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ANNOYANCE FROM AUDIBLE INFRASOUND

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INTRODUCTION

For nearly 20 years researchers and environmental authorities have been worried about possible extra-auditory effects of infrasound, such as disturbance of equilibrium and influence on the circulatory system. Experimental findings are not very concordant, but in general the effects seem to have been exaggerated (1).

However, lack of direct physiological effects from infrasound does not mean that infrasound is insignificant from an environmental point of view. Infrasound can be detected by the human ear, and when it becomes sufficiently loud, it can be annoying. Some investigations indicate that a possible "threshold of annoyance" would be only slightly above the hearing threshold.

The hearing threshold at infrasonic frequencies has been determined in several experiments and also the growth of loudness above threshold has been investigated (2, 3). Whether knowledge about the loudness of infrasound can be used in assessment of annoyance from infrasound is however uncertain and the present study was carried out.

Four experiments were included in the study. Experiment I covered annoyance from pure tones. Curves of equal annoyance were determined in the frequency range 4-31.5 Hz. Reference was made to an octave noise band at 1000 Hz. In Experiment II the significance of the exposure time was investigated. Experiment III was a study of the annoyance from non-sinusoidal infrasonic noise, while Experiment IV covered annoyance from combinations of audio and infrasonic noise.

Experiment I is described in detail in an article in the Journal of Low Frequency Noise and Vibration (4). Experiment II-IV have previously been presented at Internoise 84 (5).

This presentation is an extended version of the Internoise paper. It will cover all four experiments, though the most detailed description will be given for Experiment I, while for the other experiments only changes in method will be mentioned.

EXPERIMENT I

Subjects. 18 university students aged between 20 and 25 participated as subjects. An audiometric test ensured normal hearing.

Sound conditions. Pure tones at the following frequencies and levels were used: 4 Hz: 120 and 124 dB; 8 Hz: 109, 114, 119 and 124 dB; 16 Hz: 95, 102, 109 and 116 dB; 31.5 Hz: 75, 84, 93 and 102 dB. A 1000 Hz octave filtered pink noise presented at four levels (20, 40, 60 and 80 dB) served as reference. This made a

total of 18 different sound conditions.

Apparatus. The experiments were performed in a 16 cubic metre pressure chamber (6). The infrasound was emitted via 16 electrodynamic loudspeakers driven by a B & K 2712 power amplifier. The 1000 Hz noise was emitted via an equalized Hi-Fi sound reproduction system with the loudspeaker placed 140 cm from the subject. A computer controlled the experimental session.

Experimental design. 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 that balanced out both order and carry-over effects. Each subject was exposed to only one stimulus a day 18 days and at the same hour every day.

Procedure. A session lasted 20 minutes during which the subjects were reading newspapers. After an initial 5 minutes period of silence the sound was presented for 15 minutes. Following this the subject was asked to indicate on a graphic scale the degree of annoyance that he would probably feel at home if his neighbour produced the same sound for two hours. 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 Figure 1.

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

Results. Degree of annoyance was measured in mm from the "not at all annoying" end, and the means for each sound condition are shown in Figure 2. The relationship between sound pressure level and annoyance rating is linear for the infrasonic frequencies, and regression lines are included in the figure.

In Figure 2 points of equal annoyance are represented by horizontal lines. From each of the four 1000 Hz 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 Figure 3.

Discussion. The equal annoyance curves demonstrate that the lower the frequency the greater the sound pressure must be to cause a given amount of annoyance. Compared with 1000 Hz 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 is seen for the equal loudness curves (2), and the present results support the therory 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 will in some cases be enough to alleviate annoyance caused by infrasonic noise.

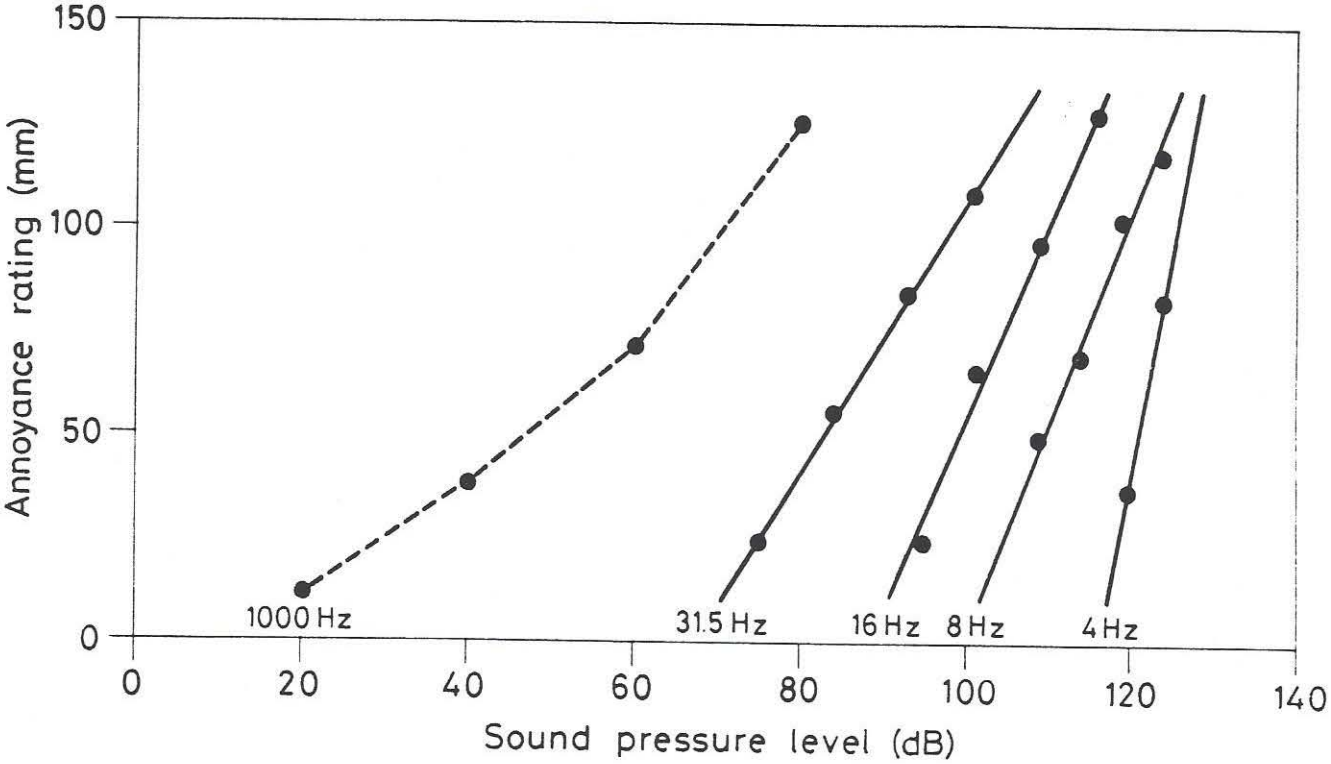

Figure 2. Annoyance ratings for pure infrasonic tones obtained in Experiment I. Filled circles represent means of 18 subjects, full lines are regression lines.

EXPERIMENT II

This experiment was carried out to show the effect of exposure time on the annoyance ratings. Subjects, sound conditions, apparatus and experimental design were the same as in experiment I.

The procedure was changed only with respect to exposure times. The entire experiment was repeated for each of the following exposure times:

a) 15 minutes preceded by 5 minutes of silence
b) 3 minutes preceded by 1 minute of silence
c) 30 seconds preceded by 10 seconds of silence.

Results in a) were obtained from Experiment I. In b) the sound condition were given on one day and immediately following each other. The same procedure was used in c), except that no newspapers were available because of the short exposure time.

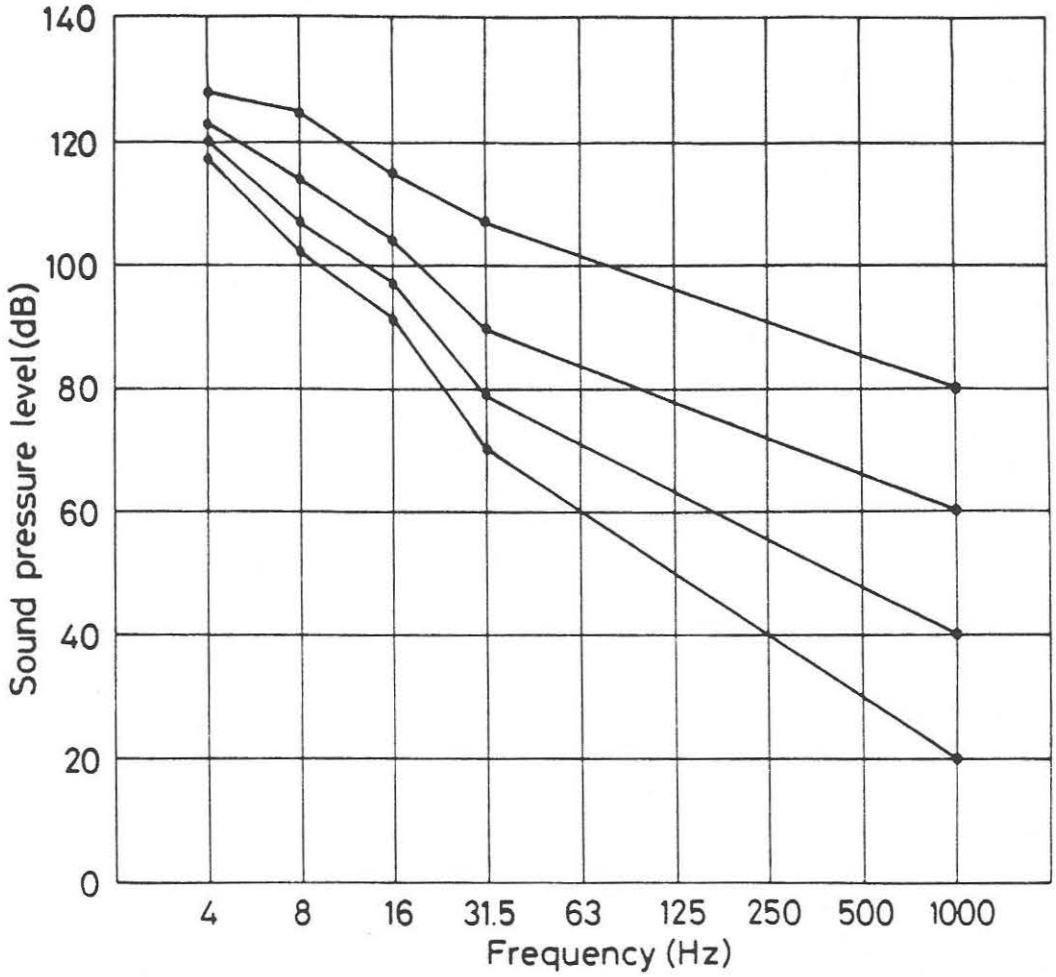

Figure 3. Equal annoyance curves for pure infrasonic tones based on results from Experiment I.

Results. A significant effect of exposure time was seen (0.1% level in an analysis of variance). Mean values for all sound conditions are shown in Figure 4. It is obvious that the exposure time should be specified for results obtained with the present procedure and rating scale..

There was no significant interaction between sound condition and duration.

Discussion. The absence of interaction between sound condition and duration means that although a variation with exposure time is present, this variation is the same for all sounds. Consequently, the procedure and rating scale are useful for comparative measurements, and the results will be independent of exposure time. Therefore, the use of shorter and resource saving experiments can be justified.

For the two remaining experiments an exposure time of 3

minutes preceded by 1 minute of silence was chosen.

When results from a) and c) are reported in the following, a correction is made to refer these results to an exposure time of 3 minutes.

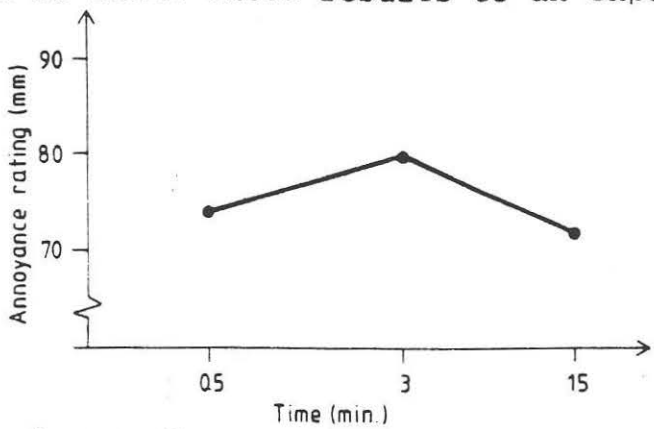

Figure 4. Dependence of annoyance rating on exposure time. The filled circles represent means of all sound conditions

EXPERIMENT III

In this experiment the annoyance of one-third-octave noise at infrasonic frequencies was rated. 16 sound conditions were used and consequently only 16 subjects participated. The infrasound exposures were: 8 Hz: 100, 105, 110, 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.

The 16 subjects were randomly chosen from the original 18 subjects. In the reported results a minor correction is made in order to refer the means to the original group.

The procedure was as in Experiment II b).

Results. The ratings for one-third-octave noise bands are shown as unfilled circles in Figure 5. The ratings are in very close agreement with ratings for pure tones obtained in Experiment I and II (filled circles).

Discussion. The close agreement means that the annoyance from a pure infrasonic tone is the same as from a one-third-octave band at the same frequency and at the same sound pressure level. This is in contrast to what is valid 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.

EXPERIMENT IV

This experiment was designed to show what effect the presence of audio frequency noise has on the annoyance from infrasound. The exposures were combinations of audio frequency and infrasonic noise. The audio frequency noise was a 1000 Hz octave-filtered pink noise that could either be absent or appear at the 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 the 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 II b) and the subjects as in Experiment III.

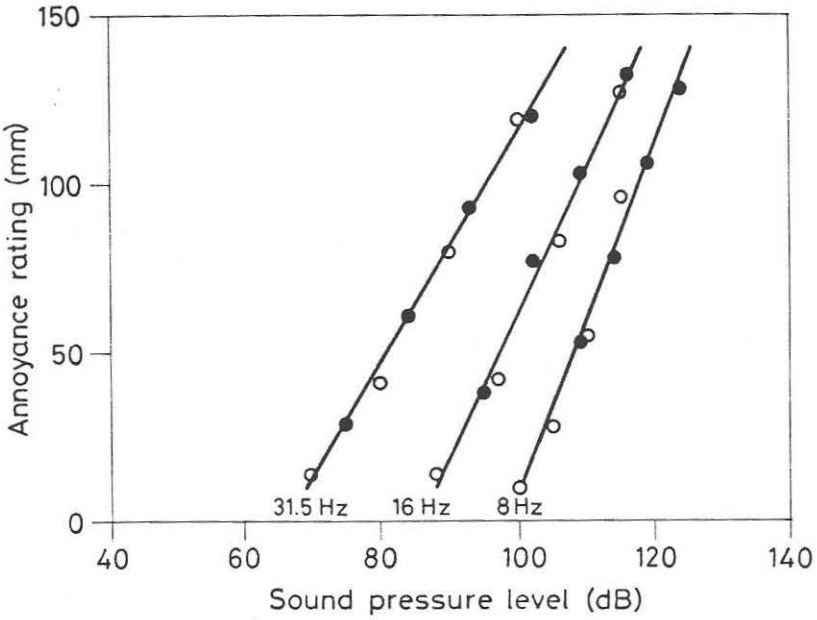

Figure 5. Annoyance ratings for one-third-octave noise bands (unfilled circles) and pure tones (filled circles). Ratings for pure tones are pooled means from Experiment II a)-c). Common regression lines are shown, r^2=0.98 (8Hz), 99 (16 Hz), 0.995 (31.5 Hz).

Results. The annoyance ratings obtained are shown in Figure 6. Each of the four diagrams shows the results for a fixed value of the 16 Hz noise. It is seen that the addition of the 1000 Hz noise changes the annoyance rating. All the significant changes appear as increases in annoyance. An increase is seen for all levels of the 16 Hz tone, although the needed level of 1000 Hz noise is different at different levels.

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

The theory has been proposed that an unbalanced spectrum (a spectrum with unusually high low frequency content) should be especially annoying (7). 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 does not happen, and the theory is not supported by our results.

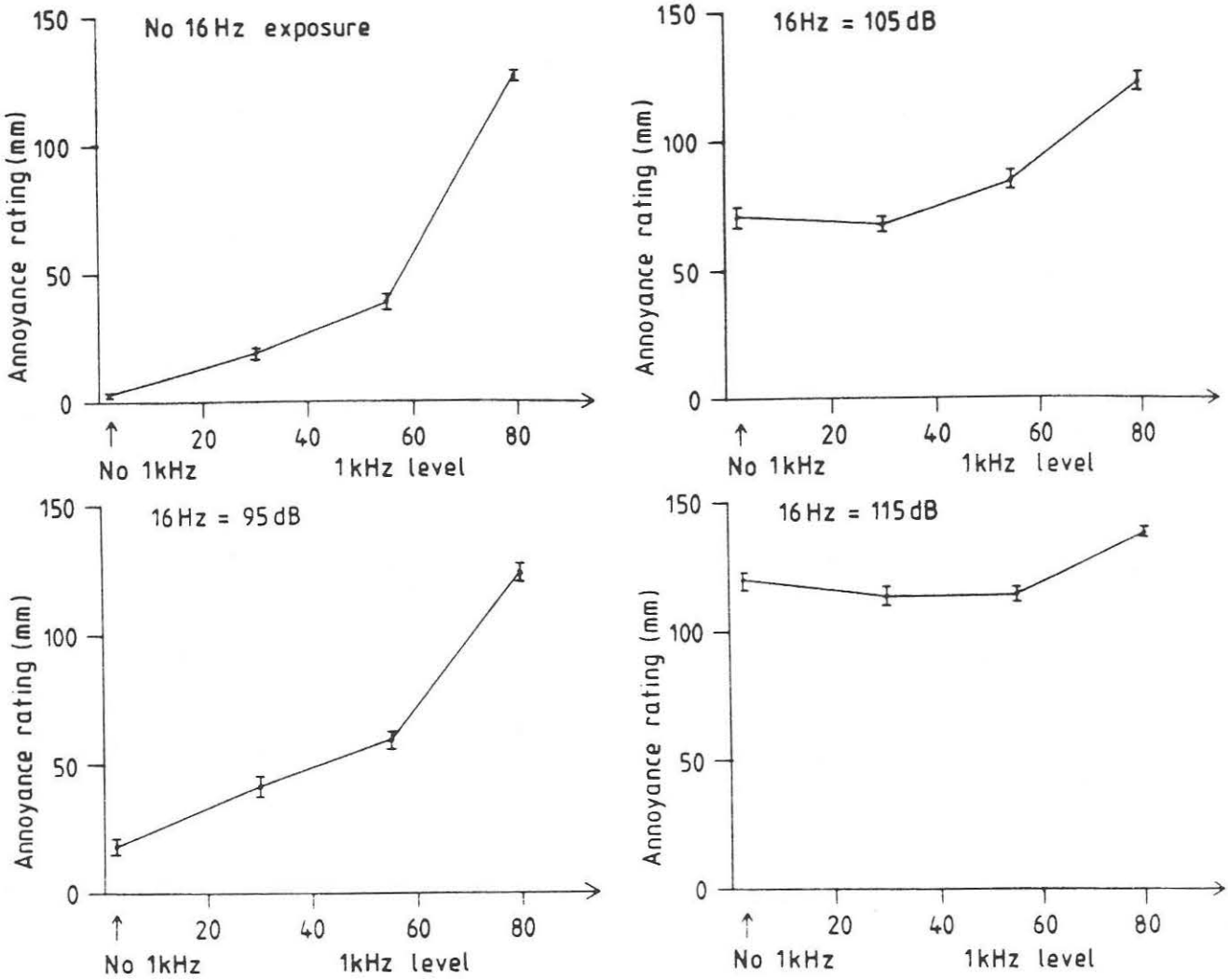

Figure 6. Annoyance ratings for combinations of audio and infrasonic noise obtained in Experiment IV. The four diagrams show results for different levels of the 16 Hz tone. The points indicate means ± one standard error of mean.

USE OF WEIGHTING CURVES

G-Weighting. Two weighting curves have recently been suggested for measurements of infrasonic noise (8). Both of them cover the frequency range 1-20 Hz and they have a gain of 0 dB at 10 Hz. The only difference is that they have different slopes, namely 12 dB per octave (G1-curve) and 6 dB per octave (G2-curve).

The curves in Figure 3 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) had 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 Figure 7 mean annoyance rating is shown versus G1-weighted infrasound level for all infrasonic exposures in Experiment I through III (filled circles). The figure shows a very close linear relationship (coefficient of correlation $r^2=0.93$).

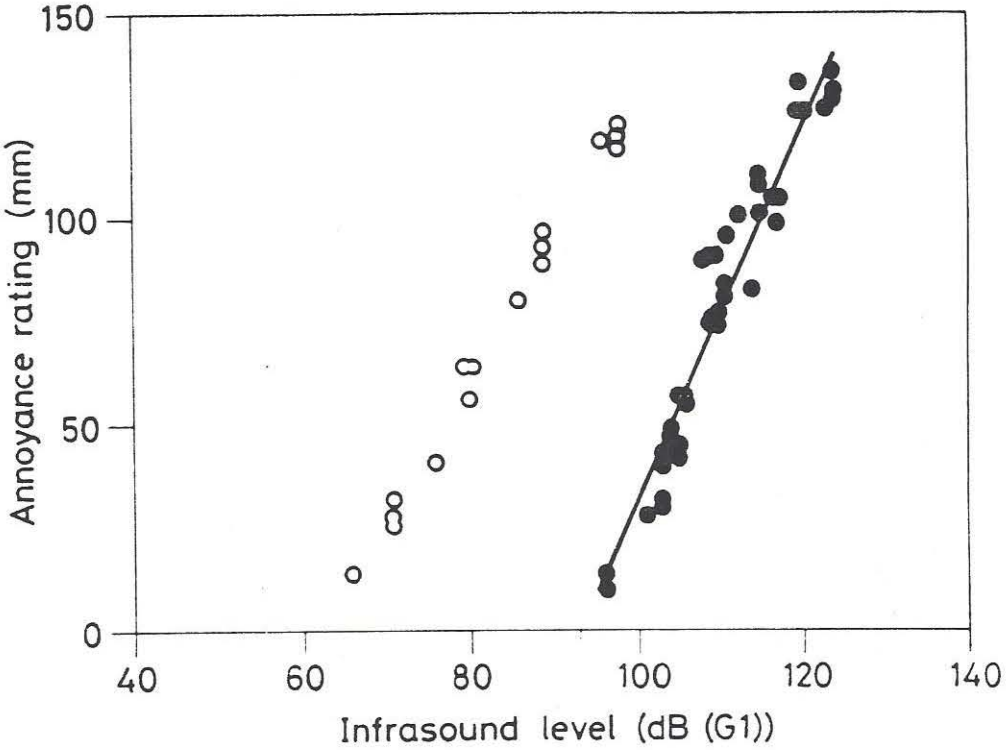

Figure 7. Annoyance rating versus G1-weighted infrasound level. Filled circles represent mean values for frequencies at 16 Hz and below. Unfilled circles represent mean values at 31.5 Hz. Values were obtained from Experiment I-III. $r^2=0.93$ for the filled circles.

Figure 8 shows the same results versus the G2-weighted infrasound level. Here $r^2=0.77$ and it is clearly illustrated that the G2-curve provides a measure of the annoyance that is much inferior to that of the G1-curve.

A-weighting. For the 1000 Hz octave-filtered pink noise that served as reference, Figure 9 shows the relation between A-weighted sound level and annoyance rating (filled circles). The coefficient of correlation $r^2=0.97$.

Low audio frequencies. In the Figures 7-9 values for 31.5 Hz are shown as unfilled circles. From Figure 7 and 8 it is obvious that the G-curves do not provide values that can be used for assessment of annoyance from 31.5 Hz. This agrees well with the

intention behind the G-curves. These curves were given a sharp cut-off above 20 Hz so that possible restrictions on G-weighted levels should not interfere with restrictions in the audio range.

31.5 Hz is within the audio range and is thus supposed to be covered by the A-curve. However, Figure 9 clearly shows that the annoyance from 31.5 Hz (unfilled circles) does not follow the same line as the annoyance from 1000 Hz. The annoyance from 31.5 Hz rises much steeper than that from 1000 Hz. The two regression lines intersect at approximately 45 dB. This result might have been predicted from Figure 3 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 reciprocal 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 that 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 Figure 9.

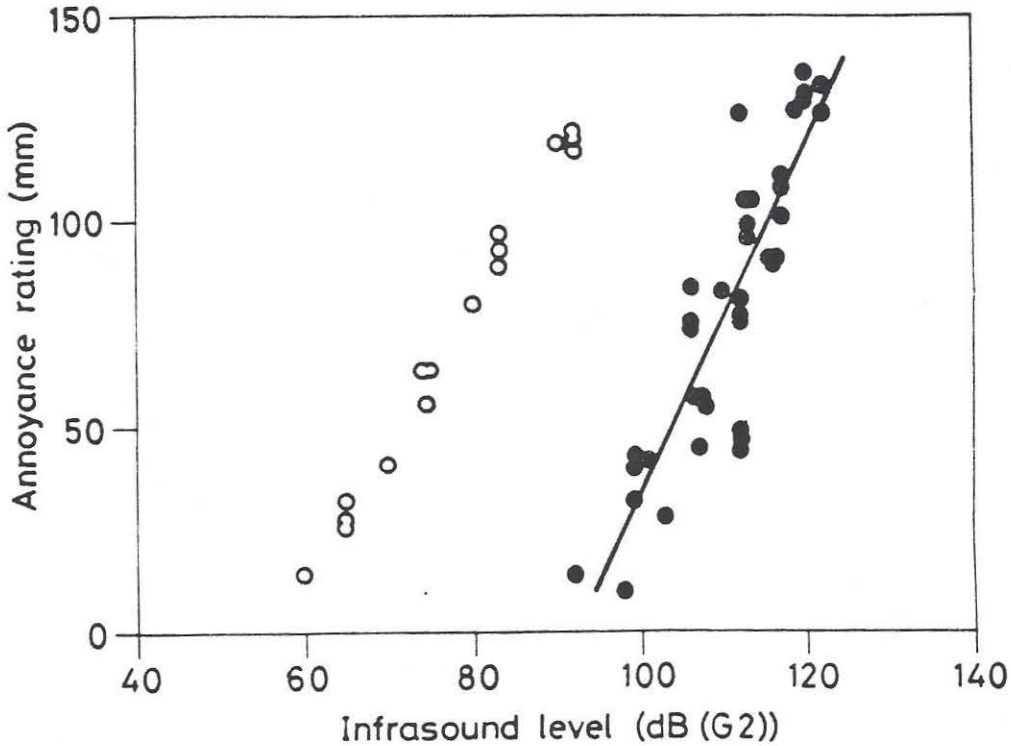

Figure 8. Annoyance rating versus G2-weighted infrasound level. Filled circles represent mean values for frequencies at 16 Hz and below. Unfilled circles represent mean values at 31.5 Hz. Values were obtained from Experiment I-III. $r^2=0.77$ for the filled circles.

A-, B- and C-weighting. Originally the intention was that the A-curve should be used only at levels around 40 phon, while the B- and 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 noises containing considerable low frequency energy.

Relation between G1- and A-numericals. Figure 7 showed a good correlation between G1-weighted infrasound levels and annoyance rating. Thus if a "one-figure" measurement is wanted for infrasound, the G1 curve might be a good choice. However, this curve provides only a frequency weighting and G1-weighted infrasound levels do not reflect the fact that the annoyance increases steeply above the threshold. Thus the conversion shown in Figure 10 may be useful. For a given G1-weighted infrasound level it can be read which A-weighted level causes the same rating of annoyance.

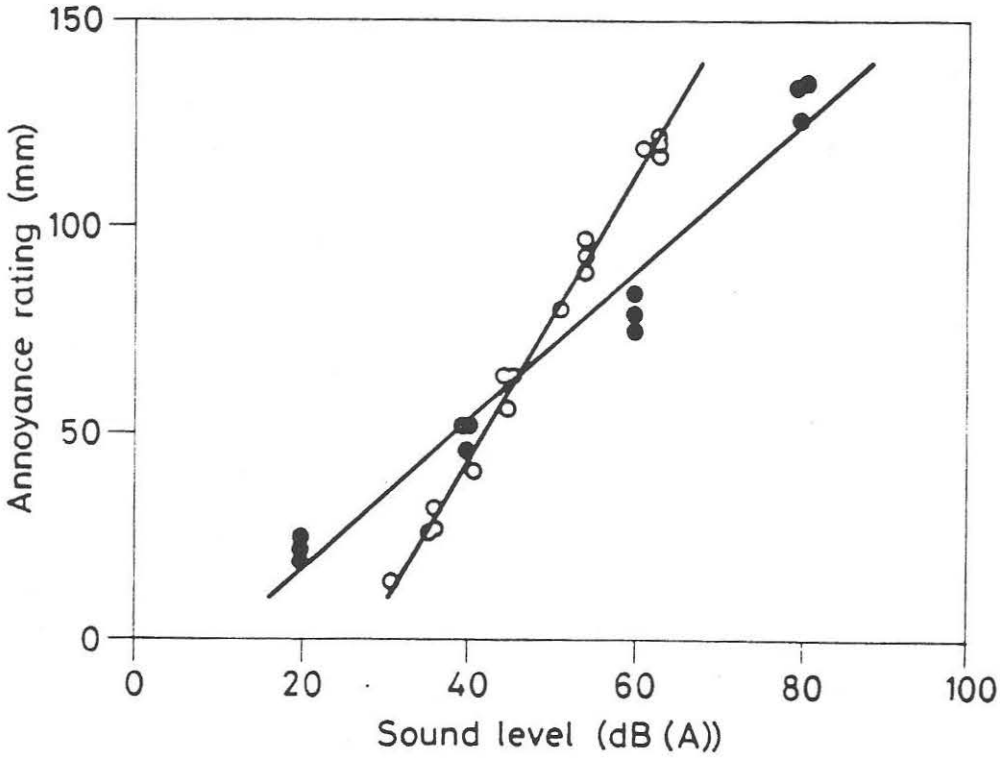

Figure 9. Annoyance rating versus A-weighted sound level. Filled circles represent mean values for 1000 Hz noise bands. Unfilled circles represent mean values at 31.5 Hz. Values were obtained from Experiment I-III. r^2=0.97 for the filled circles, 0.99 for the unfilled.

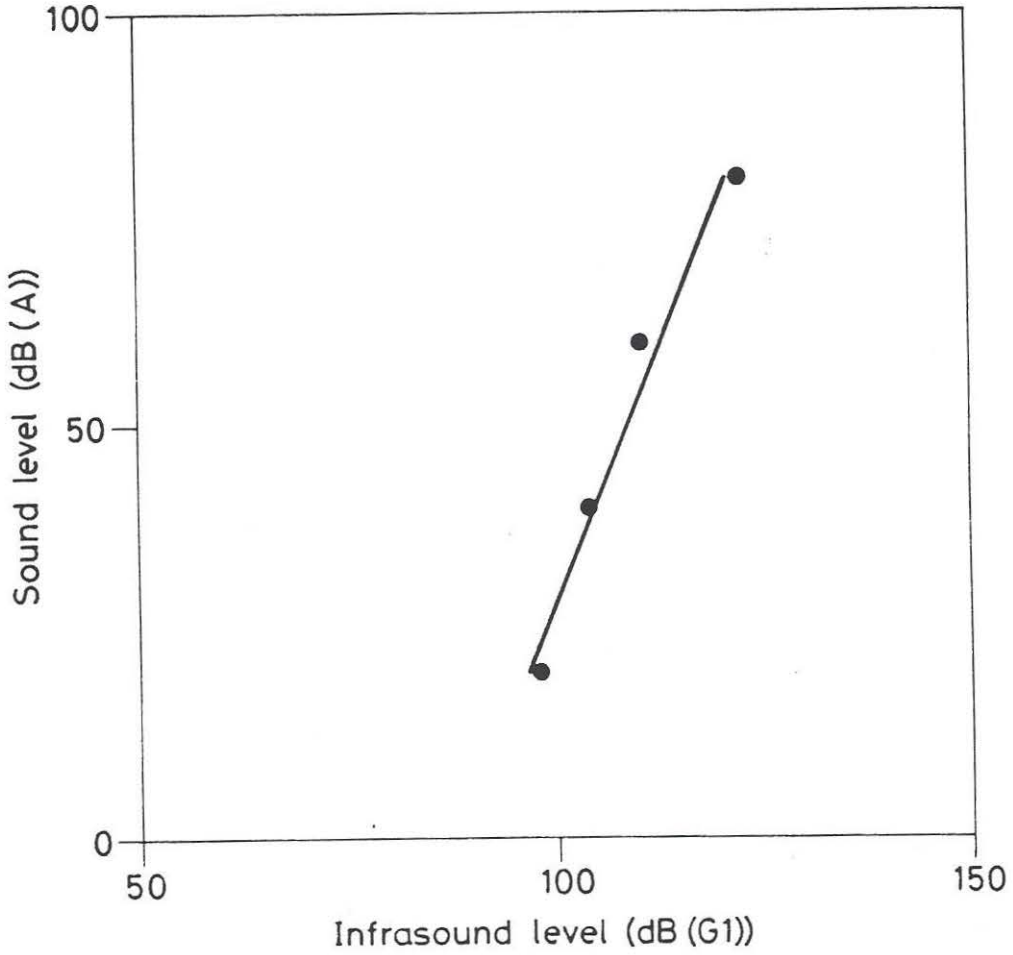

Figure 10. Conversion of G1-weighted infrasound level to the A-weighted level of an audio frequency noise that causes the same rating of annoyance. The figure is obtained from the regression line in Figure 7 and 1000 Hz ratings in Figure 2. $r^2=0.97$.

SUMMARY

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.

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.

The proposed ISO G1-weighting curve provides an objective measure that correlates very well with subjective annoyance ratings

for infrasonic frequencies. Values obtained with the proposed G2-weighting 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-weighted levels. The numerical values should not be directly compared to A-weighted levels.

Low audio frequencies - in this investigation represented by pure tones and noise bands at 31.5 Hz - are not covered by the proposed G-weighting 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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