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ANNOYANCE AND SPECTRAL CONTRAST ARE CUES FOR SIMILARITY AND PREFERENCE OF SOUNDS

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Previous research has suggested that perceived similarity is based on primarily cognitive processes, whereas preferences are based to a larger extent on affective processes. This was put to an empirical test utilizing 15 complex sounds as stimuli and 25 subjects for the assessments. Various versions of multidimensional scaling were used as a method of comparison. The results show that data analyses must take into account individual differences in similarity and non-preference. Contrary to the hypothesis expressed, both similarity and non-preference were found to be based mainly on affective responses because a major proportion of the explained variance originated from the perceived annoyance of sound. This was not true for perceived loudness or for the acoustic variables of Zwicker's loudness and Aures' sharpness. Spectral contrast calculated as the number of maxima in the normalized Zwicker's specific loudness spectra was found to be the best acoustic candidate for explaining at the individual level what properties of sound cause them to be perceived as similar or non-preferred.

1. INTRODUCTION

Noise annoyance may be defined as a feeling of displeasure evoked by noise. Apart from sleep disturbance, annoyance is the currently most used criterion for adverse effects of environmental noise in various countries [1–6]. Accumulated research results seem to agree that (perceived) loudness, and thus also its correlate sound pressure level, is the main feature of environmental sounds that determines annoyance [2, 7–9]. We contend that properties of sound related to character or quality must play a primary role in evoking feelings of annoyance in real-life situations simply because they determine what sound is perceived. Thus, a pertinent issue in noise measurement and control must be to prove that it is appropriate to collapse the qualitative properties of sound into a unidimensional scale of sound pressure, as is done for example in various frequency weighting networks, the equivalent continuous sound pressure level (L_{Aeq}, T), or Zwicker's loudness. Whether or not this is appropriate has to do with the type of adverse effects that the noise measure is supposed to be efficient for controlling. For example, L_{Aeq}, T may be a good metric for

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assessing the risk for hearing impairment, whereas it may be less well suited for estimating (perceived) annoyance evoked by sounds with a large portion of low-frequency components [10].

In the hope of revealing the key principles involved in the perception of environmental sounds, the present research approaches the annoyance problem indirectly and from a different viewpoint than before. The question posed here is to what extent perceptual attributes such as loudness and annoyance [2] and/or physical properties such as Zwicker's loudness [11, 12], Aures' sharpness [13] and spectral contrast [14–16] may explain how similar environmental sounds are perceived or what sounds are preferred in a listening situation. It was also assumed that a person's preference/non-preference choices among sounds would be based on the degrees of annoyance. A high association was thus expected between, on the one hand, the participants' responses and, on the other, the perceptual attributes and physical properties that are known to be associated with annoyance.

A major, recognized difference between the concepts of similarity and preference is their primarily cognitive and affective nature respectively. The two underlying psychological processes are believed to be independent [17]. Typically, only a minor part of the judgmental variance is common in similarity and preference data for the same set of stimuli [18]. It thus seems plausible to expect that (perceived) loudness and Zwicker's loudness would be associated with similarities of sounds (cognitive aspects) and annoyance with non-preferences of sounds (emotional aspects). If Aures' sharpness is related to the intrusiveness of sounds [9], and spectral contrast to the tonality [19] and to the pitch strength [19, 20], they would influence non-preferences more than similarities and would relate to annoyance as well.

2. METHOD

2.1. SUBJECTS

Two experiments were conducted in which 25 undergraduates at Stockholm University (ten men and 15 women) participated as volunteers. Their mean age was 27·2 (SD = 7·2) years. A standard audiogram was determined individually for all subjects. No subject had to be excluded because of hearing loss.

2.2. SOUNDS AND APPARATUS

The 15 sounds used in the experiments consisted of 11 environmental sounds and four model spectra. When presented to the subjects, the sounds were 4 s in duration. The environmental sounds were: A—passing car, B—office printer, C—ventilation fan, D—alarm clock, E—passing subway, F—departing subway, G—leaf blower, H—lunch restaurant, I—road traffic, J—food mixer, and K—coffee maker.

The four model spectra (L, M, N, & O) were created from white noise in the frequency range of 0–20 kHz and had different spectrum envelope shapes. The averaged power spectra differed as follows: L had a maximum value at 2 kHz with the slopes [40 dB/Δf(0–2 kHz) and $-$30 dB/Δf(2–20 kHz)], M at 7 kHz with the slopes [40 dB/Δf(0–7 kHz) and $-$30 dB/Δf(7–20 kHz)], N at 11 kHz with the slopes [40 dB/Δf(0–11 kHz) and $-$30 dB/Δf(11–20 kHz)], whereas O was invariant in the frequency range of 0–7 kHz and then had a decreasing slope [$-$30 dB/Δf(7–20 kHz)]. The model spectra were selected to show some similarity with the environmental sounds with regard to power spectrum envelope shape. The reason for including the four model spectra was to try to enlarge the range of spectrum envelope shapes and thus enhance the potential variation in perceived quality of the sounds.

The 11 environmental sounds were recorded on a digital audio tape recorder (SONY, TCD-D10 PRO II) using a condenser microphone (Brüel & Kjaer 4155, microphone power supply B & K 5935). A large variation was sought in both Zwicker's loudness and Aures' sharpness for the case in which all sounds were set equal in sound level (L_{Aeq},4 s). It was assumed that this arrangement would guarantee a large variation in "perceived quality". The reason for this is that we wished to avoid the situation where a dominant variation in "perceived loudness" in the set of sounds would overshadow any variation in "perceived quality" (cf. [21]). As a check, two perceptual scales, loudness and annoyance, were obtained by free-number magnitude estimation in an independent group of nine subjects (data from reference [22]).

The 15 sounds were combined in 210 unique pairs (identity pairs excluded, reverse pairs included). The 210 pairs of sounds were recorded in three random orders on three corresponding experimental tapes in which a sound pair covered a duration cycle of 15 s (sound 4 s, pause 1 s, sound 4 s, pause 6 s). The tapes were played back by a Fostex DAT tape recorder using a Pioneer (A-878) amplifier that fed two Cerwin-Vega loudspeakers (PD-3). All sounds were presented to the group of subjects as they were seated in a large conference room ($8 \times 8 \times 2{\cdot}75$ m; reverberation time 0·9 s). The equivalent continuous sound pressure level averaged for the 4-s duration was made equal to 65 dB for each sound at a listening position in the middle of the room.

2.3. SIMILARITY JUDGMENTS

The subject's task was to judge the similarity of each pair of the sounds. The perceived similarity of sound pairs was reported in percent on a scale from 0 to 100, i.e., from complete dissimilarity (0% similar) to complete similarity (100% similar). The subjects were instructed to judge the degree of "overall similarity". Any number from 0 to 100 could be used. In all, each of the 25 subjects made 630 similarity judgments (210 unique pairs presented in random orders, i.e., each pair was judged three times by each subject).

2.4. NON-PREFERENCE JUDGMENTS

Non-preference was obtained by asking the participants to mark which of the two sounds presented in a pair they would have *preferred to switch off*, if given the possibility at that time. From these choices, percentages were calculated for all pairs in which a particular sound was non-preferred, that is, the more frequently the particular sound was wished to be switched off, the higher the non-preference percent. In all, each of the 25 subjects made 630 non-preference "prefer to switch off" choices, three for each of the 210 unique pairs.

2.5. PROCEDURE

A balanced design was used with regard to the order of the similarity and non-preference experiments. The experiments were conducted with two subject groups (11 or 14 subjects) who each participated on two occasions on separate days. One subject group started with the similarity experiment and the other with the non-preference experiment. The three experimental tapes were presented to each group of subjects, in the order of Tapes 1 to 3 for one group and the reverse order (Tapes 3 to 1) for the other group. The same order of tapes was used for the similarity and non-preference experiments.

The subjects responded individually by giving each similarity (or non-preference) response in written form. For each of the three tapes, a 21-page booklet was used which allowed only ten responses per page, i.e., six booklets per subject, three for similarity judgments and three for non-preference choices. The similarity and non-preference experiments were each divided into nine 17-min sessions in which 70 sound pairs were presented. A 5-min break was given between sessions. Thus, the 210 unique pairs of sounds of one tape required three sessions. A 10-min break was taken between the playback of tapes.

3. RESULTS AND DISCUSSION

3.1. TEST–RETEST RELIABILITY OF SIMILARITIES AND NON-PREFERENCES

Individual test–retest coefficients were calculated for the different tapes that contained the 210 unique pairs of sounds in different random orders. The judgments of the pairs of sounds were thus compared for Tape 1 versus Tape 2, Tape 1 versus Tape 3 and Tape 2 versus Tape 3. Pearson's coefficient of correlation was calculated for the three tape combinations over the 25 subjects. On average, higher test–retest coefficients were obtained for similarity (mean: 0·70, range: 0·49–0·85, $n = 75$) than for non-preferences (mean: 0·65, range: 0·40–0·91, $n = 75$). Part of this difference may refer to the circumstance that stronger data were collected for similarities (quantities on an interval/ratio scale) than for non-preferences (binary choices). None of the subjects had very low test–retest reliability for both similarities and non-preferences. Individual "scale values" were thus assessed for each subject and each pair of sounds ($n = 105$) by calculating arithmetic means ($n = 6$) and arithmetic sums ($n = 6$) for similarities and non-preferences respectively.

3.2. INDIVIDUAL DIFFERENCES IN NON-PREFERENCE CHOICES

The individual non-preferences were analyzed with the MDPREF software ([23]; see also Reference [24]). MDPREF analysis considers each subject's non-preferences in creating the multidimensional solution for the sounds and seeks the best solution for each of them jointly. We chose to represent the subjects' non-preferences as vectors rather than as points in a multidimensional space (e.g., reference [24]). The goal was to try to show the interindividual differences inherent in the non-preference choices of sounds and to try to assess and value the potential relevance of the three acoustic and two perceptual external variables for individual non-preferences.

The proportion of variance accounted for by each factor or dimension in the best-fitting three-dimensional MDPREF solution was 67% for the first dimension, 16% for the second and 5% for the third. The cumulative proportion of variance explained thus adds up to 86%, which must be considered acceptable [24]. Figure 1 shows the relationship between Dimension 1 and Dimension 2 of the three-dimensional MDPREF solution. Dimension 3 is not given in this presentation due to difficulties in interpreting its meaning for the set of sounds investigated. Figure 1 shows two diagrams that display the identical base configuration of data in the first two dimensions. Each subject's vector (passing the origin) displays the highest non-preference value towards the periphery where the symbols are found. All subjects' maximum non-preferences are found within the first or fourth quadrant, and the scatter of maxima spreads evenly along the periphery of a circle (the imperfect circle

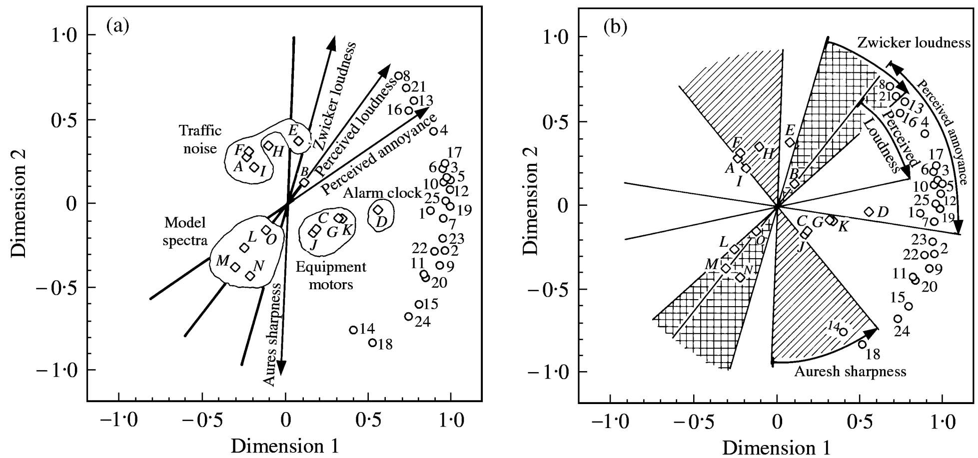

Figure 1. Structural configuration of 15 sounds determined by a three-dimensional MDPREF-solution of 25 subjects' non-preferences. Subjects are vectors and sounds are points in plots of Dimension 2 against Dimension 1 (both diagrams). Left-hand diagram displays two acoustic and two perceptual external variables as vectors. Right-hand diagram shows sectors within which each of these external variables shares $\geqslant$ 50% of their variance with individual subject's non-preference vectors ○, Subject 1–25; ◇, Sound A–O.

arrangement is due to variation in the third dimension of the MDPREF solution, which added 5% to the explained variance). No drastic reversed order of non-preferences for sounds was thus found for any individual.

The left-hand diagram of Figure 1 in the plot of Dimension 1 against Dimension 2 identifies four clusters, "traffic noise", "equipment motors", "alarm clock", and "model spectra". It was not possible to include the sound from the lunch restaurant (H) and the office printer (B) in the same clusters in all the MDS solutions, and these are left outside the enclosures drawn in the figures. These two sounds also seem to make up some of the between-groups small pattern differences found in the solutions.

The MDPREF solution allows us to make some additional comparisons more easily. In the left-hand diagram of Figure 1, external acoustic (Zwicker's loudness and Aures' sharpness) and external perceptual variables (perceived loudness and perceived annoyance [22]) have been fitted by a PREFMAP procedure into the MDPREF space. In comparing how well these external variables reflect the non-preference scales of the 25 subjects, we decided to set a Pearson's coefficient of correlation greater than $\pm 0{\cdot}70$ as the limiting criterion because it represents $\approx$ 50% explained common variance. In the right-hand diagram of Figure 1, various sectors have been marked that represent the area from the external attribute or property vector, including the accepting subjects' vectors, to the least acceptable vector according to this criterion. The non-preference vectors of 15 out of 25 subjects were associated with perceived annoyance, and seven of the same subjects' vectors were also associated with perceived loudness. Only two subjects' non-preference vectors were associated with Zwicker's loudness or with Aures' sharpness. As many as eight subjects ($\frac{1}{3}$ of the subject group) seem to have made their non-preference choices "without consideration" of the acoustic properties or perceptual attributes studied here.

3.3. INDIVIDUAL DIFFERENCES SCALING OF SIMILARITIES OF SOUNDS

Although the interindividual differences produced by the 25 subjects were low among the similarity matrices for the 15 sounds, there were minor differences. To account for these,

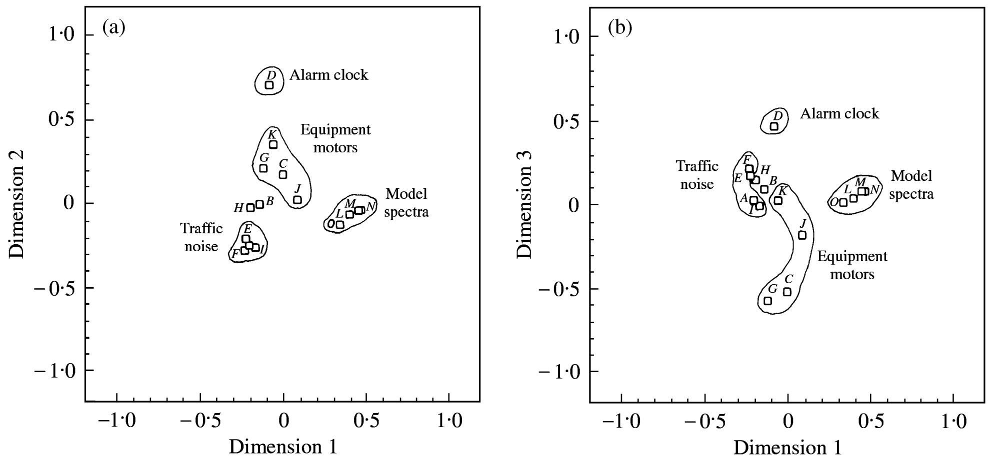

Figure 2. Structural configuration of 15 sounds determined by a three-dimensional INDSCAL solution for 25 subjects' similarities. Left-hand diagram displays Dimension 2 against Dimension 1 (□, Sound A-O) and right-hand diagram Dimension 3 against Dimension 1.

individual differences scaling was applied to the (perceived) similarity data according to the INDSCAL program [25]. In this application, the different subjects are assumed to share the same basic structure of a space defined by the similarities of sounds, while the subjects may differ in the weight they give the underlying dimensions of that space. Thus the weights obtained from this MDS solution represent a measure of the importance that each subject gives to the various underlying dimensions that define the space of the environmental sounds. A three-dimensional INDSCAL orthogonal solution seems to be stable and fits well the individual data on similarity of sounds. The variance accounted for in this INDSCAL solution is estimated to be 74%. The relative contributions were 51% for Dimension 1, 14% for Dimension 2 and 7% for Dimension 3. Three dimensions explained more than 80% of the variance in three subjects (Nos. 2, 8 and 13), between 70 and 80% in 17 subjects and between 60 and 70% in five subjects (Nos. 1, 6, 9, 19, and 24).

Dimension 1 is plotted against Dimension 2 and against Dimension 3 in the left- and right-hand diagram of Figure 2 respectively. As seen in these diagrams, most of the sounds cluster near the origin and spread somewhat along Dimension 1, although the "alarm clock" (D) contrasted to the "leaf blower" (G) and to the "ventilation fan" (C) are opposite extremes of Dimension 3. As shown in the left-hand diagram, Dimension 1 displays the "model spectra" (L, M, N, and O) and the "traffic noises" (A, E, F and I) as opposites and Dimension 2 mainly contrasts the "alarm clock" (D) with the "traffic noises".

3.4. CONCORDANCE BETWEEN SIMILARITIES AND NON-PREFERENCES OF SOUNDS

To try to display both the individual similarity data and the individual preference data jointly in the same space, we applied a PREFMAP procedure [24] to the INDSCAL solution. The weighted average dimensional structure disclosed in the similarity data by the INDSCAL solution, defined as points for the 15 sounds (Figure 2), was entered as the three-dimensional space in which the non-preferences of the 25 subjects for the same 15 sounds were also to be mapped as vectors using the PREFMAP program. The results are shown in Figure 3.

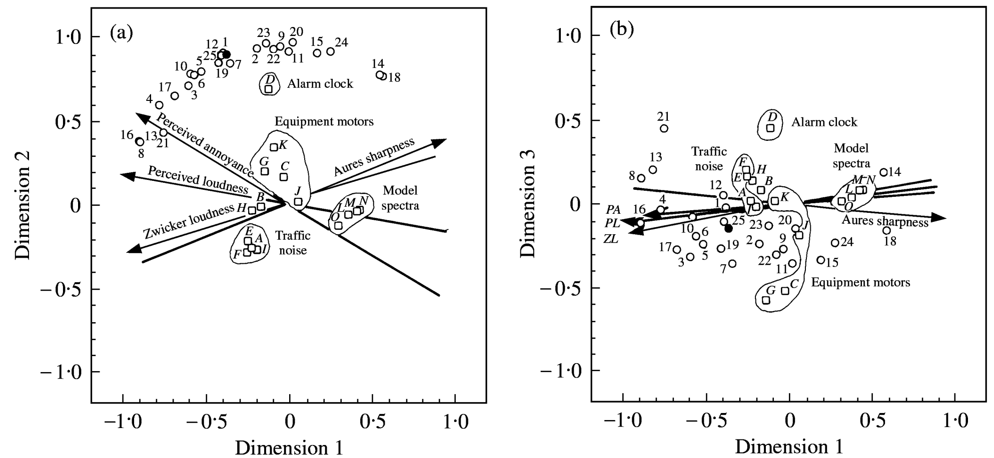

Figure 3. Non-preference vectors fitted by PREFMAP into the three-dimensional INDSCAL solution for similarities obtained for the same 25 subjects. Subjects are vectors and sounds are points in plots of Dimension 2 against Dimensions 1 and 3 against Dimension 1. Both diagrams display two acoustic and two perceptual external variables as vectors. Left-hand diagram: □, sound A-O, similarity; ○, subject 1–25, non-preference; ●, average subject, non-preference; →, external variable. Right-hand diagram: →, external variable; PA, perceived annoyance; PL, perceived loudness; ZL, Zwicker loudness.

In this PREFMAP data analysis, the 25 subjects' maximum non-preferences (open circles) fall within the first and second quadrants, with the average subject in the middle (filled circle). The external acoustic (Zwicker's loudness and Aures' sharpness) and external perceptual (perceived loudness and perceived annoyance [22]) variables were also fitted by the PREFMAP program into the INDSCAL space of similarities with the non-preference vectors. Obviously, these external variables are unable to satisfactorily explain what sounds are perceived as similar and what sounds are preferred in a listening situation. Perceived annoyance is our best explanatory candidate. However, it is natural to further explore other *acoustic* characteristics that may better explain the interindividual differences exhibited in the non-preference and similarity judgements.

3.5. SIMILARITIES BETWEEN DIFFERENT SPECTRAL REPRESENTATIONS OF SOUNDS

The sounds were analyzed with regard to the shape of the spectral envelope and spectral contrast (PULSE system, Brüel & Kjaer 7704A). The spectral envelopes were grouped according to the four clusters of sounds obtained in the previous multidimensional scaling analyses based on the data sets of individual non-preferences (Figure 1) or similarities (Figure 2). In the four diagrams in Figure 4, the 15 spectral envelopes are plotted in the form of Zwicker's loudness spectra, that is, Zwicker's specific loudness versus critical band rate.

The acoustic similarity of the spectral envelopes shown in Figure 4 was assessed by correlating (Pearson's r) Zwicker's specific loudness values for each pair of the 15 envelopes [19]. A principal component analysis was applied to the correlation matrix (105 unique cells), and three components explained 79% of the common variance (including 48, 16 and 15% for components I, II and III respectively). The results of this analysis are presented in Figure 5. In the plots of Component I against Component II (left-hand diagram), and of Component I against Component III (right-hand diagram), the same four clusters can be identified as those found in the joint non-preference and similarity space (Figure 3,

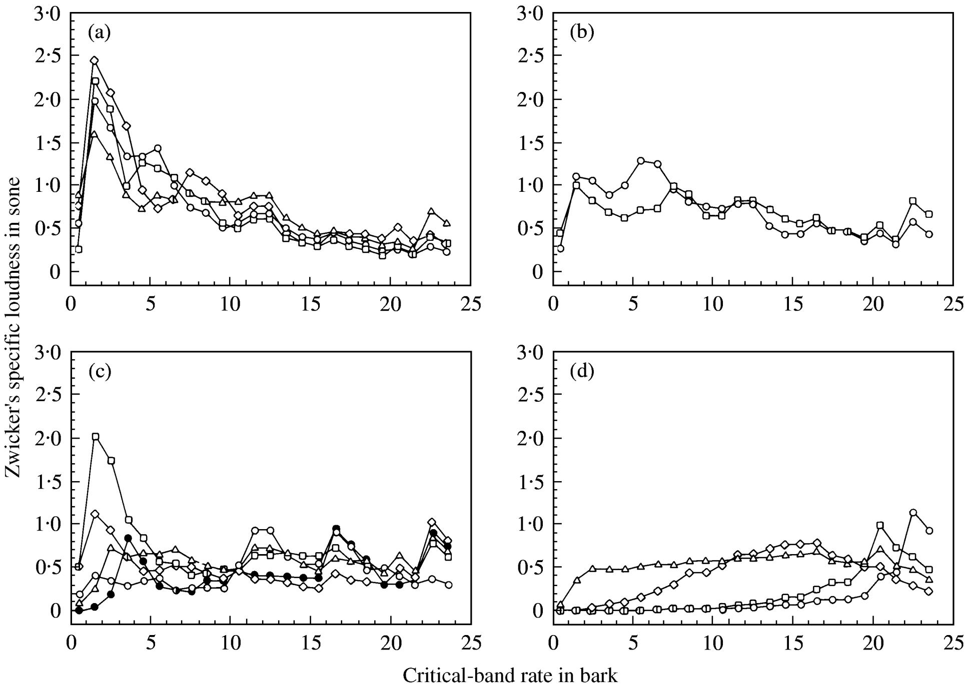

Figure 4. Groups of spectra illustrating spectral contrast among 15 sounds. The groups refer to the cluster "traffic noise" (left-hand upper diagram), ○, *F*; □, *A*; ◇, *E*; △, *L*. the two clusters "equipment motors" and " alarm clock" (left-hand lower diagram) ●, *D*: *Equipment Motors*: ○, *K*; ◇ *C*; △, *J*; □, *G*. and the cluster "model spectra" (right-hand lower diagram) ○, *N*; □ *M*; ◇, *L*; △, *O*. and for two single sounds (right-hand upper diagram): ○, *H*; □, *B*; all clusters identified by INDSCAL of similarities and MDPREF of non-preferences.

encircled). The three-dimensional solution presented in Figure 5 may be viewed as a multidimensional representation of Zwicker's total loudness values for the environmental sounds (cf. Ekman's content model [26]). These profiles are well represented in an acoustically based multidimensional space that distinctly exhibits the same four clusters (Figure 5, encircled) as the perceptually based multidimensional space of the environmental sounds (Figures 1 and 2).

The present exploration of Zwicker's loudness data shows that the qualitative information behind the specific loudness values should not be collapsed into a unidimensional variable of total loudness (cf. annoyance in reference [27]). The spectral envelopes of specific loudness vary with our sounds, but common profiles can be found and at least four clusters can be identified (Figures 4 and 5).

A visual inspection of the four clusters of Zwicker's loudness spectra (exhibited in three of the diagrams of Figure 4) shows that there were more local maxima for the "traffic noise", "alarm clock" and "equipment motors" than for the "model spectra". The two sounds of "lunch restaurant" (H) and "office printer" (B), which were not included in any cluster (e.g., Figure 2), also had fewer maxima. The number of local maxima may be considered a measure of the acoustic structure of a spectrum, here called spectrum contrast. This concept has been used earlier in speech perception [16], musical acoustics [14] and noise annoyance [15]. The present study used the following definition of spectral contrast: the average specific loudness of each spectrum (sound) is first calculated, and then all amplitudes are expressed in specific loudness values and divided by the average value. The

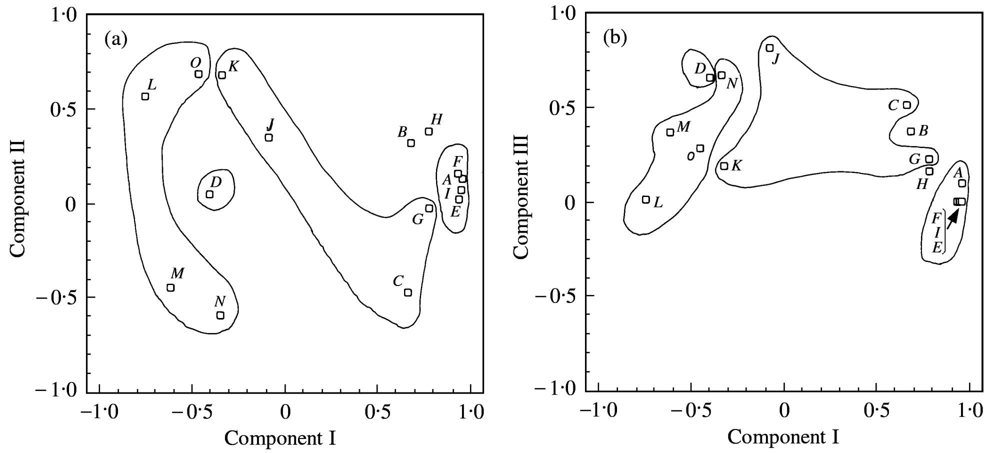

Figure 5. The relationship between three components obtained in a principal components analysis of correlations of pairs of spectral envelopes expressed as Zwicker's specific loudness as a function of critical band rate. The clusters of sounds identified by INDSCAL of similarities and MDPREF of non-preferences are encircled.

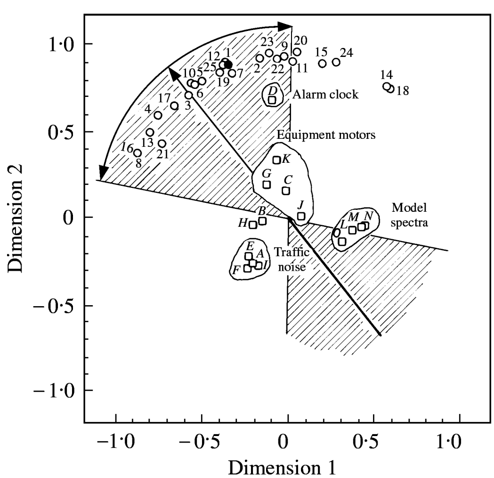

Figure 6. Non-preference vectors fitted by PREFMAP into the three-dimensional INDSCAL solution for similarities obtained for the same 25 subjects. Subjects are vectors and sounds are points in this plot of Dimension 2 against Dimension 1 (same as left-hand diagram of Figure 3). Spectral contrast is fitted and drawn as a vector. The shaded sector shows the location within which this external variable shares $\geqslant 50\%$ variance with individual subject's non-preferences. Spectral contrast comes close to explaining the average subject vector (filled circle) □, sound A-O, similarity; ○, subject 1–25, non-preference; ●, average subject, non-preference; →, external variable: spectral contrast.

local maxima are identified in this kind of normalized spectrum only if the ratios are above 1 and the neighboring values are at least 7% less [19].

Figure 6 gives the PREFMAP vectors of non-preferences in the INDSCAL solution of the similarity matrix in a form identical to that shown in the left-hand diagram of Figure 3. Spectral contrast based on the number of local maxima in Zwicker's specific loudness spectra was fitted by PREFMAP into this joint non-preference and similarity space. The spectral contrast vector falls close to the non-preference vector of Subject 3 and is thus much closer to the average subject's non-preference vector (Figure 6, filled circle) than our earlier best external variable, perceived annoyance. As suspected, the perceived annoyance and spectral contrast scales share more than half of their variance (58%). The shaded sector around the special contrast vector in Figure 6 includes subject vectors that fall within $\pm 0{\cdot}65$, expressed as Pearson's coefficient of correlation. Thus, 19 of the 25 subjects' non-preference vectors are found to be associated with the spectral contrast vector. With a criterion of $\pm 0{\cdot}70$, this number can be reduced to 15 subjects (losing subjects 2, 9 22 and 23).

Spectral contrast based on the number of local maxima in Zwicker's specific loudness spectrum is the best explanatory acoustic candidate for the perception of our 15 sounds because it best covers the large interindividual differences in the joint similarity and non-preference space. Still, however, six subjects' non-preferences seem to be dominated by some variable that we have been unable to identify.

4. CONCLUSIONS

The following main conclusions are drawn.

(1) Participants agree in principle on the perceived similarity of environmental sounds but deviate distinctly in their preference choices of the same sounds. It is, however, possible to take interindividual differences into account and create a joint space for the similarities of sounds and for every participant's non-preferences of the same sounds.

(2) Zwicker's total loudness, Aures' sharpness and perceived loudness (assessed by magnitude estimation) are unable to explain what environmental sounds are perceived as similar and non-preferred in a listening situation.

(3) The qualitative information conveyed in Zwicker's specific loudness as a function of critical band rate should not be collapsed into a unidimensional variable of Zwicker's total loudness because the similarity of these spectral envelopes produces the same clusters of environmental sounds as the joint similarity and non-preference space.

(4) Spectral contrast based on Zwicker's specific loudness is the best acoustic candidate and perceived annoyance the best perceptual candidate for explaining at the individual level what characteristics of environmental sounds cause them to be perceived as similar and non-preferred.

(5) The multidimensional structure of individual similarities and non-preferences of sound may best be modelled from the acoustic characteristic, spectral contrast, combined with the perceptual characteristic, perceived annoyance, as an intervening variable.

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