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TOTAL ANNOYANCE CAUSED BY SIMULTANEOUS IMPULSE, ROAD-TRAFFIC, AND AIRCRAFT SOUNDS

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SUMMARY

In this study total annoyance caused by different simultaneous environmental sounds is investigated. In spite of a number of confusing data in the literature, it is fairly well established that in combinations in which the annoyance of one source is considerably higher than that of the other source, total annoyance is equal to the maximum annoyance of the separate sources (dominance model). For combinations in which both sounds are about equally annoying, total annoyance seems to be higher than the maximum source-specific annoyance. The available data, however, are too rough to model total annoyance in these conditions. The present laboratory studies were therefore designed to explore further possible procedures to quantify total annoyance. Subjects rated the (total) annoyance caused by various combinations of impulse, road-traffic, and aircraft sounds.

The results support a relatively simple model in which total annoyance is predicted from the source-specific annoyance of the separate sounds (the source-specific dose-effect relationships). First, the annoyance caused by the impulse and/or aircraft sounds is expressed in the A-weighted equivalent sound level, L_{eq}, of equally annoying road-traffic sound by applying level-dependent penalties (the corrected L_{eq}). Second, total annoyance, again expressed in the L_{eq} of equally annoying road-traffic sound, is obtained by summation of the corrected L_{eq}'s of the various sources. An optimal overall fit of the data from two separate experiments was obtained when this summation of the corrected L_{eq}'s was performed with the free parameter k in $k\log\{10^{(\text{corrected Leq of Source 1})/k} + 10 \ldots\}$ set to 15.

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Hinder ten gevolge van gelijktijdig impuls-, wegverkeers- en luchtverkeersgeluid

J. Vos

SAMENVATTING

Het onderwerp van deze studie is de hinder ten gevolge van verschillende gelijktijdige geluidbronnen. Ondanks controversiële gegevens in de literatuur kunnen we toch wel stellen dat in situaties waarin de geluidhinder van de ene bron veel hoger is dan dat van een andere bron, de totale hinder van de twee bronnen samen gelijk is aan het maximum van de hinder van de afzonderlijke bronnen (dominantie model). In situaties waarin beide geluiden ongeveer even hinderlijk zijn, schijnt de totale hinder echter hoger dan dit maximum te zijn. Aangezien de beschikbare gegevens te grof zijn voor de ontwikkeling van een model voor de totale hinder in dit soort situaties, hebben we enkele laboratoriumexperimenten uitgevoerd. De door ons verzamelde experimentele gegevens zouden een voldoende basis voor het ontwerpen van een kwantitatief model moeten vormen. De proefpersonen beoordeelden de hinder van allerlei combinaties van impuls-, wegverkeers- en luchtverkeersgeluid.

Het blijkt dat op grond van een eenvoudig model de totale hinder goed uit de hinder van de afzonderlijke geluidbronnen kan worden voorspeld. In het model wordt allereerst de hinder van het impuls- en/of luchtverkeersgeluid uitgedrukt in het A-gewogen equivalente geluidniveau, L_{eq}, van even hinderlijk wegverkeersgeluid door toepassing van niveau-afhankelijke straffactoren (de "aangepaste" L_{eq}). Daarna wordt de totale hinder, die eveneens in het L_{eq} van even hinderlijk wegverkeersgeluid wordt uitgedrukt, verkregen door optelling van de "aangepaste" L_{eq}-waarden van de verschillende bronnen. Een optimale voorspelling van de totale hinder wordt verkregen wanneer bij de optelling van de aangepaste L_{eq}'s de factor k in $k\log(10^{(\text{aangepast Leq van bron 1})/k} + 10 \ldots)$ gelijk is aan 15.

1 INTRODUCTION

A considerable part of the population is exposed to simultaneous and/or successive environmental sounds from different sources. This means that in addition to research on the relationships between exposure level and annoyance for single sound sources, it is relevant to develop a model that predicts total annoyance caused by multiple sound sources.

As early as about two decades ago, Bottom (1971) investigated annoyance experienced by people who were exposed both to aircraft and road-traffic sounds. Especially for sites with high density road-traffic, total annoyance was higher than the annoyance caused by aircraft alone. Since Bottom (1971) did not ask for source-specific annoyance caused by the road-traffic sounds, his data do not allow the construction of a predictive model for total annoyance. An important contribution to the modelling of total annoyance is given by Taylor (1982), who discussed and tested an independent effects model and four energy summation models with or without different factors to account for the interactions between separate aircraft and road-traffic sounds.

However, in 16 of the 17 sites, mean total annoyance was lower than the maximum of the annoyance of the two separate sources. Comparable counter intuitive results (also see Miedema, 1985) were obtained by Cooper et al. (1984) in conditions in which aircraft at moderate and high sound levels were combined with either low or high levels of road-traffic sounds, and by Rice and Izumi (1984) in conditions in which aircraft sounds were combined with road-traffic sound at a relatively low indoor equivalent sound level, L_{eq}, of 35 dB(A). In addition, such results were reported by Flindell (1982) and by Miedema and van den Berg (1988), who investigated the annoyance caused by simultaneous road-traffic and railway sounds, and by Izumi (1988) in conditions in which railway sounds were combined with relatively low level road-traffic sounds.

Several researchers have suggested that the relatively low total annoyance ratings are related to the wording and/or the context of the question in the questionnaire, and that a general question about total noise is a less efficient cue for retrieving annoying events than source-specific questions (Cooper et al., 1984; Fields and Hall, 1987; Miedema, 1987; Rice and Izumi, 1984).

More valid data on the total annoyance caused by the cumulative sounds from road-traffic and aircraft seem to be reported by Powell (1979) and, at least with respect to combinations with relatively high levels of the road-traffic sounds, by Rice and Izumi (1984). For combinations of road-traffic sounds and impulse sounds from gunfire and jack

hammering the more interpretable data have been reported by Berglund et al. (1981) and by Rice (1985).
The overall conclusions of the latter four studies are that (1) for combinations in which the annoyance of one source is considerably different from that of the other source, total annoyance is equal to the maximum annoyance of the separate sources, and (2) for combinations in which both sounds are about equally annoying, total annoyance is higher than the maximum source-specific annoyance. The available data, however, are too rough to quantify total annoyance in these latter conditions.
The present laboratory studies were designed to explore further possible procedures to quantify total annoyance in those conditions in which integration may be relevant, that is, in the conditions with about equally annoying sounds. Conditions in which the (absolute) difference in L_{eq} of the sounds is greater than 15 dB(A) are therefore excluded. Subjects rated the (total) annoyance caused by various combinations of impulse, road-traffic, and aircraft sounds.

2 DESCRIPTION OF THE MODEL

Both in the field and in the laboratory, it has been shown that for single sources the annoyance (y) increases with L_{eq}: for a restricted range of L_{eq}, $y = a + bL_{eq}$. This does not mean, however, that impulse, road-traffic, and aircraft sounds with the same L_{eq} are also equally annoying. Moreover, the dependence of the annoyance on L_{eq} may vary (Vos, 1988; Vos and Smoorenburg, 1985). In the method of rating sounds with respect to the expected community response, these differences in slopes and intercepts may be accounted for by adding level-dependent penalties.
If for gunfire (G) the relation between annoyance and L_{eq} is given by $y = a_1 + b_1L_{eq}$, and for road-traffic sounds (T) by $y = a_2 + b_2L_{eq}$, then for each L_{eq} of G, the level-dependent penalty P_g is given by

$$P_g = [a_1 - a_2 + (b_1 - b_2)L_{eq} \text{ of } G]/b_2. \tag{1}$$

Thus, impulse sound G at a given L_{eq} is as annoying as road-traffic sound T at $L_{eq} + P_g$. If for aircraft sounds (A) the relation between annoyance and L_{eq} is given by $y = a_3 + b_3x$, then the level-dependent penalty P_a is similarly given by

$$P_a = [a_3 - a_2 + (b_3 - b_2)L_{eq} \text{ of } A]/b_2. \tag{2}$$

In this report, the predictive power of a summation model which includes level-dependent penalties will be determined. Total annoyance will be related to the total sound exposure level L_t in dB(A). With simultaneous T, G, and A, the value of L_t is given by

$$L_t = k\log\{10^{(L_{eq}\text{ of }T)/k} + 10^{(L_{eq}\text{ of }G + P_g)/k} + 10^{(L_{eq}\text{ of }A+P_a)/k}\}, \qquad (3)$$

in which k is a free parameter (Flindell, 1983).
The model is considered successful if the relation between total annoyance and L_t is the same as the relation between annoyance and L_{eq} for road-traffic sounds in isolation. As a first approach, energy summation (k=10) of the various corrected L_{eq}'s will be applied. It will be shown, however, that the predictive power of the model is enhanced when k is set to about 15.

3 EXPERIMENT 1

3.1 Method

Stimuli
Gunfire (G), road-traffic (T), and aircraft (A_1) served as distinct sources, which were presented in various combinations during 45 s periods. Remote-traffic sound at an L_{eq} of 30 dB(A) served as continuously present background noise (BN). Although with slightly different spectral contents, G, T, and BN had been used in previous experiments (Vos, 1986; Vos and Geurtsen, 1987; Vos and Smoorenburg, 1985) and described at length.
Briefly, G consisted of 18 pistol shots. The sound of a pistol fired in a reverberant room was digitally recorded. The sampling frequency was 20 kHz, the reverberation time was about 1 s. This shot was reproduced at variable intervals with some weak reflections added to it in order to improve naturalness. The time intervals between the onsets of the successive shots consisted of a fixed period of 1.4 s added to a variable interval, randomly sampled from a poisson-like distributed set of intervals. The intervals ranged from 1.4 to 5 s, with a standard deviation (sd) of 1 s. The rising portions of the temporal envelopes of the impulse sounds had a duration of 0.2 ms.
T was based on two recordings made at 10 m distance from busy free-flowing road-traffic. These recordings were mixed and compressed in amplitude so as to keep the fluctuations in sound level within limits of about ± 6 dB.

A_1 consisted of the sound of a two-propeller airplane. The sound of A_1 was recorded and played back with a tape-recorder (Nagra IV-BL).
BN was based on a recording (about 20 min in duration) of remote road-traffic sound, characterized by very small fluctuations in sound level. Since BN had to be present throughout the experimental sessions without interruption, the tape prepared comprised a series of these 20 min recordings.
To simulate indoor conditions, all sounds passed an equalizer comprising a set of 1/3-octave filters and attenuators. The central frequencies of the 1/3-octave bands ranged from 40 Hz to 16 kHz. For central frequencies between 40 and 200 Hz, the attenuators were set to 0 dB. From 250 Hz up to 4000 Hz, the attenuation was 3 dB/oct; for the frequency region above 4000 Hz, the attenuation was 15 dB/oct.

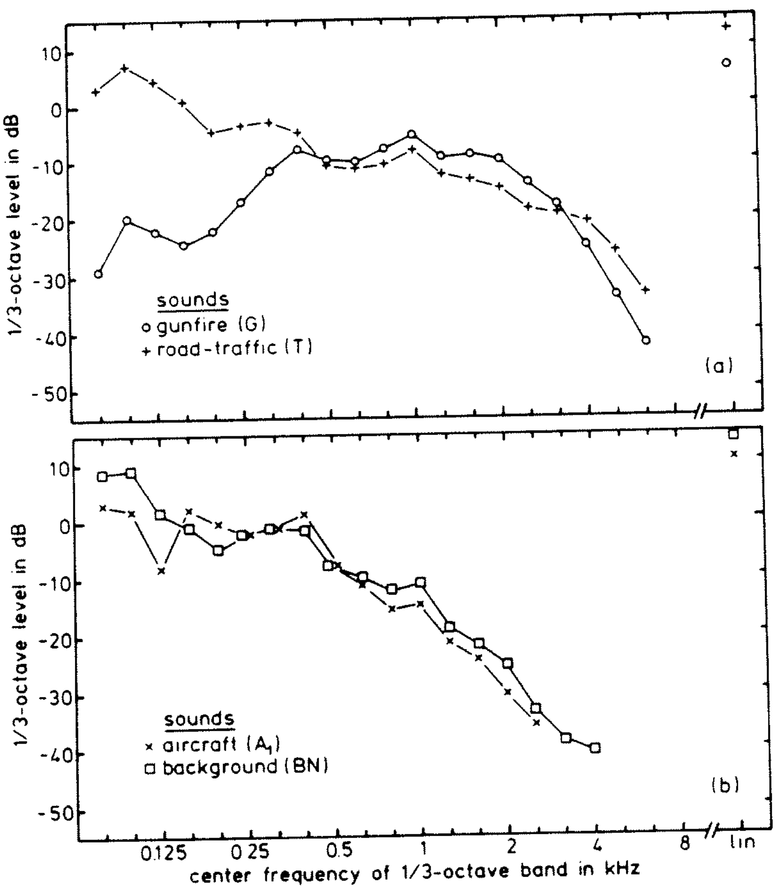

Fig. 1 (a) Spectra of gunfire and road-traffic sounds. (b) Spectra of aircraft and background sounds. For both panels 1/3-octave equivalent levels are plotted relative to the overall A-weighted level. All spectra were measured at the ears of the subjects.

The sound spectra of G, T, A_1, and BN, measured at the ears of the subjects, are shown in Figs. 1a and 1b relative to the overall A-weighted level of the sounds. These spectra were determined with a Rohde and Schwarz real time audio spectrum analyzer (type FAR) in the position "fast" (integration time equal to 0.1 s, sample time every 0.1 s) connected to a precision sound level meter (Brüel & Kjaer, type 2218) mounted with a 1-inch microphone (Brüel & Kjaer, type 4145).
All levels were obtained by averaging the sound energy of the 0.1 s samples. The level fluctuations of BN and T were much smaller than those of A_1 and G. For BN and T, the differences between L_{10} (the A-weighted level exceeded 10% of the time) and L_{90} were 3 and 6 dB, respectively. For A_1 and G, these values were 42 dB.

Apparatus

The experiments were run under the control of a PDP-11/34 computer. The G sounds were reproduced by means of a digital-to-analog converter (12 bit, sample rate 20 kHz). These sounds passed a Krohn-Hite filter (-48 dB/oct) with the function switch in the low-pass RC mode and with a cutoff frequency of 10kHz. The T, A_1, and BN sounds were played on tape-recorders (Akai, type GX-400 DSS; Nagra, type IV-BL). The levels of the sounds were controlled by programmable attenuators. The mixed sounds were fed into the equalizer and were reproduced in a sound-proof room by means of a Quad electrostatic loudspeaker that was hidden behind a curtain. Special attention was given to proper seating of the subjects so that the directional output characteristics of the loudspeaker did not affect the results. The sound-proof room (2.5 x 4.5 m) was fitted with a window and with sound-absorbing walls covered by perforated plates. For frequencies above 100 Hz, the reverberation time of the room was shorter than 0.5 s.

Subjects

Sixteen subjects, nine males and seven females, between 18 and 30 years of age, participated in the experiment. Before the experimental sessions, their hearing thresholds were determined with pure tones between 250 and 8000 Hz. Only one of the testees had a hearing loss greater than 15 dB Hearing Level [ISO/R 389 (1975)] in any part of the audiogram. For both ears, this subject had a loss of 16-17 dB Hearing Level at a frequency of 2000 Hz. None of the subjects reported having suffered from pain or noises in the ear during the last year. The experimental sessions took place in the morning, in the afternoon, or in the evening. A session lasted three hours; breaks of ten minutes were given after about each hour. The subjects were paid for their services.

Experimental design

The sounds to be rated consisted of various combinations of G, T, and A_1. In these conditions, one sound was fixed at an (indoor) L_{eq} of 40 dB(A), whereas the levels of the second and/or third sounds were varied between conditions in steps of 5 dB between 25 and 55 dB(A). The L_{eq}-values of the sounds in the various combinations were chosen in such a way that each separate sound could be identified for at least part of the presentation time. In addition to these combinations, each sound was also presented for rating in isolation at various levels within the same range of 25 up to 55 dB(A). The total number of experimental conditions was 65.

Procedure

After hearing levels had been tested, the subjects were told that they were going to be presented with various environmental sounds which could consist of impulse, road-traffic, and/or aircraft sounds, each sound or sound combination lasting for 45 s. They were instructed to rate after each period the annoyance caused by these sounds. When rating the sounds, they had to imagine that they heard these sounds all the time in the living room against the same kind of background sound. They were told before that this background sound was included simply because in normal conditions at home or at work, it is never completely quiet either. Inconsistent results from previous studies on total annoyance, as discussed above, prevented us from asking the subjects to differentiate between source-specific and total annoyance.

All 65 stimuli were randomly assigned to eight experimental blocks of 8 or 9 trials each. Presentation order of the different blocks was balanced according to 8x8 Latin squares. Presentation order of the stimuli within an experimental block was randomized. Before starting with the first block, the subjects were presented with two familiarisation blocks comprising five or six representative trials. The subjects were told that the purpose of these blocks was to give them a frame of reference within which they had to rate the annoyance. They were encouraged to use the whole range of scale values from 0 ("not annoying at all") to 9 ("extremely annoying").

After the eight experimental blocks, the subjects were presented with 25 of the 65 trials for the second time. These replications were randomly assigned to three blocks; again, presentation order within a block was randomized. Subjects responded by pressing the keys of a keyboard. Part of the instructions was presented visually on a display.

Since about 38% of the conditions was presented twice, we had an indication of reliability. For each subject separately, we computed the Pearson correlation coefficient (r) between the ratings given for the first and for the second times. One subject had an r-value of 0.15, which was much lower than those of the other 15 subjects. Her data were dropped from further analysis and replaced by those of a new participant. For the 15 subjects and the substitute together, the mean r-value was 0.77 (sd = 0.16).

3.2 Results

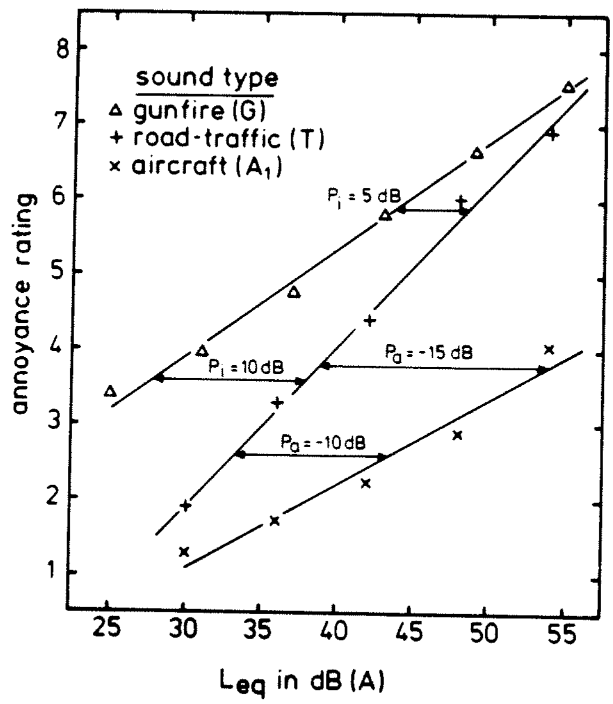

Fig. 2 Mean annoyance rating as a function of the A-weighted L_{eq} for three different sounds. Solid lines are linear regression functions.

Sounds in isolation

Mean annoyance ratings for G, T, and A_1, averaged across the 16 subjects, are shown in Fig. 2 as a function of the A-weighted L_{eq} of the sounds. Overall, G is more annoying than T, whereas A_1 is less annoying than T. This main effect of sound type was tested in an analysis of variance (ANOVA) [16(subjects) x 3(sound types) x 5(L_{eq}), all repeated measures]. The L_{eq} of 25 dB(A) of G was excluded; other L_{eq}-values of G did not exactly correspond to those of T and A_1. To achieve a comparison between the sounds at identical levels, constants were added to the raw data of the G sounds. These constants were determined by the regression line $y = -0.39 + 0.143L_{eq}$ ($r=0.997$) that fitted the mean values of G. The overall differences between G, T, and A_1 were significant [$F(2,30)=28.7$, $p < 0.00001$]. The ratings increased with L_{eq} [$F(4,60)=107.0$, $p < 0.000001$]. This increase was greatest for T and smallest for A_1 [$F(8,120)=4.90$, $p < 0.0001$]. The linear regression lines inserted in Fig. 2 explain 96% to 99% of the variance in the mean annoyance ratings. For T, the equation is $y = -4.48 + 0.214L_{eq}$ ($r=0.997$); for A_1 the equation is $y = -2.23 + 0.112L_{eq}$ ($r=0.98$).

The relevance of the level-dependency of P_g (Eq. 1) was confirmed by the significant interaction effect between sound type and level that was obtained in a separate ANOVA performed on the data for G and T only [$F(4,60)=3.45$, $p=0.01$]. After substitution of the relevant slopes and intercepts in Eq. (1), the level-dependent penalty for G relative to T is given by $P_g = 19.14 - 0.33L_{eq}$ of G.

The A_1 sounds were less annoying than the T sounds, and this difference increased rather than decreased with L_{eq}. To express the annoyance caused by the A_1 sounds in the L_{eq} of the equally annoying T sounds, a negative level-dependent penalty has to be added to the L_{eq} of A_1. After substitution of the relevant slopes and intercepts in Eq. (2), the level-dependent penalty for A_1 relative to T is given by $P_a = 10.51 - 0.477L_{eq}$ of A_1.

Two different sounds in combination

G and T. The mean total annoyance ratings for G sounds presented in combination with T sounds, the L_{eq} of the T sounds always fixed at 40 dB(A), are given in the third column of Table 1 and are shown in Fig. 3a as a function of the L_{eq} of G. The ratings significantly increase with the L_{eq} of G [$F(5,75)=22.5$, $p < 0.000001$]. The linear regression function (see Fig. 2) for G only and the annoyance caused by T only are given in Fig. 3a as references. In general, the ratings for G in combination with T at an L_{eq} of 40 dB(A), G+T40, are higher than for G only [$F(1,15)=10.4$, $p < 0.01$]. In condition G30+T40 the ratings for the separate G30 and T40 sounds are about equal. A dominance model would predict that total annoyance of G30+T40 is equal to the annoyance of G30 or T40 in isolation, whereas an integration model such as the model proposed here, would predict that the total annoyance is higher than the annoyance of the constituing sounds. T-tests on the difference between these means (Hays, 1970) showed that the annoyance caused by G30+T40 is significantly higher than the rating for T40 ($t = 1.56$; $p \sim 0.06$) and the rating for G30 ($t = 1.80$; $p < 0.05$) in isolation.

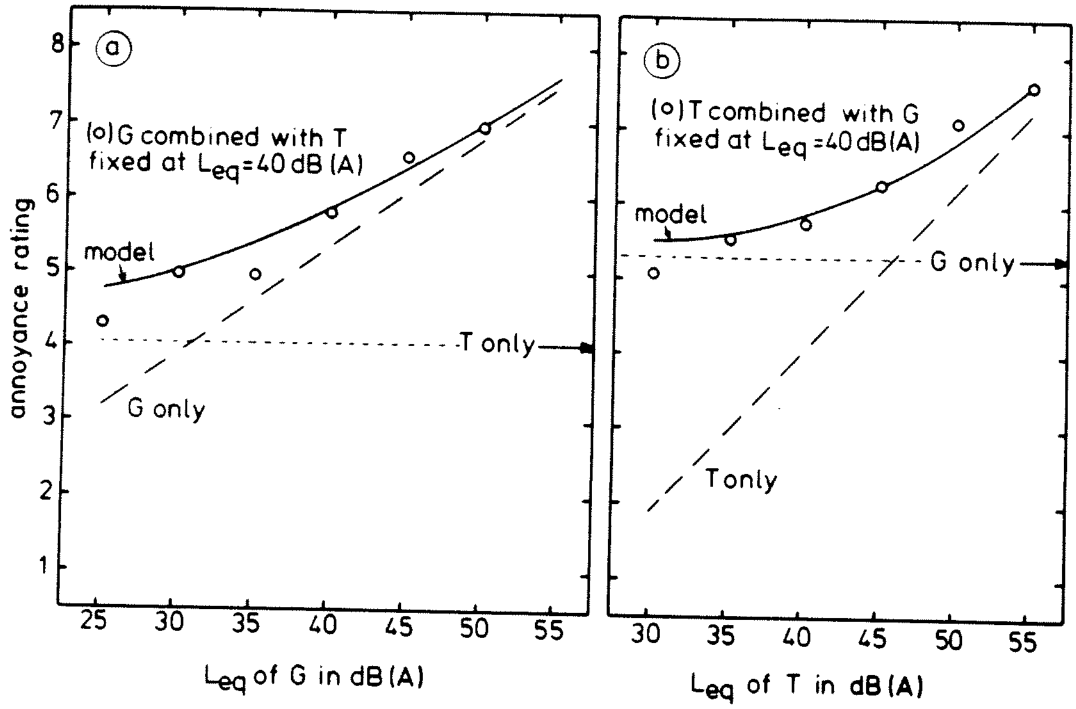

Fig. 3 (a) Total annoyance for G presented in combination with T at an L_{eq} of 40 dB(A), as a function of the L_{eq} of G. The linear regression function for G only and the annoyance caused by T only (see Fig. 2) are given as references. (b) Total annoyance for T presented in combination with G at an L_{eq} of 40 dB(A), as a function of the L_{eq} of T. The linear regression function for T only and the annoyance caused by G only (see Fig. 2) are given as references. In both panels (a) and (b), the solid line represents the predictions of the model [Eq. (3)] with $k=16$.

Fig. 3b and Table 1 show the mean annoyance ratings for T sounds presented in combination with G sounds at an L_{eq} of 40 dB(A), for various L_{eq}-values of T. The ratings significantly increase with the L_{eq} of T [$F(5,75)=23.1$, $p < 0.000001$]. The linear regression function for T only and the annoyance caused by G only (see Fig. 2) are given in Fig. 3b as references. In general, the ratings for T in combination with G at an L_{eq} of 40 dB(A), T+G40, are higher than those for T presented alone [$F(1,15)=22.2$, $p < 0.0005$]. This difference in annoyance between T+G40 and T decreases significantly with the L_{eq} of T [$F(5,75)=11.6$, $p < 0.000005$]. T-tests revealed that the total annoyance for T45+G40 is significantly higher than the annoyance for G40 ($t = 1.67$; $p < 0.05$) and T45 ($t = 1.98$; $p < 0.05$) in isolation.

The predictions of the total sound exposure level L_t, as defined in Eq. (3) with k=10, are given in the fifth column of Table 1 for all combinations of T and G. The power of the model is tested by comparing these predictions with the L_{eq} of the equally annoying T sounds in isolation given in the fourth column of Table 1. The sixth column of this table shows that, in general, the differences between the predictions of L_t and the experimental results are small. The model tends to underestimate total annoyance by about 1 dB; the root of the mean of the squared differences (rms) equals 1.4 dB.

Table 1 Values of L_t (Eq. 3) are compared with the results for conditions in which combinations of T and G sounds were rated for total annoyance.

combination				summation model			
				k = 10		k = 16	
T	G	rating	corresp. L_{eq} of T	L_t	L_t-L_{eq} of T	L_t	L_t-L_{eq} of T
40	25	4.31	41.1	41.4	0.3	43.1	2.0
40	30	4.97	44.2	42.6	-1.6	44.4	0.2
40	35	4.94	44.0	44.5	0.5	46.2	2.2
40	40	5.75	47.8	46.9	-0.9	48.4	0.6
40	45	6.56	51.6	49.8	-1.8	50.9	-0.7
40	50	6.94	53.4	52.8	-0.6	53.6	0.3
30	40	5.06	44.6	46.0	1.4	46.6	2.0
35	40	5.53	46.8	46.2	-0.6	47.2	0.4
40	40	5.75	47.8	46.9	-0.9	48.4	0.6
45	40	6.28	50.3	48.5	-1.8	50.3	0.0
50	40	7.13	54.3	51.4	-2.9	53.1	-1.2
55	40	7.63	56.6	55.5	-1.1	56.7	0.1
					M = -0.8		M = 0.5
					RMS = 1.4		RMS = 1.1

G and A_1. The mean total annoyance ratings for G sounds presented in combination with A_1 sounds at an L_{eq} of 40 dB(A), G+$A_1$40, are given in the third column of Table 2 and are shown in Fig. 4a as a function of the L_{eq} of G. The ratings significantly increase with the L_{eq} of G [$F(5,75)=36.4$, $p < 0.000001$]. Again, the linear regression function for G only and the annoyance caused by A_1 only are given in Fig. 4a as references.

It should be clear that the ratings for G+$A_1$40 are not significantly different from G only. This can be understood from the low annoyance rating of 2.25 for A_1 only at the L_{eq} of 40 dB(A).

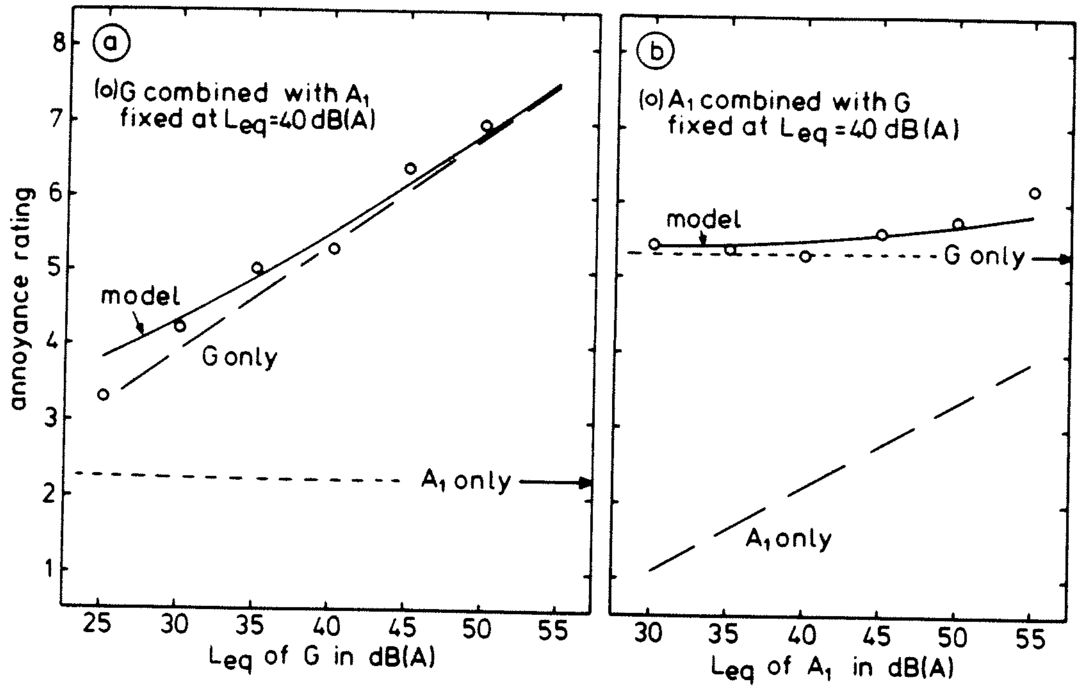

Fig. 4 (a) Total annoyance for G presented in combination with A_1 at an L_{eq} of 40 dB(A), as a function of the L_{eq} of G. (b) Total annoyance for A_1 presented in combination with G at an L_{eq} of 40 dB(A), as a function of the L_{eq} of A_1. In both panels (a) and (b), linear regression functions for the relevant sounds and the annoyance caused by the sounds with the L_{eq} fixed at 40 dB(A) are given as references. Again, the solid lines represent the predictions of the model with $k=16$.

Fig. 4b shows the mean annoyance ratings for A_1 presented in combination with G at an L_{eq} of 40 dB(A), for various L_{eq}-values of A_1. There is a significant effect of L_{eq} of A_1 on the ratings [$F(5,75) = 3.37$, $p < 0.01$]. A Newman-Keuls paired-comparison test (Winer, 1970) showed that only the rating at the L_{eq} of 55 dB(A) was significantly higher ($\alpha = 0.05$) than the ratings obtained at L_{eq}-values between 30 and 40 dB(A). The small increase in total annoyance for $A_1$55+G40 relative to G40 in isolation may be explained by the low annoyance rating for A_1 only at the L_{eq} of 55 dB(A). This increment is not significant ($t = 1.4$, $0.05 < p < 0.10$).

Table 2 Values of L_t are compared with the results for various conditions in which combinations of A_1 and G sounds were rated for total annoyance.

combination				summation model			
				k = 10		k = 16	
A_1	G	rating	corresp. L_{eq} of T	L_t	L_t-L_{eq} of T	L_t	L_t-L_{eq} of T
40	25	3.31	36.4	37.2	0.8	38.8	2.4
40	30	4.22	40.7	39.9	-0.8	41.2	0.5
40	35	5.00	44.3	42.9	-1.4	43.9	-0.4
40	40	5.31	45.8	46.0	0.2	46.7	0.9
40	45	6.38	50.8	49.4	-1.4	49.8	-1.0
40	50	6.94	53.4	52.6	-0.8	52.9	-0.5
30	40	5.43	46.3	45.9	-0.4	46.3	0.0
35	40	5.38	46.1	46.0	-0.1	46.5	0.4
40	40	5.31	45.8	46.1	0.3	46.7	0.9
45	40	5.63	47.3	46.2	-1.1	47.1	-0.2
50	40	5.75	47.8	46.4	-1.4	47.5	-0.3
55	40	6.19	49.9	46.5	-3.4	48.2	-1.7
					M = -0.8		M = 0.1
					RMS = 1.3		RMS = 1.0

The predictions of L_t are given in the fifth column of Table 2 for all combinations of A_1 and G. The L_{eq} of equally annoying T sounds in isolation is given in the fourth column of Table 2. The sixth column shows that, in general, the differences between the predictions of L_t and the experimentally obtained results are small. The model tends to underestimate total annoyance by about 1 dB, the rms is 1.3 dB.

T and A_1. The mean total annoyance ratings for T presented in combination with A_1 at an L_{eq} of 40 dB(A), T+$A_1$40, are shown in Fig. 5a as a function of the L_{eq} of T. The ratings significantly increase with the L_{eq} of T [$F(5,75)=28.1$, $p < 0.000001$]. In general, the ratings for T+$A_1$40 tend to be slightly higher than for T in isolation. Only at T35+T40 is the total annoyance significantly higher than the rating for T in isolation at the L_{eq} of 35 dB(A) ($t = 1.93$; $p < 0.05$).

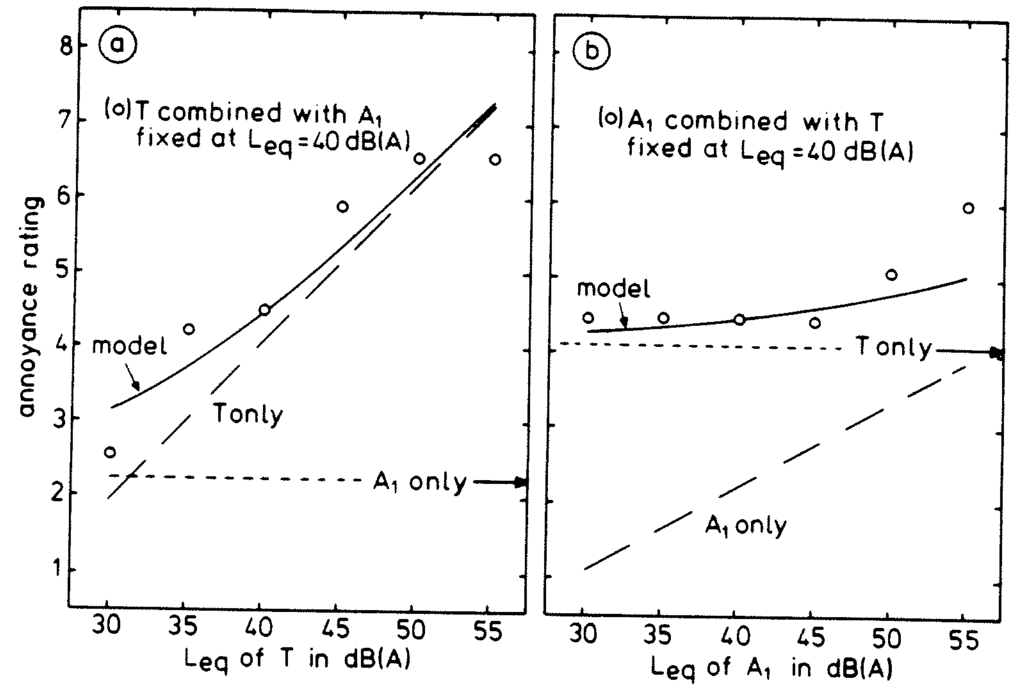

Fig. 5 (a) Total annoyance for T presented in combination with A_1 at an L_{eq} of 40 dB(A), as a function of the L_{eq} of T. (b) Total annoyance for A_1 presented in combination with T at an L_{eq} of 40 dB(A), as a function of the L_{eq} of A_1. In both panels (a) and (b), linear regression functions for the relevant sounds and the annoyance caused by the sounds with the L_{eq} fixed at 40 dB(A) are given as references. Again, the solid lines represent the predictions of the model with $k=16$.

Fig. 5b shows the mean total annoyance ratings for A_1 presented in combination with T at an L_{eq} of 40 dB(A), for various L_{eq}-values of A_1. There is a significant effect of L_{eq} of A_1 on the ratings [$F(5,75)=5.94$, $p < 0.0005$]. A Newman-Keuls paired-comparison test showed that the mean ratings at L_{eq}-values of 50 and 55 dB(A) are significantly higher than those at the lower L_{eq}-values at the 0.05 and at the 0.01 level, respectively. A t-test showed that the mean rating obtained in the condition in which A_1 at an L_{eq} of 55 dB(A) was combined with T only was significantly higher than the mean rating for T only at 40 dB(A) [$t=3.23$, $p < 0.005$].
This set of data provides another occasion to test our summation model. The predictions of L_t are given in the fifth column of Table 3 for all combinations of A_1 and T. The sixth column of Table 3 shows that in five of the 12 conditions, the (absolute) discrepancies between the predictions from our model and the experimental results are

larger than or equal to 3 dB. Especially in the conditions with relatively high levels of A_1 combined with T at an L_{eq} of 40 dB(A) (Fig. 5b), total annoyance is underestimated by our summation model, at least with k=10.

Table 3 Values of L_t are compared with the results for various conditions in which combinations of A_1 and T sounds were rated for total annoyance.

combination				summation model			
				k = 10		k = 16	
A_1	T	rating	corresp. L_{eq} of T	L_t	L_t-L_{eq} of T	L_t	L_t-L_{eq} of T
40	30	2.56	32.9	33.8	0.9	35.6	2.7
40	35	4.19	40.5	36.6	-3.9	38.2	-2.3
40	40	4.47	41.8	40.6	-1.2	41.8	0.0
40	45	5.88	48.4	45.2	-3.2	45.9	-2.5
40	50	6.56	51.6	50.1	-1.5	50.5	-1.1
40	55	6.56	51.6	55.0	3.4	55.2	3.6
30	40	4.44	41.7	40.2	-1.5	40.9	-0.8
35	40	4.47	41.8	40.3	-1.5	41.3	-0.5
40	40	4.47	41.8	40.6	-1.2	41.8	0.0
45	40	4.44	41.7	41.0	-0.7	42.5	0.8
50	40	5.09	44.7	41.7	-3.0	43.4	-1.3
55	40	6.00	49.0	42.7	-6.3	44.5	-4.5
					M = -1.6		M = -0.5
					RMS = 2.8		RMS = 2.2

Three different sounds in combination

G and T at various levels, A_1 at L_{eq} = 40 dB(A). The mean total annoyance ratings for G and T sounds presented in combination with A_1 sounds at an L_{eq} of 40 dB(A), G+T+$A_1$40, are given in Fig. 6 as a function of the L_{eq} of the G and T sounds. The ratings significantly increase with L_{eq} [$F(5,75)=32.9$, $p < 0.000001$]. Fig. 6 shows that the ratings for G+T+$A_1$40 are all higher than they are for G (and T) only. This effect is highly significant [$F(1,15)=22.8$, $p < 0.0005$].

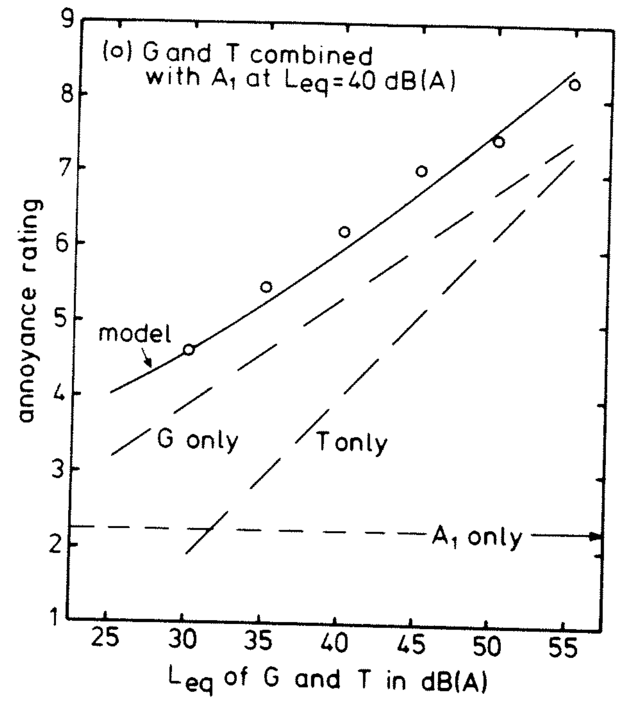

Fig. 6 Total annoyance for G and T presented in combination with A_1 at an L_{eq} of 40 dB(A), as a function of the L_{eq} of G and T. The regression functions for G and T only, and the annoyance caused by A_1 only are given as references. The solid line represents the predictions of the model with k=16.

The predictions of L_t are given in the first section of Table 4. The model tends to underestimate total annoyance by about 2 dB, the rms is 2.4 dB.

<u>G and A_1 at various levels, T at L_{eq} = 40 dB(A).</u> The mean total annoyance ratings for G and A_1 presented in combination with T at an L_{eq} of 40 dB(A), G+A_1+T40, are plotted in Fig. 7 as a function of the L_{eq} of the G and A_1.

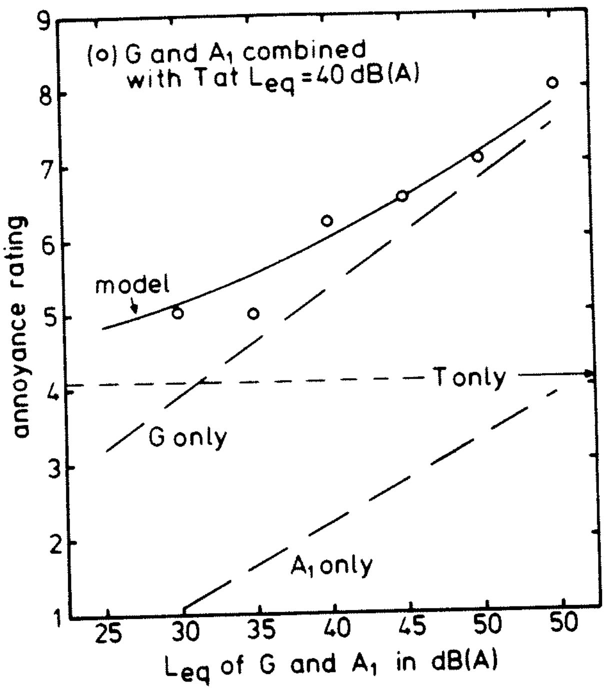

Fig. 7 Total annoyance for G and A_1 presented in combination with T at an L_{eq} of 40 dB(A), as a function of the L_{eq} of G and A_1. The regression functions for G and A_1 only, and the annoyance caused by T only are given as references. The solid line represents the predictions of the model with k=16.

The ratings significantly increase with L_{eq} [$F(5,75)=37.9$, $p < 0.000001$]. Fig. 7 shows that the ratings for G+A_1+T40 are all higher than for G only. This effect is significant [$F(1,15)=16.7$, $p=0.001$]. A more conservative t-test showed that there is only a tendency that the total annoyance for G30+$A_1$30+T40 is higher than the annoyance for T40 in isolation ($t = 1.51$; $0.10 > p > 0.05$).

Table 4 Values of L_t are compared with the results for various conditions in which combinations of G, T, and A_1 sounds were rated for total annoyance.

combination					summation model			
					k = 10		k = 16	
G	T	A_1	rating	corresp. L_{eq} of T	L_t	L_t-L_{eq} of T	L_t	L_t-L_{eq} of T
30	30	40	4.63	42.6	40.3	-2.3	42.4	-0.2
35	35	40	5.44	46.4	43.6	-2.8	45.6	-0.8
40	40	40	6.22	50.0	47.0	-3.0	49.0	-1.1
45	45	40	7.06	53.9	50.7	-3.2	52.6	-1.3
50	50	40	7.44	55.7	54.5	-1.2	56.4	0.7
55	55	40	8.25	59.5	58.5	-1.0	60.4	0.9
					m =	-2.3	m =	-0.3
					rms =	2.4	rms =	0.9
30	40	30	5.06	44.6	42.7	-1.9	44.9	0.3
35	40	35	5.00	44.3	44.6	0.3	46.8	2.5
40	40	40	6.22	50.0	47.0	-3.0	49.0	-1.1
45	40	45	6.56	51.6	49.9	-1.7	51.5	-0.1
50	40	50	7.06	53.9	52.9	-1.0	54.2	0.3
55	40	55	8.00	58.3	56.2	-2.1	57.2	-1.1
					m =	-1.6	m =	0.2
					rms =	1.9	rms =	1.2
40	30	30	5.59	47.1	46.1	-1.0	46.9	-0.2
40	35	35	5.75	47.8	46.3	-1.5	47.7	-0.1
40	40	40	6.22	50.0	47.0	-3.0	49.0	-1.1
40	45	45	6.44	51.0	48.6	-2.4	50.9	-0.1
40	50	50	7.31	55.1	51.6	-3.5	53.7	-1.4
40	55	55	8.13	58.9	55.6	-3.3	57.2	-1.7
					m =	-2.5	m =	-0.8
					rms =	2.6	rms =	1.0
					M =	-2.1	M =	-0.3
					RMS =	2.3	RMS =	1.0

The predictions of L_t are given in the second section of Table 4. In general, the differences between predictions and observations are rather small. The model tends to underestimate total annoyance by about 1.5 dB.

T and A_1 at various levels, G at L_{eq} = 40 dB(A). The total annoyance ratings for T and A_1 presented in combination with G at an L_{eq} of 40 dB(A), T+A_1+G40, are shown in Fig. 8 for the various levels of T and A_1. The ratings significantly increase with L_{eq} [$F(5,75)=26.7$, $p < 0.000001$]. A t-test showed that the annoyance for T45+$A_1$45+G40 is

significantly higher than the annoyance for G40 in isolation (t = 1.82; $p < 0.05$).
At low levels of T and A_1, the total ratings are determined by the annoyance caused by G at L_{eq}=40 dB(A), whereas at higher levels of T and A_1, the combined effect of especially T and G is responsible for the total rating. Yet, the ratings for T+A_1+G40 are consistently higher than those for T+G40 [$F(1,15)=10.2$, $p < 0.01$], which suggests that the presence of A_1 may become relevant in conditions with already moderate or high annoyance.

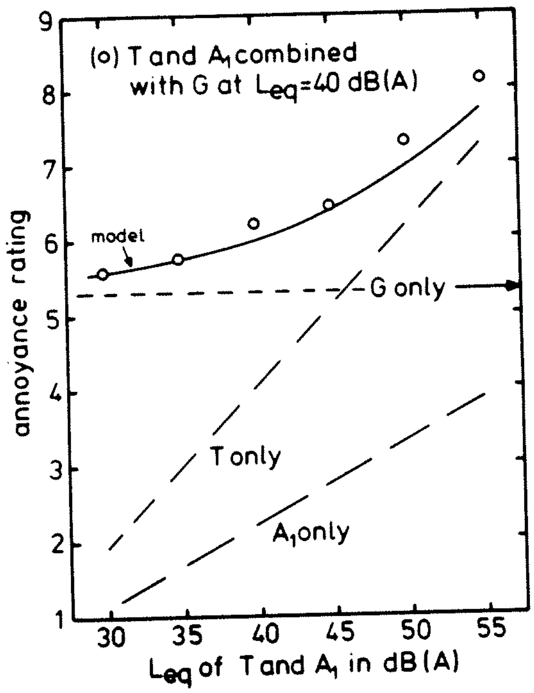

Fig. 8 Total annoyance for T and A_1 presented in combination with G at an L_{eq} of 40 dB(A), as a function of the L_{eq} of T and A_1. The regression functions for T and A_1 only, and the annoyance caused by G only are given as references. The solid line represents the predictions of the model with k=16.

The predictions of L_t are given in the third section of Table 4. With k=10, the model underestimates total annoyance by about 2.5 dB, rms equals 2.6 dB.

3.3 Discussion

The differences between the values of L_t and the experimental data in dB are small. Overall, the mean underestimation was 1.3 dB, with an rms of 2 dB and seemed to depend on the number of combined sounds. To cope with the small but systematic underestimation, the free parameter k in Eq. (3) was changed from 10 into 16. For all combinations investigated, the new values of L_t are shown in the last two columns of Tables 1-4. For three of the four sets of combinations (TG, A_1G, and GTA_1), the rms has been reduced to 1.1 dB.

4 EXPERIMENT 2

The annoyance caused by the aircraft sounds in isolation (Fig. 2) was much lower than expected. As a result, the number of conditions in which the relevance of the model proposed could be optimally tested was smaller than originally designed. This was especially the case for the combinations with three simultaneous sounds (Figs. 6-8). Experiment 2 was designed to select an aircraft sound which is about as annoying as T. This aircraft sound will be used in Experiment 3 to be carried out as a final and a more optimal test of the model proposed.

4.1 Method

Stimuli and Apparatus

In addition to G, T, and A_1 from Experiment 1, three other aircraft sounds served as distinct sources. These aircraft sounds comprised one passage of either a Trident (3 jet engines) [Sound effects 1, BBC records, Red 47 M] (A_2), or a Boeing 727 (A_3), or two passages of a lightning twinjet fighter [Sound effects 8, BBC records, Red 126 M] (A_4).

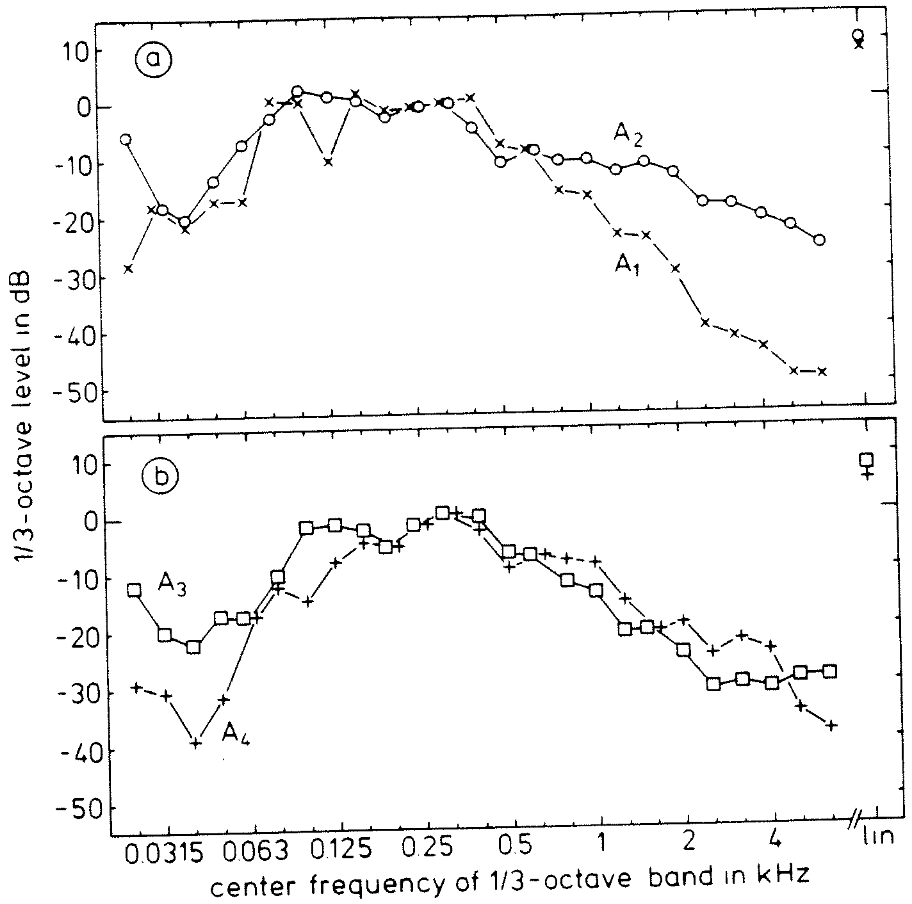

Fig. 9 Spectra of the four different aircraft sounds [two in each panel (a) and (b)] used in experiment 2. The 1/3-octave equivalent levels are plotted relative to the overall A-weighted level. All spectra were measured at the ears of the subjects.

The sound spectra of A_1 and A_2 are given in Fig. 9a, and those of A_3 and A_4 in Fig. 9b. Fig. 10 shows the A-weighted L_{eq} within successive 100 ms periods for each aircraft sound separately. It can be seen that the maximum levels of A_2 and A_4 are reached within the first 6 s, whereas for A_1 and A_3 it takes 19 or even 23 s to reach the maximum sound level.

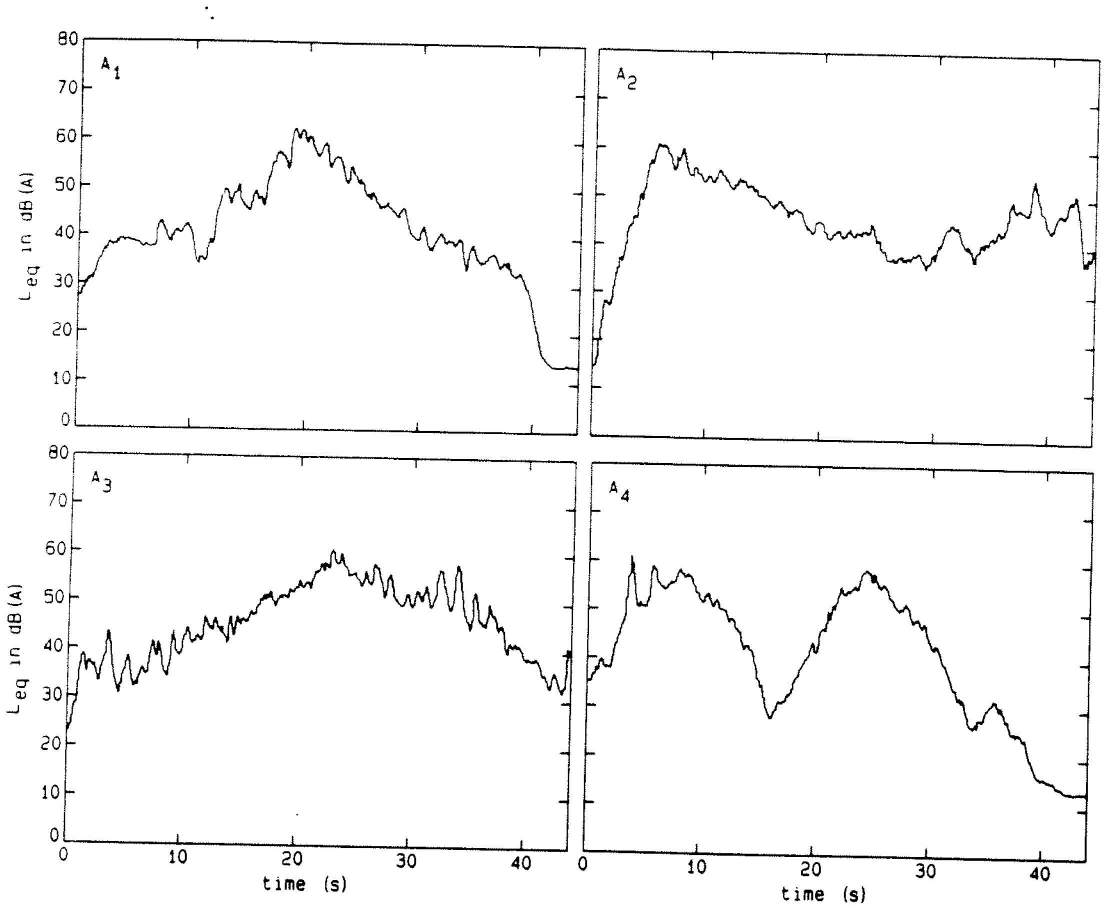

Fig. 10 A-weighted L_{eq} within successive 100 ms periods, for each of the four aircraft sounds separately.

BN at an L_{eq} of 30 dB(A) again served as the continuously present background noise. The apparatus was the same as in Experiment 1. The A_1-A_4 sounds, however, were played on a dat recorder (Luxman KD-117) that was under the control of the computer.

Subjects

Sixteen subjects, twelve males and four females between 20 and 40 years of age, participated in the experiment. None of them had prior experience with this kind of noise annoyance studies.

Experimental design

There were two independent variables: a) sound type (G, T, A_1, A_2, A_3, and A_4), and b) the A-weighted L_{eq} of the sounds (31, 39, 47, and 55 dB). In addition to these 24 different conditions G was presented for rating at an L_{eq} of 25 dB(A).

Procedure
The instructions to the subjects were basically the same as those in Experiment 1. Presentation order of the 25 different conditions was randomized. Before starting with this experimental block, the subjects were presented with one familiarisation block comprising five representative trials. The session lasted about 45 min.

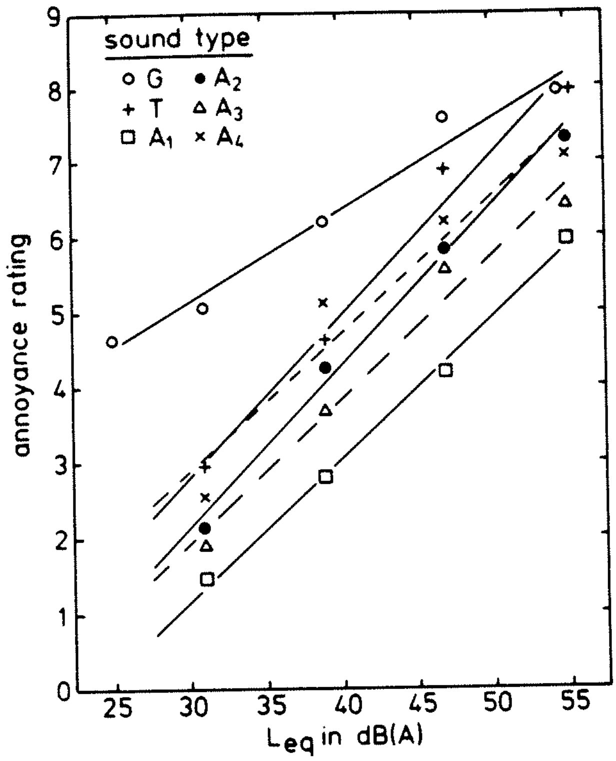

Fig. 11 Mean annoyance rating as a function of the A-weighted L_{eq} for six different sounds. The straight lines are linear regression functions.

4.2 Results

Mean annoyance ratings for G, T, and A_1-A_4, averaged across the 16 subjects, are shown in Fig. 11 as a function of the A-weighted L_{eq} of the sounds. The regression lines inserted in Fig. 11 explain 93% to 99% of the variance in the mean annoyance ratings. For G and T, the equations are $y = 1.54 + 0.120L_{eq}$ ($r = 0.986$) and $y = -3.59 + 0.213L_{eq}$ ($r = 0.990$), respectively. For A_1-A_4, the corresponding equations are $y = -4.40 + 0.186L_{eq}$ ($r = 0.998$), $y = -4.32 + 0.214L_{eq}$ ($r = 0.996$), $y = -3.77 + 0.190L_{eq}$ ($r = 0.988$), and $y = -2.59 + 0.182L_{eq}$ ($r = 0.964$).
As always, G is more annoying than T at relatively low L_{eq}-values and, as expected, this difference gradually decreases with increasing L_{eq} of

the sounds. The significant interaction between sound type (G and T) and L_{eq} [$F(3,45) = 5.35$, $p < 0.003$] once more emphasizes the relevance of the level-dependent penalty for impulse sound. Overall, the aircraft sounds A_1-A_4 are all less annoying than T, and this does not depend on L_{eq} ($p > 0.10$). A Newman-Keuls paired comparison test (Winer, 1970) showed that three of the four aircraft sounds are significantly less annoying than T: A_1 and A_3 at a level of 0.01, and A_2 at a level of 0.05.

4.3 Discussion

In spite of the fact that L_{eq} is a relatively adequate measure for the prediction of annoyance [see, e.g., Fields and Hall (1987), and Vos and Geurtsen (1987)], the data from Experiment 2 show that there may be much spread in the annoyance caused by sounds that belong to one category. Within the aircraft noise category, difference may extend to 8-9 dB (Fig. 11). The spectral data in Figs. 9a and 9b suggest that the differences in annoyance are related to the sound levels in the octave bands between 500 and 4000 Hz: the higher the levels, the more annoying.

The data on temporal fluctuations in level during the 45 s periods (Fig. 10) suggest that annoyance increases with the rate of fluctuation: the more annoying A_2 and A_4 sounds reach their maximum levels within the first 6 s, whereas the less annoying A_1 and A_3 sounds do so within as long as 19-23 s.

Based on the overall annoyance rating it would be obvious to select A_4 as the sound to be included in Experiment 3. The masked threshold for A_4 in a T background, however, is higher than that for A_2. For this reason we decided to use the slightly less annoying A_2 in Experiment 3.

5 EXPERIMENT 3

5.1 Method

Stimuli and Apparatus

G and T from Experiments 1 and 2, and A_2 from Experiment 2 served as distinct sources. BN at an L_{eq} of 30 dB(A) again served as the background noise. The apparatus was the same as in Experiment 2.

Subjects
Sixteen subjects, eight males and eight females, between 18 and 30 years of age, participated in the experiment. Only two of the testees had a hearing loss greater than 15 dB Hearing Level in any part of the audiogram. For both ears these subjects had a loss of about 20 and 28 dB Hearing Level at a frequency of 6 kHz. None of the subjects had prior experience to this kind of annoyance studies. The subjects were paid for their services.

Experimental design
The sounds to be rated consisted of various combinations of G, T, and A_2. A detailed description of these combinations is given in Tables 5-8. Each sound was also presented for rating in isolation at indoor L_{eq}-values of 30, 36, 42, 48, and 54 dB(A). In addition, G was presented at the lower level of 24 dB(A). All 64 conditions were presented twice.

Procedure
The instructions to the subjects were identical to those in Experiment 1. All 64 conditions were randomly assigned to eight experimental blocks of eight trials each. Presentation order of the different blocks was balanced according to 8x8 Latin squares, and the stimuli within each block were presented in a random order. Before starting with the first block, the subjects were presented with a familiarisation block comprising ten representative trials. After the eight experimental blocks, the subjects were presented with the 64 stimuli for the second time. Again, presentation order of the different blocks was balanced according to (new) Latin squares, and the stimuli within each block were presented in a random order. A session lasted about 3.5 h; breaks of 10 min were given after about each hour.
The correlation coefficients between the ratings given for the first and for the second times were unexpectedly high: 11 subjects had r-values between 0.80 and 0.90, whereas four subjects had r-values between 0.63 and 0.75.

5.2 Results

ANOVAs performed on the data from the various subsets of conditions showed that the ratings given in the first presentation were not significantly different from those in the second presentation and, more importantly, in no single subset was the effect of L_{eq} different for the first and the second ratings. All results given below will therefore be averaged across replication.

Sounds in isolation

Mean annoyance ratings for G, T, and A_2, averaged across the 16 subjects (and the two replications), are shown in Fig. 12 as a function of the A-weighted L_{eq} of the sounds. The linear regression lines inserted in Fig. 12 explain 98% or 99% of the variance in the mean annoyance ratings. For G, the equation is $y = -1.34 + 0.179L_{eq}$ ($r = 0.997$), for T the equation is $y = -6.65 + 0.241L_{eq}$ ($r = 0.992$), and for A_2 the equation is $y = -5.75 + 0.210L_{eq}$ ($r = 0.999$).

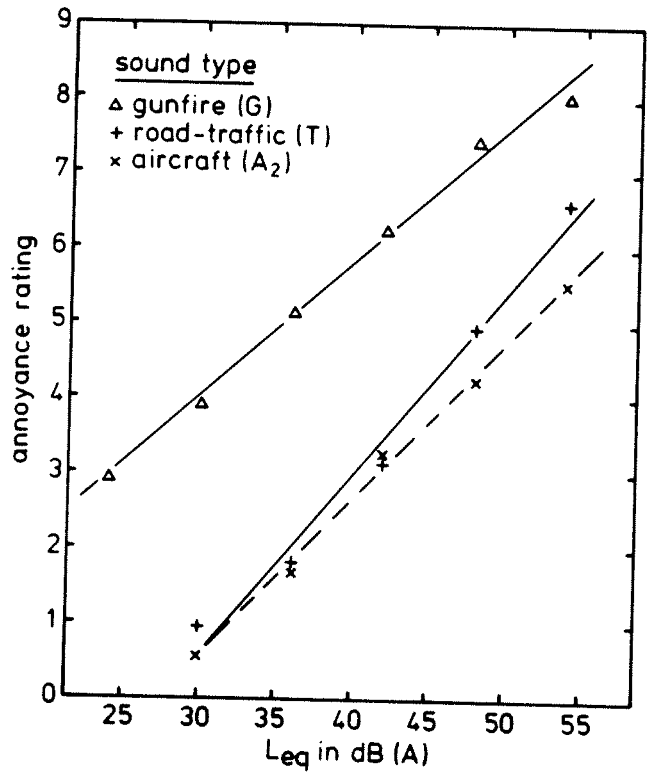

Fig. 12 Mean annoyance rating as a function of the A-weighted L_{eq} for three different sounds. Straight lines are linear regression functions.

The ratings were subjected to an ANOVA [a 16(subjects) x 3(sound types) x 5(L_{eq}) factorial design, all repeated measures and with replication as a within-cell variable]. The ratings obtained with G at an L_{eq} of 24 dB(A) were excluded. The overall effect of sound type was significant [$F(2,30) = 38.7$, $p < 0.000001$], which means that G is more annoying than T and A_2. The most powerful effect on the ratings was caused by L_{eq} [$F(4,60) = 170.0$, $p < 0.0000001$]. The increase of the ratings with L_{eq} was greater for T than for G and A_2 [$F(8,120) = 3.34$, $p < 0.002$]. The significance of the level-dependent penalty of G relative to T was confirmed in a separate ANOVA performed on the data for G and T only [$F(4,60) = 6.86$, $p < 0.0003$]. After substitution of the relevant slopes and intercepts in Eq. (1), this penalty is given by $P_g = 22.0 - 0.26L_{eq}$ of G. A separate ANOVA performed on the data for A_2 and T in isolation showed that it is justified to apply a level-dependent penalty for A_2 as well [$F(4,60) = 2.55$, $p < 0.05$]. This penalty (Eq. 2) is given by $P_a = 3.7 - 0.13L_{eq}$ of A_2.

Two different sounds in combination

G and T. The mean total annoyance ratings for G presented in combination with T, the L_{eq} of T always fixed at 43 dB(A), are given in the third column of Table 5 and are shown in Fig. 13a as a function of the L_{eq} of G. As in previous figures and in several figures that will follow, the annoyance of the separate sounds of the combination is given as a reference (see Fig. 12). In none of the conditions shown in Fig. 13a is the total annoyance rating significantly different from the rating of the more annoying source.

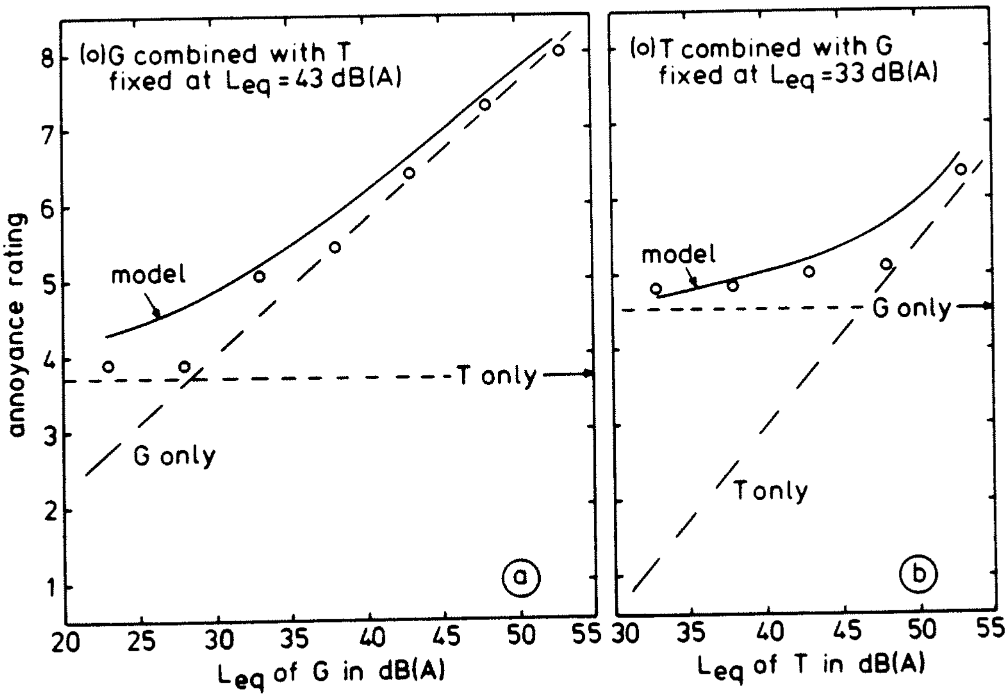

Fig. 13 (a) Total annoyance for G presented in combination with T at an L_{eq} of 43 dB(A), as a function of the L_{eq} of G. (b) Total annoyance for T presented in combination with G at an L_{eq} of 33 dB(A), as a function of the L_{eq} of T. In both panels (a) and (b), linear regression functions for the relevant sounds and the annoyance caused by the sounds with the fixed L_{eq} are given as references. The solid lines represent the predictions of the model with k=14.

Fig. 13b shows the mean annoyance ratings for T presented in combination with G at an L_{eq} of 33 dB(A), for various L_{eq}-values of T. The total annoyance ratings are slightly higher than the ratings of the more annoying sounds. A t-test on the difference between the ratings obtained in, for example, the T43+G33 and the G33 conditions showed that total annoyance is not significantly higher than the annoyance rating for G only at the L_{eq} of 33 dB(A).

Table 5 Values of L_t are compared with the results for conditions in which combinations of T and G sounds were rated for total annoyance.

combination				summation model			
				k = 10		k = 14	
T	G	rating	corresp. L_{eq} of T	L_t	L_t-L_{eq} of T	L_t	L_t-L_{eq} of T
43	23	3.91	43.8	44.5	0.7	45.6	1.8
43	28	3.91	43.8	45.9	2.1	47.1	3.3
43	33	5.06	48.6	48.1	-0.5	49.2	0.6
43	38	5.44	50.2	51.0	0.8	51.9	1.7
43	43	6.41	54.2	54.3	0.1	54.9	0.7
43	48	7.31	57.9	57.8	-0.1	58.2	0.3
43	53	8.03	60.9	61.5	0.6	61.7	0.8
33	33	4.81	47.6	46.7	-0.9	47.1	-0.5
38	33	4.84	47.7	47.1	-0.6	47.8	0.1
48	33	5.13	48.9	50.3	1.4	51.5	2.6
53	33	6.34	53.9	53.9	0.0	54.8	0.9
					M = 0.3		M = 1.1
					RMS = 0.9		RMS = 1.6

The predictions of L_t, as defined in Eq.(3) with k=10, are given in the fifth column of Table 5 for all combinations of T and G. The L_{eq} of equally annoying T sounds in isolation is given in the fourth column of Table 5. In general, the differences between the predictions of L_t and the experimentally obtained results are small (see sixth column). The discrepancies of 2.1 (T43+G28) and 1.4 dB (T48+G33) are of importance because they are obtained in conditions in which the annoyance of the separate sounds is about equal. The reason to prefer application of the present model to application of a dominance model is that the present model accounts for the increased total annoyance that is generally found in such conditions. The subset of data shown in Fig. 13 would not justify such a preference.

G and A_2. The mean total annoyance ratings for G presented in combination with A_2 at an L_{eq} of 49 dB(A) are shown in Fig. 14a as a function of the L_{eq} of G. Fig. 14a clearly shows that especially in the conditions in which the differences between the annoyance ratings for the separate sounds are relatively small (which is the case in G28+$A_2$49, G33+$A_2$49, and G38+$A_2$49), the total annoyance rating is higher than the rating of the more annoying sound. A t-test showed that the annoyance caused by G33+$A_2$49 is significantly higher than (1) the annoyance for G33 in isolation ($t = 3.1$, $p < 0.005$), and (2) the annoyance for $A_2$49 in isolation ($t = 3.6$, $p < 0.001$).

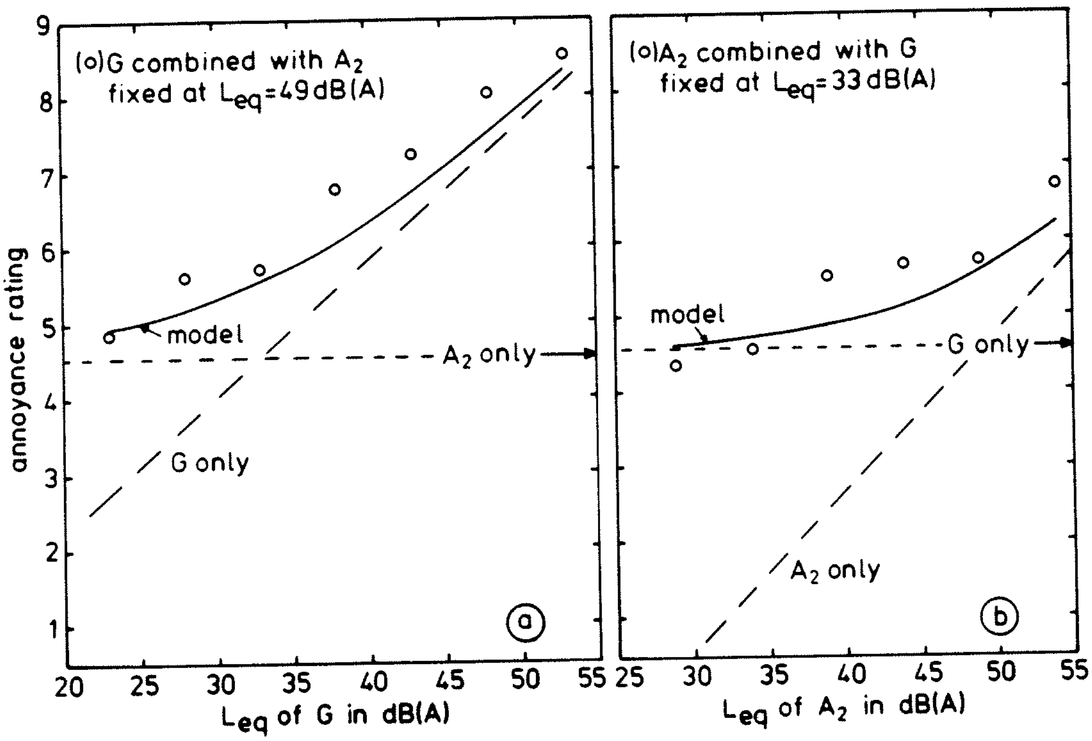

Fig. 14 (a) Total annoyance for G presented in combination with A_2 at an L_{eq} of 49 dB(A), as a function of the L_{eq} of G. (b) Total annoyance for A_2 presented in combination with G at an L_{eq} of 33 dB(A), as a function of the L_{eq} of A_2. In both panels (a) and (b), linear regression functions for the relevant sounds and the annoyance caused by the sounds with the fixed L_{eq} are given as references. Again, the solid lines represent the predictions of the model with k=14.

Fig. 14b shows the mean annoyance ratings for A_2 presented in combination with G at an L_{eq} of 33 dB(A), for various L_{eq}-values of A_2. In the conditions in which the differences between the annoyance caused by the separate constituing sounds are relatively small (such as in $A_2$44+G33, $A_2$49+G33, and $A_2$54+G33), the total annoyance ratings are, again, higher than the ratings of the more annoying sound in the combination.

Table 6 Values of L_t are compared with the results for conditions in which combinations of A_2 and G sounds were rated for total annoyance.

combination				summation model			
				k = 10		k = 14	
A_2	G	rating	corresp. L_{eq} of T	L_t	L_t-L_{eq} of T	L_t	L_t-L_{eq} of T
49	23	4.84	47.7	47.2	-0.5	48.0	0.3
49	28	5.59	50.8	48.0	-2.8	49.1	-1.7
49	33	5.69	51.2	49.5	-1.7	50.7	-0.5
49	38	6.75	55.6	51.8	-3.8	52.9	-2.7
49	43	7.22	57.6	54.7	-2.9	55.5	-2.1
49	48	7.97	60.7	58.0	-2.7	58.6	-2.1
49	53	8.50	62.9	61.5	-1.4	61.9	-1.0
29	33	4.34	45.6	46.6	1.0	46.8	1.2
34	33	4.53	46.4	46.7	0.3	47.2	0.8
39	33	5.50	50.4	47.1	-3.3	47.8	-2.6
44	33	5.66	51.1	47.9	-3.2	48.9	-2.2
54	33	6.69	55.4	52.2	-3.2	53.2	-2.2
				M =	-2.0	M =	-1.2
				RMS =	2.5	RMS =	1.8

The predictions of L_t are given in the fifth column of Table 6. The sixth column shows that when k is set to 10, there are many conditions in which our integration model underestimates the total annoyance by about 3 dB.

<u>T and A_2.</u> The mean total annoyance ratings for T presented in combination with A_2 at an L_{eq} of 48 dB(A) are shown in Fig. 15a as a function of the L_{eq} of T. In the conditions in which the differences between the annoyance ratings for T and A_2 in isolation are relatively small, the total annoyance rating is higher than the rating of the more annoying sound. A t-test showed that the total annoyance caused by T43+$A_2$48 is significantly higher than the annoyance for $A_2$48 in isolation ($t = 3.71$, $p < 0.001$).

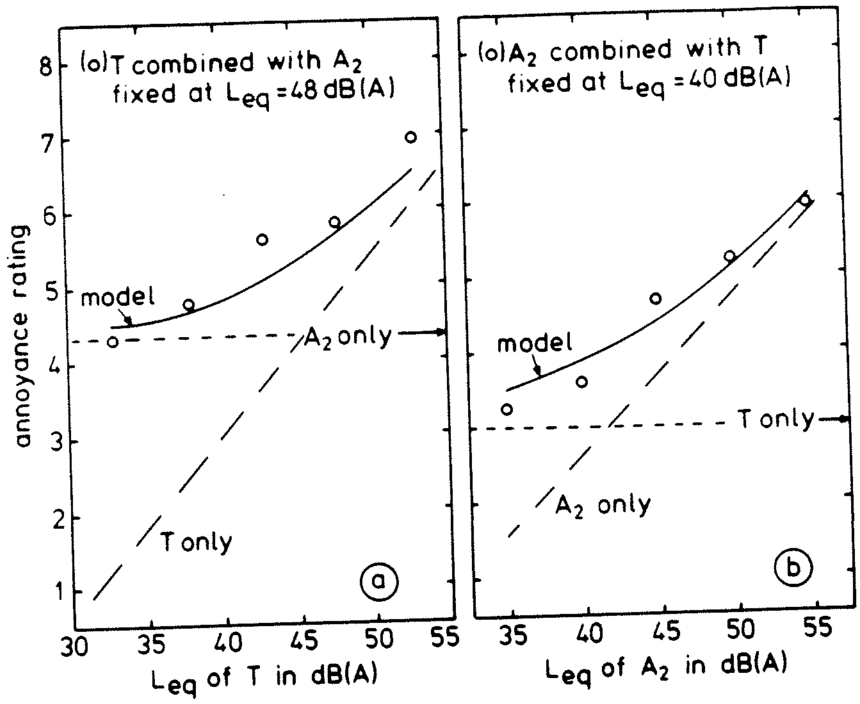

Fig. 15 (a) Total annoyance for T presented in combination with A_2 at an L_{eq} of 48 dB(A), as a function of the L_{eq} of T. (b) Total annoyance for A_2 presented in combination with T at an L_{eq} of 40 dB(A), as a function of the L_{eq} of A_2. In both panels (a) and (b), linear regression functions for the relevant sounds and the annoyance caused by the sounds with the fixed L_{eq} are given as references. Again, the solid lines represent the predictions of the model with k=14.

Fig. 15b shows the ratings for A_2 presented in combination with T at an L_{eq} of 40 dB(A). Again, the total annoyance rating is higher than the rating of the more annoying sound in the combination for those conditions in which the differences between the annoyance rating for T and A_2 in isolation are relatively small. T-tests showed that (1) the annoyance caused by $A_2$40+T40 is significantly higher than the annoyance for T40 only ($t = 1.80$, $p < 0.05$), and (2) the annoyance caused by $A_2$45+T40 is significantly higher than the annoyance for $A_2$45 in isolation ($t = 2.52$, $p < 0.01$).

Table 7 Values of L_t are compared with the results for conditions in which combinations of A_2 and T sounds were rated for total annoyance.

combination				summation model			
				k = 10		k = 14	
A_2	T	rating	corresp. L_{eq} of T	L_t	L_t-L_{eq} of T	L_t	L_t-L_{eq} of T
48	33	4.28	45.4	45.8	0.4	46.3	0.9
48	38	4.75	47.3	46.3	-1.0	47.1	-0.2
48	43	5.59	50.8	47.5	-3.3	48.7	-2.2
48	48	5.78	51.6	50.0	-1.6	51.1	-0.5
48	53	6.88	56.1	53.7	-2.4	54.6	-1.5
35	40	3.25	41.1	41.0	-0.1	42.0	0.9
40	40	3.59	42.5	42.4	-0.1	43.6	1.1
45	40	4.66	46.9	44.7	-2.2	45.8	-1.1
50	40	5.19	49.1	48.0	-1.1	48.9	-0.2
55	40	5.91	52.1	51.9	-0.2	52.5	0.4
					M = -1.2		M = -0.2
					RMS = 1.6		RMS = 1.1

The predictions of L_t are given in the fifth column of Table 7 for all combinations of A_2 and T. The sixth column of Table 7 shows that there are three conditions in which the model underestimates total annoyance by 2 or 3 dB. Overall, however, the underestimation is not greater than 1.2 dB, with a rms of 1.6 dB.

Three different sounds in combination

G and T at various levels, A_2 at L_{eq} = 49 dB(A). The mean total annoyance ratings for G and T in combination with A_2 at an L_{eq} of 49 dB(A) are given in Fig. 16 as a function of the L_{eq} of G. Again, the annoyance of the separate sounds in the combination is given as a reference. Since the L_{eq}-values of T were not completely correlated with those of G, the annoyance ratings of T in isolation are represented by discrete points in stead of by a single linear function.

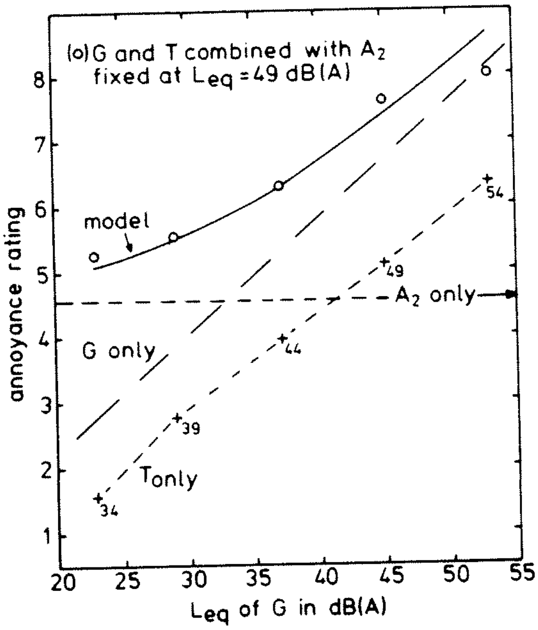

Fig. 16 Total annoyance for G and T presented in combination with A_2 at an L_{eq} of 49 dB(A), as a function of the L_{eq} of G. The regression function for G only, and the annoyance caused by A_2 only are given as references. In addition, the annoyance caused by T only is included as a reference. The solid line represents the predictions of the model with k=14.

In the conditions in which the differences between the annoyance ratings for G and A_2 in isolation are relatively small, the total annoyance ratings are higher than the ratings of the more annoying sounds. T-tests showed that (1) the annoyance caused by G29+T39+$A_2$49 is significantly higher than the annoyance for $A_2$49 only ($t = 2.91$, $p < 0.005$), and (2) the annoyance caused by G37+T44+$A_2$49 is significantly higher than the annoyance for G37 in isolation ($t = 2.78$, $p < 0.005$).

Table 8 Values of L_t are compared with the results for various conditions in which combinations of G, T, and A_2 sounds were rated for total annoyance.

combination			rating	corresp. L_{eq} of T	summation model			
					k = 10		k = 14	
G	T	A_2			L_t	L_t-L_{eq} of T	L_t	L_t-L_{eq} of T
23	34	49	5.25	49.4	47.4	-2.0	48.6	-0.8
29	39	49	5.53	50.5	48.7	-1.8	50.4	-0.1
37	44	49	6.31	53.8	52.0	-1.8	53.7	-0.1
45	49	49	7.59	59.1	56.8	-2.3	58.2	-0.9
53	54	49	7.97	60.7	62.2	1.5	63.4	2.7
					m =	-1.3	m =	0.2
					rms =	1.9	rms =	1.3
23	40	35	3.25	41.1	43.2	2.1	44.9	3.8
30	40	40	4.91	48.0	46.5	-1.5	48.2	0.2
36	40	45	6.22	53.4	50.2	-3.2	51.7	-1.7
42	40	50	6.94	56.4	54.4	-2.0	55.6	-0.8
49	40	55	7.94	60.5	59.3	-1.2	60.4	-0.1
					m =	-1.2	m =	0.3
					rms =	2.1	rms =	1.9
33	32	35	5.22	49.3	46.9	-2.4	47.7	-1.6
33	37	40	5.22	49.3	47.6	-1.7	48.9	-0.4
33	42	45	5.50	50.4	49.1	-1.3	50.8	0.4
33	47	50	6.25	53.5	51.7	-1.8	53.6	0.1
33	52	55	7.22	57.6	55.4	-2.2	57.2	-0.4
					m =	-1.9	m =	-0.4
					rms =	1.9	rms =	0.8
					M =	-1.4	M =	0.0
					RMS =	2.0	RMS =	1.4

The predictions of L_t with k set to 10 are given in the first section of Table 8. Overall, the model tends to underestimate total annoyance by about 1 dB. The ratings given in Fig. 16 may be compared with those shown in Fig. 14a. The essential difference between the stimuli considered in Fig. 14a and Fig. 16 is that T was added as the third sound in the combinations included in Fig. 16. Since the total ratings in Fig. 14a are very close to those in Fig. 16, we may conclude that the less annoying and always subdominant T sound had no effect on the total annoyance, which is in consonance with the predictions (compare the relevant values in Tables 6 and 8).

G and A_2 at various levels, T at L_{eq} = 40 dB(A). The mean total annoyance ratings for G and A_2 presented in combination with T at an L_{eq} of 40 dB(A) are shown in Fig. 17 as a function of the L_{eq} of G. These ratings are all higher than the ratings for G only. An ANOVA performed on the relevant data showed that overall, total annoyance is higher than the annoyance of G only [$F(1,15) = 4.54$, $p < 0.05$]. In the G33+$A_2$35+T40 condition, however, the total rating is not significantly higher than the rating for T40 in isolation.

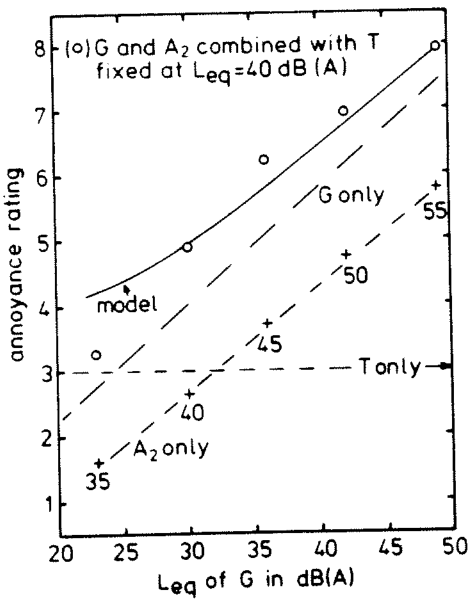

Fig. 17 Total annoyance for G and A_2 presented in combination with T at an L_{eq} of 40 dB(A), as a function of the L_{eq} of G. The regression function for G only, and the annoyance caused by T only are given as references. In addition, the annoyance caused by A_2 only is included as a reference. The solid line represents the predictions of the model with k=14.

The predictions of L_t are given in the second section of Table 8. Overall, the model tends to underestimate total annoyance by about 1 dB.

T and A_2 at various levels, G at L_{eq} = 33 dB(A). The total annoyance ratings for T and A_2 presented in combination with G at an L_{eq} of 33 dB(A) are shown in Fig. 18 for the various levels of T and A_2. In all conditions the total annoyance rating is significantly higher than the rating of the more annoying sound in the combination. T-tests showed that (1) the annoyance caused by T42+$A_2$45+G33 is significantly higher than the annoyance for G33 at the 0.01 level ($t = 2.40$), and (2) the annoyance caused by T47+$A_2$50+G33 is significantly higher than the annoyance caused by $A_2$50 at the 0.001 level (t = 4.46).

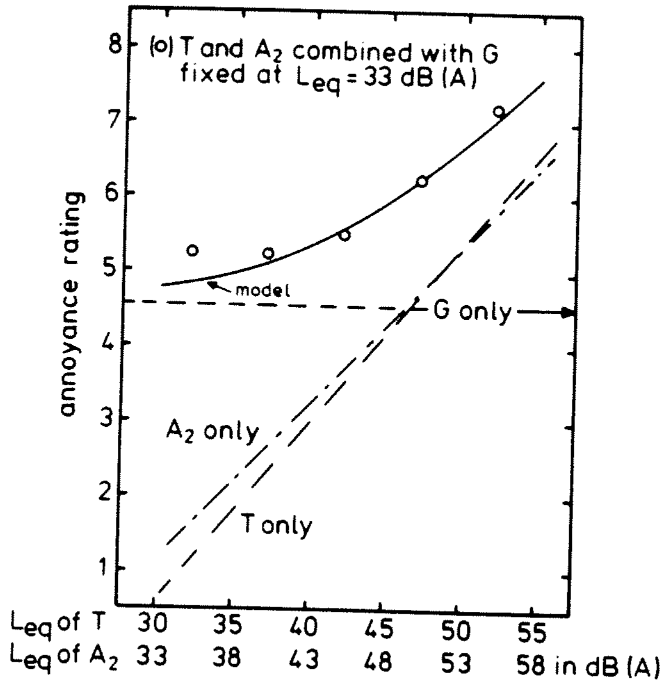

Fig. 18 Total annoyance for T and A_2 presented in combination with G at an L_{eq} of 33 dB(A), as a function of the L_{eq} of T and A_2. The regression functions for T and A_2 only, and the annoyance caused by G only are given as references. The solid line represents the predictions of the model with k=14.

The predictions of L_t are given in the third section of Table 8. Overall, total annoyance is underestimated by about 2 dB when k is set to 10.

5.3 Discussion

In Experiment 3, there were two conditions in which the model with k=10 overestimated total annoyance by at least 2 dB. These conditions were G28+T43 (Table 5) and G23+T40+$A_2$35 (Table 8). There were 16 conditions in which the model underestimated total annoyance by at least 2 dB, and there were 30 conditions in which the absolute differences were all smaller than 2 dB. The mean underestimation was 1.1 dB, which is slightly lower than the value of 1.3 dB that we found in Experiment 1. With the free parameter k set to 14, the systematic underestimation could be cancelled. For all combinations investigated, the new values of L_t are shown in the last two columns of Tables 5-8. In none of the subsets was the rms greater than 2 dB.

6 GENERAL CONCLUSION

The present summation model accurately predicts total annoyance caused by different simultaneous sound sources from the source-specific annoyance of each separate sound, both in conditions in which two or more sounds are about equally annoying and in conditions in which one of the sounds is much more annoying than the sounds of the remaining sources.
In the model proposed the annoyance caused by the impulse and/or aircraft sounds is expressed in the A-weighted L_{eq} of equally annoying road-traffic sound by applying level-dependent penalties (the corrected L_{eq}). An optimal prediction of total annoyance is obtained by summation of the corrected L_{eq}'s of the various sources with the free parameter k in $k\log\{10^{(\text{corrected Leq of Source 1})/k} + 10 \ldots\}$ set to 15.
Since summation of the L_{eq}'s of the separate sources is performed after addition of the level-dependent penalties, the total annoyance model represents a mental integration of annoyance judgements rather than an integration of the L_{eq}'s from separate sources. In this respect our model resembles the independent effects model discussed in Taylor (1982).

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REFERENCES

Berglund, B., Berglund, U., Goldstein, M., and Lindvall, T. (1981). Loudness (or annoyance) summation of combined community noises, J. Acoust. Soc. Am. 70, 1628-1634.

Bottom, C.G. (1971). A social survey into annoyance caused by the interaction of aircraft noise and traffic noise. J. Sound and Vibration 19 (4), 473-476.

Cooper, P.J., Diamond, I.D., Rice, C.G., and Walker, J.G. (1984). The modelling of source specific and total noise annoyance using source specific noise measurements. Proceedings of the Institute of Acoustics, pp. 301-308.

Fields, J.M., and Hall, F.L. (1987). Community effects of noise, in Transportation Noise Reference Book, edited by P.M. Nelson (Butterworths, London, Great Britain) Chap. 3.

Flindell, I.H. (1982). Community response to multiple noise sources. Ph. D. Thesis (University of Southampton, United Kingdom).

Flindell, I.H. (1983). Pressure L_{eq} and multiple noise sources: A comparison of exposure-response relationships for railway noise and road traffic noise. J. Sound and Vibration 87(2), 327-330.

Flindell, I.H., and Rice, C.G. (1986). 1984-1985 Joint CEC Project on annoyance due to impulse noises: Laboratory studies. ISVR Contract Report No. 86/22 (ISVR, Southampton, United Kingdom).

Hays, W.L. (1970). Statistics (Holt, Rinehart, and Winston: London).

ISO (1975). ISO R 389, Standard reference zero for the calibration of pure-tone audiometers (International Organization for Standardization, Switzerland).

Izumi, K. (1988). "Annoyance due to mixed source noises - a laboratory study and field survey on the annoyance of road traffic and railroad noise," J. Sound and Vibration 127 (3), 485-489.

Miedema, H.M.E. (1985). "Annoyance caused by two noise sources," J. Sound and Vibration 98 (4), 592-595.

Miedema, H.M.E. (1987). Annoyance from combined noise sources, in Proceedings Environmental Annoyance (Elsevier, Amsterdam), 313-320.

Miedema, H.M.E., and van den Berg, R. (1988). "Community response to tramway noise," J. Sound and Vibration 120 (2), 341-346.

Powell, C.A. (1979). A summation and inhibition model of annoyance response to multiple community noise sources. NASA Technical Paper 1479 (Langley Research Center, Hampton, Virginia).

Rice, C.G. (1985). CEC joint project on impulse noise: Effect of road-traffic noise level on judged annoyance, in Proceedings Internoise '85, Munich, Germany, Vol. 2, 913-916.

Rice, C.G., and Izumi, K. (1984). "Annoyance due to combinations of noises". Proceedings of the Institute of Acoustics, pp. 287-294.

Taylor, S.M. (1982). A comparison of models to predict annoyance reactions to noise from mixed sources. J. Sound and Vibration 81 (1), 123-138.

Vos, J. (1986). The level-dependent penalty for impulse sounds. Pro-ceedings 1986 International Conference on Noise Control Engineer-ing [Internoise '86], edited by R. Lotz (Noise Control Foundation, New York, USA), Cambridge, Massachusetts, Vol. 2, 889-894.

Vos, J. (1988). On the level-dependent penalty for impulse sound, in Proceedings 5th Int. Congr. Noise as a Public Health Problem (Swedish Council for Building Research, Stockholm, Sweden), Vol. 3, 295-300.

Vos, J., and Geurtsen, F.W.M. (1987). L_{eq} as a measure of annoyance caused by gunfire consisting of impulses with various proportions of higher and lower sound levels. J. Acoust. Soc. Am. 82, 1201-1206.

Vos, J., and Smoorenburg, G.F. (1983). Annoyance ratings for impulse and traffic sounds presented in quiet. IZF Rep. 1983-23, Soester-berg, The Netherlands.

Vos, J., and Smoorenburg, G.F. (1985). Penalty for impulse noise, derived from annoyance ratings for impulse and road-traffic sounds. J. Acoust. Soc. Am. 77, 193-201.

Winer, B.J. (1970). Statistical principles in experimental design (McGraw-Hill, London).

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15. ABSTRACT (MAXIMUM 200 WORDS, 1044 BYTE)

In this study total annoyance caused by different simultaneous environmental sounds is investigated. In spite of a number of confusing data in the literature, it is fairly well established that in combinations in which the annoyance of one source is considerably higher than that of the other source, total annoyance is equal to the maximum annoyance of the separate sources (dominance model). For combinations in which both sounds are about equally annoying, total annoyance seems to be higher than the maximum source-specific annoyance. The available data, however, are too rough to model total annoyance in these conditions. The present laboratory studies were therefore designed to explore further possible procedures to quantify total annoyance. Subjects rated the (total) annoyance caused by various combinations of impulse, road-traffic, and aircraft sounds.

The results support a relatively simple model in which total annoyance is predicted from the source-specific annoyance of the separate sounds (the source-specific dose-effect relationships). First, the annoyance caused by the impulse and/or aircraft sounds is expressed in the A-weighted equivalent sound level, L_{eq}, of equally annoying road-traffic sound by applying level-dependent penalties (the corrected L_{eq}). Second, total annoyance, again expressed in the L_{eq} of equally annoying road-traffic sound, is obtained by summation of the corrected L_{eq}'s of the various sources. An optimal overall fit of the data from two separate experiments was obtained when this summation of the corrected L_{eq}'s was performed with the free parameter k in $k\log(10^{(\text{corrected Leq of Source 1})/k} + 10 \ldots)$ set to 15.

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