Estimation of annoyance due to low level sound

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ESTIMATION OF ANNOYANCE DUE TO LOW LEVEL SOUND

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SUMMARY

The concept of sound character is introduced as a physical attribute responsible for any systematic differences in annoyance due to different sounds at the same A-weighted equivalent sound level. It is thought that this sound character is more important at low sound levels than at high ones. A pilot experiment with refrigerator sounds indicated a clear effect of sound character. In particular, sharp onsets were shown to worsen the character of such sounds.

INTRODUCTION

Annoyance

Loudness, noisiness and annoyance are subjective attributes of sound. Loudness—that is, the subjective correlate of sound intensity—can be assessed from the responses of a small number of subjects because, normally, there is fair agreement among them. Their responses can be accurately predicted on the basis of physical measurement (Zwicker *et al.*[1]).

For the assessment of noisiness—that is, the unwantedness of a sound with particular reference to its intensity—many subjects are needed in order to average out personal opinions. As opposed to loudness, there are, as yet, no general algorithms for predicting the magnitude of noisiness on the basis of physical measurement (Scharf[2]).

Annoyance, like beauty, is difficult to define precisely but can be considered as a measure of the unwantedness of a sound. It depends on personal preferences but, in addition, both the acoustic and the general environment must be taken into account. It is accepted practice to avoid these problems in research by presenting a limited set of reasonably similar sounds to a fair number of listeners who are instructed to give

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an annoyance rating or something equivalent. Theoretically, one would have to use a complex set of sounds representative of what the population is normally exposed to—traffic sounds, music, building noise, etc. This set should then be administered to an adequate sample of the population and their reactions in terms of annoyance noted.

Assume now that the above mentioned theoretical annoyance data are plotted against a great many physical parameters, measured for every sound in the set. We would then construct a multidimensional space, some of the axes representing the sound levels in various frequency bands, others representing their time derivatives and still others giving the total duration, an objective physical estimation of pitch, etc. The set of sounds is represented as a set of points in this multidimensional 'annoyance space'. These points will not be distributed randomly over the space. In fact, many investigators have found annoyance to correlate highly with sound level (e.g. Botsford[3]). Therefore the number of dimensions of the annoyance space can be reduced by projecting all intensity dimensions into one new axis, labelled L_A, without seriously affecting the original configuration of points. The choice of the A-weighting factors for this projection instead of more sophisticated weightings is not essential. We are now left with a space of lower dimensionality in which two axes are annoyance and L_A. We now collapse all other dimensions into one which gives a maximum correlation with annoyance and which is orthogonal to the annoyance axis and the L_A axis. We propose to call this third axis the sound character. Briefly, the concept of 'sound character' is introduced as the weighted combination of physical properties affecting the annoyance of a sound with the exception of the A-weighted level.

Two problems have been omitted from the above description. First, no mention has been made of the environmental 'dimensions' and, secondly, it has been tacitly suggested that the annoyance space is linear. However, restricting the discussion to one type of environment and limiting the set of sounds to a small region in the annoyance space, it seems legitimate to consider a concept of 'sound character' even though it is a local one.

Low level sound annoyance

The view is advanced that the contribution of sound character to annoyance is relatively more important at a low than a high level. Indeed, at extremely high levels the annoyance is just pain, no matter what the sound character is.

At moderately high levels—for example, 70–100 dB(A)—the literature is not unequivocal on the contribution of sound character to annoyance. There are two kinds of paper. The empirical papers, correlating L_A to community reactions, seem to indicate that L_A does gauge annoyance (ISO S 1996[4]). This does not, however, disprove that the sound character is important. A second class of papers is based on laboratory experiments and maintains the view that noisiness and annoyance cannot be described adequately by the sound level alone.

Berglund *et al.*[5] conclude that certain types of noise (jackhammer) are generally considered more noisy than loud, the more so the lower the sound level. In other words, the sound character is important, especially at a low level.

Izumi[6] investigated amplitude modulated pink noise with an equivalent level of about 70 dB(A). This stimulus proved to be noisier than loud by the equivalent of up to 10 dB(A).

Klaassen[7] presented a synthetic, complex, broad band noise of about 55 dB(A) to some hundred listeners. In comparing a steady state with a 100 per cent amplitude modulated and a 6 per cent frequency modulated version (both with a modulation frequency of 3 Hz), he found the annoyance due to AM (FM) to be the equivalent of 8 (7) dB.

It is difficult to find studies on annoyance at even lower sound levels. A paper by Viebrock *et al.*[8] deals with direct assessments of the loudness of electric clocks that produce 20 to 40 dB(A). The paper is relevant insofar as their subjects comment on what we have termed the 'sound character'. We therefore think that it is interesting to study the annoyance of sounds with a relatively low level in order to see whether factors other than the sound level must be taken into account. Figure 1 is meant to summarise the conceptual situation.

With the above considerations in mind, a study was made of the sound of the household refrigerator. It is our conviction that annoyance studies should deal with common sounds, known to the subjects. The refrigerator sound satisfies this condition. It has, moreover, a low level. Finally, although the refrigerator is possibly

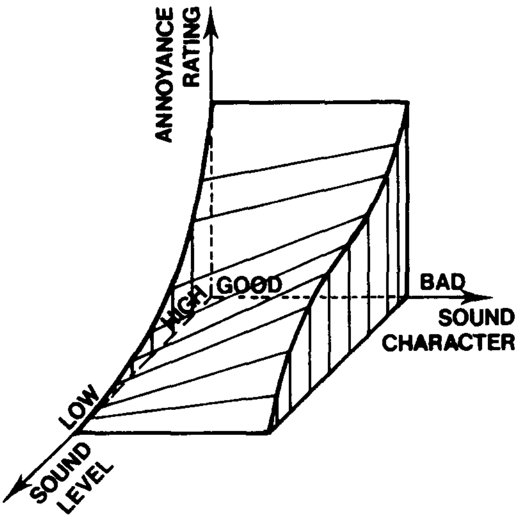


Fig. 1. Part of the annoyance space. The drawing is merely meant to illustrate the assumed effect of sound character on the annoyance.

the most silent of household machines (Jackson and Leventhall[9]), there is an increasing number of complaints about its noise, probably due to the growing number of open kitchens.

EXPERIMENTS

Preparing the test sounds

A refrigerator was placed in an anechoic room. Its sound was picked up with a B&K 4145 microphone at 1 m from the back. The sound was recorded on magnetic tape. Every recording was preceded by a recording of a 1 kHz pure tone at a level of 60 dB near the microphone for calibration purposes.

Four types of sound were recorded. (1) The normal sound during continuous operation of the compressor. (2) An abnormal, rumbling sound suggestive of improper mechanical functioning of the compressor. (3) The sudden onset sound. (4) The sudden offset sound.

From the latter two transient sounds we prepared two more test sounds. (5) The onset sound was given a very gradually rising level by passing it through a modulator which multiplied the amplitude by a factor rising linearly from 0 to 1 in 1 sec. (6) The offset sound was made gradual in the same way by starting the decrease in sound level electronically one second in advance of the actual ending of the compressor action.

Two more test sounds were added for the sake of comparison. (7) A white noise, fading in and out over periods of one second, was included as a reference signal. (8) The normal, continuous sound of the refrigerator was amplified by 16 dB in order to ensure that the stimulus set comprised one pair of sounds with the same character and with a distinct difference in sound level.

Listening sessions

In order to get an idea of the contribution of the sound character to the annoyance caused by refrigerator sound, a listening experiment was performed with 15 subjects. Every subject was presented with 56 pairs of sound samples through headphones at a level of about 50 dB(A). They had to tell whether the first or the second member of the pair was the more annoying sound. Each sample was given a 5 msec rise and decay time and there were no clicks audible at the beginning or end of the sample. Each sample lasted 3·5 sec, there was a pause of 1·5 sec between the members of the pair and each pair was followed by a response pause of 4 sec. The 56 pairs covered all possible pairs of eight test sounds, twins excepted but reversals of order included.

The subject was instructed to judge the sounds as if he were exposed to them whilst relaxing at home. The test sounds are given in Table 1.

The test sounds were used in two similar experiments. In the first the sounds were

TABLE 1

Description of test sound	*Code*	*Natural dB(A) L_{eq}*	*Equalised dB(A) L_{eq}*
Normal sound of refrigerator in CONtinuous operation	CON	39	39
RUMbling version of CON, waxing and waning	RUM	52	41
Normal ONset of refrigerator	NON	47	39
Normal OFFset of refrigerator	NOF	39	40
Processed ONset with 'improved' character	PON	40	40
Processed OFFset with 'improved' character	POF	33	44
White NOIse, reference signal	NOI	41	40
CON, Amplified by about 16 dB, serving to gauge the scale	COA	56	55

presented at the natural levels (except for NOI and COA) but in the second the sound levels were changed so as to make them more or less equal (COA and POF excepted).

RESULTS

The results are shown as 'voting tables' (Tables 2 and 3) in which the sounds have been arranged in order of increasing annoyance. For example, in Table 2 RUM was voted 24 times to be more annoying than NOF, whereas NOF was only six times judged to be more annoying than RUM. This ratio is significantly different from 15/15 at a level lower than 1 per cent. The theoretical maximum sum of annoyance

TABLE 2

VOTING TABLE FOR THE EXPERIMENTS WITH NATURAL LEVELS

Each entry gives the number of times that the sound shown at the head of each column was voted more annoying than the sound to the left of the row. Apostrophes indicate ratios significantly different from 15/15 ($P = 0{\cdot}05$), a is the normalised annoyance measure

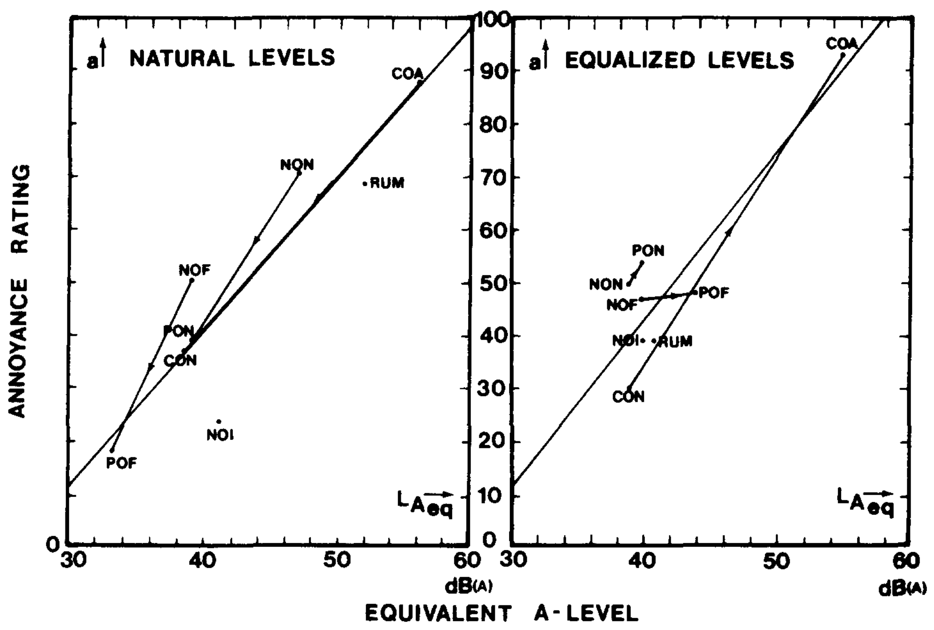
	POF	*NOI*	*CON*	*PON*	*NOF*	*RUM*	*NON*	*COA*
POF	—	15	23′	23′	26′	27′	28′	30′
NOI	15	—	25′	20′	24′	28′	22′	26′
CON	7′	5′	—	15	19	27′	28′	27′
PON	7′	10′	15	—	19	23′	24′	23′
NOF	4′	6′	11	11	—	24′	23′	27′
RUM	3′	2′	3′	7′	6′	—	18	27
NON	2′	8′	2′	6′	7′	12	—	24′
COA	0′	4′	3′	7′	3′	3′	6′	—
	38	50	82	90	104	144	149	184
a	18	24	39	43	50	69	71	88

TABLE 3
VOTING TABLE FOR THE EXPERIMENTS WITH EQUALISED LEVELS

	CON	*NOI*	*RUM*	*NOF*	*POF*	*NON*	*PON*	*COA*
CON	—	11	20′	17	19	24′	26′	29′
NOI	19	—	17	17	16	17	18	25′
RUM	10′	13	—	16	15	19	25′	30′
NOF	13	13	14	—	13	13	16	29′
POF	11	14	15	17	—	15	13	24′
NON	6′	13	11	17	15	—	14	30′
PON	4′	12	5′	14	17	16	—	28′
COA	1′	5′	0′	1′	6′	0′	2′	—
	64	81	82	99	101	104	114	195
a	30	39	39	47	48	50	54	93

votes for one test sound, 210, is used as a divisor to obtain the normalised annoyance $a/100$. Thus a ranges from 0 to 100.

Figures 2(a) and (b) present the 'natural' and 'equalised' sessions, respectively in an L_A–a diagram. Regression lines are drawn that minimise the sum of squared a deviations. From these tables and figures one can draw the following conclusions.



(a) (b)

Figs. 2(a) (b). Annoyance rating a of test sounds as a function of L_A. Linear regression lines $a = 2{\cdot}9\ L_A - 75$, $a = 3{\cdot}2\ L_A - 84$, respectively, are heavy lines. Thin lines with arrows connect similar sounds before and after processing (NON, PON, NOF, POF) or amplification (CON, COA).

DISCUSSION

First, a general remark is justified as to the feasibility of this type of experiment. Although the subjects listened with headphones in a soundproofed booth to sounds as short as 3·5 sec, they were fairly uniform in their responses. Differences of judgement centred on the white noise reference stimulus. Most subjects did not find it very annoying but some interpreted the listening instruction literally and judged it to be a very alarming sound from a *refrigerator*.

In Tables 2 and 3 the sounds have been ordered according to the average annoyance rating. This order is not the same as that of the sound level. A perusal of Table 2 shows instances where the weaker sound of a pair was judged to be more annoying. For instance, CON (39 dB(A)) was voted the more annoying sound when paired with NOI (41 dB(A)) in 25 out of 30 cases. Similarly, in Table 3 the pair PON (40 dB(A))–RUM (41 dB(A)) obtained annoyance votes contrary to the $L_{A_{eq}}$ order.

In Fig. 2(a) the eight test sounds are represented by points. The amplified continuous sound, COA, scoring highest both in annoyance and sound level, is connected to the non-amplified CON by a line that happens to coincide with the regression line for all eight points. The transient sounds NON and NOF are situated at the more annoying side of this line, while NOI and RUM are on the less annoying side. The processed 'transients', PON and POF, fall in line with CON and COA. The transient sounds are evidently of an annoying character that makes NOF and NON as annoying as a continuous sound of 4 or 3 dB(A) higher level as the case may be. In Fig. 2(b) NON and NOF are again on the annoying side of the line joining CON with COA. The regression line is now slightly different from that line. For some reason, not clear to us, the processed version of the onset sound, PON, did not join the CON–cost line, but POF did. NON and NOF are as annoying as continuous sounds of a 5 and 3 dB(A) higher level, respectively.

CONCLUSIONS

From Figs. 2(a) and (b) it is seen that the A-weighted sound level, L_A, has a preponderant influence upon the annoyance of the test sounds; 1 dB(A) corresponds to roughly three points on the centesimal annoyance scale. As a rule, the continuous sounds turn out to be less annoying than the onsets and offsets of equal level. For the normal, unprocessed sounds the difference corresponds to about 3 dB(A). It is possible that this result is an underestimation since the effect of startling is probably more important in real life than in the laboratory situation.

Making the onset and offset sounds more gradual does improve their character. The average improvement is equivalent to 3 dB(A).

Summing up, this study shows that it is feasible to use the concept of sound character as a complement to the A-weighted equivalent sound level for the description of annoyance due to sound. In listening experiments with 15 subjects it was found that in the relatively weak sound of a refrigerator, the transients have a bad character.

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