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Annoyance of Audible Infrasound

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Abstract

Contours of equal annoyance were determined for pure tones in the frequency range 4 - 31.5 Hz. The curves show a narrowing of the dynamic range of the ear at low frequencies. The same pattern is seen for equal loudness curves, and the results support the theory that the annoyance of infrasound is closely related to the loudness sensation.

Annoyance ratings of 1/3 octave noise did not deviate from ratings of pure tones with the same sound pressure level. Combinations of audio and infrasonic noise were in general given a rating close to or slightly above the rating of the most annoying of the individual noise conditions.

For infrasound the proposed G1-weighting curve is shown to give values that correlate well with subjective annoyance rating. Values obtained with the G2-curve do not correlate as well. Low audio frequencies are not covered by the G-curves, and it is shown that these are insufficiently covered by the A-curve. Further research is needed in this area.

1. INTRODUCTION

The concerns about effects of infrasound that alarmed many people some 20 years ago, were based on a number of alleged extra-auditory effects, such as disturbance of equilibrium and influence on the circulatory system. However, the experimental findings were not very consistent, and in general the effects seem to have been exaggerated.

The effects claimed were not only extra-auditory: it was also normally assumed that infrasound was inaudible. Thus people thought they might be influenced by a sound they did not even know the existence of.

However, it is not true that infrasound is inaudible. Infrasound can be heard by the human ear, and when it becomes sufficiently loud, it can be annoying. Thus the lack of direct physiological effects does not mean that infrasound is insignificant from an environmental point of view.

The hearing threshold at infrasonic frequencies was determined as early as 1936 [1], also the growth of loudness above threshold has been investigated [2,3].

The annoyance associated with exposure to audible infrasound has been the subject of a number of experiments carried out at this laboratory. The first experimental series served to determine curves of equal annoyance for pure tones at low audio and infrasonic frequencies. These results have already been reported [4], and in the following the sutdy will be referred to as Experiment A. One conclusion was that the curves did not deviate significantly from similar curves of equal loudness. Therefore it was suggested that annoyance from exposure to infrasound is closly related to the louness sensation.

Experiment A only included exposures to pure infrasonic tones, and only students were used as subjects. In order to extend the validity of the reported results, it was decided to carry out experiments with non-sinusoidal infrasonic stimuli and with exposures that were combinations of infrasonic and audio frequency noise. It was also considered appropriate to use older persons and other occupational groups as subjects, and to explore the effect of exposure time.

Apart from the experiments involving other groups as subjects, this research is now completed, and the present paper presents the results.

1.1 Survey of experiments

As the methods used in all the experiments were almost identical to Experiment A, a brief description of this is given in Section 2. This is furthermore justified as some of the results from Experiment A are included in additional analysis and discussion. For a more detailed description, please refer to the original article [4].

In Experiment A an experimental procedure was used, where each subject had to participate for about half an hour on 18 consecutive days. This is a rather extensive design, and it was decided to examine whether the same results could be obtained in a less demanding experiment. For this purpose Experiments B and C were carrried out. These were repetitions of Experiment A, but the exposure time was reduced, and for each subject all exposures were given on the same day.

Experiments B and C are described in Section 3, which also contains an evaluation of the experimental procedure, based on results from Experiments A, B and C.

The exposures in Experiment D were non-sinusoidal infrasound and low audio frequency noise; 1/3 octave filtered pink noise at 8, 16 and 31.5 Hz was chosen, and the experiment is described in Section 4.

Section 5 describes Experiment E, in which the subjects were exposed to combinations of infrasonic and audio frequency noise. The infrasound was a pure tone of 16 Hz, and the audio frequency noise was an octave noise band of 1 kHz centre frequency.

In noise measurements it is normal to use weighting curves to compensate for the frequency dependent characteristics of human hearing. Section 6 is a discussion of the utility of the A-curve and the recently proposed G-curves for predicting annoyance from audio frequency and infrasonic noise.

2. EXPERIMENT A

2.1 Method

A group of 18 normal-hearing students were exposed to 18 stimuli including various levels of pure tone at infrasonic and low audio frequencies (4,8, 16 and 31.5 Hz) and various levels of a reference noise (1 kHz octave-filtered pink noise).

Each subject was exposed to the whole range of stimuli. The order in which a subject received the 18 stimuli was determined from a latin square design which balanced out order and carry-over effects. Each subject was exposed to only one stimulus per day for 18 days.

An experimental session lasted 20 minutes, and during this period the subject was alone in the test chamber, reading newspapers. After an initial 5 minutes period of silence the sound was presented for 15 minutes. 15 seconds after the sound was turned off, the subject indicated on a graphic scale the "Degree of annoyance felt during the experiment" (Question 1). 20 seconds later he rated on the same scale the "Degree of annoyance he would probably feel at home, if his neighbour produced the same sound for two hours" (Question 2).

The scale was a 150 mm horizontal line of which the left end was marked "not at all annoying" and the right end "very annoying" (see Fig 1). Degree of annoyance was measured in mm from the "not at all annoying" end.

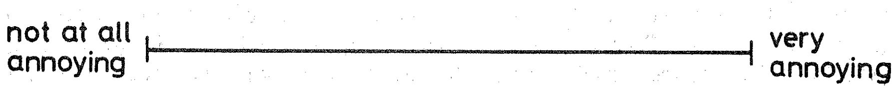

Figure 1 The graphic scale used by the subjects to indicate degree of annoyance.

In addition to the indications on the graphic scale the subject was requested to adjust, with a potentiometer, the level of an octave noise band at 1 kHz. He was asked to adjust it until the 1 kHz noise was perceived to be just as annoying as the stimulus just received. This was done 60 seconds after termination of the sound exposure.

2.2 Results

Mean ratings for each sound condition are shown in Fig 2. The relationship between sound pressure level and annoyance rating is linear for the infrasonic frequencies, and regression lines are included in the figure.

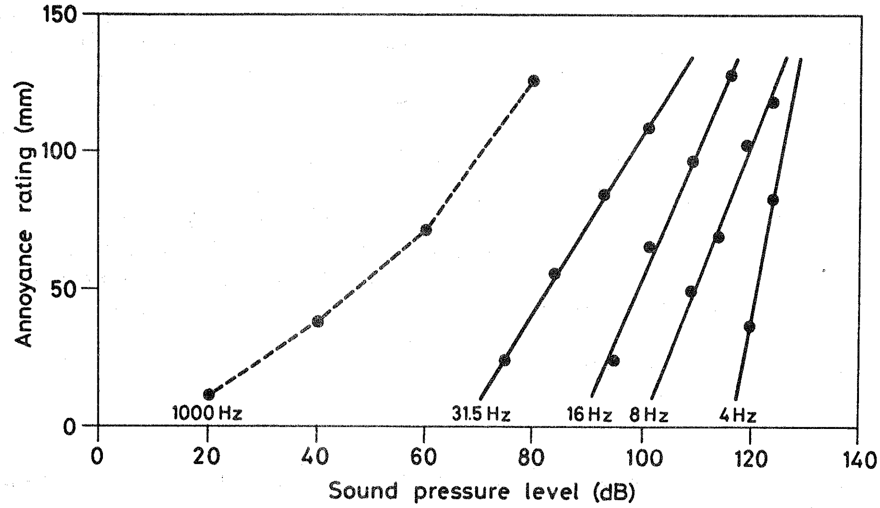

Figure 2 Annoyance ratings for pure infrasonic tones obtained in Experiment A, Question 2. The points represent means of 18 subjects; full lines are regression lines. Ratings at 1 kHz refer to the octave noise bands at this frequency.

In Fig 2 points of equal annoyance could be represented by horizontal lines. From each of the four 1 kHz points horizontal lines have been drawn, and the points where they intersect the regression lines have been determined. These points can be shown graphically as the equal annoyance contours in Fig 3. (For a detailed description of this procedure please refer to the original article [4], where results from Question 1 are also reported).

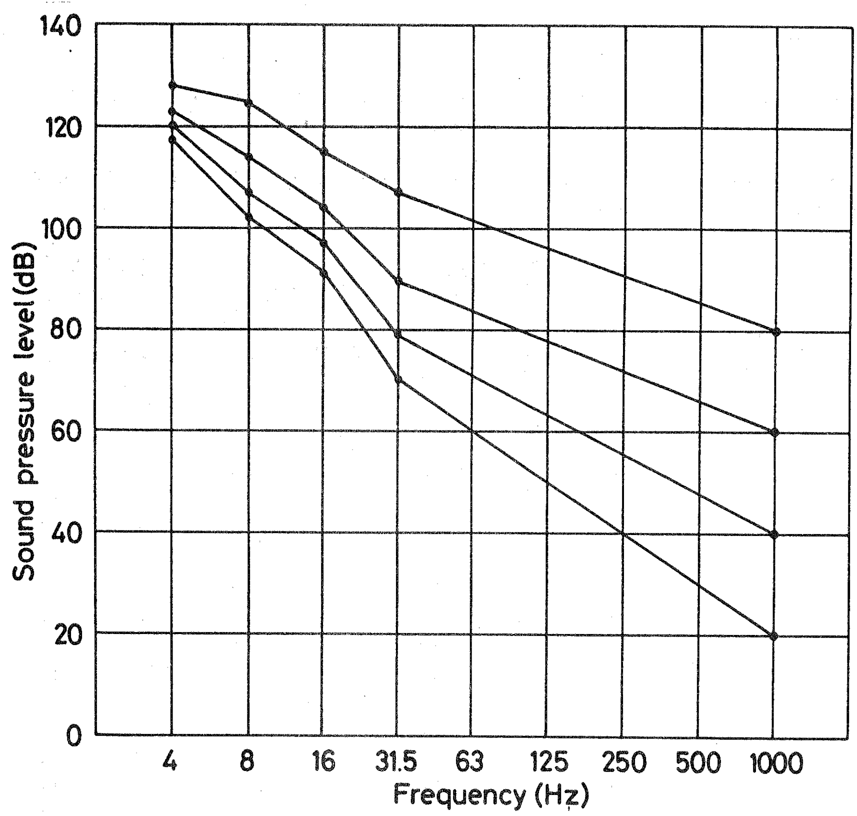

Figure 3 Equal annoyance curves for pure infrasonic tones based on results from Experiment A, Question 2.

The equal annoyance curves demonstrate that the lower the frequency the greater the sound pressure must be in order to cause a given amount of annoyance. Compared with 1 kHz the curves lie much closer in the infrasonic range. This change is already seen at 31.5 Hz, but it becomes even more pronounced with decreasing frequency.

The same general pattern and almost the same values were seen in our study of equal loudness curves [3], and the results of Experiment A support the theory that the annoyance of infrasound is closely related to the loudness sensation.

The closeness of the curves in the infrasonic region implies that relatively small changes in sound pressure may cause large changes in annoyance. From an environmental point of view this is important, since a modest reduction in sound pressure may in some cases be enough to alleviate annoyance caused by infrasonic noise.

3. EXPERIMENTS B AND C

3.1 Method

Experiments B and C served to explore the effect of exposure time on the annoyance ratings and to evaluate the experimental procedure. Subjects, sound conditions, apparatus and experimental design were the same as in Experiment A.

In Experiment B the exposure time was 3 minutes preceded by 1 minute of silence. Questions 1 and 2 were answered 15 and 35 seconds respectively after the exposure, as in Experiment A. No adjustment of the 1 kHz noise band was carried out. For each subject all exposures were given on the same day, resulting in a total duration of approximately 90 minutes.

In Experiment C the exposure time was further reduced to 30 seconds, preceded by 10 seconds of silence. Because of the short exposure time only Question 2 was answered. This was done 15 seconds after termination of the stimulus. Adjustment of the 1 kHz noise band was also omitted here. Because of the short times involved no newspapers were available. Each subject participated for approximately 20 minutes.

3.2 Results

As in Experiment A the degree of annoyance was measured in mm, and means and standard deviations for each of the 18 stimuli are presented in Table I.

Table I. Means and standard deviations (s.d.) for Experiment B (Question 1 and 2) and Experiment C (Question 2).

		EXPERIMENT B				EXPERIMENT C	
		Question 1		Question 2		Question 2	
Frequency (Hz)	SPL (dB)	mean (mm)	s.d. (mm)	mean (mm)	s.d. (mm)	mean (mm)	s.d. (mm)
1000	20	12	18	22	24	19	24
	40	35	23	52	38	46	32
	60	54	38	75	41	79	35
	80	110	33	126	30	129	28
31.5	75	14	17	26	33	21	24
	84	39	39	56	44	58	37
	93	72	36	89	43	91	37
	102	108	39	122	34	114	30
16	95	25	22	43	38	34	36
	102	64	39	84	47	69	36
	109	78	36	99	42	99	35
	116	118	32	129	30	125	27
8	109	40	32	57	48	39	32
	114	56	32	81	42	70	40
	119	83	36	108	36	95	30
	124	121	29	133	26	120	29
4	120	29	25	49	49	41	37
	124	64	36	91	41	84	39

The following sections serve the purpose of evaluating the experiments with respect to experimental design, duration of the exposure, procedure etc. In the discussion results from Experiment A are also included.

Section 3.3 is an analysis of the effect of exposure time.

The experimental design was chosen to balance out possible order and carry-over effects. Whether such effects were present is examined in Section 3.4

In the experiments, up to three different recordings of the annoyance were obtained (ratings in two questions and an adjusted 1 kHz level). Section 3.5 examines whether these recordings express independent characteristics of the annoyance sensation or they contain essentially the same information.

3.3 Effect of exposure time

The effect of exposure time on annoyance rating can be seen through a comparison of the results from Question 2 in Experiments B and C (Table I). Ratings for Question 2 in Experiment A can also be taken into consideration (Table 1 in [4]). For Question 1 a similar comparison can be carried out between results from Experiment A and Experiment B.

However, looking at the tables does not give a clear impression of the possible effects, and therefore an analysis of variance was carried out. The variables that appear in this are the main effects, sound condition, duration and subect, and the interaction between sound condition and duration.

Since subject is a random factor the most correct model would be a mixed model, where each term would be evaluated through its interaction with subjects. However, each combination of sound condition and duration was only presented once to each subject, and the experimental design does not allow calculation of interaction terms with subjects. Therefore, the less conservative fixed model is used.

The analysis of variance is given in Table II.

Table II. Analysis of variance for Question 1 (Experiments A and B) and Question 2 (Experiments A, B and C).

	df	ss	ms	F	sign
Question 1					
Sound condition	17	728285	42840	51.18	< 0.001
Duration	1	1689	1689	2.02	n.s.
Subject	17	188729	11102	13.26	< 0.001
Sound condition by duration	17	7075	416	0.50	n.s.
Residual	595	497817	837		
Total	647	1423595			
Question 2					
Sound Condition	17	1169978	68822	76.81	< 0.001
Duration	2	11424	5712	6.38	< 0.01
Subject	17	412653	24274	27.09	< 0.001
Sound condition by duration	34	11268	331	0.37	n.s.
Residual	901	807538	896		
Total	971	2412861			

Not surprisingly a significant effect of sound condition is seen for both questions. A significant effect of subject is also seen for both questions.

A significant effect of duration is seen for Question 2. This means that the ratings are dependent on the duration of the experiment. It may be a true time effect, but it may also be caused by other differences in the experimental conditions (such as: one experiment involved exposure to only one stimulus a day, while the two remaining were carried out on one day each; in two experiments newspapers were available, while in the third no reading matter was offered).

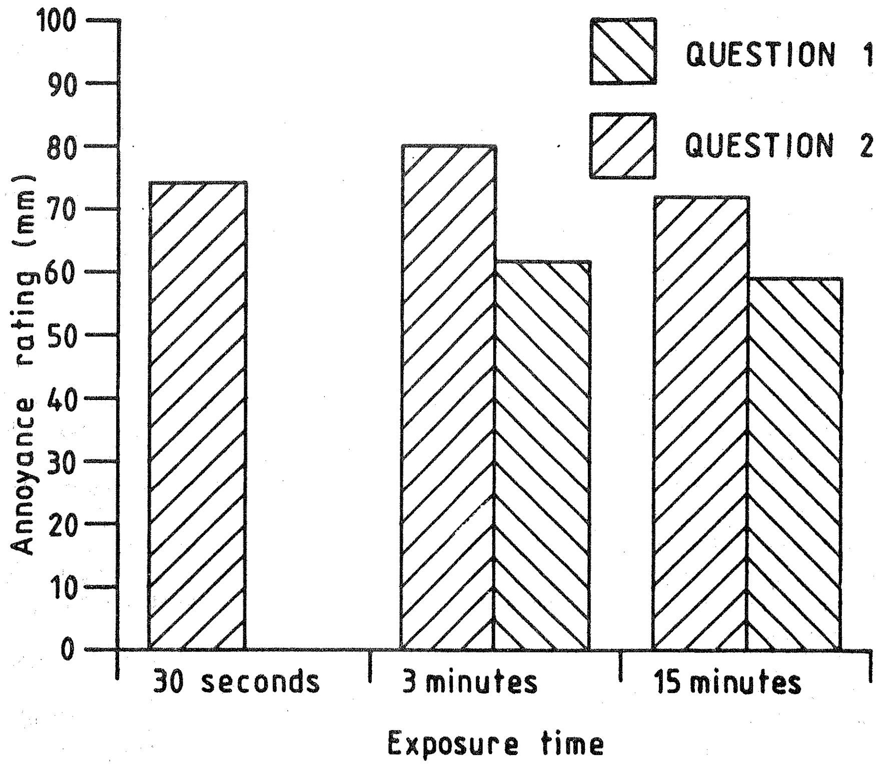

Figure 4 Dependence of annoyance ratings on exposure time. Means of all sound conditions are shown for each exposure time and question.

The effect of duration is illustrated in Fig 4.

The analysis of variance showed no interaction between sound condition and duration for annoyance rating in the two questions. This means that although a variation with exposure time is present for Question 2, this variation is the same for all sound conditions. Consequently, the procedure and rating scale are practicable for comparative measurements, and the results will be independent of the exposure time. It is obvious though, that the exposure time and other circumstances in the experiment should be carefully specified if the numerical ratings are reported, and these should not be directly compared to ratings obtained in other experiments.

The absence of interaction between sound condition and duration justifies the use of short and resource-saving experiments. In Experiments D and E an exposure time of 3 minutes was used.

3.4 Order and carry-over effects

The experimental design was constructed to balance out possible order and carry-over effects. Whether significant effects of this kind exist can be verified in an analysis of variance, in which the two terms treatment number and preceding sound condition are included. As each subject received 18 treatments, the former has 18 levels. The latter has 19 levels, since there were 18 different sound conditions and 1 level characterized by "no previous exposure". For each experiment and question an analysis was carried out, and the results are given in Table III.

For the recordings in Experiment A no effect of treatment number or preceding sound condition was seen. This applies to Questions 1 and 2 as well as to the adjustment of the 1 kHz noise band. This means that the careful procedure with relatively long exposure times and only one stimulus a day has caused the ratings to be really "independent".

For the remaining cases (Experiment B, Questions 1 and 2; Experiment C, Question 2) an effect of either treatment number or preceding sound condition was seen. In these experiments each subject was exposed to the whole range of stimuli on the same day and within a relatively short time. Therefore, these effects are not unexpected, and their presence confirms the necessity of balancing the design with respect to order and carry-over effects.

Table III. Analysis of variance carried out for each experiment and rating method separately and including terms to verify order and carry-over effects.

	df	ss	ms	F	sign
Experiment A. Question 1					
Sound condition	17	357489	21029	23.52	< 0.001
Treatment number	17	21547	1268	1.42	n.s.
Preceding sound condition	18	15003	834	0.93	n.s.
Subject	17	108003	6353	7.10	< 0.001
Residual	254	227148	894		
Total	323	729190			
Experiment A. Question 2					
Sound condition	17	412389	24258	24.55	< 0.001
Treatment number	17	20099	1182	1.20	n.s.
Preceding sound condition	18	11793	655	0.66	n.s.
Subject	17	144352	8491	8.59	< 0.001
Residual	254	251026	988		
Total	323	839659			
Experiment A. Adjustment					
Sound condition	17	73033	4296	42.33	< 0.001
Treatment number	17	1868	110	1.08	n.s.
Preceding sound condition	18	3022	168	1.65	n.s.
Subject	17	27599	1624	16.00	< 0.001
Residual	254	25778	102		
Total	323	131300			
Experiment B. Question 1					
Sound condition	17	377871	22228	34.89	< 0.001
Treatment number	17	25701	1512	2.37	< 0.01
Preceding sound condition	18	12593	700	1.10	n.s.
Subject	17	114745	6750	10.60	< 0.001
Residual	254	161806	637		
Total	323	692716			
Experiment B. Question 2					
Sound condition	17	378464	22263	30.80	< 0.001
Treatment number	17	29936	1761	2.44	< 0.01
Preceding sound condition	18	15360	853	1.18	n.s.
Subject	17	230717	13572	18.78	< 0.001
Residual	254	183573	723		
Total	323	838050			
Experiment C. Question 2					
Sound condition	17	390392	22964	33.09	< 0.001
Treatment number	17	16370	963	1.39	n.s.
Preceding sound condition	18	28989	1610	2.32	< 0.01
Subject	17	111686	6570	9.47	< 0.001
Residual	254	176291	694		
Total	323	723728			

3.5 Significance of rating method

In the original article describing Experiment A it was seen that the points of equal annoyance derived from ratings in the two questions were almost identical. In this section it is analysed in more detail as to whether the three different rating methods (Question 1, Question 2 and level adjustment) express different characteristics of the annoyance associated with infrasound, or the results simply contain the same information.

As some of the results are obtained in the same experimental settings they are not independent, and the conditions for an analysis of variance are not fulfilled. Therefore, the connection between the three different ratings has been analyzed through direct comparisons.

Fig 5 shows rating in Question 1 versus rating in Question 2 for all exposures in Experiments A and B. Lower ratings were given in Question 1 than in Question 2 (15 mm on the average). The figure reveals a close and linear connection between the two ratings. The correlation coefficient r^2 is 0.98 and the regression line is included.

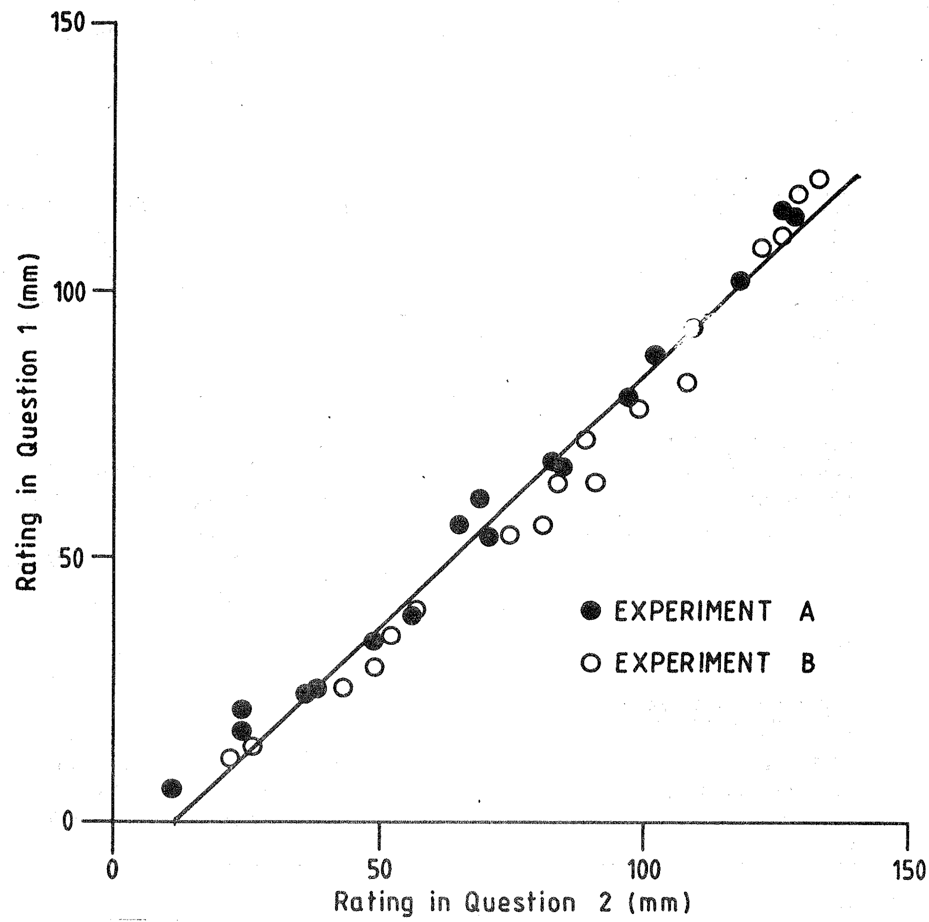

Figure 5 Comparison of rating methods. Rating in Question 1 is shown versus rating in Question 2. Means are indicated for all sound conditions in the two experiments. A regression line common to both experiments is also shown; correlation coefficient r^2 = 0.98.

The connection between adjusted 1 kHz level and rating in Question 2 is shown in Fig 6. Again a close and linear relationship is seen. The correlation coefficient r^2 is 0.95.

When correlation coefficients as high as these are obtained, it is reasonable to conclude that the three different recordings describe the same quantity, and that no further information is obtained by recording more than one variable.

On this basis it would be reasonable to use any of the recordings in Experiment A, B or C for the determination of equal annoyance curves. This has been done according to the procedure given in the original paper describing Experiment A. Those of the results not already reported, are shown in Table IV.

From Table IV it is also seen that the curves obtained are almost the same, independent of experiment and rating method.

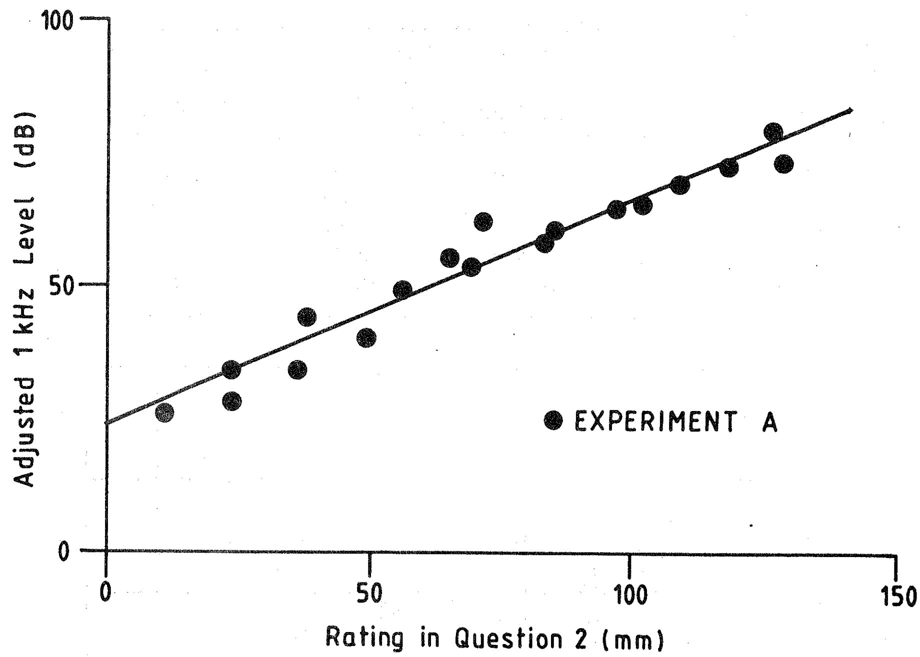

Figure 6 Comparison of rating methods. Adjusted 1 kHz level is shown versus rating in Question 2. Means are indicated for all exposures in Experiment A. A regression line is also shown; correlation coefficient $r^2 = 0.95$.

Table IV. Mean sound pressure levels in dB (and their standard deviations) for equal annoyance points calculated for various recordings.

Frequency (Hz)	Reference SPL (dB) 20	40	60	80
Experiment A. 1 kHz adjustment				
31.5	70.0 (2.5)	82.7 (1,6)	95.4 (1.5)	107.4 (2.4)
16	87.6 (2.6)	98.0 (1.6)	108.5 (1.2)	118.4 (2.0)
8	101.8 (2.7)	110.3 (1.5)	118.7 (1.1)	126.7 (2.0)
4	118.4 (1.2)	121.6 (0.6)	124.8 (1.0)	127.8 (1.8)
Experiment B. Question 1				
31.5	75.4 (2.2)	81.8 (2.1)	87.2 (2.8)	103.4 (3.0)
16	91.5 (2.1)	96.8 (1.9)	101.3 (2.4)	114.8 (2.3)
8	103.7 (2.6)	108.5 (2.1)	112.7 (2.3)	125.0 (2.5)
4	118.0 (1.4)	120.6 (1.0)	122.8 (1.2)	129.3 (2.5)
Experiment B. Question 2				
31.5	74.0 (2.7)	82.5 (2.9)	88.9 (3.0)	103.2 (3.0)
16	88.4 (3.2)	96.1 (2.9)	101.9 (2.8)	115.0 (2.6)
8	102.1 (2.7)	108.0 (2.4)	112.6 (2.2)	122.6 (1.9)
4	117.4 (1.8)	120.3 (1.3)	122.5 (1.2)	127.3 (2.1)
Experiment C. Question 2				
31.5	73.5 (2.6)	81.1 (2.5)	90.6 (2.7)	105.3 (2.9)
16	91.0 (2.3)	97.1 (2.2)	104.7 (2.1)	116.5 (2.2)
8	105.0 (1.9)	109.9 (1.8)	116.0 (1.7)	125.5 (1.8)
4	118.0 (1.4)	120.4 (1.0)	123.5 (1.1)	128.2 (2.0)

When referring to the curves of equal annoyance, it would be convenient if they could be denoted by terms that are already in use when describing annoyance or noisiness of audio frequency noise. Such terms could be perceived noisiness, PN dB or noy. It must be admitted that these units were introduced in connection with experiments where other rating methods were used. However, it is shown above that the rating method is rather insignificant, and this justifies the use of these units. In Table V and Fig 7 the means of all our results are shown, and the term PN dB is introduced.

Table V. Equal annoyance points calculated as means of all results from Experiments A, B and C.

Frequency	20 PN dB	40 PN dB	60 PN dB	80 PN dB
1000 Hz	20 dB	40 dB	60 dB	80 dB
31.5 Hz	72 dB	81 dB	90 dB	106 dB
16 Hz	90 dB	97 dB	104 dB	116 dB
8 Hz	103 dB	108 dB	114 dB	125 dB
4 Hz	118 dB	121 dB	123 dB	128 dB

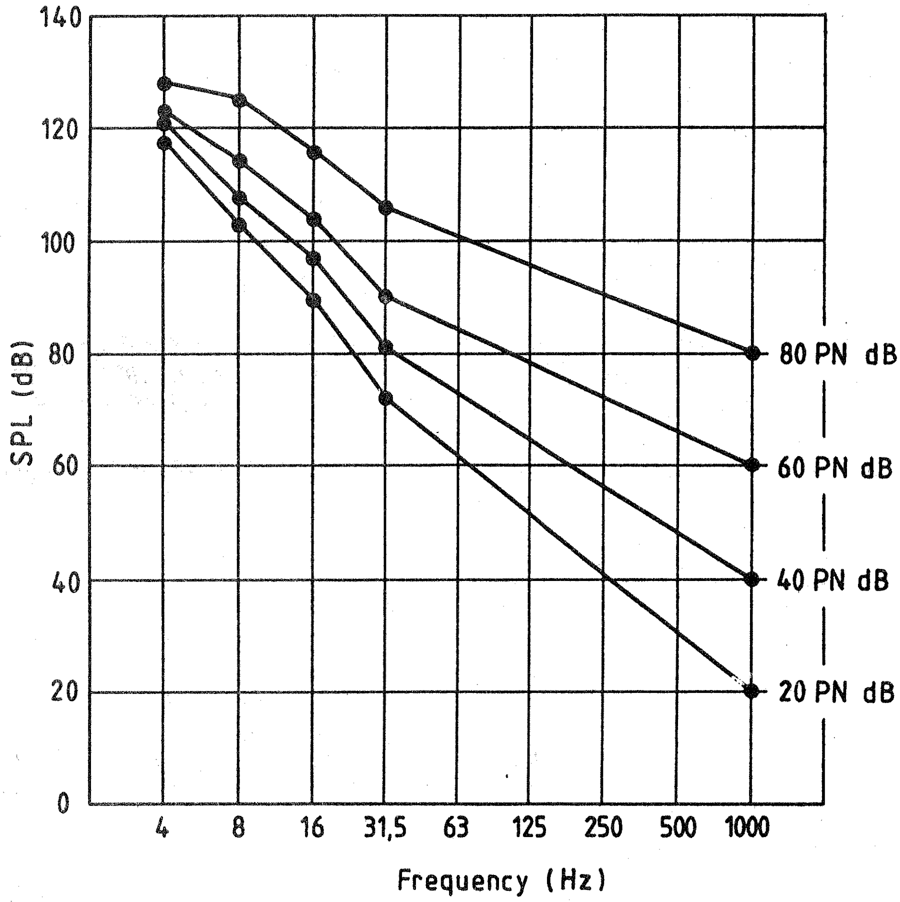

Figure 7 Curves of equal annoyance or equal noisiness based on all rating methods in Experiments A, B, and C.

4. EXPERIMENT D

In this experiment the annoyance of non-sinusoidal infrasonic and low audio frequency sound was rated.

4.1 Method

The sound conditions chosen were 1/3 octave noise bands at infrasonic and low audio frequencies. 16 sound conditions were used and consequently only 16 subjects participated. These were randomly chosen from the original 18 subjects in Experiments A, B and C.

The 1/3 octave noise bands were: 8 Hz: 100, 105, 110 and 115 dB; 16 Hz: 88, 97, 106, and 115 dB; 31.5 Hz: 70, 80, 90 and 100 dB. The references were as in previous experiments.

Based on results from Experiments A, B and C it was concluded that reliable results could be obtained even with short exposure times. It was also shown that the answers to Questions 1 and 2 as well as adjustment of a reference sound gave the same information, Therefore it was decided to use an exposure time of 3 minutes preceded by 1 minute of silence (as in Experiment B), and to record answers to Question 2 only (15 seconds after termination of the exposure).

4.2 Results

The ratings obtained in Experiment D are given in Table VI. In Fig 8 the results are shown graphically, together with results for pure tones obtained in Experiments A, B and C.

Table VI. Means and standard deviations for Experiment D, Question 2. (The means have been given a minor correction in order to refer the values to the original group of 18 subjects).

Frequency (Hz)	SPL (dB)	Mean (mm)	s.d. (mm)
1000	20	19	22
	40	35	27
	60	56	27
	80	125	26
31.5	70	14	22
	80	41	33
	90	80	35
	100	119	27
16	88	14	26
	97	42	26
	106	83	47
	115	127	30
8	100	10	11
	105	28	19
	110	55	39
	115	96	36

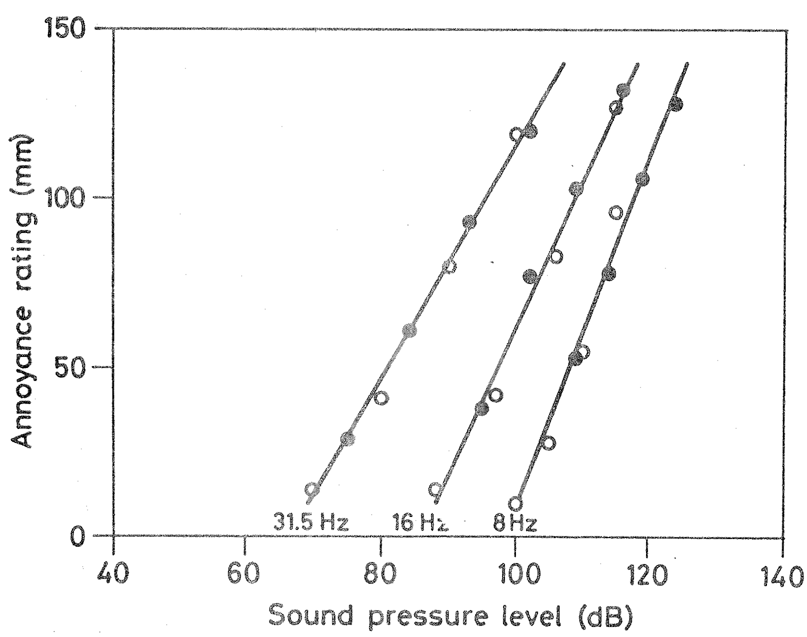

Figure 8 Annoyance ratings for 1/3 octave noise bands (unfilled circles) and pure tones (filled circles). Ratings for noise bands are from Table VI. Ratings for pure tones are pooled means from Experiments A, B, and C, Question 2 (corrected to an exposure time of 3 minutes). Common regression lines are shown, r^2 = 0.98 (8 Hz), 0.99 (16 Hz), 0.995 (31.5 Hz).

It is obvious that the ratings for 1/3 octave noise bands are in very close agreement with ratings for pure tones. This means that the annoyance from a pure infrasonic tone is the same as from a 1/3 octave noise band at the same frequency and at the same sound pressure level.

This agreement is in contrast to the situation at higher frequencies where normally several dB must be added to the A-weighted sound level of a pure tone in order to give a reasonable measure of annoyance.

5. EXPERIMENT E.

This experiment was designed to show what effect the presence of an audio frequency noise has on the annoyance from infrasound. The exposures were combinations of audio frequency and infrasonic noise.

5.1 Method

The audio frequency noise was a 1 kHz octave-filtered pink noise that could either be absent or appear at one of three levels: 30, 55 and 80 dB. The infrasonic noise was a pure tone at 16 Hz that could either be absent or appear at one of three levels: 95, 105 and 115 dB. All combinations were used, making a total of 16 different sound conditions.

The procedure was as in Experiment D and the same 16 subjects participated.

5.2 Results

The annoyance ratings obtained are given in Table VII, and are shown graphically in Fig 9.

Table VII. Means and standard deviations for Experiment E, Question 2. (The means have been given a minor correction in order to refer the values to the original group of 18 subjects).

	Level of 1kHz noise band							
	no 1 kHz		30dB		55dB		80dB	
Level of 16Hz	mean (mm)	s.d. (mm)	mean (mm)	s.d. (mm)	mean (mm)	s.d. (mm)	mean (mm)	s.d. (mm)
no 16Hz	2	7	18	20	48	26	126	19
95 dB	19	27	40	31	58	29	123	29
105 dB	70	34	68	28	84	28	123	30
115 dB	119	31	112	30	113	27	137	14

Each of the four curves in Fig 9 shows the results for a fixed value of the 16 Hz noise. It is seen that the addition of the 1 kHz noise changes the annoyance rating. All the significant changes appear as increases in annoyance as the level of the 1 kHz noise is increased. (There is a small decrease when 30 dB 1 kHz is added to 16 Hz at 105 or 115 dB. The decrease is far from being significant in a t-test. The t values were 0.21 and 0.64, respectively).

A closer look at the figure shows that the annoyance rating of a composite noise is equal to, or slightly greater than, the rating of the most annoying of the individual noises. It is greater only when the two noises are comparable in annoyance. This agrees well with existing experience for audio frequency noise.

The theory has been proposed that an unbalanced spectrum (a spectrum with an unusually high content of low frequency energy) should be especially annoying [5]. The spectrum of pure infrasound is extremely unbalanced, and if the theory were true, the addition of audio frequency noise would reduce the annoyance. This did not happen, and the theory is not supported by our results.

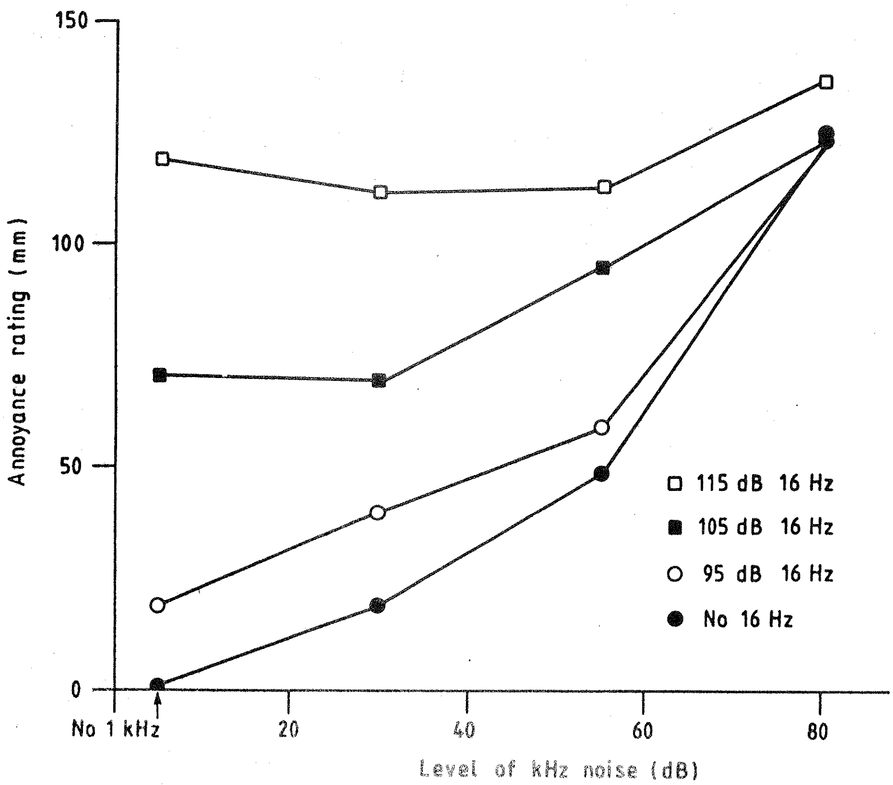

Figure 9 Annoyance ratings from exposures to combinations of audio and infrasonic noise in Experiment E (from Table VII). Mean ratings are shown versus 1 kHz level for the different levels of the 16 Hz tone.

6. THE USE OF WEIGHTING CURVES

In noise measurements weighting curves are commonly used to compensate for the frequency dependent characteristics of the human hearing.

A precondition for the use of a weighting curve is that there is a fair agreement between the weighted level and the subjective parameter which the measurement is supposed to estimate (such as loudness or annoyance).

In the above mentioned Experiments A to D, a large number of annoyance ratings were recorded from infrasound (4, 8 and 16 Hz), low audio frequency sound (31.5 Hz) and midrange audio frequency sound (1 kHz). The availability of these recordings gives an excellent opportunity to test different curves as predictors of annoyance.

In the following sections some selected curves are examined as predictors of annoyance. For infrasonic exposures the recently proposed G-curves are considered. This is discussed in Section 6.1. Section 6.2 deals with the frequencies 31.5 Hz and 1 kHz which are within the audio range, where normally the A-curve is used.

It is concluded that for infrasonic frequencies there is a fair agreement between annoyance and G1-weighted levels, and for midrange audio frequencies a connection exists between annoyance and A-weighted levels. However, the range of numerical values obtained in A-weighted and G1-weighted measurements differ considerably for the same annoyance, and care must be taken when comparing G1-weighted results with previous experience with A-weighted levels. This matter is discussed in Section 6.3.

6.1 G-weighting

Two weighting curves have recently been proposed for measurement of infrasonic noise [6]. The curves are shown in Fig 10. Both of them cover the frequency range 1-20 Hz, and each has a gain of 0 dB at 10 Hz. The only difference is that they have different slopes, namely 12 dB per octave for the G1-curve and 6 dB per octave for the G2-curve.

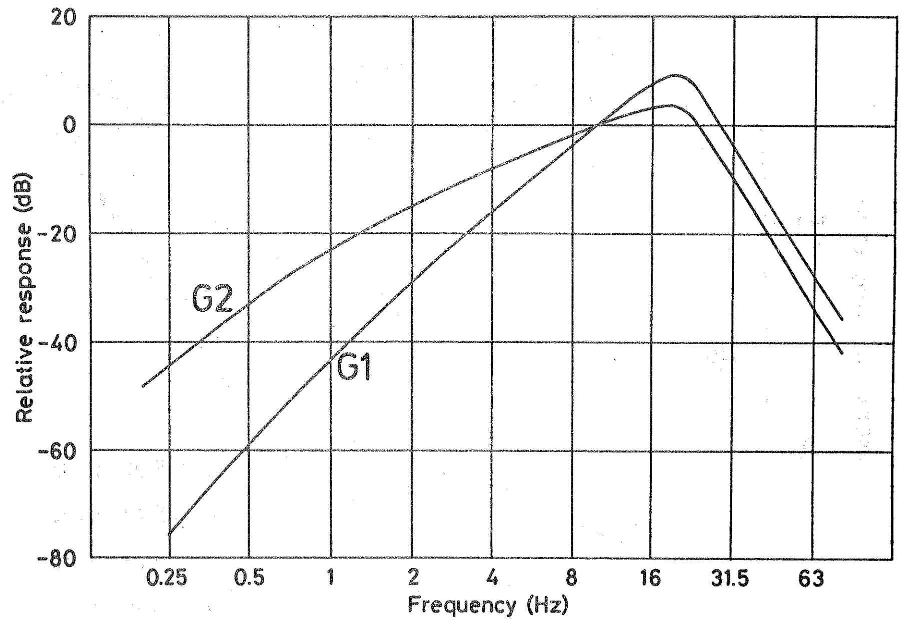

Figure 10 The proposed G-weighting curves [6]. The G1-curve has a slope of 12 dB per octave in the "pass-band" 1-20 Hz, while the G2 curve has a slope of 6 dB per octave in the same frequency range. They both intersect 0 dB at 10 Hz.

The curves in Fig 7 have a mean slope of 11.7 dB per octave in the frequency range 4 - 31.5 Hz. The equal loudness curves that were previously determined [3], have a mean slope of 12.3 dB per octave in the range 2 - 31.5 Hz. These findings suggest that measurements with the G1-curve that has a slope of 12 dB per octave would give a fair indication of the annoyance and loudness associated with infrasound.

In Fig 11 mean annoyance rating is plotted against G1-weighted infrasound level for all infrasonic exposures in Experiments A, B, C and D. The figure shows a close linear relationship. The coefficient of correlation $r^2 = 0.93$.

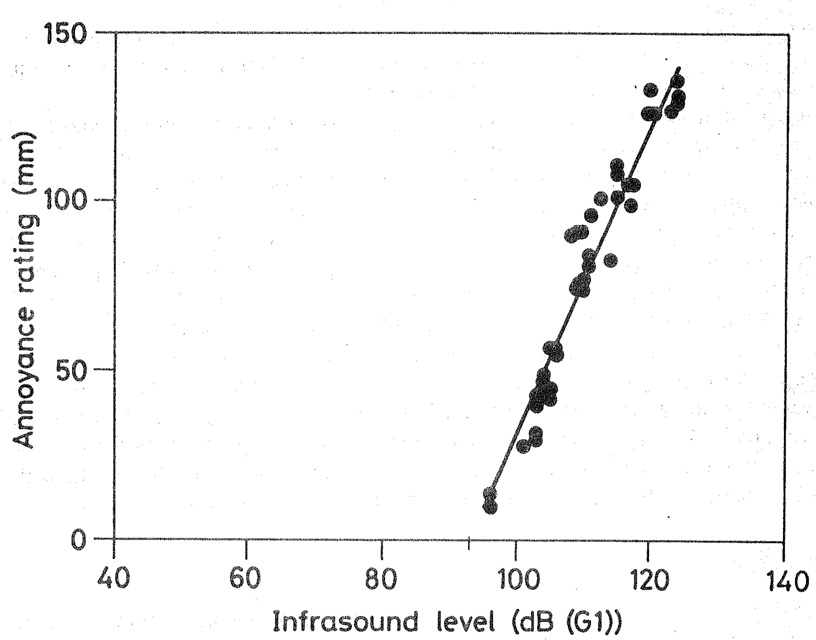

Figure 11 Annoyance rating versus G1-weighted infrasound level. The points represent mean values from exposures to 16 Hz and below. All recordings of answers to Question 2 from Experiments A, B, C and D are included (adjustments have been made in order to refer to an exposure time of 3 minutes, and for Experiment D to refer to the original group). The line is a regression line, $r^2 = 0.93$.

Fig 12 shows the same results against the G2-weighted infrasound level. Here r^2 = 0.77 and it is obvious that the G2-curve gives a measure of annoyance that is much inferior to that of the G1-curve.

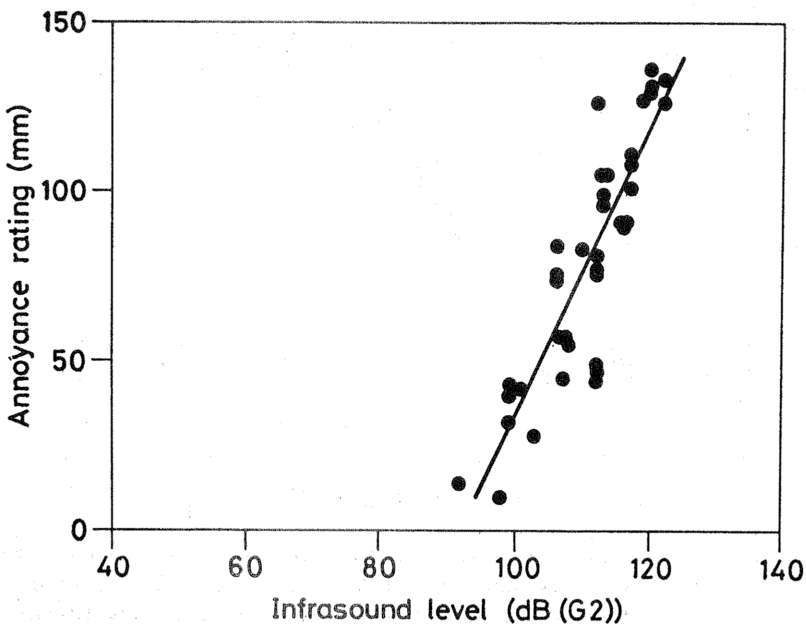

Figure 12 Annoyance rating versus G2-weighted infrasound level. The points represent mean values from exposures to 16 Hz and below. All recordings of answers to Question 2 from Experiments A, B, C and D are included (adjustments have been made in order to refer to an exposure time of 3 minutes and for Experiment D to refer to the original group). The line is a regression line, r^2 = 0.77.

6.2 A-weighting

Two frequencies in the audio range were involved: 31.5 Hz and 1 kHz. In this frequency range normally the A-curve is used. However, it has often been claimed that A-weighted sound levels do not correlate well with annoyance, if the noise contains large amounts of low frequency energy. In order to examine this assertion the two frequencies are looked upon separately.

Fig 13 shows the relation between A-weighted sound level and annoyance rating. For 1 kHz it is obvious that the connection between the two variables is good, and A-weighted levels give a fair indication of the annoyance associated with the 1 kHz noise. A regression line is also included in the figure (r^2 = 0.97).

In Fig 13 it is clearly seen that the annoyance from 31.5 Hz does not follow the same line as the annoyance from 1 kHz. The annoyance from 31.5 Hz rises much more steeply than that from 1 kHz. A regression line is also given for 31.5 (r^2 = 0.99), and the two regression lines intersect at approximately 45 dB. This result might have been predicted from Fig 7 where the narrowing of the curves for decreasing frequencies is present already at 31.5 Hz.

The origin of the A-curve also explains this. The A-curve is approximately the inverse of the 40 phon curve. Assuming a close relationship between loudness and annoyance, then A-weighted levels will reflect the annoyance of sounds with levels around 40 phon. For low frequencies at levels well below 40 phon the annoyance is expected to be lower than predicted by the A-weighted level. At levels much above 40 phon the annoyance is expected to be higher than that predicted by the A-weighted level. This is exactly what can be seen in Fig 13.

Originally the intention was that the A-curve should be used only at levels around 40 phon, while the B - abd C -curves should be used at higher levels. This procedure is almost never used in real life, and this is most probably the reason why it has been so difficult to obtain a good correlation between objective measures and subjective ratings for noise containing considerable low frequency energy.

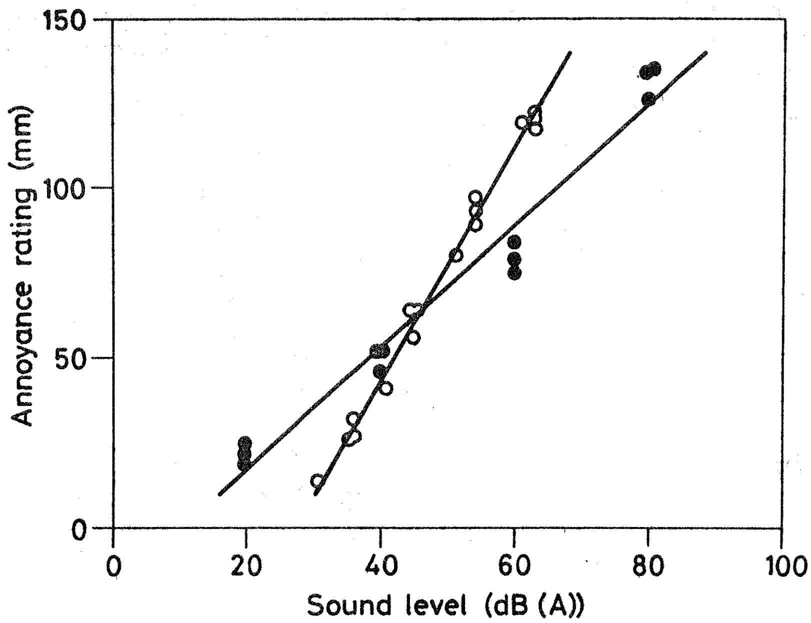

Figure 13 Annoyance rating versus A-weighted sound level. Mean values are given for 1 kHz octave noise bands (filled circles) and for 31.5 Hz pure tones and 1/3 octave noise bands (unfilled circles). All recordings of answers to Question 2 from Experiments A, B, C and D are included (adjustments have been made in order to refer to an exposure time of 3 minutes, and for Experiment D to refer to the original group). $r^2 = 0.97$ for the 1 kHz regression line, 0.99 for the 31.5 Hz.

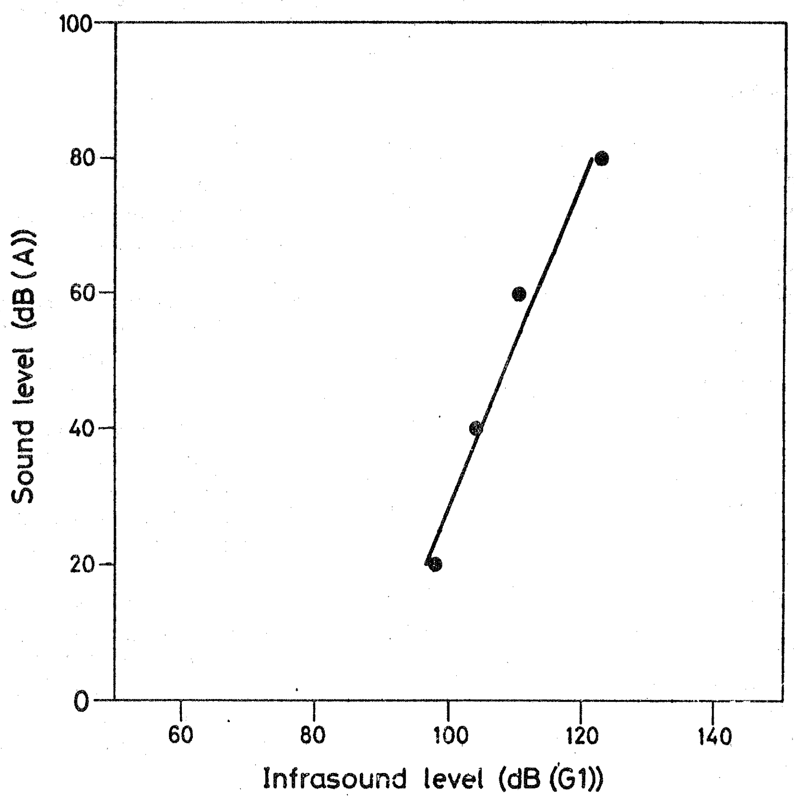

Figure 14 Conversion of G-weighted infrasound level to the A-weighted level that causes the same rating of annoyance. The figure is obtained from the regression line in Figure 11 and 1 kHz ratings in Figure 13. $r^2 =$ 0.97.

6.3 Relation between G1- and A-numericals

Fig 11 showed a good correlation between G1-weighted infrasound levels and annoyance rating. So, if a "one-figure" measurement is required for infrasound, the G1-curve will be a good choice. However, this curve provides only a frequency weighting and G1-weighted levels do not reflect the fact that the annoyance increases steeply above threshold. Thus the conversion shown in Fig 14 may be useful. For a given G1-weighted infrasound level it provides the A-weighted level which causes the same rating of annoyance.

7. CONCLUSION

Contours of equal annoyance were determined for pure tones in the frequency range 4 - 31.5 Hz. The curves show a narrowing of the dynamic range of the ear at low frequencies. The same pattern is seen for the equal loudness curves, and the results support the theory that the annoyance of infrasound is related to the loudness sensation.

The rating methods and experimental design were given a close examination, which proved the reliability of the results.

The equal annoyance curves were shown to be independent of rating method and exposure time. This justifies the use of units like perceived noisiness, PN dB, and noy, even when these terms were introduced in connection with other rating methods.

Annoyance ratings of 1/3 octave band noise did not deviate from ratings of pure tones with the same sound pressure level.

Combinations of audio and infrasonic noise were in general given a rating close to, or slightly above, the rating of the most annoying of the individual noise conditions.

The proposed ISO G1-weighting curve provides an objective measure that correlates well with subjective annoyance ratings for infrasonic frequencies. Values obtained with the proposed G2-curve do not correlate nearly as well.

Because of the low dynamic range of the ear at infrasonic frequencies, care should be taken when evaluating G1-weighed levels. The numerical values should not be directly compared to A-weighted levels.

Low audio frequencies – in this investigation represented by 31.5 Hz – are not covered by the proposed G-weighted curves, and they are insufficiently covered by the A-curve. A possible solution might be the originally intended level dependent use of the A-, B- and C-curves. Further research is needed in this area.

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