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# The Hearing Threshold of Infrasonic Frequencies

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Introduction: Any discussion of the threshold of hearing at infrasonic frequencies immediately raises the question of the lower frequency limit to hearing, or indeed whether there is any such limit. At the present time, this question has never been satisfactorily answered. In fact it seems likely that various lower limiting frequencies proposed at different times have probably all reflected limitations of the instrumentation.

Historically, the first work appears to be that of Imai, who in 1907 used a weighted tuning fork as a sound source in the 12-30 Hz region. He reported that fundamental tones as low as 12 Hz could be detected. This research was not directly reported, but was referred to by Vance (1914). Vance repeated the work and appreciated that the main difficulty was to obtain the threshold for pure tones despite the fact that the tuning forks generated harmonics. Since he could not generate sufficiently pure tones, he trained his observers to listen for the fundamental in the presence of the overtones. Vance's work, like that of Imai, suggested that the threshold existed at frequencies below 20 Hz. Brecher (1934) developed a new technique. He used a box with a membrane on one side, which was driven by an eccentric cam. The cavity of the box was directly coupled to the listener's ear. He succeeded in measuring the threshold down to about 7 Hz, and concluded that this frequency did not represent the true, lower limit of detectibility. He found that, for frequencies above 18 Hz, the stimulus had a tonal quality, but below this frequency his observers could hear separate 'puffs' and felt slight pain in the ear. He termed the range around 18 Hz the 'fusion' frequency, Brecher's technique represented a considerable step forward in infrasonic research.

In 1936 Weaver and Bray developed a pistonphone. The output of the pistonphone was carefully filtered to remove noise and harmonics, and fed to an observer who was isolated in a quiet room. They 'cautiously' limited their maximum sound pressure level to 104 dB and obtained data down to about 10 Hz. The various workers mentioned above also collected descriptions of the sensations, which mainly suggested a lack of tonal quality below 18-20 Hz.

A much more detailed study of the threshold was begun by Von Bekesy in 1936. He used both a pistonphone and a thermophone. The thermophone used a hot wire source within a small volume, and in order to produce the required low frequencies was driven by a combination of two higher frequency signals with an appropriate beat rate. His pistonphone output was carefully filtered to reduce harmonics and noise. His system included a manometer with a rubber diaphragm, which reflected a beam of light. The deflection of this beam of light allowed pressure measurements to be made at threshold levels for frequencies below 50 Hz He succeeded in obtaining threshold data down to 1 Hz, where the threshold sound pressure level was found to be about 150 dB.

After Bekesy, little work was undertaken in this field for many years. In

1958 Corso developed an electro-dynamic system, in which a diaphragm driven by a moving coil, was mounted in the side of a plywood enclosure. The enclosure was coupled to the subject's ear by a short tube. Corso gives details of the total harmonic distortion of this system as 3% at 5 Hz, but data on the individual harmonics are not given. Corso's threshold at 5 Hz is substantially (about 20 dB) more sensitive than Von Bekesy's 1936 data, and it seems possible that this discrepancy may be due to audible harmonics in his infrasound. This illustrated the major technical difficulty in the study of the threshold at very low frequencies, which is the problem of obtaining stimuli with an adequately low level of noise and distortion. It is essential that all harmonics should be below the threshold of audibility, despite the fact that the threshold sensitivity is increasing with frequency at 12-18 decibels per octave. It is also essential that there should be no audible background noise, since it is found that infrasound can produce an audible modulation, presumably due to cyclic variations in middle ear transmission, when the infrasound itself is below audibility.

<u>More Recent Research</u>: Norman Yeowart began work in 1964 (in the University of Liverpool) at which time the threshold data were too disparate to give any reliable values in the region below 20 Hz. The first problem was to devise a signal source, and it immediately became clear that available earphones were not satisfactory in this frequency range. The requirements for the transducer were:

1 High power handling capacity (to generate sound pressure levels up to 140/150 dB)

2 A large volume coupled to the ear. This was necessary to minimise physiological noise, particularly heart-beat rate, which at around 1.2 Hz can interfere with the threshold measurements.

3 Low distortion at the high sound pressure levels needed. This applies to both the transducer and its driving oscillator and amplifier.

4 A good seal to the ears to avoid leaks, and to allow the generation of high pressures.

In the development of a suitable headset various loudspeaker units were tested and found to be porous, but a 30 cm unit with roll surround operating into a flat plate was found to be satisfactory. The stimulus was coupled to the ear by an ear muff cup, and an extra large soft rubber seal was fitted. A monitoring microphone could be mounted directly into the side of the ear muff cup. The resulting 'head-phone' had a flat response from about 1 to 100 Hz with a peak at about 200 Hz. In operation it was found that the distortion content was adequately low, and the head set could be used down to 1.5 Hz where the monaural threshold was found to be 132 dB. Background noise proved rather a problem, arising from three possible sources; room noise (the loudspeaker cone provided no protection against this), amplifier noise, and air leaks. The room noise meant that the thresholds had to be determined in a quiet room. Amplifier noise was a problem since with a maximum signal level of 140 dB, amplifier noise 80 dB below this is clearly audible. It was necessary to use low pass filters between the amplifier and the head set. The threshold technique used was the method of limits, the mean of five upward and five downward thresholds. Monaural thresholds were obtained first and then binaural thresholds were investigated. Here two techniques were used, binaural equal pressure thresholds and binaural equal sensation level thresholds. In both cases a binaural advantage close to 3 dB was observed. Octave band noise thresholds were determined, and found to be about 4 decibels more sensitive than those for pure tones. (Yeowart, Bryan and Tempest, 1967, 1969).

It seemed likely at first that this difference arose because the frequencies close to the upper limit of each band were being detected, but in fact, the effect was least at the frequencies around 100 Hz, where the threshold slope was steepest. It was finally concluded that the most probable explanation was that of peak detection, ie the ear was detecting the highest peak levels in the random noise signal. This was checked using a simulation with a detector time constant of 200 m sec which produced the 4 decibel difference measured.

The final stage in the threshold studies involved the construction at Salford University of a low frequency pressure chamber of 1250 litres volume, driven by six 45 cm loudspeakers in the walls. This had a flat frequency response from 2 Hz to at least 25 Hz, and could be used at sound pressure levels up to 130 dB. It could be used for either pure tone or noise studies. (Yeoward and Evans, 1974) The National Physical Laboratory built a chamber of similar dimensions, driven from two loudspeakers mounted in a separate box and coupled by means of a 65 mm diameter steel pipe. (Whittle, Collins and Robinson, 1972). Both chambers were used independently to determine binaural free field threshold data, which were found, in both cases, to agree very well with the earlier binaural headphone data.

The results of the various more recent studies are summarised in Figure 1 below.

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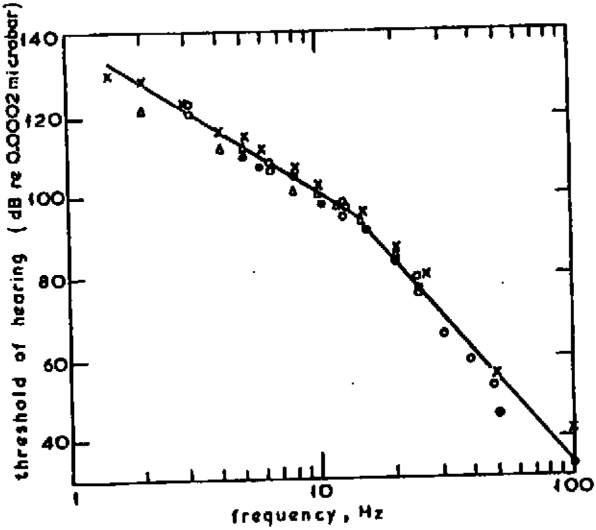


Fig 1 Comparison of recent threshold data. X monaural headphone data -3dB (Yeowart et al., 1967); ● binaural headphone data (Yeowart, 1972); ▲ binaural chamber data (Yeowart and Evans, 1974); O binaural chamber data (Whittle et al., 1972).

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# LOW FREQUENCY NOISE ANNOYANCE

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It is now well established that low frequency noises (below 100 Hz) cause considerably more disturbance than their rating on such scales as dB(A), NR and PLdB would predict. Various examples are given by Bryan (1). Although it is not clear which are the important parameters of the low frequency noise in determining this extreme subjective reaction. The suggestion was made in this reference that annoyance might be related to either the slope or the turnover point of the noise spectrum.

Recently we have come across situations where community disturbance has been produced by low frequency noise composed of discreet tonal components rather than broad band noise. Opportunity has arisen to replicate these problems in the laboratory and to quantify the psychological disturbance as well as to attempt to measure the physiological responses produced.

Problem 1 was caused by the shaker table, used for reclaiming sand in casting, at a small foundry in the middle of a village in North Lancashire. Sound pressure levels of 116 dB at 12 Hz were measured immediately above the table when it was in operation. The Environmental Health Department had received many complaints from residents in the village when the table was running. These were of windows and ornaments shaking, feelings of uneasiness, headaches and other symptoms of extreme annoyance. Vibration measurements ruled out transmission through the ground, however sound pressure levels from 79 dB - 91 dB (at 12 Hz) were measured at the houses of some of the complainants. The highest level was just about audible to the investigators (the binaural pure tone threshold is approximately 97 dB SPL at 12 Hz (2).

It is most interesting that modifications at the edges of the shaker table, which reduced the levels by only 5 dB, were sufficient to stop complaints.

Problem 2. The cupola furnace at another iron foundry in Yorkshire intermittantly went into resonance at a frequency of 48-50 Hz. This had been occurring over a period of six months and had caused frequent "walk-outs" by the men in an adjacent toolroom. They were extremely concerned about the effects that the noise had upon their health and complained of headaches, feelings of uneasiness etc. The sound pressure level at the furnace when resonance occurred was 118-119 dB (at 48-50 Hz) and as high as 107 dB in the toolroom. Although the "hum" from the furnace only increased the toolroom noise level from 73-77 dB(A), the 48-50 Hz tone was in fact some 54 dB above the threshold of hearing.

Little or nothing is known about the mechanism of annoyance due to low frequency noises or what levels will provoke these extreme reactions. We therefore decided to study the problem in the laboratory.

Experiment 1 was a replication of the cupola furnace, 50 Hz, problem.

LOW FREQUENCY NOISE ANNOYANCE

Thirty students, one at a time, were presented with three listening conditions in the Audiology Group's 30 $m^3$ low frequency test cha ber. These were 1 minute duration of the following:

1. A recording of typical toolroom noise at 75 dB(A)

2. A recording of typical toolroom noise at 75 dB(A) plus 50 Hz tone at 100 dB SPL. Overall level approximately 78 dB(A).

3. 50 Hz tone at 100 dB SPL.

The students were asked to rate each noise on a scale of 0 - 10 where 0 = no effect and 10 = extreme annoyance. They were also asked to comment on each of the three noises and to state whether they felt they could work under these conditions.

Table I

Laboratory Expt. 1 - 50 Hz foundry noise

| Condition Comparison | chi squared | Correlation |
|---|---|---|
| Workshop noise vs workshop noise + 50 Hz tone | 57 (0.1%) | 0.45 (1%) |
| Workshop noise vs 50 Hz tone | 78 (0.1%) | 0.25 (25%) |
| Workshop noise + 50 Hz vs 50 Hz tone | 0.9 (80%) | 0.42 (2%) |

Figure 1 shows the distribution of annoyance rating for each of the three conditions. Table I compares the different conditions and also gives the correlation between them. It is immediately clear that either the workshop noise plus the 50 Hz tone condition or the 50 Hz tone condition alone are significantly more annoying than the workshop condition alone ($chi^2$ values 57 and 78 respectively, both of which are highly significant). However the workshop noise plus 50 Hz condition and the 50 Hz condition alone do not give significantly different values from each other ($chi^2 = 0.94$). From this we conclude that the presence of the 50 Hz tone makes a marked increase in the annoyance rating (from a mean value of 4.3 to mean values of 8.3 and 8.6 respectively). Also the presence of the 50 Hz tone is equally annoying whether it is on its own or heard together with the workshop noise.

There is a weak but significant correlation between the workshop noise condition and the workshop noise plus 50 Hz tone condition ($r = 0.45$, $p = 1\%$). On the other hand there is no correlation between the workshop noise condition and the 50 Hz tone alone, condition ($r = 0.25$, $p = 25\%$). This can be taken as implying that the annoyance due to the 50 Hz tone is very weakly related to the annoyance due to the workshop noise. It could well be that the mechanisms of annoyance for normal frequency (greater than 100 Hz) noise and low frequency (less than 100 Hz) noise are not the same.

The subjective reaction to the 50 Hz tone were strong and adverse i.e.

Not possible to work in this noise - (30%)

Caused vibration of chest and head - (35%)

Other comments were:

"it is bugging me"
"feel sick"
"pain in the ear"
"would give me a headache"
"would drive one mad"

Experiment 2 Recently another experiment has been initiated to investigate psychological and physiological response to low frequency tones over the range 5 Hz - 30 Hz.

The aim is to establish "thresholds" at which annoyance due to the low frequency tones chosen were 5 Hz, 7 Hz, 12 Hz, 20 Hz and 30 Hz at levels from 85-110 dB SPL.

ECG have been taken at the highest levels and changes in heart rate and decreases in irregularity of heart-beat rate (sinusarrhythma) (3) are to be related to annoyance rating. The performance for a number of mental tasks and reaction time are also being monitored for the various low frequency tone conditions.

## Conclusions:

The work on low frequency annoyance is still in its very early stages. However the laboratory experiment described above confirms the field studies that extreme annoyance is caused by low frequency tones of less than 100 Hz just at or above the threshold of hearing. As with low frequency noise the annoyance is considerably greater than would be predicted from dB(A) measurements.

The mechanism by which annoyance occurs for such low frequencies is largely unknown but it only appears to be loosely related to that causing annoyance from normal frequency noises.

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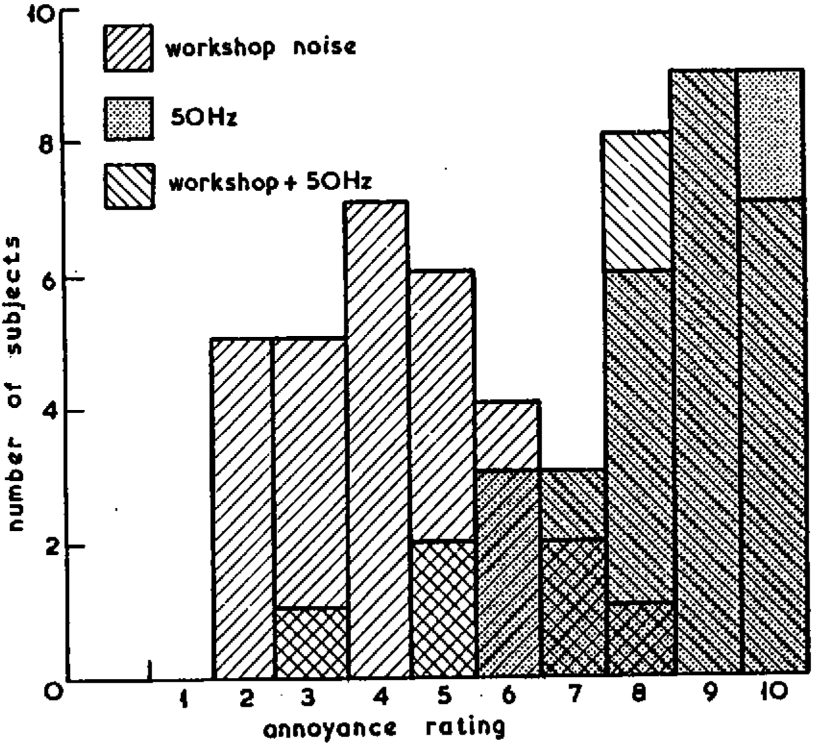


Figure 1

Distribution of annoyance due to workshop noise,
50 Hz tone and workshop noise + 50 Hz tone for Experiment 1.