Simultaneous Manipulation of Parameters of Auditory Icons to Convey Direction, Size, and Distance: Effects on Recognition and Interpretation

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Abstract

Auditory icons – or environmental sounds – have the potential to convey information by non-verbal means quickly and accurately. In addition, human listeners are quick to determine many qualities of an auditory object, such as location, distance, size, and motion, from acoustics of the signal. An experiment tests these two coupled assumptions in a controlled laboratory context. Stimuli consisted of auditory icons "loaded" with information achieved through systematic manipulation of the acoustic parameters pitch, volume ramping, and reverberation. Sixty adult listeners were asked to recognize and describe four auditory icons wherein object size, distance and direction of motion were captured in the parameters of each 1-second sound. Participants were accurate at recognizing and interpreting the icons 70-80% of the time. Recognition rate was consistently high when participants responded to one, two or three parameters. However, recognition was significantly poorer when in response to all four parameters. There was a significant effect of icon type and parameter manipulation: dog bark was the most easily recognized icon, and the direction parameter interpreted most accurately. Implications of the findings for applied contexts are discussed.

1. Introduction

Auditory signals are now commonplace in complex environments such as aviation cockpits, factories, and power plants, particularly where the visual system is at risk of overload [1,2,3]. The ease of recognition of synthesized or pre-recorded speech, auditory icons or environmental sounds, abstract sounds and alarms, e.g., [4,5,6,7] has been investigated. Speech and environmental sounds are effective means of communication in conditions demanding low or high cognitive load. By contrast, only a limited number of abstract warning signals are able to be learned and recalled, particularly in demanding or stressful situations. Moreover, loud alarms mask other messages such as speech and elicit a startle response that may interfere with an action required urgently [8,9]

There appears to be general consensus on two points. First, auditory icons are not subject to the recognition limits of abstract sounds and second, the urgency of a situation may be conveyed using abstract auditory warnings wherein acoustic parameters such as speed have been manipulated. The present research builds on these two assumptions. Our aim is to investigate the ease with which listeners with minimal training can recognize and interpret four auditory icons whose acoustic parameters convey identity, size, distance and direction of motion. This basic research informs theories of auditory cognition and provides a conceptual framework for the development of sets of auditory icons that maximise message transmission in particular operational contexts.

1.1. Choosing the Most Effective Type of Auditory Signal

Operating system characteristics, such as complexity and urgency of information being transmitted, the number of potential warnings, concurrent task demands, and environmental conditions, generally dictate the type of auditory signal to be used. For example, although speech is suitable for communicating complex information and requires minimal learning, its use has been cautioned against in high workload, noisy operating systems on the grounds that it may take a relatively long time to transmit and is susceptible to masking in environments with a high level of background speech and noise [10,8].

Research has highlighted significant constraints in the design and use of abstract sounds. Alarms that blare, beep or ring, involve an arbitrary and abstract mapping between a signal and the event to which it refers. A litany of weaknesses of auditory alarms has been documented, including that they are loud and repetitive and may mask other communication, annoy rather than inform; do not convey the urgency of a situation, may be too loud and elicit a startle response that interferes with the necessary reaction, go unrecognised 40% of the time when there are more than seven or so different alarms, and require excessive training and retraining [11,3,8]. Accordingly, Patterson [8] made detailed recommendations about how to select the frequency components of a warning sound's spectral profile to lessen the likelihood of masking by noise and other warnings. He also recommended the use of no more than four to nine warning signals. A system with four signals and two attensons that signalled different levels of urgency was regarded as the optimal design – the purpose of the attenson being to inform the operator of the type of warning and that more information is available.

Earcons are a type of abstract sound manipulated to form hierarchical families of music-like motives for representing compound messages [4,12]. For example, a particular interval between two pitches and a particular waveform could be used to stand for a certain kind of system error. Earcons have to be learned as the mapping between signal and referent is symbolic and metaphoric. There is debate as to whether musical acuity such as that developed in formal musical training is necessary for recognition of earcons. Stevens [13] found that musicianship was not significant whereas Brewster et al [12] found that it was [14]. Lemmens, Bussemakers and de Haan [15] reported that earcons have an inhibitory effect on picture categorisation relative to auditory icons while the latter have a facilitatory effect. Leung, Smith, Parker and Martin [16] reported poor recognition of earcons relative to speech and auditory icons. Given the extensive training required and problems retaining or retrieving associations between abstract sounds and events it is unlikely that earcons are suitable where threatening situations are terminal (e.g., hospitals, aviation) and/or where there is high cognitive load.

1.2. Recognizing Auditory Icons

Auditory icons or caricatures of everyday sounds [17] circumvent a number of the problems associated with arbitrary alarms or abstract symbolic sounds. Recognition of auditory icons requires “everyday listening” which is the “experience of listening to determine the source itself” [17]. Auditory icons can be short, are not easily masked, and are generally recognizable and distinguishable. Using the terminology of Familant and Detweiler [18], auditory icons may involve either direct or indirect reference. In the former, there is only one referent involved in the signal-referent relation and this denotative referent is the event that is the target of the warning or message. An example would be to use the sound of machine gun fire to signal firing machine gun. Indirect reference occurs when there are at least two referents. Typically the signal refers to the denotative referent through an intermediate sign referent – sign referents in indirect relations serves as surrogates for denotative referents that may be difficult to portray. For example, on the desktop of a Macintosh computer, the file removal program (the denotative referent) is represented by the visual image of a trashcan (the sign referent). Although indirect relations may require an additional cognitive step to link and learn to associate target and referent, once learned, recognition speed and accuracy can be comparable with that of direct relations [19].

Gaver, Smith and O’Shea [20] demonstrated good performance of novice operators using auditory icons in the simulation of a bottling plant. Up to 14 auditory icons were presented at once, understood, and remembered. Begault [11] noted that auditory icons could be classified and identified by operators who had no musical training. In an applied setting, Graham [6] demonstrated that learning and response time were reduced using auditory icons relative to earcons. Two auditory icons (car horn, screeching tyres) were tested together with tonal and speech warnings in a collision warning context; even without training, participants recorded significantly faster reaction times in response to auditory icons compared with other signals. Graham concluded that greater urgency was implied by auditory icons. In summary, the advantages of auditory icons over abstract warning signals and symbolic musical sounds are the availability of a large number of distinguishable sounds and their ease of recognition under conditions of low or high cognitive workload.

Factors affecting sound source identification. Theories of auditory cognition, e.g., [21,22,23,24,25], refer to the various stages of processing in sound source identification as sensory transduction, auditory grouping, feature analysis, and the matching of sound signals with representations stored in memory. Several variables have been found to influence progression through these stages and consequently the probability of identification. These include acoustic properties, ecological frequency (how often the signal occurs in the environment), causal uncertainty (whether the signal is easily confused with other signals), and sound typicality (how typical the signal is of a particular source) [26]. These factors may affect whether identification proceeds automatically (i.e. with negligible cost in terms of attentional resources) or effortfully [27,28,29].

In the present experiment, four auditory icons (bell, horn, bark, footsteps) are used that are caricatures of objects in an urban driving scene and that stand in direct relation to bicycle, car, dog, and pedestrian, respectively. The sounds were chosen for their distinctiveness and causal certainty (even under conditions involving manipulations made to pitch), comparable ecological frequency [26,30], and high sound typicality as reflected in pilot testing. The particular sounds were non-continuous, percussive versions of a bell, bark, horn, and steps. The duration of each was 1 second consisting of repetition of the discrete sound three times in succession. The repetition structure served four purposes: the initial sound burst acted as an attenson, repetition enabled confirmation of the particular icons, fast repetition within the 1 s period conveyed a sense of urgency albeit consistent across the four icons, and repetition enabled perceptible manipulation of volume ramp, hpf ramp and reverberation.

Although auditory icons, such as rooster crow and baby cry, are easily identified and distinguished [26,31,19], they do not maintain their direct reference status when placed in an operational context – there are few low-flying roosters or babies in an aviation or driving context! Research into perceived urgency of warning signals has shown that the speed parameter conveys urgency, e.g., [8]. The present research investigates the advantage of coupling direct relations (bark-dog, bell-bicycle, footsteps-pedestrian, horn-car) with systematic manipulation of acoustic parameters, such as speed, to maximise message content of an auditory icon.

1.3. Deriving Meaning from Acoustic Parameters

In Gaver's [32] taxonomy of auditory icons, classification is based on the degree to which a sound signal has direct physical correspondence to its referent event. In nomic mappings, meaning depends on the physics of the situation. For example, the sound of a metal or wooden object being struck can be used to indicate its size [33,34]. Larger objects tend to bring about low frequency changes in air pressure that may be perceived as low pitch and slow tempo, relative to sounds made by smaller objects. Gaver hypothesizes a perceptual advantage for nomic mappings relative to metaphoric and symbolic mappings.

Building on the assumption of nomic mappings and the perceptual advantages of direct relations, we propose a scheme wherein the acoustic parameters of sound are also used deliberately to convey information. The sound of a banging door, for example, may enable a listener to infer the type of door, and their distance and direction from the door. It is plausible that the parameters of auditory icons could be "loaded" to augment the information carried by the icon. One way to load them is to generate dichotomous categories for a small set of acoustic parameters such that the categories themselves are iconic and, like the icons themselves, are recognized rapidly. Parameters such as amplitude and pitch can be considered as nomic mappings to distance and size. Consider the nature of a direct signal-referent relation that involves tempo. Tempo and urgency are directly and nomically related; urgent things travel quickly. Tempo in this context is iconic, and adult listeners should require little if any training to recognize which is the more urgent when presented with two similar sounds that differ in tempo. The interaction, of course, between tempi and two different environmental sounds is an open question.

The theory under investigation is that auditory icons can involve direct or indirect relations and that acoustic parameters pitch, reverberation and volume ramping stand in direct, nomic relations to object size, distance and motion direction, respectively. Frequency, as indicated, is related nomically to object *size*. The four icons, bell, horn, bark, and footsteps will be presented either six semitones higher or six semitones lower than the original icon. Aural perception of the *distance* of an object is determined by the reflections that reach the ear and inter-aural time and intensity differences. We hypothesize that distance categories near/far can be conveyed iconically by toggling reverberation off/on. *Direction of motion* of an object is detected from localisation cues, pitch and tempo. The direction categories, approach/recede, will be caricatured using volume ramp (20 db) and hpf ramp (20K-2K).

Combining auditory icons with iconic/meaningful manipulation of acoustic parameters situates the type of listening as neither purely everyday nor musical [17]. Recognizing the identity of the icon should be achieved using everyday and naturalistic listening involving the distal stimulus [17], whereas recognition of the direction, size and distance of an object implicates the proximal stimulus and sensitivity to psychophysical properties such as pitch and loudness [35]. By loading the pitch, ramping and reverberation parameters of auditory icons, the amount of information conveyed in a burst of sound should be enhanced. The present experimental investigation is essential to: assess the validity and perceptibility of these particular parameter–information mappings; measure whether different parameter values interact and whether the interaction enhances or impedes recognition, e.g., [36], investigate the load demanded by a 1 second event that requires interpretation of up to four units of information. The first issue to be addressed is to identify the number of parameters of 1 s auditory icons that can be recognized by untrained listeners. The following experiment manipulated four parameters relative to the listeners in an imagined driving context: the identity of an object (bicycle, car, dog, pedestrian), the distance of an object (near, far), the direction of motion of an object (toward, away), and the size of an object (small, large).

1.4. Aim and Hypothesis

The aim was to investigate the ease with which listeners recognize and interpret the meaning of one, two, three and four features of each sound: identity, distance, direction and size. It was hypothesized that recognition accuracy decreases as the number of parameters increases.

2. Method

2.1. Participants

The sample comprised 47 female and 13 male student and staff volunteers from the University of Western Sydney (M=21.02 years, SD=6.08). All participants had self-reported normal hearing.

2.2. Stimuli

Four levels of icon identity were prepared (bicycle bell, dog bark, car horn, footsteps) with a fifth icon (baby cry) used in the practice trials. A 1 s sound file was created for each icon. To convey size, the pitch of the sound sample was raised six semitones for small and lowered six semitones for large. Reverberation and low pass filtering were used to convey distance. For near distance there was no modification; for far distance reverberation was added and low pass filtered (3KHz, 24 db slope). Volume and low pass filter ramping were manipulated for direction. The direction away was achieved by volume being ramped down 12 db over the duration of the sample and low pass filtering being ramped down from 15KHz to 3KHz over duration of the near sample and from 3KHz to 1 KHz over duration of the far sample. The direction toward involved volume being ramped up 12db over duration of the sample and low pass filtering being ramped up from 3KHz to 15KHz over duration of the near sample and from 1KHz to 3Khz over duration of the far sample. All audio stimuli were 1 s, 16 bit mono, 44,100 Hz samples.

Icon (4) x size (2) x distance (2) x direction (2) variables yielded 32 manipulations. These were randomly ordered in a sequence (Sequence 1) with a 10 s pause between each item. A second sequence (Sequence 2) was prepared using the reverse stimulus order of Sequence 1. The duration of each sequence was six minutes. Some participants were asked to identify two parameters during each sequence presentation. For example, identity (A) and size (B) during Sequence 1, and distance (C) and direction (D) during Sequence 2. Other combinations used were A/C (Sequence 1) and B/D (Sequence 2), and A/D (Sequence 1), B/C (Sequence 2). Other participants were asked to identify three parameters during Sequence 1 and one parameter during Sequence 2. For example, A, B, and C for Sequence 1 and D in Sequence 2. Other variations used were ABD (C), ACD (B), and BCD (A). Finally some participants were asked to identify all four on the Sequence 1 (ABCD) with no second sequence being played. This format of presentation enabled presentation of all combinations across the sample and investigation of single and multiple parameter recognition and interpretation.

2.3. Equipment

Parameter manipulation was achieved using the audio tools in Logic Audio Platinum 6.0 on an Apple ibook (700mhz). Audio in/out during stimulus development was an MOTU 828 firewire digital audio interface. Stimuli sequences were saved to CD and played to participants through the MOTU 828, a Jands SR400 studio monitor and a single Alesis Monitor 2 studio reference speaker.

2.4. Procedure

Practice trials used the baby cry icon. The unmodified baby cry sample was played followed by the two levels of size, two levels of distance, and two levels of direction. Participants were told of the parameter manipulation in each example but were given no advice as to how they should identify the different manipulations. Practice in identifying various manipulations of the baby cry was provided until the participant indicated their readiness to commence the experimental trials.

The experimental trials consisted of 32 manipulations presented twice as Sequence 1 and 2. Participants identified between one and four of the stimulus parameters for each individual stimulus. For example, each trial consisted of a sound that realized one level of each of the four variables and participants had to recognize and interpret one, two, three, or four dimensions of the stimulus. In the case of the stimulus parameter icon identity participants wrote down, in one or two words, what they believed described the identity of the sound. For the stimulus parameters for size, distance and direction the two levels of each were listed on a response sheet and participants circled one or the other1. After a two-minute rest, the alternate sequence to the initial sequence was presented. In the second sequence participants completed the set of parameter manipulations omitted from the first sequence. For example, participants who had responded to and listed the identity, size and distance for the first sequence listed direction for the second sequence whereas participants who had listed size and direction for the first sequence listed identity and distance for the other sequence. Participants who listed all four parameters for the first sequence were not required to complete a second sequence. The experiment lasted 20 minutes.

3. Results

In the case of the size, distance and direction parameters correct/incorrect scores were assigned according to the two parameter levels that had been circled. In the case of icon identity, a response of correct was recorded if the response included an exact word from the icon description i.e. bicycle bell, dog bark, car horn, footsteps. Data refer to recognition accuracy reported as a proportion of the total sample and set of particular stimulus items.

It was hypothesized that recognition accuracy decreases as the number of parameters increases. As a single group of participants supplied results for one parameter and three parameters it was not possible to include both these data sets when conducting this analysis. Consequently data relating to one, two and four parameters were assessed. With a Shavelson adjusted alpha set to .02, a series of planned contrasts revealed no significant difference between one and two parameters, $F(1,59)=2.72$, $p=.05$ and no significant difference between two and four parameters $F(1,59)=1.99$, $p=.08$. There was a significant difference between one and four parameters $F(1,59)=9.97$, $p=.002$. The mean accuracy scores shown as a function of the number of parameters recognized are listed in Table 1.

Table 1. Mean Accuracy and Standard Deviations (in brackets) as a Function of Number of Parameters

Number of Parameters	Mean (*SD*)
1	.82 (.11)
2	.79 (.07)
3	.79 (.08)
4	.74 (.07)

A research question addressed whether there was a difference between the four icon types. With alpha set to .05 a repeated measures ANOVA showed a significant main effect for icon identity $F(1,59)=21.00$, $p<.001$. Six post hoc comparisons (paired *t* tests) were conducted using a Bonferroni adjusted alpha of .0083. These showed that bark was recognized significantly more often than the three other icons: bell, $t(59)=7.41$, $p<.001$, horn, $t(59)=4.38$, $p<.001$, and steps, $t(59)=6.96$, $p<.001$. There was no significant difference between bell and horn, bell and steps, or horn and steps. Mean accuracy by icon type is shown in Table 2.

Table 2. Mean Accuracy for the Four Icon Types

Identity	Mean (*SD*)
Bell	.74 (.10)
Bark	.85 (.08)
Car	.78 (.12)
Steps	.75 (.11)

A second research question addressed whether accuracy differed across the four parameter manipulations. With alpha set to .05, a repeated measures ANOVA showed a significant main effect for parameter manipulation $F(1,59)=8.09$, $p<.001$. Mean accuracy scores recorded in response to each parameter are shown in Table 3. Six post hoc comparisons (paired *t* tests) were conducted using a Bonferroni adjusted alpha of .008. These showed that manipulation of direction was recognized significantly more often than the three other manipulations: identity, $t(59)=2.95$, $p=.005$, size, $t(59)=4.79$, $p<.001$, and distance, $t(59)=4.69$, $p<.001$. There was no significant difference between identity and size, identity and distance, or size and distance.

Table 3. Mean Accuracy for Recognition of Size, Distance, and Direction Parameters

Parameter	Mean (*SD*)
Identity	.79 (.12)
Size	.76 (.11)
Distance	.75 (.14)
Direction	.85 (.07)

Recognition of parameters as a function of icon identity is summarised in Table 4 and recognition accuracy for combinations of parameters (collapsed across identity) is shown in Table 5.

Table 4. Parameter Recognition as a Function of Identity

	Parameter			
ICON TYPE	Identity	Size	Distance	Direction
Bell	.75	.74	.65	.82
Bark	.94	.84	.78	.85
Car	.82	.71	.70	.88
Steps	.66	.75	.76	.81
TOTAL	.79	.76	.72	.84

Table 5. Parameter Combinations Collapsed across Identity

Parameter Combinations	Mean
Small, near, away	.79
Small, near, toward	.82
Small, far, away	.74
Small, far, toward	.75
Large, near, away	.78
Large, near, toward	.83
Large, far, away	.75
Large, far, toward	.77

4. Discussion

Recognition accuracy results all exceeded the level predicted by chance (in general, 50%) indicating that auditory icons can be identified even when gross manipulations to acoustic parameters have been made. Although we had expected a reduction in recognition rate as the number of parameters increased, only the four parameter condition was recognized more poorly than the one parameter condition. Recognition of one to three parameters was in the range 79-82% whereas recognition of all four parameters dropped to 74%. All manipulations – identity, direction, distance and size – appeared to be intuitive and relatively easy to recognize and interpret.

Auditory icons differ in their recognizability [16] and this may interact with parameter manipulation. Of the set of four icons used here, dog bark was recognized most readily and this was retained during all parameter manipulation conditions. It is important for theory development to speculate on reasons for dog bark being effective within the current set. One reason is because it is a natural event and category [37,38]. It is also a natural warning signal with an onset and amplitude that effectively attracts attention. Dog bark was responded to most accurately under all conditions suggesting that its identity was least affected by manipulations to pitch, reverberation and volume ramping. The basis for its efficacy could be determined by comparing it with synthesized warning signals, natural alarm signals, and sounds with similar acoustic properties but from different types of categories.

The use of environmental sounds of relatively short duration was effective (1 s). In our previous research, sounds of 5 to 6 s had been used to minimise perceptual ambiguity and ensure that the icon was discernible, e.g., [19]. In the present experiments, discrete percussive sounds were used that contained a common temporal structure, for example, three repetitions of bark, horn, steps, or bell sound in quick succession. The use of discrete percussive sounds enabled the acoustic manipulations to be carried on the three repetitions. In this way, the onset of the event was akin to that of an attenson [8] serving to attract attention and then followed swiftly by an informative signal. A variation in the future would be to construct hybrid sounds such that the sudden onset sound acts as the attenson followed by a new sound that contains information not only in the acoustic parameters but also in the nature of the event and/or the relation in which the attenson and subsequent icon stand to one another. For example, an indirect ecological or metaphorical relation (see [19] for examples). These hybrid structures may prove useful in actual operational settings where cognitive demand of task is high.

The present experiment consisted of a recognition paradigm. However, a pilot study revealed that, at least without a period of substantial training, *recall* of an icon's identity as well as its three acoustic parameters is difficult and demanding. Poor recall of parameters may be analogous to the way in which the meaning of a spoken statement is extracted and retained while, in most instances, the acoustic properties such as intonation and stress are perceived but not memorized. This issue may be addressed in an applied setting by designing systems where recognition is required rather than recall, or including an intensive period of parameter training and testing. At a theoretical level, the present results inform theories of auditory cognition as well as providing a framework for constructing sets of auditory icons that maximise message transmission in a specific operational setting.

One of the most informative results was the relative ease with which direction was recognized. Accuracy scores were significantly higher for the direction parameter than for the three other parameters (identity, size, distance). The likely explanation for the salience of the direction parameter is that it requires recognition of absolute qualities (toward, away) rather than the more continuous, relative judgments of size (small, large) and distance (near, far). If only two values of size and distance are used in future experiments or applied settings, it should be effective to briefly train participants and demonstrate the number of possible levels of parameters that vary in degree as well as quality. On the other hand, the high recognition rate for absolute parameter manipulations has important implications for the design of icons in operational settings. The next logical step is to investigate the current set of icons in a more naturalistic setting and infer their efficacy from indirect measures including reaction time and recognition of the threat posed by pairs of auditory icons that differ in size, distance and direction of motion.

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