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What determines auditory similarity? The effect of stimulus group and methodology

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Two experiments on the internal representation of auditory stimuli compared the pairwise and grouping methodologies as means of deriving similarity judgements. A total of 45 undergraduate students participated in each experiment, judging the similarity of short auditory stimuli, using one of the methodologies. The experiments support and extend Bonebright's (1996) findings, using a further 60 stimuli. Results from both methodologies highlight the importance of category information and acoustic features, such as root mean square (RMS) power and pitch, in similarity judgements. Results showed that the grouping task is a viable alternative to the pairwise task with $N > 20$ sounds whilst highlighting subtle differences, such as cluster tightness, between the different task results. The grouping task is more likely to yield category information as underlying similarity judgements.

Keywords: Auditory cognition; Auditory processing; Multidimensional scaling; Categorical perception; Hierarchical cluster analysis.

It is widely acknowledged that the study of nonverbal auditory cognition lags behind that of visual cognition and speech perception (e.g., Gygi, Kidd, & Watson, 2004; McAdams, 1993). While there has been a tradition of psychoacoustic research investigating the low-level perceptual end of audition, issues such as the stages of processing of a nonverbal auditory signal, the nature of auditory input representations, the matching process between input and stored representation, and the nature of the stored representation itself have received little attention.

The reasons for this lack of research have been partly pragmatic; until recently it was technically difficult to synthesize and control auditory stimuli. In addition, the fact that auditory stimuli must necessarily be presented sequentially has meant that, from a methodological perspective, experiments can often only investigate a very limited number of stimuli before they become too long for participants to manage. For example, presenting 20 stimuli in a pairwise comparison task results in 190 stimulus comparisons.

In the research presented here we investigate the nature of auditory representation. By understanding what it is about sounds that make them similar we can make inferences about how acoustic stimuli are internally represented. Two methodologies are also compared: pairwise comparisons and a grouping task. The former presents a pair of sounds sequentially and requires a similarity rating from the listener. The latter presents icons

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representing each sound simultaneously on a screen and asks the listener to group the sounds by similarity. The grouping method is a means of presenting stimulus sets of more than 20 to participants without requiring them to make multiple comparisons. However, while the grouping task can potentially overcome the problems associated with multiple sequential presentations of auditory stimuli, the extent to which the groupings obtained depend on the particular methodology selected is not yet clear. Scavone, Lakatos, Cook, and Harbke (2002) suggested that the pairwise task sets unnecessary limits on participants' perceptual, cognitive, and decisional strategies so that, as a matter of economy, they make decisions based on the most salient dimensions only (which could be acoustic, descriptive, or categorical) depending on the stimuli presented. Some of the problems levied against the pairwise task are that it is impossible for participants to adjust a similarity rating in light of a new criterion that may be generated on the basis of later comparisons. Further, the continuous use of a rating scale may encourage participants to think unidimensionally about the similarities between stimulus pairs.

Both the pairwise and grouping tasks have been used in a range of auditory research, and both lead to analysis by multidimensional scaling (MDS) or hierarchical cluster analysis (HCA). For example, Guillaume, Pellieux, Chastres, and Drake (2003) used the pairwise comparison task to assess the urgency of nonvocal auditory warning signals and identified pitch and tone duration as salient sound features. Gygi et al. (2004) used the grouping task to investigate similarity judgements of environmental sounds and identified rhythmicity and spectral temporal complexity as important determinants thereof. However, there have only been a few comparisons between the two task types in the literature (e.g., Bonebright, 2001) and little on the similarities and differences in the results obtained.

Bonebright (1996, 2001) compared pairwise and grouping tasks using the same stimuli. She found that the same stimulus parameters were represented in MDS outputs for both methodologies but that the spread of the stimuli differed. The grouping stimuli were more closely clustered than those judged by the pairwise method. In addition, emotional cues were reflected in the clusters produced by the grouping task but not by pairwise comparisons.

In order to investigate the factors that underlie stimulus similarity and the relative merits of each methodology, sets of sound stimuli that varied in source characteristics were selected. The source characteristics have been identified as an important feature of sounds (Cermak & Cornillon, 1976), but stimuli that have varied in source characteristics have not previously been investigated using multidimensional scaling. Multidimensional scaling has previously been used to investigate complex underwater sounds (Howard, 1977), auditory graph representations and vocal effect stimuli (Bonebright, 1996), traffic noise (Cermak & Cornillon, 1976), sonar sounds (Solomon, 1959), and complex unfamiliar sounds (Howard & Silverman, 1976).

The sound–source relationship is important in determining and explaining effects in many areas of auditory cognition that relate to the nature of auditory stimulus representation. In perceptual priming the notion of source is essential in determining whether different exemplars that originate from the same source prime a target, or whether the effect is exemplar specific (e.g., Stuart & Jones, 1996); in categorization source is important in determining whether sounds are categorized by source or acoustic characteristics. Surface features and family resemblance have been described as important by Medin and Wattenmaker (1987) for object categorization; could they be equally important for auditory stimuli alongside the more obviously acoustic features? In the development of models of sound recognition (e.g., McAdams, 1993) the interaction of top-down notions of source with bottom-up perceptual stimulus attributes still needs to be specified in more detail. Although work has been conducted (e.g., Ballas, 1993; Gaver, 1993) the literature still lacks detail in terms of what descriptive and acoustic features are salient in representing sounds. This work aims to contribute to our understanding of the salient features used in representing sounds and to consider the extent to which the features that are identified depend on the methodology used to elicit them.

This paper is based on work that investigated whether acoustic features may underpin more psychological or descriptive judgements about sounds (Aldrich, 2005). McAdams' (1993) stages of processing model suggests the importance of both auditory properties and the perceptual features of sounds for matching to memory representations. The distinctive features involved in sound identification are poorly specified in the literature but there are features worthy of further investigation. Loudness (measured here using root mean square, RMS, as a measure of intensity) is an underexplored acoustic feature highlighted by Howard and Silverman (1976) and Susini, McAdams, and Winsberg (1999) as contributing to an MDS dimension. Gygi et al. (2004) identified spectral spread within the 1200–2400-Hz range as important, and therefore a cut-off at 2000 Hz was implemented in the present work. Finally bandwidth, measured by Bonebright (2001), is included. It was identified by Edworthy, Hellier, and Hards (1995) that many descriptive features are likely to be underpinned by acoustic features—for example, the adjective "dangerous" was shown to have a significant relationship to pitch. Although not measured directly, Howard and Silverman (1976) speculated that pitch was an important acoustic feature, and Intons-Peterson (1980) identified it as salient in auditory imagery. As a result high pitch/low pitch is measured both as an acoustic and as a descriptive measure here.

Gaver (1993) highlighted the importance of going beyond auditory measures and including perceptual dimensions. Ballas (1993) took the work conducted by Solomon (1958, 1959) using adjective word pairs, combined it with questions about the familiarity of a sound, and developed a set of statements to measure descriptive features. With the further work conducted by Bonebright (1996, 2001) there was a firm foundation for using word pair data to try to identify some of the salient descriptive sound features. The features measured here are a subset of measures used by Ballas (1993). It was necessary to include a measure of familiarity since both Ballas (1993) and McAdams (1993) found that identification of sounds was often made in terms of their source. This identification on the grounds of source would not be possible without familiarity, and a lack of familiarity could lead to different groupings. An "unfamiliar" sound set was included to facilitate comparison with the familiar sounds.

Three groups of stimuli were created for the experiments; the first two were complex real-world sounds, selected in part to avoid knowing the underlying acoustic parameters *a priori* as has been the case with much previous research (Howard, 1977). Similar acoustic sounds (SAS) were 10 acoustically and perceptually similar pairs used to investigate the salience of acoustic features in similarity judgements. They were selected on the basis of subjective acoustic/perceptual similarity (Howard, 1977) and originated from different sources (e.g., food frying and rain falling). Similar source sounds (SSS) were five groups of four sounds all originating from the same source but not sounding the same (e.g., burp, cough, sneeze, and yawn—all human noises); they were used to investigate the salience of category information in similarity judgements. The last group, unfamiliar sounds (US), were not paired or grouped but were all rated as difficult to identify and unfamiliar (Aldrich, 2005). These stimuli were used to investigate grouping choices when a sounds source was not identifiable or familiar.

EXPERIMENT 1: PAIRWISE COMPARISON METHOD

Method

Participants

A total of 45 undergraduate students from the University of Plymouth participated for course credit. All participants had self-reported normal or corrected-to-normal hearing.

Stimuli and materials

There were 10 pairs of familiar sounds in the similar acoustic sounds group, five groups of 4 familiar sounds in the similar source sounds group, and 20 unfamiliar sounds in the unfamiliar sounds group. The 20 sounds in each group are specified in Appendix A.

The stimuli were presented using a purpose-written program that paired every stimulus with every other stimulus once within a group; this resulted in 190 stimulus pairs (Aldrich, 2003b). The stimuli in each pair were separated by a 1-s interval. The experiment was presented to each participant on a PC (Windows XP operating on Hewlett Packard Vectra PIII) through headphones.

Procedure

A total of 15 different participants judged each of the stimulus groups (SSS, SAS, or US). After presentation of a stimulus pair participants were asked to rate similarity on a 10-point scale from very similar to very dissimilar. In order to encourage participants to make their own judgements about similarity, no other instructions were given. The selection of a rating triggered the presentation of the next pair of sounds and the rating scale through a total of 105 pairs. There was a 20-s break every 24 trials.

Results and discussion

MDS using the INDSCAL method and HCA were performed separately for each group of stimuli to investigate the similarity groupings. The INDSCAL method highlights any differences between participants' use of the identified dimensions. Uniform judgements through both experiments mean that this aspect is not discussed.

Similar acoustic sounds

For the similar acoustic sounds MDS (INDSCAL) analysis identified (using a scree plot) a three-dimensional solution (Figure 1) as the most appropriate fit to the data, $R^2 = .60$, stress = .21. The INDSCAL method allows the selection of an MDS configuration guided by both the stress and variance scores. With 60% of the variance accounted for, a three-dimensional solution, even with a relatively poor stress score, is acceptable (Kruskal & Wish, 1984). Each member of a pair of acoustically similar stimuli is indicated on Figure 1 by the same superscript letter; this shows that most pairs are located together in the three-dimensional space.

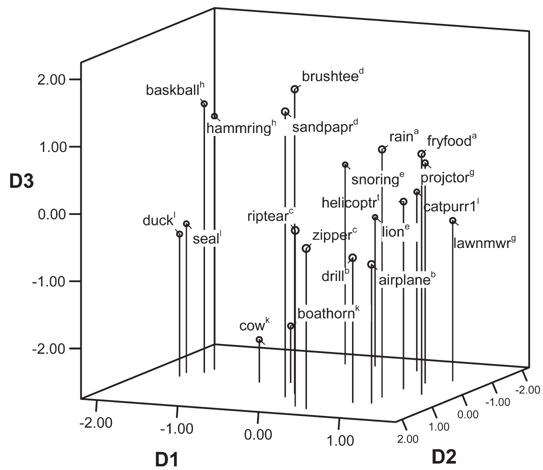

Figure 1. *Multidimensional scaling (MDS) solution for similar acoustic sounds derived from paired comparisons.*

To suggest possible meanings for each dimension, correlations were performed between the MDS positions of the stimuli and acoustic and descriptive measures of them obtained previously (Aldrich, 2005). The previous measures are detailed in Appendices B and C listing the acoustic features and descriptive measures, respectively.

Dimension 1 showed only one significant correlation, the percentage of sound versus silence in the whole wave file, $r_s = .623$, $n = 20$, $p < .001$. This reflects intermittent to continuous sounds along Dimension 1, with continuous sounds (e.g., lawnmower, fryfood) at one end and intermittent sounds (e.g., seal, duck) at the other. Dimension 2 showed two significant correlations, average RMS dB, $r_s = -.641$, $n = 20$, $p < .001$, and total RMS dB, $r_s = -.688$, $n = 20$, $p < .001$. This is reflected by the more powerful sounds (e.g., cow, boathorn) at the negative end of the dimension and less powerful sounds (e.g., teeth brushing) on the positive end. Dimension 3 also showed two significant correlations, RMS > 2000 Hz, $r_s = .476$, $n = 20$, $p < .05$, and high/low pitch, $r_s = .791$, $n = 20$, $p < .001$.

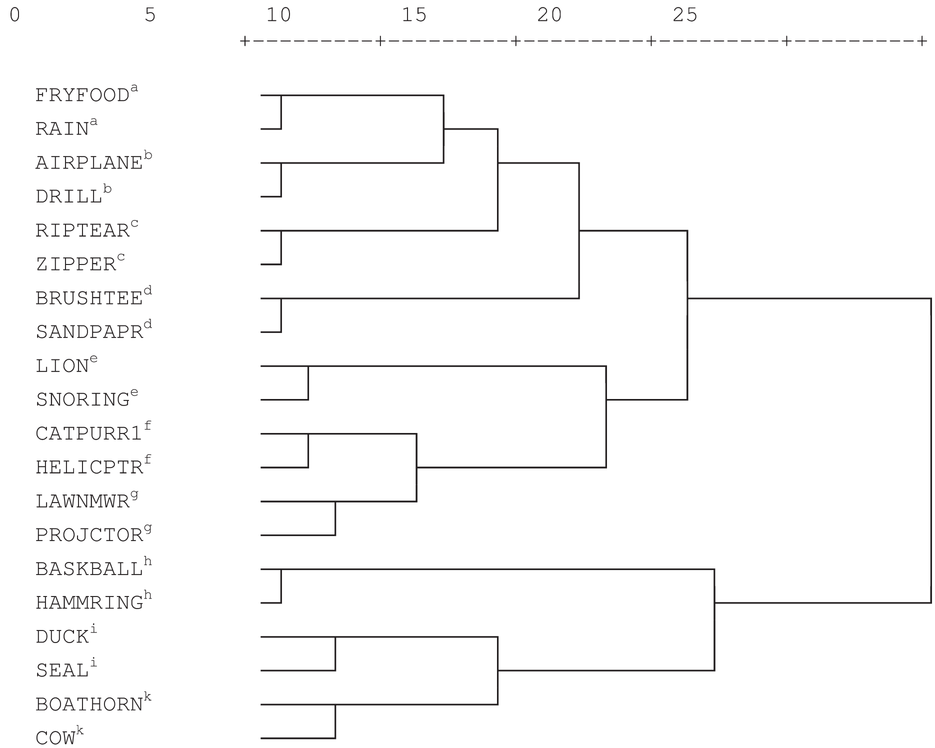

Figure 2. *Dendogram for similar acoustic sounds derived from paired comparisons.*

The HCA in Figure 2 supports the MDS analysis by showing clear clusters by pairs. The acoustically similar pairs are denoted by the same superscript letters.

Both the MDS and the HCA reveal that participants' similarity judgements group similar acoustic sounds by their original acoustically similar pairs. Correlations between the MDS dimensions and the acoustic and descriptive measures also suggest that participants are relying on acoustic rather than descriptive or perceptual measures to group stimuli.

Similar source sounds

MDS (INDSCAL) identified a three-dimensional solution as the most appropriate fit to the data, $R^2 = .56$, stress = .21 (Figure 3). The sounds are grouped loosely by their category membership, for example the uppermost group is made up from duck, seagull, rooster, and nightingale, all birds

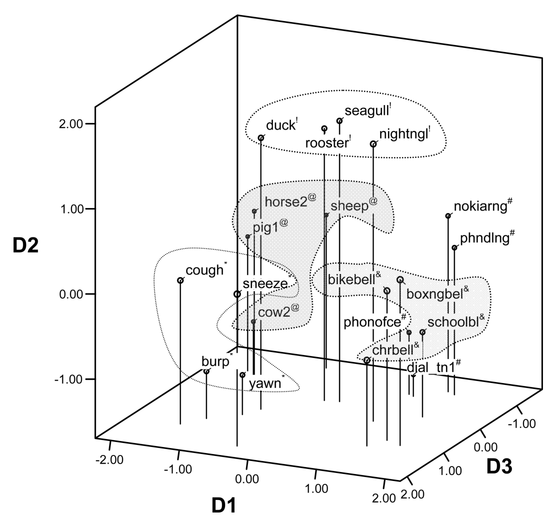

Figure 3. *Multidimensional scaling (MDS) solution for similar source sounds derived from paired comparisons.*

(groups identified by superscript symbols and ringed).

Correlations were performed between the MDS positions of the stimuli and acoustic and descriptive measures of them obtained previously (Aldrich, 2005). Dimension 1 appears to order the stimuli by pitch, showing two significant correlations, RMS < 2000 Hz, $r_s = .563$, $n = 20$, $p < .001$, and pitch as rated, $r_s = -.908$, $n = 20$, $p < .001$. Thus nightingale and cow2 appear at opposite ends of the dimension. Dimension 2 showed one significant correlation, with the adjective scale pleasing/annoying, $r_s = -.452$, $n = 20$, $p < .05$, so that animal and bird noises at one extreme are pleasing whereas a phone and bells, at the other extreme, are annoying. Dimension 3 appears to measure the power of the sound, with three significant correlations, RMS < 2000 Hz, $r_s = .492$, $n = 20$, $p < .05$, total RMS dB, $r_s = .570$, $n = 20$, $p < .001$, and average RMS dB, $r_s = .464$, $n = 20$, $p > .001$. The sneeze is placed at the positive end of this dimension, and the dial tone and nokiaring at the negative end.

HCA (Figure 4) highlights five distinct clusters (see brackets), which reflect the categories originally chosen for inclusion (bells, phone noises, birds, farm animals, and human noises). The originally selected sound categories are denoted by the same superscript letters.

Both the MDS and the HCA reveal that participants' similarity judgements group similar source sounds by their original category groups. The clearest of these is the bell group, which is clustered on all three dimensions. The correlations between MDS locations and acoustic measures suggest that besides category information, participants are also relying on the acoustic features of the sounds to group them.

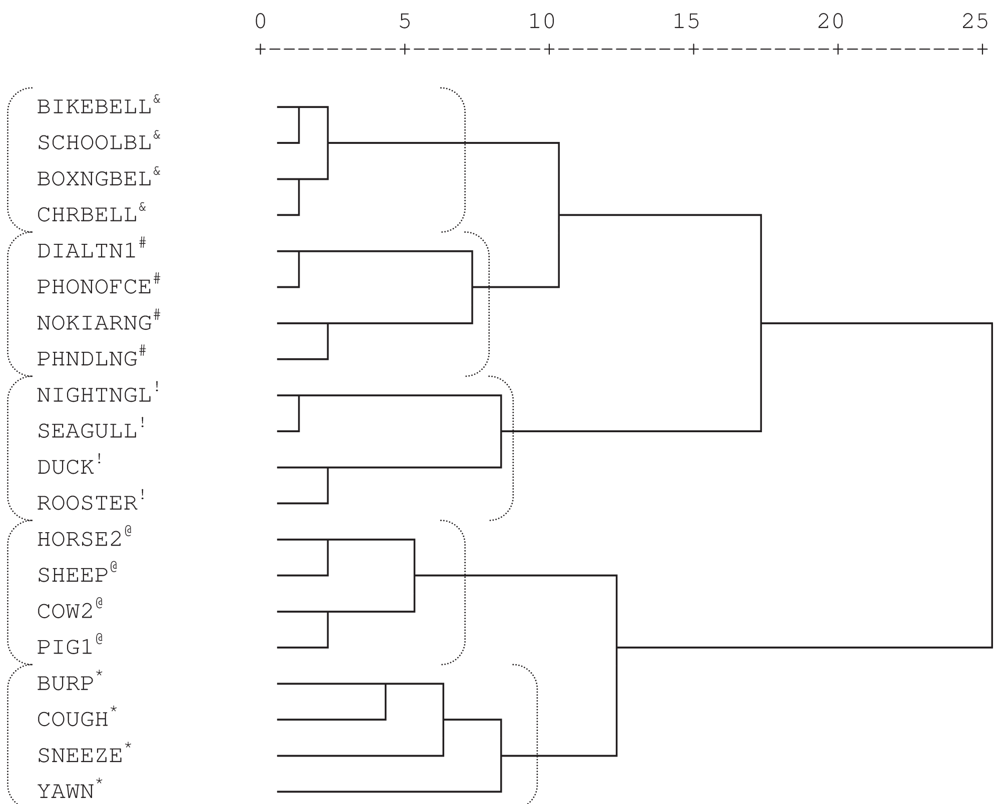

Figure 4. *Dendogram for similar source sounds derived from paired comparisons.*

Unfamiliar sounds
MDS identified a three-dimensional solution as the most appropriate fit to the data, $R^2 = .44$, stress = .24 (Figure 5). The multidimensional configuration does not show any particular clustering of stimuli.

Correlations between the MDS positions of the stimuli and acoustic and descriptive measures obtained previously (Aldrich, 2005) showed eight significant correlations with Dimension 1: calming/exciting, $r_s = .471$, $n = 20$, $p < .05$; pitch as rated, $r_s = .767$, $n = 20$, $p < .001$; RMS < 2000 Hz, $r_s = -.727$, $n = 20$, $p < .001$; average RMS, $r_s = -.589$, $n = 20$, $p < .001$; total RMS, $r_s = -.583$, $n = 20$, $p < .001$; average pitch, $r_s = .638$, $n = 20$, $p < .001$; pitch range, $r_s = .459$, $n = 20$, $p < .05$; and sound length, $r_s = .456$, $n = 20$, $p < .05$. Dimension 2 showed four significant correlations, with the adjective scale safe/dangerous, $r_s = -.614$, $n = 20$, $p < .001$; RMS > 2000 Hz, $r_s = -.454$, $n = 20$, $p < .05$; average RMS, $r_s = -.538$, $n = 20$, $p < .05$; and total RMS, $r_s = -.504$, $n = 20$, $p < .05$. Dimension 3 showed one significant correlation, with minimum pitch, $r_s = -.529$, $n = 20$, $p < .05$.

HCA (Figure 6) shows a few stimulus pairs clustered together (e.g., electricbell and starwars),

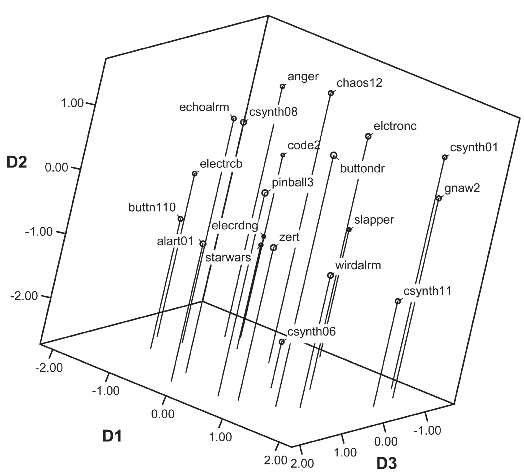

Figure 5. *Multidimensional scaling (MDS) solution for unfamiliar sounds derived from paired comparisons.*

but in general, the sounds are not formed into tight clusters.

For the unfamiliar sounds, there is little clustering on the MDS and less variance in the data explained by the MDS output. Similarly, the HCA does not show clear stimulus groups. Despite this lack of apparent clustering a substantial number of acoustic and descriptive measures correlated with the sounds' location in multidimensional space. The spread of acoustic measures for the unfamiliar sounds were compared to those from the similar acoustic sounds and similar source sounds groups to check whether there was a significantly different spread or range for the unfamiliar sounds but no clear differences were found between the three groups. Safe/dangerous and RMS power were important features of Dimension 2 while the minimum pitch of the sound defined Dimension 3.

EXPERIMENT 2: GROUPING METHOD

Method

Participants
A total of 45 undergraduate students, who did not take part in Experiment 1, from the University of Plymouth participated for course credit. All participants had self-reported normal or corrected-to-normal hearing.

Stimuli and materials
The stimuli (identical to those from Experiment 1) were presented as on-screen icons that allowed free grouping (Aldrich, 2003a). The experiment was presented on a PC (Windows XP operating on Hewlett Packard Vectra PIII) through headphones.

Procedure
A total of 15 participants judged each of the different groups of stimuli (SSS, SAS, or US). Following briefing and practice screens (sorting coloured squares), participants were presented with a screen showing the 20 sounds in their stimulus group. Participants were instructed to arrange the sounds

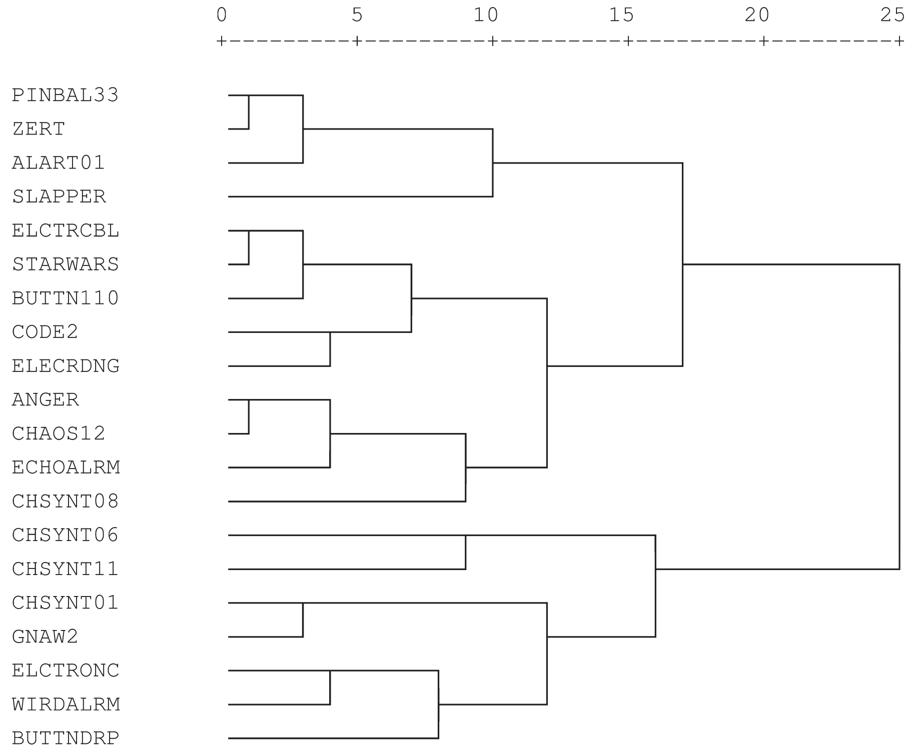

Figure 6. *Dendogram for unfamiliar sounds derived from paired comparisons.*

into groups, based on similarity, on the screen (as many or as few groups as they wished), by rearranging the icons on the screen. There was no time restriction on the grouping task, and participants could listen to any sound as often as they wanted to by clicking the icon.

Results and discussion

To obtain a dissimilarity matrix from the data, sounds that were sorted into the same group were given a score of 0 (no distance), and sounds in different groups given a score of 1.

Similar acoustic sounds

MDS identified a four-dimensional solution (based on a scree plot) as the most appropriate fit to the data. Based on the complexity of interpreting a four-dimensional solution the three-dimensional solution is presented here, $R^2 = .92$, stress $= .09$ (Figure 7; Kruskal & Wish, 1984). The stimuli are only loosely grouped in their original acoustically similar pairs (identified using superscript letters and ringed on Figure 7).

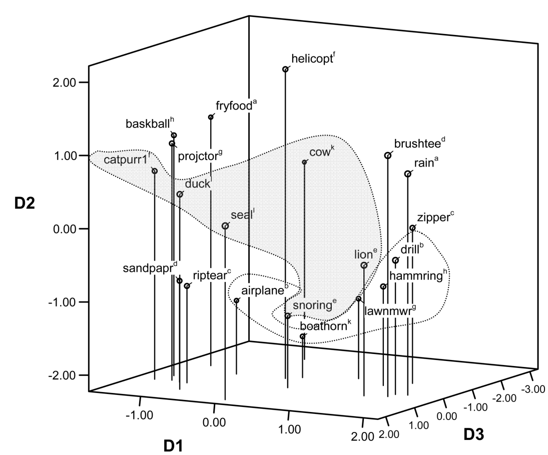

Figure 7. *Multidimensional scaling (MDS) solution for the similar acoustic sounds derived from grouping task.*

To suggest possible meanings for each dimension, correlations were performed between the MDS positions of the stimuli and acoustic and descriptive measures of them obtained previously (Aldrich, 2005). Dimension 1 showed no significant correlations. Visual inspection of Dimension 1 suggests that the dimension may represents a continuum from unnatural objects (e.g., engines) to natural objects (e.g., a cow). Without measured features it is normal practice to interpret MDS solutions in this subjective way especially for descriptive dimensions (Hair, Anderson, Tatham, & Black, 1995). Dimension 2 showed one significant correlation with the word pair pleasing/annoying, $r_s = -.518$, $n = 20$, $p < .05$; Dimension 3 showed two correlations, with total RMS dB, $r_s = .489$, $n = 20$, $p < .05$, and with average RMS dB, $r_s = .567$, $n = 20$, $p < .001$.

HCA (Figure 8) shows that some of the stimuli are clustered in their acoustically similar pairs (e.g., rain/fryfood; zipper/riptear). There are also two clear larger clusters: engine noises and animal sounds (including snoring) highlighted on Figure 8.

The MDS and the HCA analysis derived from the grouping task revealed that similar acoustic sounds did not cluster closely together. Only a few pairs were grouped together, and this is only clear on the HCA analysis.

Similar source sounds

MDS identified a three-dimensional solution as the most appropriate fit to the data, $R^2 = .96$, stress = .07 (Figure 9). The stimuli appear to be grouped loosely in their original categories (see superscript symbols and cluster marking).

Correlations between the MDS positions of the stimuli and acoustic and descriptive measures of them (Aldrich, 2005) showed two significant correlations with Dimension 1 (average RMS dB, $r_s = .507$, $n = 20$, $p < .05$, and RMS <

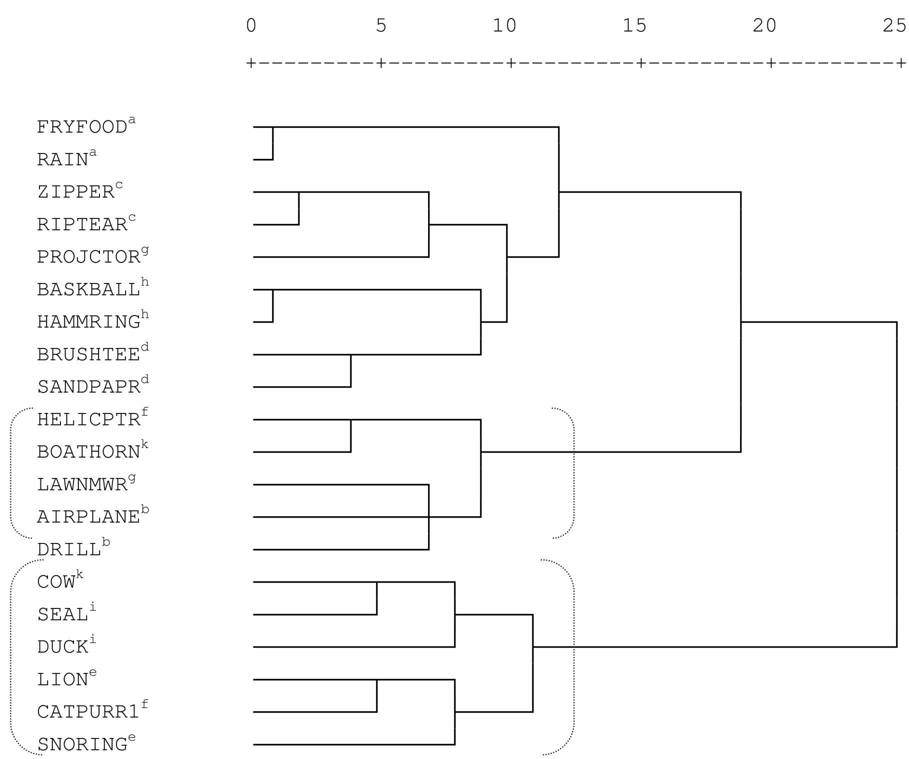

Figure 8. *Dendogram for similar acoustic sounds derived from grouping task.*

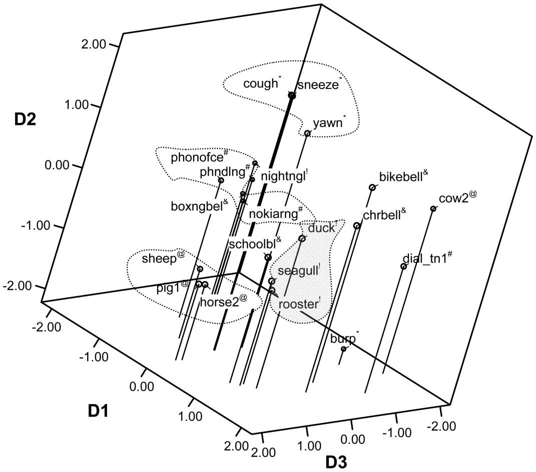

Figure 9. *Multidimensional scaling (MDS) solution similar source sounds derived from grouping task.*

2000 Hz, $r_s = .555$, $n = 20$, $p < .05$), which appear to represent the power of the sounds. Dimension 2 picked up the descriptive features of the sounds and showed three significant correlations, with pleasing/annoying, $r_s = .838$, $n = 20$, $p < .001$; calming/exciting, $r_s = .573$, $n = 20$, $p < .05$; and safe/dangerous, $r_s = .713$, $n = 20$, $p < .001$. Dimension 3 showed two correlations, with RMS > 2000 Hz, $r_s = .590$, $n = 20$, $p < .001$, and with pitch as rated, $r_s = .459$, $n = 20$, $p < .05$.

HCA (Figure 10) shows that stimuli have clustered in their original category groups without exception.

Both the MDS and the HCA analyses have identified that the similar source sounds have clustered clearly in their original category groups. As previously, this grouping is clearer from the HCA output.

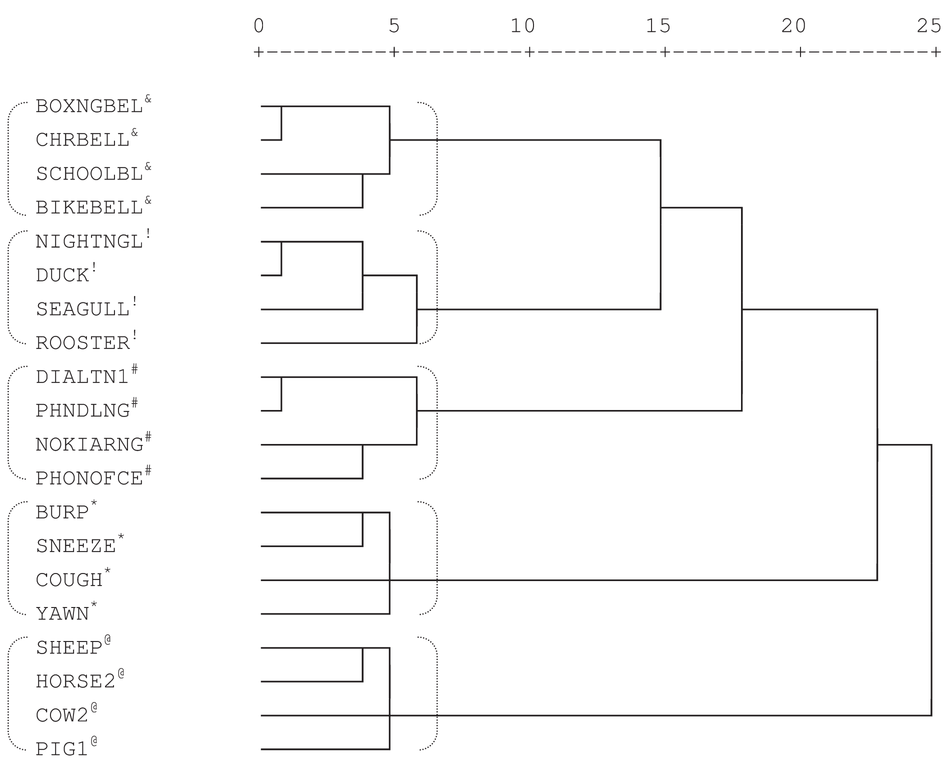

Figure 10. *Dendogram for similar source sounds derived from grouping task.*

Unfamiliar sounds

MDS identified a two-dimensional solution as the most appropriate fit to the data, $R^2 = .96$, stress = .09 (Figure 11).

There is little clustering of the stimuli into groups. Correlations between the MDS stimuli positions and acoustic and descriptive measures (Aldrich, 2005) revealed one significant correlation for Dimension 1, familiarity with sound, $r_s = .-.511$, $n = 20$, $p < .05$. Dimension 2 correlated with three measures: bandwidth, $r_s = .477$, $n = 20$, $p < .05$; RMS > 2000 Hz, $r_s = .632$, $n = 20$, $p < .001$; and pitch range, $r_s = .481$, $n = 20$, $p < .05$.

Neither MDS nor HCA (Figure 12) analyses on the unfamiliar sounds found evidence for stimulus clustering with just a few acoustic and descriptive measures related to the sounds locations on the MDS dimensions.

Mantel tests

To facilitate comparison between the outputs derived from the different methodologies, Mantel tests were conducted to establish the levels of association between the composite similarity matrices for similar acoustic sounds and similar source sounds between experiments. Mantel tests do not directly compare the results gathered from the MDS or the HCA analysis but compare the raw similarity judgments. The Mantel test for association between the data collected in Experiments 1 and 2 was significant for the SAS data, $r = .32$, $t(190) = 4.40$, $p < .001$, and for the SSS data, $r = .22$, $t(190) = 3.03$, $p < .001$. No Mantel tests were performed for the US data between the two experiments as no clusters of interest were identified in either MDS solution.

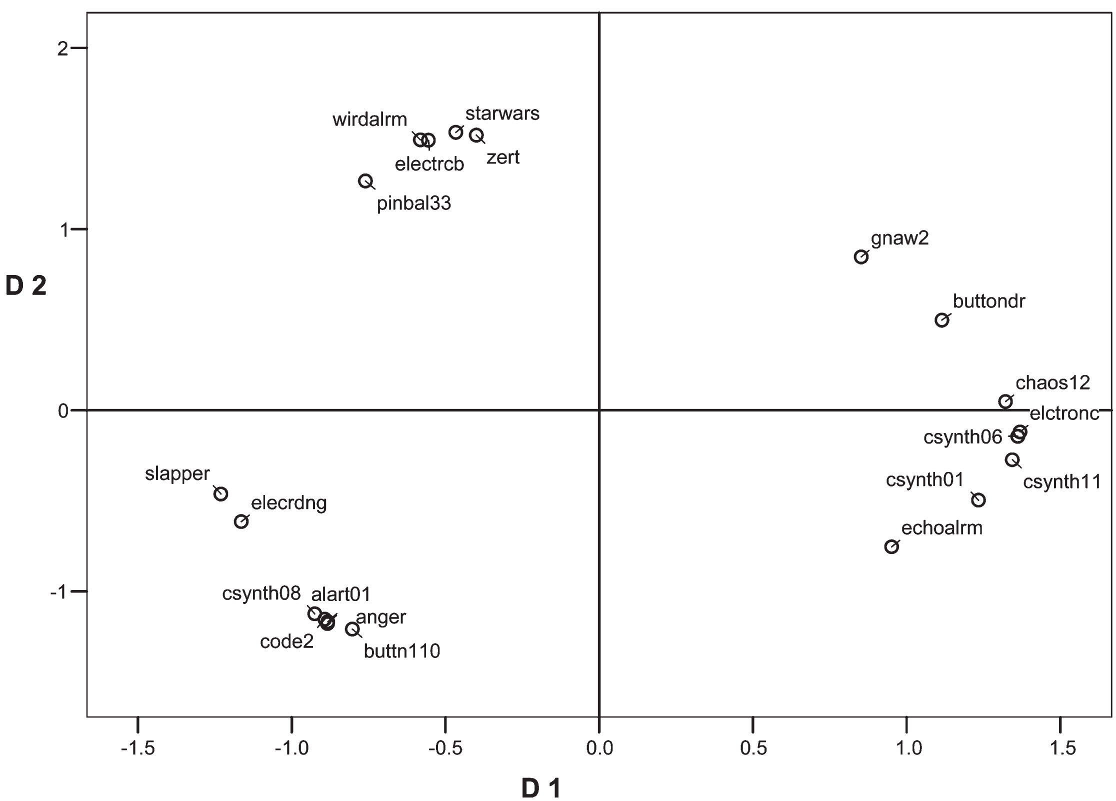

Figure 11. *Multidimensional scaling (MDS) solution for the unfamiliar sounds derived from grouping task.*

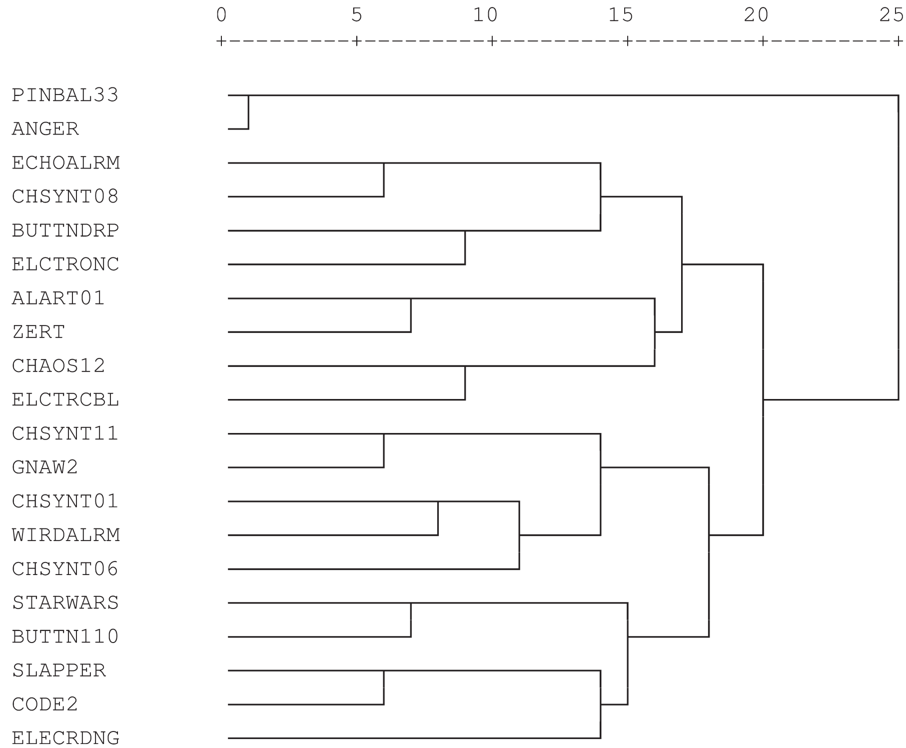

Figure 12. *Dendogram for unfamiliar sounds derived from grouping task.*

To further demonstrate the similarities and differences between the methodologies, Figures 13, 14, and 15 show the MDS configurations for the pairwise and grouping methodologies for each of the sound sets. The Mantel tests show that much of the variance remains unexplained, and the comparisons of these figures helps to illustrate this point.

GENERAL DISCUSSION

This research has added to the limited understanding of what determines similarity of acoustic stimuli and how the grouping and pairwise tasks compare when assessing similarity judgements.

Mantel tests revealed that the similarity matrices between the pairwise and grouping tasks for similar acoustic sounds and similar source sounds data were correlated. Some variance between the methodologies is accounted for by similarities between the solutions but the Mantel tests also highlight differences between the methodologies. For the similar acoustic sounds, the paired comparisons methodology resulted in stimuli being grouped primarily by acoustic information and showed only acoustic descriptors of the stimuli as being correlated with those groupings. The grouping task also showed some stimuli grouped by their acoustic features, but category-based clusters were also evident, and adjectival as well as acoustic descriptors were shown to be correlated with the groupings. It could be suggested that methodological features of the grouping task encourage participants to make more use of categorical over acoustic information. The paired comparisons task resulted in narrower, acoustic-based stimulus clusters.

For the similar source sounds, both methodologies showed clear evidence of stimulus clustering by category. Although the category-based clusters were more clearly demonstrated by the grouping task, their existence in the pairwise data is noteworthy. In the pairwise task, sound pairs are presented in isolation, and so participants are unaware of the categories on which the presented sounds were selected. Nevertheless, results from the paired comparison task suggests that category membership is playing an important role in the stimulus groupings; both the MDS and the HCA showed loose but clear clusters that reflected the categories originally chosen for inclusion in the experiment. The acoustic and descriptive features identified as being relevant to the stimulus groupings were also similar for the two methodologies; both identified RMS power as being correlated with the similarity

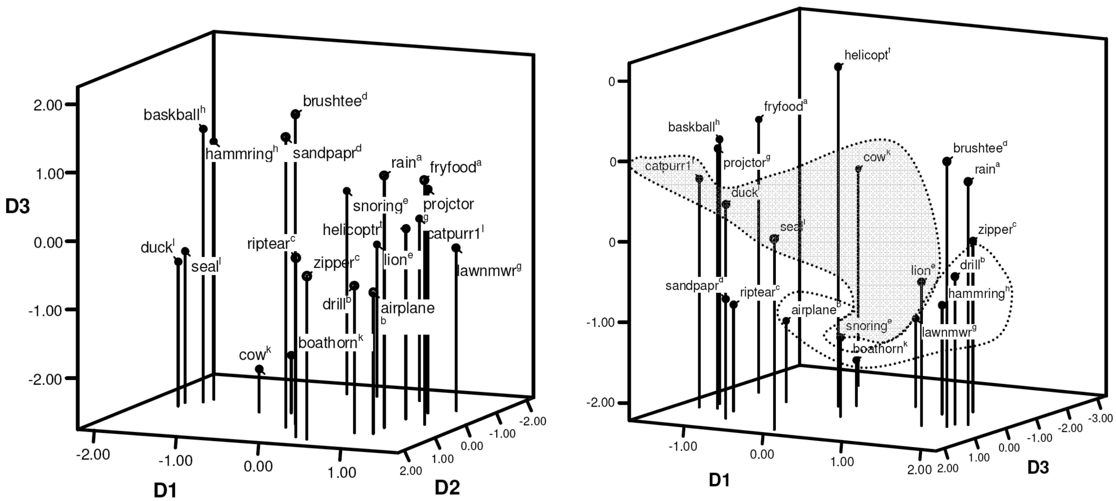

Figure 13. *Comparison of multidimensional scaling (MDS) solutions for similar acoustic sounds for pairwise and grouping methodologies, respectively.*

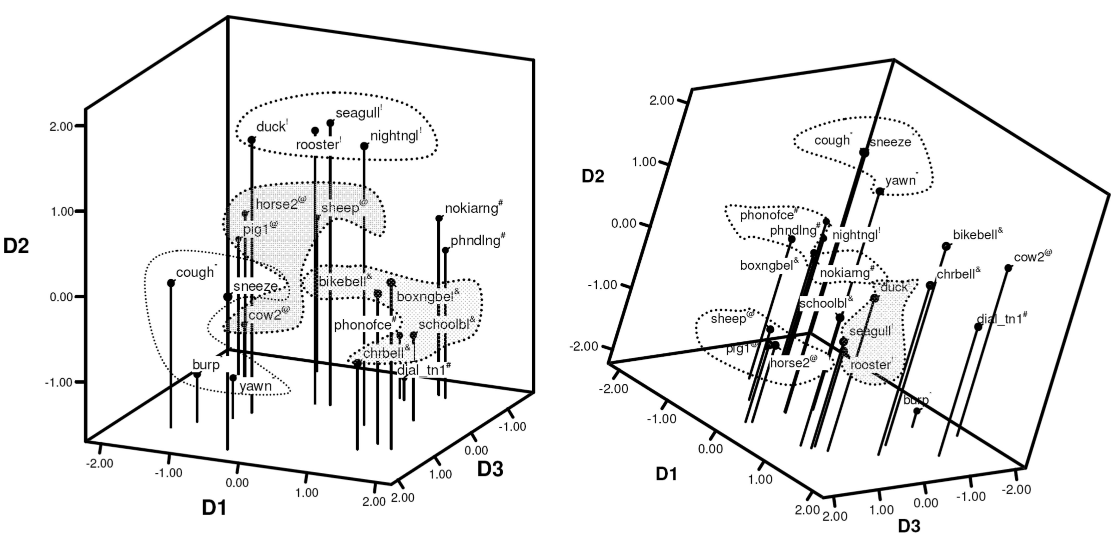

Figure 14. *Comparison of multidimensional scaling (MDS) solutions for similar source sounds for pairwise and grouping methodologies, respectively.*

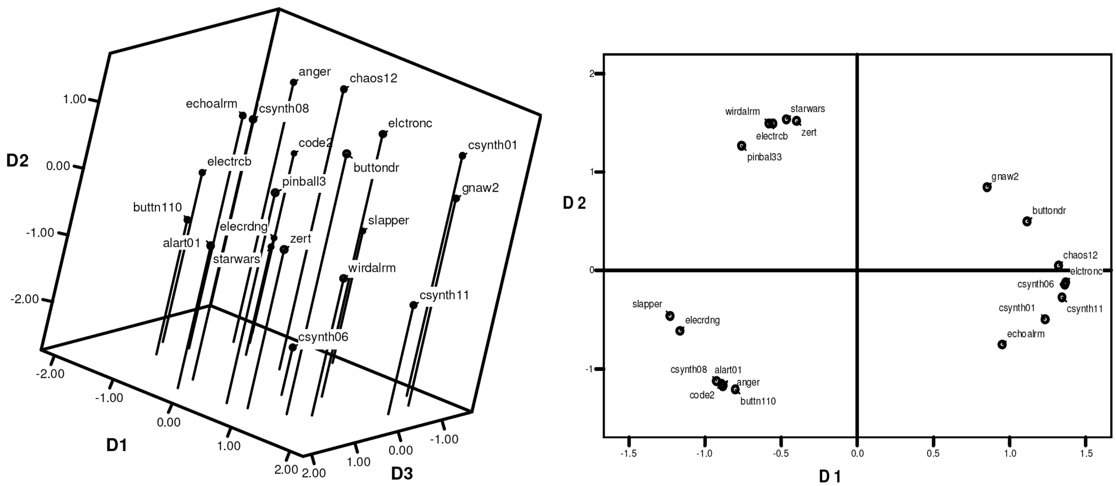

Figure 15. *Comparison of multidimensional scaling (MDS) solutions for unfamiliar sounds for pairwise and grouping methodologies, respectively.*

ratings of the similar source sounds. The grouping methodology, rather than the paired comparisons task, highlighted the relevance of adjective descriptors to the stimulus groups.

For the unfamiliar sounds participants appear to be grouping the unfamiliar sounds differently from one another, and therefore no clear clusters are identifiable. There may be little stability in participants' similarity judgement processes for unfamiliar sounds when they are unable to use knowledge of the source of the sound or its function, and their grouping strategies are likely to be less uniform. This issue would benefit from further research looking at individual differences in grouping strategies for familiar versus unfamiliar sounds.

For the unfamiliar sounds, neither methodology revealed strong evidence of clustering. However both methodologies revealed a large number of salient acoustic or adjectival features that correlated with the MDS dimensions. The salient features are largely the same across Experiments 1 and 2 with the exception of the RMS power measures that are identified by the pairwise but not the grouping task.

These results provide an opportunity to compare the outputs derived from paired comparisons and a grouping task on three identical sound sets. The clearest difference between the two tasks was the way that the results reflected the original selection of sounds. The pairwise task clearly reflected the original basis for selection with similar acoustic sounds in pairs and similar source sounds in category groups.

The grouping task reflected the original selections more loosely, and participants showed a tendency to group by category whenever possible. It is important to note that people are likely to group sounds according to the most salient features, which could be categorical or acoustic and to some extent are likely to be predetermined by the stimulus sets. Experiments 1 and 2 provide clear evidence, from the MDS configurations and the HCA analyses, that the participants were making use of category information as part of their similarity judgement strategies if the sounds were familiar. There was no evidence for the use of category information for the unfamiliar sound set on either task. The unfamiliar group, showing no clear clusters for either methodology, is a good example of the inability to categorize all sounds. Each methodology suggested a large number of salient features that correlated with the identified dimensions. For unfamiliar sounds categorization based on the sounds' source cannot be employed, and so participants cannot rely on common, everyday categories such as animals.

Cognitively, it is probably more economical to form large categories such as animals and machines than to work out which sounds are the most similar on a range of different acoustic features. About half the sounds in the similar acoustic sounds group were fitted into new categories (animals and machines). The partitioning of the world into concepts allows us to decrease the amount of information we have to process (Smith, 1989).

The different methodologies also showed differences in the acoustic and descriptive features identified as salient in participants' judgements of similarity. Participants were using acoustic features for both the pairwise and the grouping tasks, especially measures of RMS power. Whilst descriptive measures were found to show significant relationships, these were more variable across methodologies and sound groups.

These comparisons reflect those of Bonebright (1996) who used different stimulus sets (auditory graphs and actors' portrayals of vocal affect) but also compared pairwise and grouping methodologies. The present results identified a difference in the closeness of the groups identified by the MDS analysis, with pairwise comparisons revealing closer clusters than the grouping task. Bonebright (1996) found this difference for her auditory graphs. The other finding from Bonebright that is reflected here is that in general the two methodologies provide comparable results.

These experiments further the suggestion by Bonebright (1996) that the grouping task is a viable alternative to the pairwise task with large ($N > 20$) sound sets, but have highlighted differences between the methodologies. In particular, the grouping task is likely to yield category information. In addition, these studies have suggested acoustic dimensions, such as RMS power, pitch as identified, and affective features (e.g., connotations of danger), which underlie the similarity of acoustic stimuli and could be important in the representation of sounds.

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APPENDIX A

Alphabetical list of 60 sounds with descriptions

Group	*Sound*	*Description*
SAS	Airplane[b]	Jet plane flying overhead
	Baskball[b]	5 almost even bounces of a basketball, 1240 Hz
	Boathorn[b]	2 long blasts (1 s +) on monotone horn, 141 Hz
	Brushtee(th)	Uneven pattern of brushing (teeth) sounds, 1546 Hz
	Catpurr1	Cat purrs, 3 breaths, 402 Hz
	Cow[b]	2 × moo, 171 Hz
	Drill[b]	Electric drill starting, 1.5 s long, stopping (av. 1191 Hz)
	Duck	10 quacks (various), 209 Hz
	Fryfood[b]	Spitting sound as food is frying, 3204 Hz
	Hamm(e)ring[b]	3 × (2 hammer sounds), 155 Hz
	Helicopt(e)r	Helicopter in flight, 225 Hz
	Lawnm(o)w(e)r	Lawnmower engine
	Lion	2 × lion roar, 211 Hz
	Proj(e)ctor	Old fashioned film projector, 284 Hz
	Rain	Heavy rain fall, 6690 Hz
	Riptear	Tearing fabric, 1 short tear then long tear, 661 Hz
	Sandpap(e)r[b]	11 × forward and back sandpaper sounds, 1327 Hz
	Seal[b]	6 × seal barks, 238 Hz
	Snoring[b]	Man snoring two breaths, 3419 Hz
	Zipper[b]	Long zipper being fastened quickly, 109 Hz

(*Continued overleaf*)

Appendix A (Continued)

Group	*Sound*	*Description*
SSS	Bikebell	Ring ring × 2 of old-fashioned bicycle bell, 832 Hz
	Boxingb(el)l	7 short rings of single bell, 548 Hz
	Burp[b]	Burp sound × 2, 631 Hz
	Chrbell	Three church bell strikes, 198 Hz
	Cough	Man coughing 3 times, repeated once, 783 Hz
	Cow2	2 × deep moo, 119 Hz
	Dial_t(o)n(e)[1][a]	Consistent UK dial tone, 88 Hz
	Duck[b]	10 quacks (various), 209 Hz
	Horse2	2 × horse neigh, 404 Hz
	Night(i)ng(a)l(e)	Nightingale song, 2781 Hz
	Nokiar(i)ng[a]	Nokia signature tune, 876 Hz
	Ph(o)n(e)d(ia)l(i)ng[a]	7 × tones (3 different) made by dialling a phone number, 350 Hz
	Phonof(fi)ce[a]	2 long rings of modern office phone, 493 Hz
	Pig1	Long pig squeal × 2, 841 Hz
	Rooster	2 rooster calls, 116 Hz
	Schoolb(el)l[a]	1 long single-pitch school bell, 1192 Hz
	Seagull	Seagull call, 358 Hz
	Sheep[b]	2 × bleats, 1323 Hz
	Sneeze[b]	3 × ladies' sneeze, 1567 Hz
	Yawn	Man yawning once, 173 Hz
US	Alart01[a]	5 fast upward scales (1 octave) & 5 low tone pulses (av. 526 Hz)
	Anger[a]	Fast high melodic pattern finishing with trill (av. 1004 Hz)
	Butt(o)n110[a]	Repeated electric buzz, low to high pitch, 2235 Hz
	Buttondr(oo)p[a]	Buzzing rising in pitch across approx 10 notes, 256 Hz
	Chaos12[c]	Descending fast scale with volume pulses too, 534 Hz
	Ch(ao)synth11[c]	Electronic noise similar to strumming across piano strings, 195 Hz
	Ch(ao)synth01[c]	Very low, even pitch, buzzing sound, 631 Hz
	Ch(ao)synth06[c]	Complex choppy melody, electronic, 159 Hz
	Ch(ao)synth08[c]	Pulse slowing down, even pitch, 254 Hz
	Code2[a]	High-pitched uneven clicks (av. 2728 Hz)
	Echoal(a)rm[a]	Two-tone echo sounds played 4 ×, no spaces, 210 Hz
	Elec r(ea)d(i)ng[a]	6 uneven pulses of high-pitched warbling sound, 2217 Hz
	Electr(i)cb(e)ll[a]	5 × (high high then low low, 4 tones), 3153 Hz
	Electron(i)c[a]	Low uneven pulses/buzzing sound, 241 Hz
	Gnaw2[a]	"Boom" then descending buzzing scale, 787 Hz
	Pinball33[a]	Electric pinball sounds, various, 903 Hz
	Slapper[a]	3 × one click then echoes, 1549 Hz
	Starwars[a]	High random length and pitch bleeps, 214 Hz
	W(e)ird al(a)rm[a]	Low tone, 3 short tones 1 octave higher, 270 Hz
	ZERT[a]	2 × (4 rasping sounds), 321 Hz

Note: Parentheses include sound name letters excluded from SPSS analysis. SAS = similar acoustic sounds. SSS = similar source sounds. US = unfamiliar sounds.
[a]Used by Aldrich (2005). [b]Used by Marcell, Borella, Greene, Kerr, and Rogers (2000). [c]Used by Miranda, Correa, and Wrights (2000).

APPENDIX B

Acoustic features for the 60 sound stimuli

Group	*Sound*	*Bandwidth Hz*	*RMS < 2000*	*RMS > 2000*	*Average RMS dB*	*Total RMS*	*Av pitch Hz*	*Min pitch*	*Max pitch*	*Pitch range*	*Length*	*% sound*
SAS	Airplane[b]	11025	0.05	0.13	− 14.97	0.18	?	?	?	?	3.808	100
SAS	Baskball[b]	11025	0.06	0.04	− 20.23	0.10	1240.69	114.82	2819.40	2704.58	3.35	55.54
SAS	Boathorn[b]	11025	0.18	0.04	− 13.07	0.22	141.15	139.69	142.68	2.99	3.89	100.00
SAS	Brushtee(th)	11025	0.07	0.05	− 18.94	0.11	1546.89	111.27	5323.70	5212.43	3.38	100.00
SAS	Catpurr1	4000	0.17	0.03	− 15.48	0.20	402.71	77.71	2675.13	2597.43	3.06	100.00
SAS	Cow[b]	11025	0.13	0.07	− 13.58	0.20	171.18	98.37	1668.96	1570.59	3.00	81.97
SAS	Drill[b]	11025	0.05	0.07	− 17.95	0.13	1191.96	1178.83	1205.09	26.26	3.37	100.00
SAS	Duck	11025	0.15	0.05	− 14.27	0.19	209.38	88.68	602.41	513.72	4.10	90.00
SAS	Fryfood[b]	11025	0.03	0.05	− 21.74	0.08	3204.22	2034.33	5649.86	3615.53	2.95	100.00
SAS	Hamm(e)ring[b]	11025	0.13	0.04	− 14.98	0.18	155.35	88.82	216.42	127.60	3.65	48.24
SAS	Helicopt(e)r	11025	0.11	0.02	− 17.48	0.13	225.05	103.53	1318.21	1214.67	4.27	100.00
SAS	Lawnm(o)w(e)r	11025	0.25	0.11	− 8.81	0.36	?	?	?	?	3.35	100.00
SAS	Lion	11025	0.17	0.04	− 13.77	0.20	211.73	90.56	360.06	269.50	4.12	100.00
SAS	Proj(e)ctor	11025	0.06	0.04	− 19.79	0.10	284.94	86.96	420.46	333.51	3.52	100.00
SAS	Rain	11025	0.07	0.07	− 16.9	0.14	6690.89	6690.89	6690.89	0.00	3.84	100.00
SAS	Riptear	11127.5	0.06	0.09	− 16.96	0.14	?	?	?	?	3.93	100.00
SAS	Sandpap(e)r[b]	11025	0.02	0.09	− 19.18	0.11	116.60	80.21	153.03	72.83	3.39	100.00
SAS	Seal[b]	11025	0.16	0.06	− 12.85	0.23	358.89	100.09	613.25	513.15	3.05	100.00
SAS	Snoring[b]	11025	0.03	0.02	− 25.29	0.05	1567.31	1185.58	1750.08	564.51	3.65	83.94
SAS	Zipper[b]	11025	0.11	0.03	− 14.91	0.14	109.8906	76.28048	174.9789	98.70	2.232879	100
SSS	Bikebell	11025	0.03	0.03	− 19.04	3.81	832.08	813.92	844.37	30.45	3.31	81.01
SSS	Boxingb(el)l	4000	0.06	0.07	− 17.57	0.13	548.06	88.17	959.27	871.10	2.55	100.00
SSS	Burp[b]	11025	0.39	0.03	− 7.4	0.43	631.90	607.88	658.05	50.17	1.29	77.78
SSS	Chrbell	11025	0.11	0.04	− 16.58	0.15	197.86	61.24	509.14	447.90	3.97	100.00
SSS	Cough	5512.5	0.09	0.02	− 18.71	0.11	783.29	170.98	2906.32	2735.34	4.18	81.35
SSS	Cow2	5512.5	0.10	0.03	− 17.84	0.13	119.06	75.64	221.24	145.60	4.08	86.83
SSS	Dial_T(o)n(e)[1][a]	5512.5	0.10	0.02	− 18.1	0.12	87.86	87.55	88.01	0.46	4.00	100.00
SSS	Duck[b]	11025	0.15	0.05	− 14.27	0.19	209.38	88.68	602.41	513.72	4.10	90.00
SSS	Horse2	4000	0.15	0.02	− 15.28	0.17	404.25	79.50	1800.47	1720.98	3.37	88.34
SSS	Night(i)ng(a)l(e)	5512.5	0.03	0.23	− 11.79	0.26	2781.79	891.65	3588.94	2697.30	3.65	100.00
SSS	Nokiar(i)ng[a]	11025	0.02	0.04	− 25.54	0.05	876.60	513.06	4590.24	4077.18	4.11	73.59
SSS	Ph(o)n(e)d(ia)l(i)ng[a]	5512.5	0.08	0.00	− 20.14	0.08	350.78	81.81	2015.75	1933.94	3.97	89.26
SSS	Phonof(fi)ce	5512.5	0.09	0.00	− 16.58	0.10	493.56	431.85	572.05	140.20	4.20	41.76
SSS	Pig1	5512.5	0.18	0.05	− 12.66	0.23	841.41	84.11	1715.33	1631.23	3.99	98.71

SSS	Rooster	11025	0.23	0.05	− 11.14	0.28	661.04	267.68	882.25	614.58	4.10	96.97
SSS	Schoolb(el)l[a]	5512.5	0.01	0.03	− 28.5	0.04	1327.19	1262.33	5444.25	4181.92	4.00	100.00
SSS	Seagull	5512.5	0.08	0.03	− 19.03	0.11	1192.99	476.30	1704.65	1228.35	3.99	100.00
SSS	Sheep[b]	11025	0.08	0.07	− 15.99	0.15	238.10	93.62	971.25	877.63	3.46	81.52
SSS	Sneeze[b]	11025	0.25	0.09	− 9.24	0.34	1549.04	234.44	4362.77	4128.33	2.78	63.64
SSS	Yawn	5512.5	0.11	0.03	− 16.98	0.14	173.05	87.09	701.43	614.34	3.82	100.00
US	Alart01[a]	4000	0.05	0.01	− 24.38	0.06	526.03	87.83	991.68	903.84	4.42	100.00
US	Anger[a]	4000	0.07	0.00	− 23.85	0.07	1004.77	713.87	1884.61	1170.74	3.46	100.00
US	Butt(o)n110[a]	11025	0.04	0.04	− 23.86	0.07	2235.33	1229.26	1229.26	0.00	4.18	100.00
US	Buttondr(oo)p[a]	11025	0.17	0.01	− 13.62	0.18	256.65	76.35	2785.91	2709.57	3.94	100.00
US	Chaos12[c]	22050	0.15	0.04	− 14.05	0.19	534.20	253.17	917.02	663.84	3.75	100.00
US	Ch(ao)synth01[c]	22050	0.42	0.09	− 5.77	0.51	631.09	96.39	96.39	0.00	4.00	100.00
US	Ch(ao)synth06[c]	22050	0.23	0.06	− 10.66	0.29	159.79	70.88	249.61	178.73	3.87	100.00
US	Ch(ao)synth08[c]	22050	0.09	0.02	− 18.97	0.11	254.87	79.41	845.07	765.65	3.88	100.00
US	Ch(ao)synth11[c]	22050	0.10	0.03	− 17.53	0.13	195.04	75.88	662.57	586.69	3.95	100.00
US	Code2[a]	11025	0.01	0.02	− 32.42	0.02	2728.07	841.18	7733.96	6892.79	4.10	62.26
US	Echoal(a)rm	4000	0.02	0.01	− 27.05	0.04	209.58	79.28	321.77	242.50	4.29	82.48
US	Electr(i)cb(e)ll[a]	11025	0.02	0.06	− 22.44	0.08	3153.72	738.12	8977.00	8238.88	4.10	100.00
US	Elecr(ea)d(i)ng[a]	22050	0.01	0.04	− 26.03	0.05	2217.47	408.22	10873.38	10465.16	4.02	100.00
US	Electron(i)c[a]	4000	0.06	0.00	− 24.48	0.06	241.77	77.78	608.30	530.52	3.99	100.00
US	Gnaw2[a]	11025	0.34	0.00	− 7.87	0.36	787.42	114.30	2137.38	2023.08	4.04	100.00
US	Pinball33[a]	5512.5	0.08	0.02	− 19.45	0.10	903.41	93.27	5086.05	4992.77	3.69	100.00
US	Slapper[a]	11025	0.02	0.03	− 24.25	0.05	1323.30	76.55	4845.25	4768.70	1.50	100.00
US	Starwars[a]	22050	0.04	0.09	− 21.77	0.08	3419.68	630.99	9508.56	8877.57	4.00	64.60
US	Wi(e)rd al(a)rm[a]	5512.5	0.11	0.09	− 17.44	0.12	214.71	77.81	619.75	541.94	4.04	100.00
US	ZERT[a]	11127.5	0.07	0.09	− 20.65	0.10	321.43	99.30	2880.93	2781.63	4.00	87.46

Note: Parentheses include sound name letters excluded from SPSS analysis. SAS = similar acoustic sounds. SSS = similar source sounds. US = unfamiliar sounds. RMS = root mean square. ? = data unobtainable. [a]Used by Aldrich, 2005. [b]Used by Marcell, Borella, Greene, Kerr, and Rogers (2000). [c]Used by Miranda, Correa, and Wrights (2000).

APPENDIX C

Mean scores on the descriptive measures for the 60 sound stimuli

Category	*Sound*	*Familiar?*	*Difficult to id?*	*High pitch/low pitch*	*Pleasing/annoying*	*Safe/dangerous*	*Calming/exciting*
SAS	Airplane[b]	6.75** (familiar)	1.45** (easy to id)	4.50* (low pitch)	3.60	4.35	5.60** (exciting)
	Baskball[b]	6.50**	1.70*	4.05	4.40	2.65	4.50*
	Boathorn[b]	6.40**	1.40**	1.95*	4.10	3.40	4.00*
	Brushtee(th)	6.80**	1.40**	3.65	4.40*	1.75**	3.25
	Catpurr1	6.35**	1.75**	2.15*	2.00**	1.75**	2.00*
	Cow[b]	6.90**	1.30**	2.60*	3.05	1.95**	3.00
	Drill[b]	4.80*	3.30	4.05	5.60**	4.55	4.65**
	Duck	6.75**	1.35**	3.75	3.50	1.95*	3.25
	Fryfood[b]	6.40**	1.45**	3.50	3.20	2.60	2.95
	Hamm(e)rng[b]	5.70*	2.00**	2.65*	5.95**	4.95**	4.55**
	Helicopt(e)r	6.40**	2.10*	2.10**	3.95	4.60	4.55*
	Lawnm(o)w(e)r	6.00**	2.70	2.35*	5.85**	5.00*	4.55**
	Lion	6.35**	1.55**	2.05*	3.75	6.20**	5.80**
	Proj(e)ctor	4.20	4.20	3.15	4.85*	3.45	4.25*
	Rain	6.70**	1.50**	3.65	3.10	2.25*	2.55
	Riptear	5.85*	2.15*	3.75	5.45**	3.75	4.60**
	Sandpap(e)r[b]	5.10**	2.70	4.05*	5.75**	2.95	4.05**
	Seal[b]	6.00**	2.15*	3.50	3.55	2.95	4.05*
	Snoring[b]	6.85**	1.10**	2.85	5.85**	2.25*	3.50
	Zipper[b]	3.00	5.30*	5.10*	6.25**	4.35*	4.55**
SSS	Bikebell	6.90**	1.15**	5.90**	3.90	2.15*	3.65
	Boxingb(el)l	6.55**	2.10*	5.05*	5.25*	3.75	4.95**
	Burp[b]	6.80**	1.05**	2.25*	6.05**	2.65	3.80**
	Chrbell	6.85**	1.15**	4.60	3.70	2.05**	2.85
	Cough	6.95**	1.05**	3.00*	6.15**	4.75*	4.00**
	Cow2	6.60**	1.50**	2.00**	3.80	2.10**	3.60
	Dial_t(o)n(e)[1]	6.90**	1.20**	4.00	6.25**	2.30	3.55*
	Duck[b]	6.65**	1.35**	4.15	3.25	2.25*	3.30
	Horse2	6.65**	1.25**	3.30	2.45*	2.00**	3.15
	Night(i)ng(a)l(e)	6.75**	1.15**	6.70**	2.30*	1.65**	2.05*
	Nokiar(i)ng[a]	6.70**	1.00**	6.10**	6.30**	2.55	4.75**
	Ph(o)n(e)d(ia)l(i)ng[a]	6.85**	1.45**	5.20**	5.30**	2.15*	4.10**
	Phonof(fi)ce[a]	6.60**	1.05**	3.90	4.55*	2.30	4.60*
	Pig1	5.80*	1.85**	3.90	5.20**	3.80	4.70**
	Rooster	6.95**	1.05**	5.60**	3.20	1.70**	3.10
	Schoolb(el)l[a]	6.40**	1.55**	5.75**	5.10*	4.10	5.00**
	Seagull	6.95**	1.05**	6.25**	4.05	2.15**	2.30
	Sheep[b]	6.95**	1.00**	4.55*	3.55	1.90**	3.05
	Sneeze[b]	6.95**	1.00**	4.65*	5.55**	4.10	4.25**
	Yawn	6.85**	1.10**	2.65*	4.30*	1.60**	2.70
US	Alart01[a]	2.55*	5.25*	4.45	5.50**	3.85	4.70**
	Anger[a]	2.60	5.80*	5.40**	4.80*	3.40	4.75**
	Butt(o)n110[a]	2.00*	5.60*	6.05**	2.90**	4.20*	4.95**
	Buttondr(oo)p[a]	1.95*	5.85*	3.25	5.95**	4.30*	4.45**
	Chaos12[c]	1.95*	6.50**	4.40*	5.45**	3.70	4.30*

(*Continued overleaf*)

Appendix C (Continued)

Category	*Sound*	*Familiar?*	*Difficult to id?*	*High pitch/low pitch*	*Pleasing/annoying*	*Safe/dangerous*	*Calming/exciting*
	Ch(ao)synth01[c]	2.15*	5.35*	1.70**	5.70**	4.60*	4.15*
	Ch(ao)synth06[c]	3.15	4.90	4.10*	5.30*	4.20	4.65**
	Ch(ao)synth08[c]	2.25*	5.50*	3.70	4.95**	3.95	3.90**
	Ch(ao)synth11[c]	1.80**	6.05**	4.80*	5.35**	4.95*	4.85**
	Code2[a]	1.55**	5.90*	5.30*	5.40*	3.15	4.30*
	Echoal(a)rm[a]	2.25*	5.60**	4.00	4.80*	4.15*	4.25*
	Elec r(ea)d(i)ng[a]	2.80	4.85	5.85**	6.00**	3.39*	4.85**
	Electr(i)cb(e)ll[a]	1.65**	5.85*	6.25**	6.10**	3.90*	4.90**
	Electron(i)c[a]	2.75	5.30*	2.45*	4.35	3.30	4.35*
	Gnaw2[a]	2.50	5.65*	3.50	5.15**	4.60*	5.95**
	Pinball33[a]	2.25*	5.25*	4.75*	5.70**	3.95	4.60**
	Slapper[a]	2.70	5.25*	3.50	5.70**	3.80	4.65**
	Starwars[a]	2.65*	4.60	5.30*	5.75**	4.50*	4.75**
	W(e)ird al(a)rm[a]	2.05*	5.85**	3.45	5.10**	4.15*	4.65**
	ZERT[a]	1.80**	6.70**	2.80	5.35**	4.15	4.50**

Note: SAS = similar acoustic sounds. SSS = similar source sounds. US = unfamiliar sounds. Parentheses include sound name letters excluded from SPSS analysis.

[a]Used in experimental previous work in series (Aldrich, 2005). [b]Sounds used by Marcell, Borella, Greene, Kerr, and Rogers (2000). [c]Sounds used by Miranda, Correa, and Wrights (2000). For all statements: 1 = strongly disagree to 7 = strongly agree. Familiar? = This sound seems very familiar to me. Difficult to id? = This sound is difficult to identify. Bipolar adjective scales: high pitch/low pitch, pleasing/annoying, safe/dangerous, and calming/exciting.

*Significant at $< .05$ alpha level. **Significant at $< .001$ alpha level.