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Loudness of Pure Tones at Low and Infrasonic Frequencies.

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ABSTRACT

Contours of equal loudness were determined in the frequency range 2-63 Hz and the loudness range 20-100 phon. The loudness curves run almost parallel in the infrasonic frequency range and much closer than in the audio region. Infrasound only a few dB above the hearing threshold will therefore seem loud and possibly annoying. The subjects were 20 normal hearing students aged between 18 and 25, and the psychometric method was based on maximum-likelihood estimation of psychometric functions.

1. 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 consistent, but in general the effects seem to have been exaggerated (Ref. 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 (Refs. 2,3).

A number of experiments deal with the hearing threshold at infrasonic frequencies (Refs. 2,4,5,6,7), but the loudness function has previously been the subject of only one investigation (Ref. 5).

In the present study equal loudness curves were determined for pure tones in the frequency range 2-63 Hz and the loudness range 20-100 phon. Preliminary results from a pilot study were presented at Internoise 81 (Ref. 8), and a report of the main experiment was given at Internoise 83 (Ref. 9).

2. METHOD

2.1 Subjects

20 students (16 male and 4 female) aged between 18 and 25 participated as subjects. Audiometric tests ensured normal hearing within ±15 dB at the octave frequencies 125 Hz to 4 kHz and ±20 dB at 8 kHz.

2.2 Stimuli

The references for loudness curves are pure tones at 1 kHz. However, it is very difficult to compare tones that are spaced as far apart in frequency as infrasound and 1 kHz, and in this investigation a supporting point was introduced at 63 Hz. Thus, individual points of equal loudness measured at 63 Hz were used as references for comparisons with 2, 4, 8, 16 and 31.5 Hz. Points of equal loudness were determined at 5 loudness levels: 20, 40, 60, 80 and 100 phon.

2.3 Psychometric method

A point on an equal loudness contour is determined through comparisons between a reference tone with a fixed sound pressure and another tone, of which the sound pressure can be varied. The task is to find the level of the variable, which makes the two tones seem equally loud to a listener. Unfortunately there is usually a range of several dB, where sometimes the variable, and sometimes the reference tone appears to be loudest. Therefore some statistical procedure must be incorporated in the experiment. A modified version of the adaptive procedures based on maximum-likelihood estimation of psychometric functions as given by Hall (Ref. 10) and Lyregaard and Pedersen (Ref. 11) was chosen.

Figure 1 shows the psychometric function. This function gives the relation between the variable level and the probability of the subject perceiving the variable as louder than the reference. The psychometric function is assumed to be a cumulative normal distribution with mean μ and standard deviation σ. μ represents the point of equal loudness, while information about the size of the area of uncertainty can be obtained from σ.

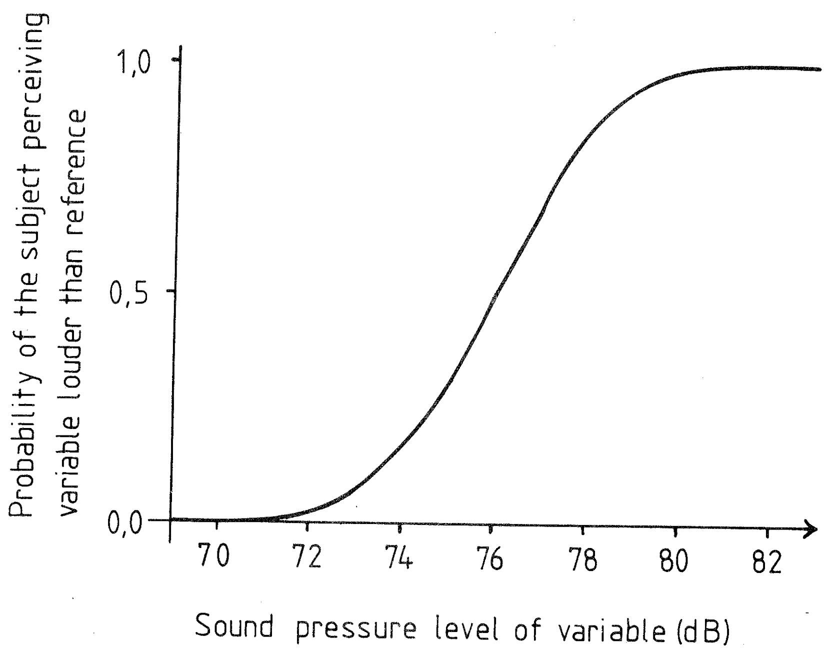

Figure 1 Psychometric function for a given subject, for fixed values of reference frequency, reference level and frequency of the comparison signal

A point on an equal loudness curve was determined in the following way: Successive pairs of reference and variable tones were presented to the subject. The tones each had a duration of 2 seconds and were separated by an interval of 1 second. The order in which they appeared was random. After each pair of tones the subject indicated which one he perceived as loudest, and μ and σ were estimated by means of the method of maximum-likelihood (Ref. 12). Then a new variable level was chosen for presentation, and the procedure was repeated several times, until the estimated parameters were believed to be sufficiently exact. A flow chart is shown in Figure 2.

In order to make a maximum-likelihood estimation of the psychometric function it is necessary to know at least one level which is louder than the reference, and one which is perceived as softer. A special start procedure is therefore necessary. The first level presented was the experimenter's best guess at the point of equal loudness. If the subject found the variable louder than the reference, then the variable level was decreased by 10 dB for the second presentation, while if the subject found it softer, it was increased by 10 dB. Usually the second judgement was the opposite of the first, and the experiment was continued according to Figure 2. If the two answers were identical, the experimenter had to make a new guess.

In order to obtain a reasonable amount of information from each answer, the levels presented were chosen in the region of uncertainty. The 5 values $\hat{\mu}-2\hat{\sigma}$, $\hat{\mu}-\hat{\sigma}$, $\hat{\mu}$, $\hat{\mu}+\hat{\sigma}$ and $\hat{\mu}+2\hat{\sigma}$ were given equal probability; levels already given were however excluded ($\hat{\mu}$ and $\hat{\sigma}$ denote the estimates of μ and σ). The experiment was terminated when answers were obtained at these 5 levels. Note that this criterion is dynamic, since $\hat{\mu}$ and $\hat{\sigma}$ will change during the experiment.

The resolution of the sound producing equipment was 1 dB, and during the experiment $\hat{\mu}$ and $\hat{\sigma}$ were assumed to be integers. $\hat{\sigma}$ was also given the restriction 0 dB $<\hat{\sigma}<$11 dB. After termination of each experiment $\hat{\mu}$ and $\hat{\sigma}$ were calculated with an accuracy of 0.1 dB. In order to make it possible to adapt to a time-varying point of equal loudness, calculations at any time only included the 10 immediately previous answers. A typical experiment is most easily illustrated by looking at the experimenter's monitor terminal as shown in Figure 3.

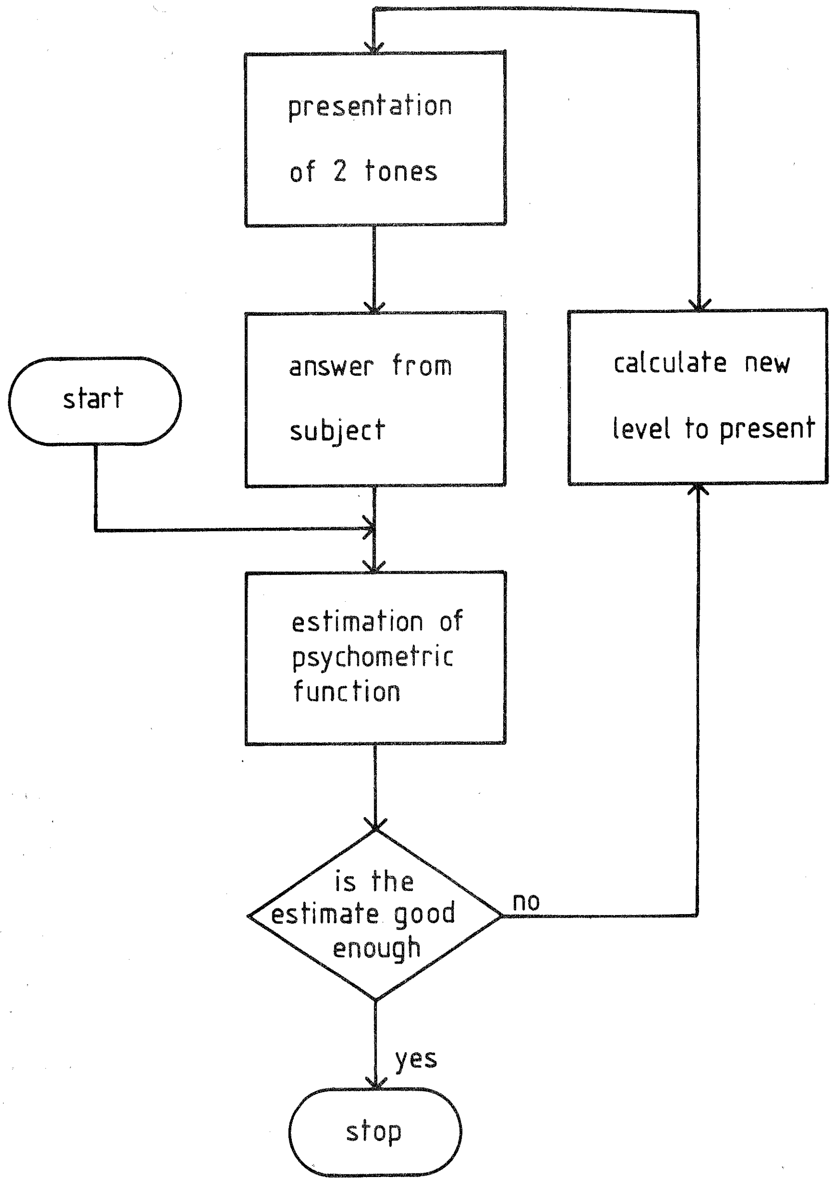

Figure 2 Flow chart of the psychometric method

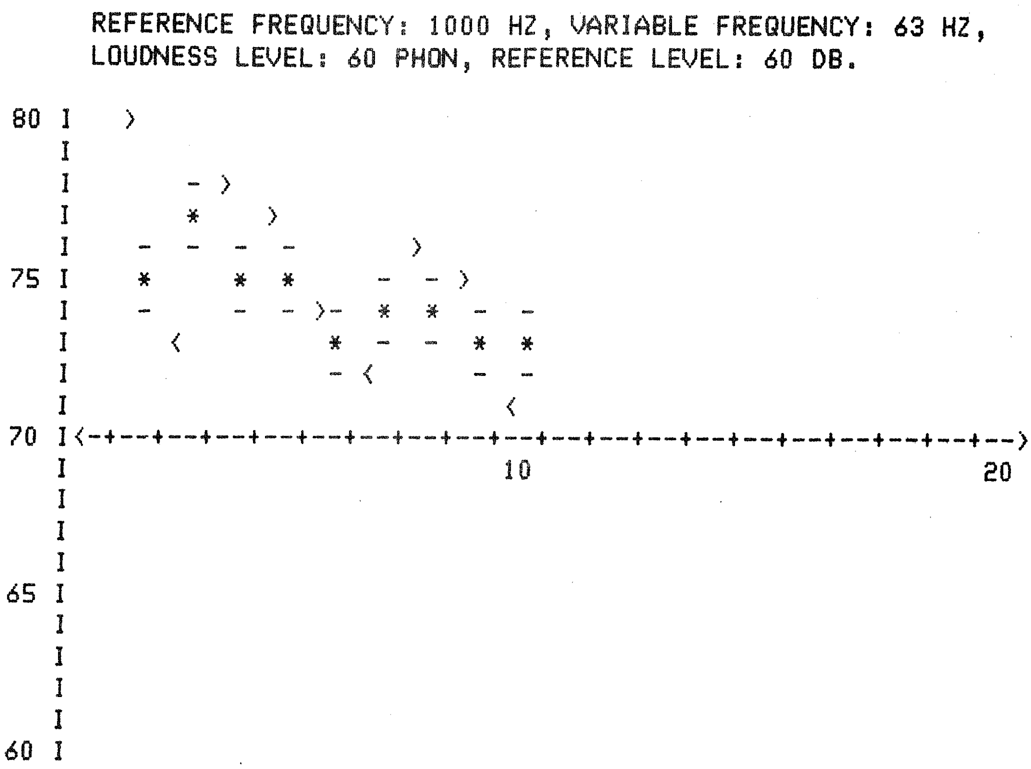

Figure 3 Typical experiment as seen by the experimenter on the monitor terminal. The horizontal axis is a time-axis showing presentation numbers from 1 to 20. The vertical axis shows the sound pressure level. Presented levels and associated answers are indicated by ⟩: "variable is louder than reference", and ⟨: "variable is softer than reference". * shows the running value of $\hat{\mu}$, and $\hat{\mu}-\hat{\sigma}$ and $\hat{\mu}+\hat{\sigma}$ are shown with –. The first presentation was at 70 dB, which was perceived "softer" than the reference (⟨). For the second presentation the level was increased by 10 dB to 80 dB, and the answer was now "louder" (⟩). After this answer the maximum-likelihood estimation gave $\hat{\mu}$ = 75 dB, $\hat{\sigma}$ = 1 dB. Then $\hat{\mu}-2\hat{\sigma}$ = 73 dB was selected for the third presentation, the answer "softer" was obtained, and new estimates were $\hat{\mu}$ = 77 dB, $\hat{\sigma}$ = 1 dB. The fourth presentation was at $\hat{\mu}+\hat{\sigma}$ = 78 dB, the answer was "louder", and new estimates were $\hat{\mu}$ = 75 dB, $\hat{\sigma}$ = 1 dB, etc. After the 10th presentation $\hat{\mu}$ = 73 dB and $\hat{\sigma}$ = 1 dB; 71, 72, 73, 74 and 75 dB had all been presented, and the experiment was terminated

2.4 Apparatus

The comparisons between 1 kHz and 63 Hz were carried out in an anechoic chamber, where the sound was produced by eight 13" (33 cm) loudspeakers mounted in a 2 by 4 array in one wall of a box. The loudspeakers were driven by two 120 W amplifiers (Bang & Olufsen, Beolab 5000). The subject was seated in a chair facing the loudspeakers at a distance of 1.1 m.

The comparisons between 63 Hz and the lower frequencies were carried out in a specially designed test chamber, where 16 electrodynamic loudspeakers produced the sound (Ref. 13). In this experiment the 5 cubic metre room behind the loudspeakers was used, instead of the normal 16 cubic metre test chamber, since the smaller volume allowed a higher sound pressure to be obtained.

The systems were calibrated by measuring the sound pressure at the position of the subject's head, but without a subject present. The sound measuring equipment comprised the following; (Bruel & Kjaer) microphones 4133/4147, preamplifiers 2619/2619, measuring amplifiers 2606/2607, real time analyzer 2131 and pistonphone 4220.

The maximum sound pressure levels that could be obtained are shown in Table 1, together with harmonic distortion levels and deviations in sound pressure resulting from changes in position.

Table 1 Properties of the sound field in the anechoic room and the infrasound test chamber. Distortion levels are given relative to the fundamental at maximum sound pressure level and at 10 dB below maximum level. The maximum deviation in sound pressure level given in the last row refers to the range resulting from a ±10 cm change in position up/down, left/right or forward/backward

	Anechoic room		Infrasound test chamber					
frequency ... Hz	1000	63	63	31.5	16	8	4	2
max. SPL ... dB	100	117	125	125	133	133	133	133
2nd harmonic at max. SPL ... dB	-53	-26	-41	-33	-44	-42	-36	-35
3rd harmonic at max. SPL ... dB	-57	-37	-55	-61	-39	-34	-30	-29
2nd harmonic at 10 dB below max. SPL .. dB	-62	-37	-48	-37	-55	-51	-46	-45
3rd harmonic at 10 dB below max. SPL .. dB	-58	-53	-59	-64	-60	-55	-47	-44
max. deviation in SPL ... dB	1.8	0.7	0.4	0.2	0.1	<0.1	<0.1	<0.1

The presentation of the tones was controlled from an HP 21MX computer by means of two purpose-made attenuators (0 to −120 dB with 1 dB resolution) and two switches that gradually turned the signal on and off within periods of 500 milliseconds. The envelope of the signals is shown in Figure 4. The computer also recorded the answers, made the calculations, and presented the course of the experiment on the monitor terminal.

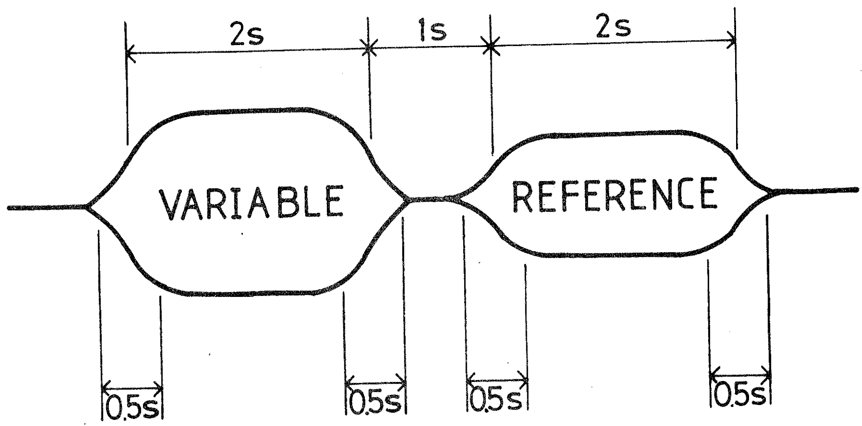

Figure 4 Envelope of the test tones

2.5 Experimental design

As values at 63 Hz served as references for the lower frequencies, comparisons between 1 kHz and 63 Hz were carried out at the beginning of the experiment, and for each subject mean values of two determinations were used. The order in which the subjects received the lower frequencies (2, 4, 8, 16 and 31.5 Hz) was determined from a latin square design that balanced out both order and carry-over effects (Ref. 14). Within each frequency a similar design was used to determine the order in which the subjects received the five loudness levels (20, 40, 60, 80 and 100 phon).

2.6 Procedure

In each experimental session two subjects were tested in turn for periods of approximately 10 minutes (the time to finish one frequency at 5 loudness levels). The duration of a session was around 3.5 hours, including calibration before each new frequency.

The subjects were given written instructions asking them to listen to the tone-pairs, and after each pair to indicate by pressing a button which one he perceived as loudest, the first or the second tone. The meaning of "loudness" was explained as the quality that is altered by the volume control of a radio receiver. In order to make them familiar with the experimental procedure all subjects went through an experiment at 60 phon before any results were used.

After the experiments the subjects answered a questionnaire. In the answers they were in general satisfied with the conditions of the experiment (test rooms, duration of the tones and pauses, duration of the experiment). The questions also concerned the difficulty in comparing the tones and the possible annoyance from the tones. Answers to these questions will be reported in section 3.

3. RESULTS

Usually a point of equal loudness was determined after 8-10 tone-pairs. In a few cases where the answers showed serious inconsistency or an unstable point of equal loudness, up to 20 presentations were necessary.

At the highest loudness levels some subjects had equal loudness points above the dynamic range of the sound producing systems, and no values could be determined. At points where a value exists for all subjects simple statistics are used, and in the case of missing values the procedure for a curtailed normal distribution is used (Ref. 15). Any point where more than 50% are missing is omitted. Results are given in tabular form (Table 2) and as curves of equal loudness (Figure 5).

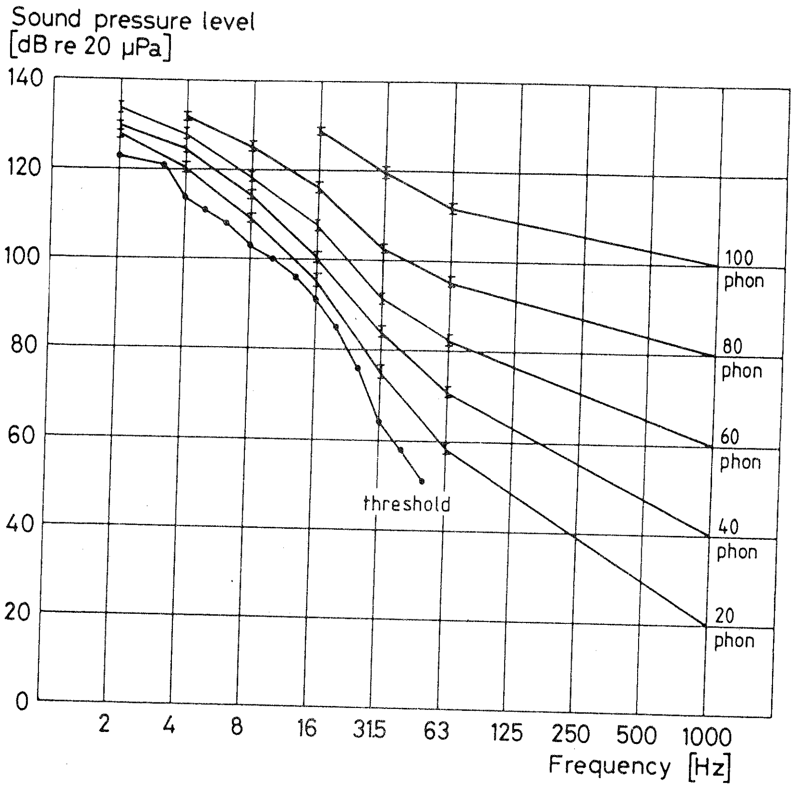

Figure 5 Curves of equal loudness. Vertical bars indicate ±1 standard error of the mean. The threshold curve is based on four recent studies: Whittle *et al.* (Ref. 5), Table 3 "continuous" column; Yeowart *et al.* (Ref. 6), Table 3 converted to binaural hearing by subtraction of 3 dB; Yeowart *et al.* (Ref. 7), Table IV; Yeowart *et al.* (Ref. 7), Table VI. A few interpolations had to be made to convert to the standardized one-third octave frequencies

Table 2 Points of equal loudness in the frequency range 2-63 Hz

Loudness level, phon	Frequency, Hz	Mean value, dB	Standard deviation, dB	Number of subjects	s.e. of mean, dB
20	63	58.0	6.6	20	1.5
20	31.5	75.1	6.5	20	1.5
20	16	95.1	5.8	20	1.3
20	8	109.4	5.9	20	1.3
20	4	120.7	5.2	20	1.2
20	2	127.6	3.5	20	0.8
40	63	71.7	6.1	20	1.4
40	31.5	83.4	7.3	20	1.6
40	16	101.3	8.4	20	1.9
40	8	114.3	6.4	20	1.4
40	4	124.8	5.7	19	1.3
40	2	129.7	4.1	16	0.9
60	63	82.8	4.8	20	1.1
60	31.5	90.9	7.4	20	1.7
60	16	106.9	7.8	20	1.7
60	8	118.1	6.6	20	1.5
60	4	127.4	5.5	18	1.3
60	2	132.6	5.0	11	1.3
80	63	95.6	4.3	20	1.0
80	31.5	102.5	9.0	20	2.0
80	16	116.5	8.6	19	1.9
80	8	125.6	8.6	18	2.0
80	4	132.6	6.3	10	1.7
100	63	112.3	3.7	20	0.8
100	31.5	119.5	7.3	16	1.7
100	16	128.4	7.8	15	1.8

The overall mean of $\hat{\sigma}$ was 1.38 dB. In 49% of the cases, completely consistent answers were given, leading to a $\hat{\sigma}$ of 0.1 (the lowest possible value).

In the answers to the questionnaire 75% of the subjects indicated that they found the comparisons "difficult", 25% found them "reasonably easy", while none found them "easy". Some 40% indicated that they would prefer to hear the tone-pairs more than once before answering. The subjects were also asked whether they found some of the tones annoying. 35% indicated "yes, very", 60% "yes, somewhat", and 5% "not at all". The complaints concerned pressure in the ear, large and sometimes painful movements of the eardrum, tickling in the ear, and the like.

4. DISCUSSION

From Figure 5 it can be seen that the loudness curves run almost parallel in the infrasound region, and are much closer than in the audio region. For example, the distance between the 20 and the 80 phon curves has decreased from 60 dB at 1 kHz to approximately 16 dB at 8 Hz. Consequently, infrasound only a few dB above the hearing threshold will seem loud and possibly annoying. It is also possible to explain the fact that a small change in the infrasound content of a complex sound may change the loudness of the sound considerably.

In order to demonstrate the extent to which the results are in agreement with existing knowledge about the hearing at low frequencies, the following three sections show comparisons with 1) the threshold curve, 2) existing loudness curves for infrasonic frequencies and 3) ISO/R 226 equal loudness curves (Ref. 16).

4.1 Threshold curves

Figure 5 also includes a threshold curve based on a weighted mean of 4 recent studies (Refs. 5,6,7). The threshold curve and the loudness curves complement each other remarkably well. The shape of the threshold curve is very close to that of our 20 phon curve, lying just below it at a distance close to the distance between the loudness curves (which are themselves at 20 phon intervals).

4.2 Existing loudness curves for infrasonic frequencies

Whittle *et al.* have given curves of equal loudness in the frequency range 3.15-50 Hz. The frequencies used were not the standardized octave frequencies, so a direct point to point comparison is not possible. Figure 6 shows the results together with the results of the present study. The agreement between the two sets of curves is very good with respect to shape and slope.

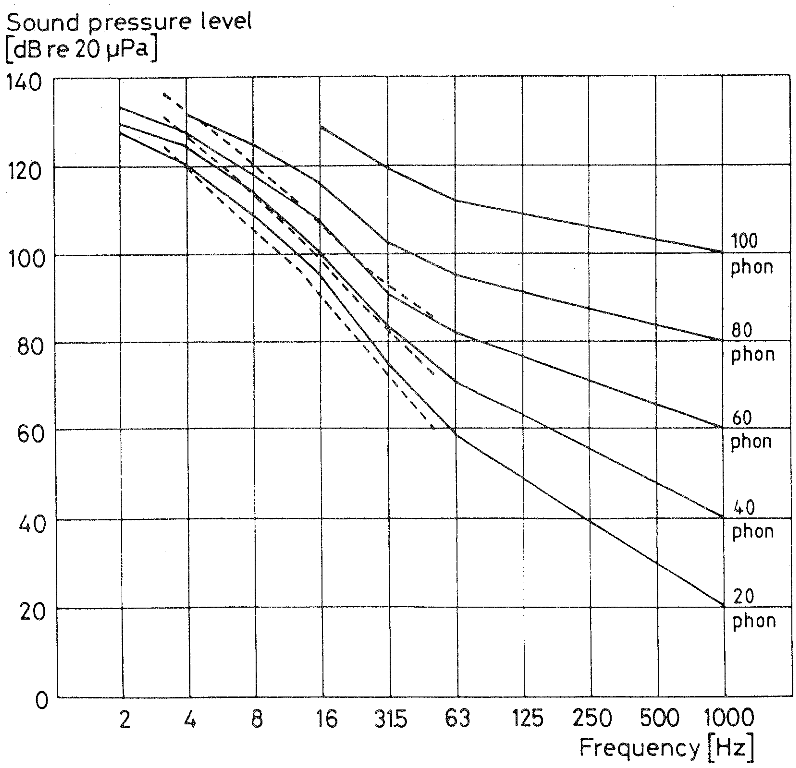

Figure 6 Comparison between equal loudness curves of Whittle *et al.* (Ref. 5) (dotted lines) and the present study

There is a minor disagreement at the lowest frequencies where the curves of Whittle *et al.* seem to keep their slope, while ours become less steep. This may be caused by the gating of the signal (Figure 4), which changes the spectrum from the line spectrum of a pure tone to a continuous spectrum centred around the tone. This effect is dependent on the duration of the tones and the rise and decay times, and it is most prominent at the lowest frequencies. Whittle *et al.* did not report the exact envelope of their signals. The significance of the gating effect will be investigated in a later experiment.

Whittle *et al.* did not make comparisons with 1 kHz, so a direct labelling of their curves with phon values was not possible. Instead they used the ISO/R 226 curves to find the loudness level of their 50 Hz reference tones, and the curves were labelled with the values: 33.5, 53 and 70 phon. As it will be seen in section 4.3, there are discrepancies between the ISO curves and those of the present study, and of course, this leads to a disagreement in the labelling of our curves and those of Whittle *et al.* Their lowest curve is for example labelled 33.5 phon, although it is below our 20 phon curve in almost the entire frequency range.

4.3 ISO/R 226 equal loudness curves

The frequencies 31.5 and 63 Hz are already covered by the ISO/R 226 loudness curves (Ref. 16). A comparison with those is shown in Table 3. The present values are generally higher than those of ISO, the difference being statistically significant at most points.

Table 3 A comparison between ISO/R 226 loudness curves and results from the present study at 63 and 31.5 Hz

Frequency, Hz	Loudness level, phon	ISO/R 226 dB	Present study, dB	s.e. of mean, dB	t	Significant level
63	20	45.7	58.0	1.5	8.2	0.001
63	40	59.5	71.7	1.4	8.7	0.001
63	60	74.3	82.8	1.1	7.7	0.001
63	80	90.4	95.6	1.0	5.2	0.001
63	100	107.9	112.3	0.8	5.6	0.001
31.5	20	64.3	75.1	1.5	7.2	0.001
31.5	40	75.4	83.4	1.6	5.0	0.001
31.5	60	87.6	90.9	1.7	1.9	0.1
31.5	80	101.3	102.5	2.0	0.6	n.s.
31.5	100	116.6	119.5	1.7	1.7	n.s.

Two conditions of ISO/R 226 have not been fulfilled in this study: 1) Mean values were reported instead of modal values. Mean values were chosen, since 20 observations were considered too few to determine the distribution accurately enough to find the modal values. The distributions did not show any obvious skewness, and the mean and the modal values are equal if the distribution is assumed to be normal. 2) The sound field was only approximately a free progressive plane wave. The changes in sound pressure level for changes in position given in Table 1 illustrate the deviations from a plane wave. The deviations are small and cannot explain differences as great as 12.6 dB.

At present we are not able to explain the disagreement between our curves and those of ISO/R 226. A similar discrepancy exists between the ISO/R 226 threshold curve and the curve based on the four recent investigations, as can be seen in Figure 7.

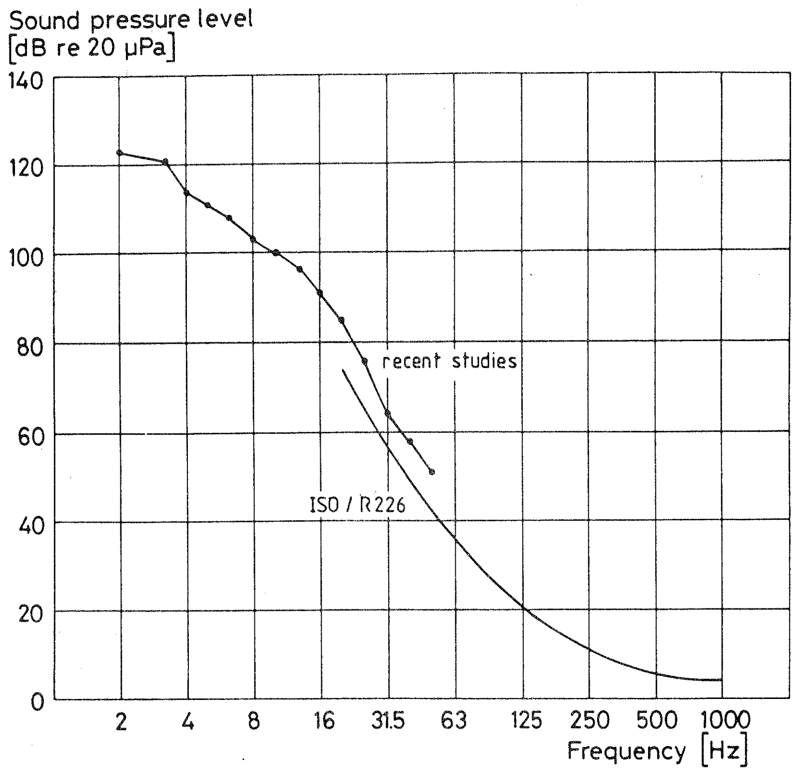

Figure 7 Comparison of threshold values from ISO/R 226 and from four recent studies (see Figure 5)

4.4 Difficulties in the comparisons

In the answers to the questionnaire the subjects reported difficulties in comparing the tones, especially when the frequencies were far from each other. Nevertheless, the low values of $\hat{\sigma}$ show that the answers were in general very consistent, and in spite of the subjects' own reservations the results seem very reliable.

4.5 Annoyance

The annoyance indicated in the answers to the questionnaire is not surprising, since tones louder than 100 phon were included. It is not possible to attach the annoyance to specific frequencies and levels. Whether the annoyance of infrasound is related to the loudness sensation is not known at present, and a projected experiment deals with determination of equal annoyance contours at low and infrasonic frequencies.

5. CONCLUSION

A set of equal loudness contours for low and infrasonic frequencies have been determined. The contours agree well with existing knowledge about the hearing at infrasonic frequencies, although there are minor but statistically significant disagreements with the low-frequency part of the ISO/R 226 loudness curves. Some uncertainty is also attached to the exact values at 2 Hz.

It is obvious that existing curves, such as the A-weighting curve cannot be used to measure the loudness of sounds containing infrasound, unless they are given an appropriate extension down to 2 Hz or lower. It is also obvious that a single curve to be used at all loudness levels cannot be developed, since different relative weighting of high and low frequencies is required at different loudness levels. This phenomenon is also known from the audio region, and it has led to the development of the three weighting curves A, B, and C. However, the effect becomes even more prominent when the infrasonic range is included.

As the loudness curves run almost parallel in the infrasonic region, it may be possible to develop a weighting curve suitable for measuring loudness of infrasound. The curve should be restricted in frequency and thus not provide any large overlapping into the audio region, and users should be aware of the steep rise in loudness with an increase in sound pressure above the hearing threshold.

ACKNOWLEDGEMENTS

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