noted that changes in pulse width would change the period over which vibrato cycles could occur, so making it harder to identify increases or decreases in vibrato rate. This effect also occurred for tremolo, which we operationalized as the number of tremolo cycles per pulse in Experiment 1. As pulse width changed, the time interval in which the tremolo was contained changed, effectively changing the number of tremolo cycles per second, even though the number of tremolo cycles remained constant. This could have affected the detection of both tremolo and width changes. First, when tremolo was the target dimension and pulse width the distractor, participants might have responded that tremolo cycles per pulse had changed even when it had not, because tremolo cycles per second, or Hz, increased or decreased when pulse width changed. Second, and similarly, when pulse width changed and there was no distractor, it might have been harder to tell whether and how pulse width had changed because there were changes in tremolo Hz that occurred simply as a result of the change in pulse width. The data showing lower accuracy for tremolo when combined with width changes support this argument. Third, pulse width changes were harder to detect when there were also tremolo changes. Instead of judging width by estimating time participants might have used tremolo to judge width, leading to inaccurate judgments of width when tremolo also changed.

Finally, there were interactions between tonal and temporal dimensions. Changes in harmonics reduced accuracy in detecting width changes and changes in harmonics and frequency reduced accuracy for detecting width changes. These effects were further explored in Experiment 2.

Experiment 2

In Experiment 2 we again investigated the relative effectiveness of six dimensions for carrying information in a sonification and the patterns of interaction between them. Our aim was to test the stimulus configuration used in Experiment 1 but with tremolo operationalized as cycles per second: tremolo hertz (Hz) would then remain constant when pulse width changed. We hypothesized that the patterns of temporal interactions would be different from the previous results. First, accuracy for detecting tremolo changes would not be affected by concurrent changes in width and so accuracy for tremolo distracted by width would be higher compared to Experiment 1. Second, width changes with no distraction would be higher compared to Experiment 1 because a change in width would no longer lead to an unintended tremolo change.

Method

Participants

There were 10 participants aged between 20 and 46 years ($M = 29.4$, $SD = 9.31$). They were a mixture of volunteers from the research community and students who participated for course credit. There were eight males and two females and all reported having normal hearing. Six participants reported having received formal musical training, ($M = 6.83$ years, $SD = 3.92$).

Stimuli

The stimuli were identical to those used in Experiment 1 with one important distinction; tremolo was operationalized as tremolo cycles per second (Hz). Preliminary testing was conducted to determine the increments that should be used to ensure that changes in tremolo Hz were audible. The tremolo values that were tested were therefore different from those tested in Experiment 1 and can be found in Table 1.

Procedure

The procedure was identical to the previous experiment.

Results

Accuracy

Results for accuracy are graphed in Figure 5. A repeated measures ANOVA with the factors target auditory dimension and number of distractors found a significant main effect for dimen-

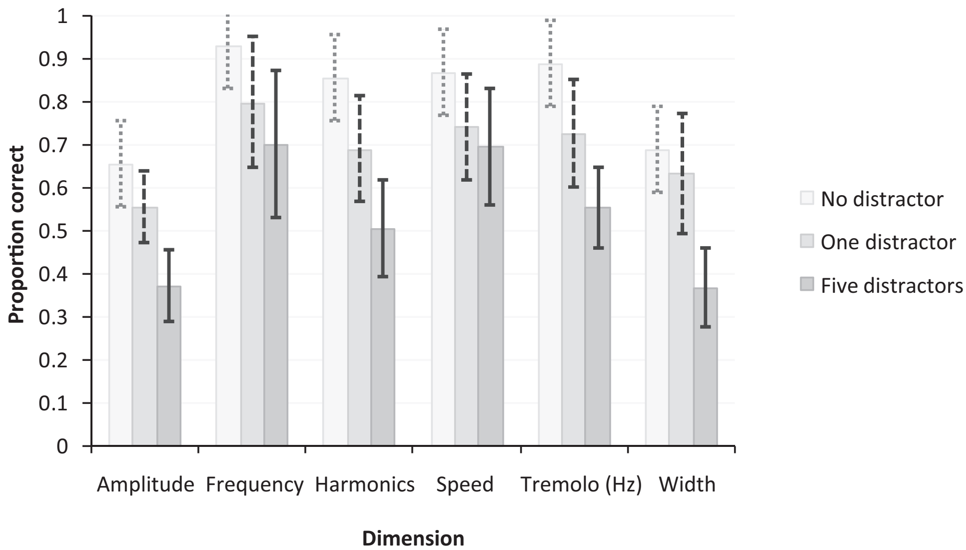

Figure 5. Mean accuracy (proportion correct) for dimensions in Experiment 2, across no, one, and five distractors. Error bars show the 95% confidence interval.

sion, $F(5, 45) = 19.69$, $MSE = .019$, $p < .001$, $f = .64$ and for distractors, $F(2, 18) = 55.422$, $MSE = .021$, $p < .001$, $f = .75$, and a significant two-way interaction between dimensions and distractors, $F(10, 90) = 2.149$, $MSE = .010$, $p < .028$, $f = .18$.

Amplitude was significantly less accurate than frequency $t(9) = 6.82$, $p < .001$, $d = 2.08$, harmonics $t(9) = 4.65$, $p < .001$, $d = 1.41$, speed $t(9) = 6.55$, $p < .001$, $d = 2.18$, and tremolo $t(9) = 5.88$, $p < .001$, $d = 1.88$. Frequency was significantly more accurate than width, $t(9) = 7.13$, $p < .001$, $d = 1.88$, speed was significantly more accurate than width $t(9) = 6.10$, $p < .001$, $d = 1.65$, and tremolo was significantly more accurate than width $t(9) = 4.72$, $p < .001$, $d = 1.36$.

Post hoc analysis of the distractor main effect using two-tailed *t* tests showed that the no distractor condition was most accurate ($M = .81$), the one-distractor condition significantly less accurate ($M = .69$), $t(9) = 3.93$, $p < .003$, $d = 1.01$, and the five-distractor condition ($M = .53$) significantly less accurate than the no distractor $t(9) = 11.35$, $p < .001$, $d = 2.88$ and one distractor conditions $t(9) = 6.69$, $p < .001$, $d = 1.26$. The lower limits of the confidence intervals were at or above the chance level of 33% for all dimensions in the no distractor and one distractor conditions and for all except amplitude and width in the five distractor condition.

Patterns of Interference

Post hoc two-tailed *t* tests were performed to see if each distractor dimension by itself significantly increased or decreased participants' ability to discriminate changes in each target dimension. As previously reported the *p* value required for significance was adjusted for the five tests performed for each target dimension and was $p = .01$. Unadjusted results are also reported. Results are shown in Table 3 and mapped in Figures 3 and 4b.

Results showed that participants' discrimination of changes in amplitude was significantly worsened by simultaneous changes in frequency and harmonics. Perception of frequency changes was worsened by harmonics changes. Changes in harmonics were less accurate when there were simultaneous changes in frequency, speed, and width. Speed changes were less accurately monitored when tremolo and width also changed, and accuracy for tremolo changes was worsened by simultaneous changes in harmonics, speed, and width. Width changes were less accurate when tremolo also changed.

Subjective Ratings

Participants rated the difficulty of the judgments for each dimension in each condition. A two-way repeated measures ANOVA with the factors of target dimension and number of distractors found a main effect for dimension $F(2.86, 25.775) = 8.70$, $MSE = 4.29$, $p < .001$, $f = .64$ and distractors $F(2, 18) =$

Table 3
Experiment 2 Results of t Tests Showing a Significant Effect on Detection of a Target Dimension by a Distractor Dimension

Target dimension	Distractor dimension	*t*	*df*	*p* value	*d*
Amplitude	Frequency	3.51	9	<.007	2.44
Amplitude	Harmonics	4.06	9	<.003	2.38
Frequency	Harmonics	3.40	9	<.008	1.34
Harmonics	Frequency	4.70	9	<.001	1.77
Harmonics	Speed	2.66	9	<.026*	.82
Harmonics	Width	4.15	9	<.002	.94
Speed	Width	.457	9	<.001	1.51
Speed	Tremolo Hz	2.77	9	<.022*	1.26
Tremolo Hz	Harmonics	3.47	9	<.007	.49
Tremolo Hz	Speed	3.19	9	<.011*	.63
Tremolo Hz	Width	5.03	9	<.001	1.16
Width	Tremolo Hz	2.28	9	<.048*	.98

Note. Unless otherwise indicated, all cases are significant at the Bonferroni adjusted rate of $p < .01$.
* Significant at unadjusted rate of $p < .05$.

.8.58, *MSE* = 1.93, $p < .002$, $f = .31$ and the interaction was not significant, $F(10, 90) = .99$, *MSE* = .85, *ns*. Post hoc *t* tests showed that amplitude was judged significantly more difficult than frequency $t(9) = 4.81$, $p < .001$, $d = 1.83$, frequency was significantly easier than harmonics $t(9) = 4.34$, $p < .002$, $d = 1.90$ and width $t(9) = 3.94$, $p < .003$, $d = 1.66$. The no distractor condition was rated as significantly easier than the five distractor condition $t(9) = 4.24$, $p < .002$, $d = .85$.

Discussion

The relative accuracy of the dimensions was similar to that found in Experiment 1. However, there were unexpected differences in levels of accuracy. Unexpectedly, higher accuracy was found for tremolo overall in the no distractor condition in Experiment 2 ($M = .71$) compared to Experiment 1 ($M = .63$). Although this difference could not be tested statistically, a difference of eight percent accuracy is likely to be important for an operator monitoring a sonification. It is probable that operationalizing tremolo using cycles per pulse in Experiment 1 caused confusion for some participants who may have interpreted tremolo changes as changes in Hz. Although participants detected changes in tremolo Hz more accurately than in tremolo cycles per pulse, changes in tremolo Hz are undetectable at some pulse widths. In all experiments only the middle of the range for all dimensions was tested so the problem of poor discriminability of tremolo Hz changes at the ends of the range of pulse width, identified in preliminary testing, was not exposed in this experiment. Nevertheless the poor discrimination of tremolo Hz at the ends of its range would greatly limit its usefulness as a dimension for sonification if pulse width also carried information.

Accuracy for amplitude in the no distractor condition was lower in Experiment 2 ($M = .65$) compared to Experiment 1 ($M = .77$). This is also likely to be an important difference in accuracy in an applied setting, but it is unclear why it occurred because no changes were made to the amplitude stimuli in Experiment 2.

The pattern of interaction between the temporal dimensions was complex. First, contrary to expectations, width changes did significantly worsen accuracy for tremolo compared to the no distractor condition. Accuracy for tremolo with width distraction was substantially better in Experiment 2 ($M = .61$) than in Experiment 1 ($M = .40$) as expected, indicating some success in improving tremolo performance with width distraction. However, accuracy for tremolo in the no distractor condition was also higher in Experiment 2 ($M = .88$) than in Experiment 1 ($M = .78$), thus preserving the significant interaction between width and tremolo found in Experiment 1.

Although we expected that performance for width in the no distractor condition would be better in Experiment 2 ($M = .68$) than in Experiment 1 ($M = .70$), this was not the case. This finding suggests that people's ability to discriminate change in width is limited. The low accuracy for width that we found in Experiment 1 appears not to have occurred because of the unintended changes in tremolo cycles per second that occurred in Experiment 1. Width accuracy was not improved when these unintended changes did not occur.

Perceptual interactions between tonal dimensions of auditory stimuli are well documented. Experiments 1 and 2 have extended our knowledge of perceptual interactions to the temporal characteristics of auditory stimuli. There is little information about whether perceptual interactions can be reduced. Given that perceptual interactions could be a major factor limiting the intelligibility of sonifications, this is surprising. Whether perceptual interactions can be reduced by using different dimensions or by configuring the sound in a different way are questions that are addressed in Experiment 3.

Experiment 3

The aim of Experiment 3 was to investigate whether the perceptual interactions that occurred in Experiments 1 and 2 could be minimized. In Experiments 1 and 2 there was interference between frequency and harmonics. An alternative operationalization of timbre might decrease this problem. In Experiments 1 and 2, harmonics in different frequency regions were filtered to create changes in the sound quality. Because a filtered sound with equal strength harmonics was used, there was minimal variation in the sound level in different frequency regions. However, the harmonic spectrum is also important in perceptions of timbre (Handel, 1989; Houtsma, 1997; Moore, 1997). Subjective judgments of differences in sound quality are related to differences in the level of a sound in each frequency band (e.g., Plomp, 1976; Pols, Kamp, & Plomp, 1969). Using formants to operationalize timbre could take advantage of the salience of changes in the harmonic spectrum and might therefore be less vulnerable to confusion with pitch changes.

In Experiments 1 and 2, participants may have found it difficult to perceive auditory properties of the pulse when pulse width was very short. In Experiment 3 we designed the stimuli so that listeners could perceive the auditory properties of the pulse in a soft background continuation of the pulse (the "echo") between the pulses. Instead of hearing a stream of pulses separated by silence, participants heard a stream of distinct pulses separated by a quieter background echo of the same sound. The required number of tremolo cycles was now fitted into the pulse and the echo, or the pulse-echo period. For example, if the value for tremolo was six cycles per pulse, the six cycles were now fitted into the pulse and the echo. Information about tremolo, frequency, and formants was carried by both the pulse and the echo, whereas information about amplitude, pulse speed, and pulse width depended entirely upon the pulse. We operationalized tremolo as cycles per pulse-echo period because we wanted to investigate whether distributing the tremolo cycles across the pulse and the echo reduced the interaction between tremolo and pulse width that was found in Experiment 1.

Several other changes were made to the scaling of the stimuli to investigate whether discrimination performance could be improved. First, to ensure that steps of equal subjective magnitude were heard, amplitude values were converted to decibels and frequency values were converted to mels. Second, to assess whether the discriminability of amplitude could be improved, the number of steps in the amplitude range was reduced from nine to seven. Although reducing the number of steps in an auditory dimension raises concerns about whether it can still carry information effectively, accuracy is also desirable. Moreover, with seven steps an auditory dimension can still carry three values on each side of a "normal" middle value. The three values can indicate that a physiological variable is slightly, moderately, or dangerously below or above normal.

There were four hypotheses for Experiment 3. First, it was hypothesized that changes in frequency would not affect participants' ability to identify changes in timbre (formants) and that changes in timbre (formants) would not affect participants' ability to identify changes in frequency. Second, it was hypothesized that interactions between the temporal dimensions would be changed. Specifically, width would have no effect on participants' ability to identify changes in tremolo. Third, tremolo cycles would now be heard in the inter onset interval, not just the pulse. This meant that as pulse speed changed the tremolo cycles per second would change and so we expected there to be a significant negative effect of speed on accuracy for tremolo judgments.

Finally, although we could make no firm predictions about the relative accuracy of the dimensions because of the complexity of the stimulus set, we expected the relative accuracy of the dimensions to be different from that found in Experiments 1 and 2. We expected amplitude to be more accurate because of the reduced number of steps, and width to be more accurate because width changes would no longer result in a potentially distracting change to tremolo cycles per second in the no distractor condition. Additionally, we expected that accuracy for speed judgments in the no distractor condition would be lower than in Experiment 1 because as pulse speed changed, the number of tremolo cycles per second would also change (even though the number of tremolo cycles per pulse remained constant) therefore potentially adding distraction from tremolo Hz changes in the no distractor condition. Although we could not compare statistically the results of experiments we tested the final group of hypotheses by examining the patterns of relative accuracy for the dimensions in each experiment.

Method

Participants

The participants in this study were 12 undergraduate psychology students who participated in the study for course credit. Their ages ranged between 18 and 45 years, with a mean of 23.33 years ($SD = 9.03$). They all reported having normal hearing. Ten participants had received musical training ($M = 6.1$ years, $SD = 4.3$).

Stimuli

The auditory dimensions tested were amplitude, frequency, timbre (formant frequencies), pulse speed, tremolo (cycles per pulse-echo period), and pulse width.

Timbre

Timbre was implemented using formant frequencies generated using the Csound formant frequency synthesis module. A range of nine values was developed. For each of the nine values, five different formant frequencies with different amplitudes and bandwidths were used, each sharing the same fundamental frequency. The sounds were filtered with a bandpass filter to between 100 and 4,000 Hz and a slight vibrato of 15 Hz was added to enhance the speech-like qualities of the sounds.

To create a linear dimension in which progression toward one end of the range or the other was clearly recognizable and easily remembered the dimension was designed to represent the sounds of the English vowels "a-e-i-o-u," with intermediate steps interpolated between the five vowels to make nine steps. To reinforce the association between the sounds and the vowels, participants were provided with a visual reference sheet that they used to identify the vowel sounds while listening to the examples. The reference sheet contained an example word for each formant in which the vowel sound was similar to the sound of the formant.

Amplitude Contour

A major change was also made to the amplitude contour of each pulse. The pulses were separated by a softer background sound that formed an echo of the pulse. The echo was created by reducing amplitude between the pulses to between 25% (at the onset of tremolo) and 7.5% (at the softest part of the tremolo) of the amplitude of the pulse itself. Figure 6 shows an example of the waveform. The pulses can clearly be seen, followed by a softer echo, and the tremolo cycles can be seen within both the pulse and the echo. Table 1 shows the values that were used for each auditory dimension. If a dimension was the target dimension the values changed, but at other times the value was held constant.

Procedure

The equipment, procedure and the number of trials in each condition were identical to those employed in Experiment 1.

Results

Accuracy

The results for accuracy are graphed in Figure 7. A repeated measures ANOVA with the factors target dimension and number of distractors found a significant main effect for dimension, $F(5, 55) = 49.669$, $MSE = .012$, $p < .001$, $f = .80$, and distractors, $F(1.26, 13.82) = 138.564$, $MSE = .014$, $p < .001$, $f = .70$, and a significant two-way interaction of distractors with dimensions, $F(10, 110) = 3.937$, $MSE = .009$, $p < .0001$, $f = .22$.

Post hoc analysis of the dimension main effect showed that amplitude accuracy was significantly lower than frequency $t(11) = 4.62$, $p < .001$, $d = 1.38$, but significantly higher than formants $t(11) = 5.80$, $p < .001$, $d = 3.05$, tremolo $t(11) = 7.09$, $p < .001$, $d = 2.42$, and width $t(11) = 8.92$, $p < .001$, $d = 5.06$. Accuracy for frequency was significantly higher than formants $t(11) = 7.84$, $p < .001$, $d = 3.74$, speed $t(11) = 7.19$, $p < .001$, $d = 2.02$, tremolo $t(11) = 10.40$, $p < .001$, $d = 3.24$, and width $t(11) = 7.85$, $p < .001$, $d = 3.70$. Formants accuracy was significantly lower than speed $t(11) = 5.26$, $p < .001$, $d = 2.48$, and accuracy for speed was significantly higher than for tremolo $t(11) = 7.75$, $p < .001$, $d = 2.75$ and width $t(11) = 11.89$, $p < .001$, $d = 2.61$.

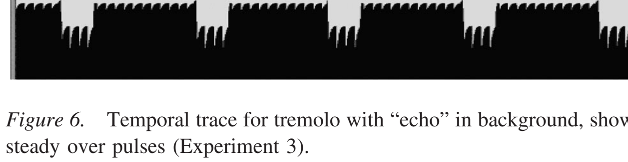

Figure 6. Temporal trace for tremolo with "echo" in background, shown steady over pulses (Experiment 3).

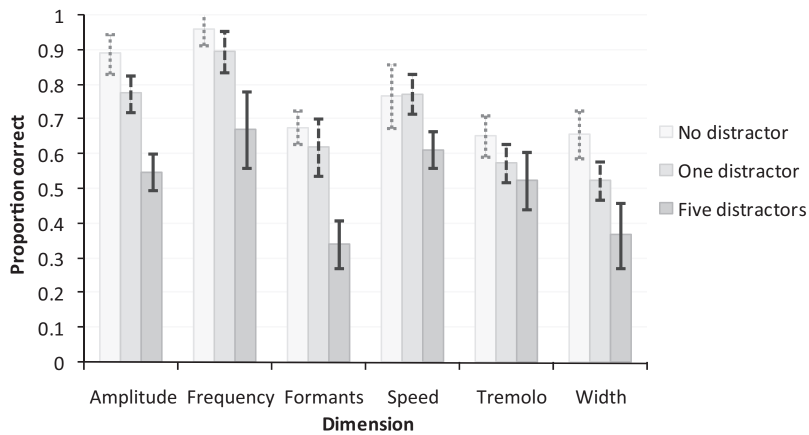

Figure 7. Mean accuracy (proportion correct) for dimensions in Experiment 3, across no, one, and five distractors. Error bars show the 95% confidence interval.

Post hoc analysis of the distractor main effect with the adjusted p value of .016 showed that the no distractor condition was most accurate (M = .76), the one-distractor condition significantly less accurate (M = .69), $t(11) = 8.70$, $p < .001$, $d = 1.48$, and the five-distractor (M = .51) condition significantly less accurate than the no distractor $t(11) = 12.78$, $p < .001$, $d = 4.11$ and one distractor conditions $t(11) = 10.90$, $p < .001$, $d = 3.15$. The lower limit of the confidence interval was at or above the chance level of 33% for all dimensions when there was no distractor and one distractor, and for all dimensions except formants and width in the five distractor condition.

Patterns of Interference

The pattern of interference between dimensions is mapped in Figures 3 and 4c. Post hoc two-tailed t tests were performed to see if each distractor dimension by itself significantly increased or decreased ability to discriminate changes in each target dimension. As in Experiments 1 and 2, the p value required for significance was adjusted for the five tests performed for each target dimension, but results significant at the unadjusted value are also reported. The adjusted p value was $p = .01$. Results, summarized in Table 4, showed that discrimination of changes in speed was unaffected by simultaneous changes in any one distractor dimension. Discrimination of amplitude changes was significantly worsened by simultaneous changes in frequency, formants, and speed, but significantly helped by changes in width. Discrimination of changes in formants was significantly worsened by simultaneous changes in frequency, but helped by simultaneous changes in speed. Discrimination of changes in tremolo was significantly worsened by simultaneous changes in frequency, formants, and speed, but helped by changes in width. Width judgments were worsened by simultaneous changes in frequency and formants.

Figure 4c shows the positive or negative effect of distractor dimensions (at source of arrow) on target dimensions (at destination). Of note is the facilitating effect of the temporal dimensions speed and width on identifying changes in other dimensions.

Subjective Ratings

Subjective ratings of the difficulty of identifying changes were obtained. A two way repeated measures ANOVA with the factors of target dimension and number of distractors found a main effect for dimension only, $F(5, 55) = 21.83$, $MSE = 1.67$, $p < .001$, $f = .78$. The main effect for distractor was not significant, $F(2, 22) = .033$, $MSE = 2.94$, *ns* and the interaction was not significant, $F(10, 110) = 2.17$, $MSE = 1.06$, *ns*. Amplitude was rated as significantly easier than formants $t(11) = 6.06$, $p < .001$, $d = 1.58$, tremolo $t(11) = 4.50$, $p < .001$, $d = 1.39$, and width $t(11) = 4.59$, $p < .001$, $d = 1.31$, frequency was rated as easier than formants, $t(11) = 6.77$, $p < .001$, $d = 2.29$, tremolo $t(11) = 6.95$, $p < .001$, $d = 2.59$, and width $t(11) = 6.76$, $p < .001$, $d = 2.28$ and speed was easier than tremolo $t(11) = 4.62$, $p < .001$, $d = 1.43$ and width $t(11) = 4.91$, $p < .001$, $d = 1.31$.

Discussion

The results of Experiment 3 were broadly similar to those of the previous experiments in that the dimension that was being moni-

Table 4
Experiment 3 Results of t Tests Showing a Significant Effect on Detection of a Target Dimension by a Distractor Dimension

Target dimension	Distractor dimension	t	df	p value	d
Amplitude	Frequency	4.66	11	<.001	1.99
Amplitude	Formants	3.51	11	<.005	1.46
Amplitude	Speed	2.37	11	<.037*	.92
Amplitude	Width	−2.13	11	<.050*	.77
Frequency	Formants	3.37	11	<.006	1.22
Formants	Frequency	8.65	11	<.001	2.92
Formants	Speed	−3.43	11	<.006	.91
Tremolo	Frequency	2.52	11	<.028*	.79
Tremolo	Formants	3.74	11	<.003	1.23
Tremolo	Speed	3.00	11	<.012*	1.28
Tremolo	Width	−2.50	11	<.030*	1.00
Width	Frequency	6.50	11	<.001	1.50
Width	Formants	4.55	11	<.001	1.70

Note. A negative t value indicates distractor had a positive effect on detection of change in target dimension.
Unless otherwise indicated, all cases are significant at the Bonferroni adjusted rate of $p < .01$.
* Significant at unadjusted rate of $p < .05$.

tored and the number of distractors had large effects on discrimination accuracy. Contrary to expectations, there was a significant interaction between formants and frequency. Formant accuracy was .67 with no distractor, but it was only .29 when there were simultaneous frequency changes. Formant changes also reduced accuracy for detecting frequency changes. Combined with the relatively low mean accuracy of the formant dimension overall ($M = .54$) compared to harmonics (Experiment 1: $M = .69$), the susceptibility of formants to perceptual interactions suggests that it is not a good choice for sonification.

One problem with formants is that it is difficult to create a linearly ordered set of formants. Providing a linear structure by analogy with vowel sounds had limited success because of the inherently categorical nature of speech. It is likely that the lack of linearity overcame any advantage of the distinctiveness of the formant dimension. As Walker and Kramer (2004) have noted, when sonifying ordinal data it is better to use sound dimensions that already have a clearly linear characteristic, such as pitch and speed. The formant dimension may be more suitable for representing categorical data than ordinal data.

The pattern of interactions between the temporal dimensions was different in Experiment 3 than in Experiments 1 and 2. We predicted that the echo would eliminate the negative effect of changes in pulse width on accuracy of identifying changes in tremolo. This was confirmed. We also hypothesized that changes in pulse speed would significantly reduce accuracy for tremolo changes. This was confirmed but the results showed significance only at the unadjusted level of .05 ($p = .012$) for this comparison. With tremolo cycles now distributed across the pulse and the echo, changes in pulse speed—rather than in pulse width as in Experiment 1—changed the time interval over which tremolo cycles occur, so it is surprising that this was not reflected more strongly in the results.

Although it was not possible to compare statistically the accuracy for identifying changes in width in both experiments, inspection of the overall means suggests that across experiments there is very little difference in participants' ability to identify changes in width (Experiment 1 $M = .54$, Experiment 2 $M = .56$, Experiment 3 $M = .51$). Such differences would probably not be important in an applied domain. We infer that the unintended changes in tremolo Hz that occurred in Experiment 1 when pulse width changed account only partially for the difficulties participants had in identifying changes in width. With the confound removed in Experiments 2 and 3, accuracy for detecting pulse width changes was still not high.

Performance for amplitude was better in Experiment 3 than previously (Experiment 1 $M = .61$, Experiment 2 $M = .52$, Experiment 3 $M = .73$) suggesting that reducing the number of steps in the range improved the discriminability of amplitude.

Contrary to expectations, accuracy for speed did not appear to be worse in Experiment 3 than in Experiment 1. Previously accuracy for speed was significantly higher than for amplitude and width and in this experiment it was significantly higher than formants, tremolo, and width. There was little difference in participants' ability to identify speed changes between the experiments. (Experiment 1 $M = .74$, Experiment 2 $M = .76$, Experiment 3 $M = .71$.) In Experiment 3 changes in pulse speed now resulted in unintended changes to tremolo Hz, compared to Experiment 1 where changes in pulse width resulted in unintended changes to tremolo Hz. The present results suggest that judgments about pulse speed are not susceptible to this unintended distraction from changes to tremolo Hz.

In contrast to the results of Experiment 2, participants did not report that an increasing number of distractors made it harder to identify changes in the target dimension. The extreme subjective difficulty of handling the formants may have disrupted the previous pattern of results.

The results of Experiment 3 showed that the changes made to the stimuli did not improve participants' ability to identify changes in the predicted dimensions. The pattern of interactions was complex and overall accuracy was lower than expected, leading us to conclude that our original approach to identifying potential auditory dimensions that would be sensitive and independent should be pursued further.

General Discussion

The experiments reported here examined the operation of selective attention with a single sound stream with six changing auditory dimensions. The broad aim was to examine the factors that determine how accurately participants can identify changes in a dimension that is in selective attention. The results indicated that there are three factors that affect people's ability to identify changes: (a) the specific dimensions used, (b) how many other dimensions also change, and (c) the specific design of the sound. These three factors are discussed in the sections that follow.

Effect of Dimensions

The dimension being monitored had a large effect on participants' accuracy at identifying changes. The studies reported here showed that with minimal training people can very accurately monitor frequency, harmonics, speed, and tremolo (Hz) for a change of a single increment when no other dimension changed. The studies clearly demonstrated that these dimensions are useful for sonification. Tremolo was identified for the first time as a potential dimension for sonification, although it might be effective for only some of the range of pulse widths when operationalized as cycles per second. Frequency was most accurately monitored and amplitude and width were less accurately monitored than the other dimensions. Nonetheless, amplitude and width could be useful with fewer steps in the range or when used in parallel with other dimensions.

The studies did not evaluate the accuracy of the dimensions against a criterion level indicating adequate performance. Deciding the level of accuracy required when monitoring auditory dimensions is a complex process and depends on the nature of the processes being monitored. For anesthesia, there are two considerations.

First, the time available for safe clinical decision making in a given clinical scenario will determine how quickly changes in a sonified variable will need to be perceived. Although one of the most important potential advantages of sonification is that it could provide early notification of evolving problems (Watson & Sanderson, 2004), it is unlikely that changes of one increment will need to be detected with 100% accuracy. The trend over several increments is more likely to be important clinically. Thus, determining the length of time available and therefore the exact level of monitoring accuracy required demands a thorough analysis of clinical indicators and decision-making processes.

Second, the diagnostic meaning of changes is likely to be different for different variables. For example, small numerical changes in oxygen saturation (e.g., 100–95%) are more critical than small numerical changes in blood pressure (120/70 to 115/65). Not all variables need to be monitored with the same degree of accuracy. Moreover, discriminability is not equal for all auditory dimensions, so designers might need to match less critical physiological variables with less discriminable dimensions. To do this, designers need information about the relative variability of auditory dimensions.

Such considerations were outside the scope of the present studies, which were designed simply to provide empirical data based on the customary number of dimensions monitored by anesthetists and a representative range of discriminations needed. We propose that a full sonification design will involve two complementary processes. One will focus on knowledge of auditory attention and perception to guide decisions about the number of streams, choice of dimensions and the configuration of the stimulus. The second will focus on analyzing the domain to determine the requirements for an auditory display. Our studies contributed to the first process.

Effect of Distractors

Distractors also had a large effect on accuracy. Accuracy declined as the number of distractors increased from zero to one to five. Simultaneous changes across some dimensions might be so difficult for listeners to interpret that a sonification might function simply to draw attention to changes, which are then identified by referring to visual information. In domains in which there are few simultaneous changes, however, and in which operators do not have to discern changes in one dimension at a time, strong effects of simultaneous changes should do little harm.

Most studies of perceptual interactions have focused on interactions between frequency and loudness (Neuhoff et al., 2002), frequency and timbre (Krumhansl & Iverson, 1992; Melara & Marks, 1990a), and timbre and loudness (Melara & Marks, 1990a), with a few studies investigating interactions between tonal and temporal dimensions (Boltz, 1998; Collier & Hubbard, 2001; Jones, Boltz, & Kidd, 1982; Tekman, 1997, 2002). Our research uncovered many interactions between the temporal properties of the sound and between the tonal and temporal dimensions.

Two possible explanations for perceptual interactions can be found in the literature: (a) selective attention is made difficult by dimensional integrality (Garner, 1974) and (b) the context created by changes in one dimension influences the perception of another dimension (Melara & Marks, 1990b). However, our results suggest that these explanations could be too limited. We used a wide range of stimuli in which both tonal and temporal dimensions were varied. The patterns of interaction we found suggest that the dimensions that interact will vary, depending on the properties of other dimensions and, thereby, the properties of the whole stimulus. For example, the pattern of interaction between temporal dimensions changed when the stimulus was redesigned for Experiment 3. The context of the whole stimulus, rather than the context created by just one other changing dimension, appears to determine whether and how particular dimensions interact. Therefore, our results support and extend the context interpretation of perceptual interaction. One effect of stimulus context might be that particular features of the sound attract attention and make selective attention to other dimensions difficult. For example, tremolo might attract attention and make selective attention to pulse speed, another rate variable, difficult.

Unlike studies of dimensional integrality (Garner, 1974) the data were not analyzed separately for trials in which distractor dimension changes were correlated or uncorrelated with changes in the target dimension. Further investigation and more fine grained analyses of the effect of change direction in each dimension on discrimination accuracy are required. This was not possible in the present studies because of the relatively small number of trials in each condition.

Because the distractor conditions were presented in the order no distractors, one distractor, five distractors, the results could conceivably be confounded with fatigue. This is unlikely, because participants took rest breaks between each block of trials and the experiment was not long. Practice effects are equally plausible, but would have improved rather than worsened scores for the one and five distractor conditions. Given the above, we argue that the effect of distractors on change identification performance is robust, but the results should be interpreted with caution until tested in future studies.

Influence of Design

The introduction in Experiment 3 of a new sonification design, in which pulses were heard in the context of a quieter background echo, had a major impact on discrimination accuracy. The new design reduced interactions between some dimensions and also helped discrimination performance for some others. Unexpectedly, with the new sonification design changes in speed helped identification of changes in formants. At present, it is unclear what mechanisms underlie this facilitation effect. One possibility is that an interaction between the presence of the echo and speed helped listeners to discriminate changes more accurately by drawing attention to formant changes. However, it is not clear why this effect did not then occur for all dimensions when participants were distracted by speed changes.

Subjective Experience

We gathered data about the perceived level of difficulty of identifying changes after each block of trials. The profile of difficulty ratings closely matched the profile of the accuracy scores. Participants reported that the trials in which they had the lowest accuracy were also the most difficult, indicating that their perceptions matched the level of their performance. Understanding how potential users experience a sonification is important because its eventual adoption and use will depend on how well it is tolerated by users. Future research could investigate users' subjective views of these aspects in more detail.

Conclusions

These studies provide guidance in the choice of dimensions for sonification designers but the limitations should also be recognized. In these studies participants indicated whether a dimension had increased, decreased or stayed the same, but a sonification user may have to identify the absolute values of data dimensions and the meaning of changes. Future studies could investigate performance with these dimensions with a more complex task. In these studies similar general patterns were found across the experiments, but the exact values for some dimensions differed. The values should therefore be used as general guidance rather than absolute until the studies have been replicated and the stability of the range of values has been established (Walker, 2007). The low numbers of participants in the experiments and therefore the potentially low statistical power reinforce the need to use the results as general guidance.

Other factors should also be considered when designing auditory displays. Users' expectations are important in determining the dimensions to be used and the polarity mapping used (Edworthy, Hellier, Aldrich, & Loxley, 2004; Guillaume, Pellieux, Chastres, & Drake, 2003; Walker, 2007). Cognitive factors such as expectancies and goals are also likely to be important. Studies with visual displays have shown that selective attention to information sources is guided by environmental factors such as the salience of a change and the effort of attending, as well as cognitive factors such as expectancies about event probability and the value of attending to a particular information source (or the cost of missing it) (Wickens, 2008). Future studies could examine how these cognitive processes guide users' interaction with a sonification and whether the patterns and relationships found here will change when domain experts monitor real physiological data streams. The natural patterns that exist in physiological data will influence how domain experts monitor the sound and expectations derived from domain knowledge could change performance.

These findings emphasize the need for further studies that elaborate the interactions, both positive and negative, that occur between dimensions in complex, dynamic stimuli. Although perceptual interactions might reduce the intelligibility of sonified data, careful sonification design, based on a complete understanding of the mechanisms causing perceptual interactions, could overcome such problems. Our studies have highlighted the difficulties of manipulating six auditory dimensions in an orthogonal manner. However, they have also uncovered complex patterns of interaction between auditory dimensions and unexpected effects that demonstrate the importance of empirically testing the effectiveness of proposed sonification dimensions and their interactions.

References

Anderson, J. (2004). *Sonification design for complex work domains: Streams, mappings and attention.* Unpublished PhD thesis. School of Psychology, The University of Queensland, St Lucia, Queensland.

Anderson, J. (2005). Creating an empirical framework for sonification design. *Proceedings of ICAD 05 Eleventh meeting of the International Conference on Auditory Display, Limerick, Ireland,* July 6–9, 2005.

Anderson, J., & Sanderson, P. (2002). Sonification design for real-time processes: Issues and a demonstration. *Proceedings of the 46th Annual Meeting of the Human Factors and Ergonomics Society* (pp. 1574–1578). Santa Monica, CA: HFES.

Anderson, J., & Sanderson, P. (2004). Designing sonification for effective attentional control in complex work domains. *Proceedings of the 48th Annual Meeting of the Human Factors and Ergonomics Society* (pp. 1818–1822). Santa Monica, CA: HFES.

Anderson, J., Sanderson, P., & Norris, M. (2002). The role of auditory attention and auditory perception in the design of real-time sonification of anaesthesia variables. *Proceedings of the ESA/CHISIG Conference on Human Factors (HF2002). Melbourne, Australia,* November 25–27.

Barrass, S. (1998). *Auditory information design.* Unpublished PhD thesis. Department of Computer Science, Australian National University, Canberra.

Barrass, S., & Kramer, G. (1999). Using sonification. *Multimedia Systems, 7,* 23–31.

Boltz, M. G. (1998). Tempo discrimination of musical patterns: Effects due to pitch and rhythmic structure. *Perception and Psychophysics, 60,* 1357–1373.

Boulanger, R. (Ed.). (2000). *The Csound book: Perspectives in software synthesis, sound design, signal processing, and programming*. Cambridge, MA: MIT Press.

Bradrakumar, A., Ball, D. R., Jefferson, P., & Lindhoff, G. (2001). Pulse oximetry: To bleep or not to bleep? (Letter to the Ed.). *Anesthesia, 56,* 184.

Cohen, J. (1988). *Statistical power analysis for the behavioural sciences* (2nd ed.). Hillsdale, NJ: Erlbaum.

Collier, W. G., & Hubbard, T. L. (2001). Judgments of happiness, brightness, speed, and tempo change of auditory stimuli varying in pitch and tempo. *Psychomusicology, 17,* 36–55.

Drake, C., Botte, M., & Baruch, C. (1992). Tempo sensitivity in auditory sequences. *Journal of the Acoustical Society of America, 92,* 2318–2342.

D'Amato, M. R. (1970). *Experimental psychology. Methodology, psychophysics and learning.* New York: McGraw-Hill.

Edworthy, J., Hellier, E., Aldrich, K., & Loxley, S. (2004). Designing trend-monitoring sounds for helicopters: Methodological issues and an application. *Journal of Experimental Psychology: Applied, 10,* 203–218.

Fitch, W. T., & Kramer, G. (1994). Sonifying the body electric: Superiority of an auditory over a visual display in a complex, multivariate system. In G. Kramer (Ed.), *Auditory display: Sonification, audification, and auditory interfaces* (pp. 79–94). Reading, MA: Addison-Wesley.

Garner, W. (1974). *The processing of information and structure.* New York: Wiley and Sons.

Gaver, W. (1997). Auditory interfaces. In M. Helander, T. Landauer, & P. Prabhu (Eds.). *Handbook of human-computer interaction* (pp. 1003–1041). Amsterdam: Elsevier Science.

Grau, J. W., & Kemler Nelson, D. G. (1988). The distinction between integral and separable dimensions: Evidence for the integrality of pitch and loudness. *Journal of Experimental Psychology: General, 117,* 347–370.

Guillaume, A., Pellieux, L., Chastres, V., & Drake, C. (2003). Judging the urgency of nonvocal auditory warning signals: Perceptual and cognitive processes. *Journal of Experimental Psychology: Applied, 9,* 196–212.

Haas, E., & Edworthy, J. (1996). Designing urgency into auditory warnings using pitch, speed and loudness. *Computing and Control Engineering Journal, 7,* 193–198.

Handel, S. (1989). *Listening: An introduction to the perception of auditory events.* Cambridge, MA: MIT Press.

Hellier, E., & Edworthy, J. (1999). On using psychophysical techniques to achieve urgency mapping in auditory warnings. *Applied Ergonomics, 30,* 167–171.

Hirsh, I., Monahan, C., Grant, K., & Singh, P. (1990). Studies in auditory timing: I. Simple patterns. *Perception and Psychophysics, 47,* 215–226.

Houtsma, A. J. M. (1997). Pitch perception. In B. Moore (Ed.), *Hearing* (pp. 267–295). San Diego: Academic Press.

Jones, M., Boltz, M., & Kidd, G. (1982). Controlled attending as a function of melodic and temporal context. *Perception and Psychophysics, 32,* 211–218.

Kemler Nelson, D. G. (1993). Processing integral dimensions: The whole view. *Journal of Experimental Psychology: Human Perception and Performance, 19,* 1105–1113.

Kramer, G. (1994a). An introduction to auditory display. In G. Kramer

(Ed.), *Auditory display: Sonification, audification, and auditory interfaces* (pp. 1–77). Reading, MA: Addison Wesley.

Kramer, G. (1994b). Some organising principles for representing data with sound. In G. Kramer (Ed.), *Auditory display: Sonification, audification, and auditory interfaces* (pp. 79–94). Reading, MA: Addison Wesley.

Kramer, G., Walker, B., Bonebright, T., Cook, P., Flowers, J., Miner, N., et al. (1999). *The sonification report: Status of the field and research agenda.* Report prepared for the National Science Foundation by members of the International Community for Auditory Display. Santa Fe NM: ICAD.

Krumhansl, C. L., & Iverson, P. (1992). Perceptual interactions between musical pitch and timbre. *Journal of Experimental Psychology: Human Performance and Perception, 18,* 739–751.

Loeb, R. G., & Fitch, W. T. (2002). A laboratory evaluation of an auditory display designed to enhance intra-operative monitoring. *Anesthesia and Analgesia, 94,* 362–368.

Manser, T., Howard, S., & Gaba, D. (2008). Adaptive coordination in cardiac anaesthesia: A study of situational changes in coordination patterns using a new observation system. *Ergonomics, 51,* 1153–1178.

Melara, R. D., & Marks, L. E. (1990a). Interaction among auditory dimensions: Timbre, pitch, and loudness. *Perception and Psychophysics, 48,* 169–178.

Melara, R. D., & Marks, L. E. (1990b). Perceptual primacy of dimensions: Support for a model of dimensional interaction. *Journal of Experimental Psychology: Human Perception and Performance, 16,* 398–414.

Moore, B. C. J. (1997). *An introduction to the psychology of hearing*. London: Academic Press.

Neuhoff, J., Kramer, G., & Wayand, J. (2002). Pitch and loudness interact in auditory displays: Can the data get lost in the map? *Journal of Experimental Psychology: Applied, 8,* 17–25.

Neuhoff, J., & McBeath, M. (1996). The Doppler illusion: The influence of dynamic intensity change on perceived pitch. *Journal of Experimental Psychology: Human Perception and Performance, 22,* 970–985.

Neuhoff, J., McBeath, M., & Wanzie, W. (1999). Dynamic frequency change influences loudness perception: A central, analytic process. *Journal of Experimental Psychology: Human Perception and Performance, 25,* 1050–1059.

Phipps, D., Meakin, G., Beatty, P., Nsoedo, C., & Parker, D. (2008). Human factors in anaesthetic practice: Insights from a task analysis. *British journal of anaesthesia, 100,* 333–343.

Plomp, R. (1976). *Aspects of tone sensation.* London: Academic Press.

Pols, L., Kamp, L., & Plomp, R. (1969). Perceptual and physical space of vowel sounds. *Journal of the Acoustical Society of America, 46,* 458–467.

Sanderson, P. M., Anderson, J., & Watson, M. (2000). Extending Ecological Interface Design to auditory displays. *Proceedings of the 2000 conference of the Computer-Human Interaction Special Interest Group (CHISIG) of the Ergonomics Society of Australia (OzCHI2000).* Sydney: CSIRO, 259–266.

Seagull, F. J., & Sanderson, P. M. (2001). Anesthesia alarms in surgical context: An observational study. *Human Factors, 43,* 66–77.

Stanton, N., & Edworthy, J. (1999). Auditory warnings and displays: An overview. In Stanton, N. & Edworthy, J. (Eds.), *Human factors in auditory warnings* (pp. 3–35). Aldershot, England: Ashgate.

Stoelting, R. K., & Miller, R. D. (1994). *Basics of anesthesia.* New York: Churchill Livingstone.

Tekman, H. G. (1997). Interactions of perceived intensity, duration, and pitch in pure tone sequences. *Music Perception, 14,* 281–294.

Tekman, H. G. (2002). Perceptual integration of timing and intensity variations in the perception of musical accents. *Journal of General Psychology, 129,* 181–191.

Walker, B. (2007). Consistency of magnitude estimations with conceptual data dimensions used for sonification. *Applied Cognitive Psychology, 21,* 579–599.

Walker, B., & Ehrenstein, A. (2000). Pitch and pitch change interact in auditory displays. *Journal of Experimental Psychology: Applied, 6,* 15–30.

Walker, B., & Kramer, G. (2004). Ecological psychoacoustics and auditory displays: Hearing, grouping and meaning making. In J. Neuhoff (Ed.), *Ecological psychoacoustics* (pp. 149–174). New York: Academic Press.

Watson, M., & Sanderson, P. (2007). Designing for attention with sound: Challenges and extensions to Ecological Interface Design. *Human Factors, 49,* 331–346.

Watson, M., & Sanderson. (2004). Sonification helps eyes-free respiratory monitoring and task time-sharing. *Human Factors, 46,* 497–517.

Wickens, C. D., & McCarley, J. S. (2008). *Applied attention theory*. Boca Raton, FL: CRC Press.

Woods, D. D. (1995). The alarm problem and directed attention in dynamic fault management. *Ergonomics, 38,* 2371–2394.

Xiao, Y., Mackenzie, C., Seagull, J., & Jaberi, M. (2000). Managing the monitors: An analysis of alarm silencing activity during an anesthetic procedure. *Proceedings of the joint meeting of the Human Factors and Ergonomics Society and the International Ergonomics Association (IEA2000/HFES2000)* (pp. 250–253). Santa Monica, CA: HFES.

Received October 1, 2008
Revision received March 23, 2009
Accepted March 30, 2009 ■