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Hearing at Low and Infrasonic Frequencies

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The human perception of sound at frequencies below 200 Hz is reviewed. Knowledge about our perception of this frequency range is important, since much of the sound we are exposed to in our everyday environment contains significant energy in this range. Sound at 20-200 Hz is called low-frequency sound, while for sound below 20 Hz the term infrasound is used. The hearing becomes gradually less sensitive for decreasing frequency, but despite the general understanding that infrasound is inaudible, humans can perceive infrasound, if the level is sufficiently high. The ear is the primary organ for sensing infrasound, but at levels somewhat above the hearing threshold it is possible to feel vibrations in various parts of the body. The threshold of hearing is standardized for frequencies down to 20 Hz, but there is a reasonably good agreement between investigations below this frequency. It is not only the sensitivity but also the perceived character of a sound that changes with decreasing frequency. Pure tones become gradually less continuous, the tonal sensation ceases around 20 Hz, and below 10 Hz it is possible to perceive the single cycles of the sound. A sensation of pressure at the eardrums also occurs. The dynamic range of the auditory system decreases with decreasing frequency. This compression can be seen in the equal-loudness-level contours, and it implies that a slight increase in level can change the perceived loudness from barely audible to loud. Combined with the natural spread in thresholds, it may have the effect that a sound, which is inaudible to some people, may be loud to others. Some investigations give evidence of persons with an extraordinary sensitivity in the low and infrasonic frequency range, but further research is needed in order to confirm and explain this phenomenon.

Keywords: low-frequency sound, infrasound, hearing thresholds, equal-loudness-level contours, binaural advantage, sensitive persons

Introduction

It is traditionally said that the human hearing covers a certain frequency range, called the *audible range* or the *audio frequency range*. The lower limit of this range is usually given as 16 or 20 Hz, and the upper limit is typically said to be 16 or 20 kHz.

The upper limit is fairly sharp in the sense that the hearing threshold rises rather steeply above the upper limit - meaning that the hearing almost "stops" at this frequency. The lower limit is more smooth, and the hearing threshold follows a curve that gradually goes to higher levels for decreasing frequency. As a surprise to most people (even to many acousticians), the threshold curve continues below 20 and even 16 Hz, and - as it will be seen in the following sections - humans can perceive sound at least down to a few Hertz. This applies to all humans with a normal hearing organ, and not just to a few persons.

Since the threshold curve goes up for decreasing frequency, it reaches quite high sound pressure levels at the lowest frequencies. Even when rather high sound pressure levels are needed to cause a perception, there are many sources in our everyday environment that do produce audible sound in this frequency range. Engines, compressors, ventilation systems, traffic and musical instruments are examples of man-made sources, but also natural sources exist like thunder, ocean waves and earthquakes. Driving a car at highway-speed with an open window is a situation, where many people expose themselves to perceivable levels of 10-20 Hz sound.

The ear is most sensitive in the frequency range from 200-300 Hz to around 10 kHz, and this is the frequency range we mainly use in communication. As a natural consequence it is also the frequency range, where most hearing research has been made. However, it is important to have insight in the hearing function also outside this frequency range, in particular at frequencies below, since much of the sound that we are exposed to in our everyday environment contains significant energy in this range. The present article gives a review of studies of the hearing function below 200 Hz, focussing on the hearing threshold and the loudness function.

Terminology

Sound with frequencies below 20 Hz is called *infrasound*, infra being Latin and meaning below. Thus the term refers to the widespread understanding that these frequencies are below the range of (audible) "sound". As mentioned, this understanding is wrong, and the use of the term infrasound for these frequencies has resulted in many misunderstandings. Nevertheless, the term is widely used, and it will also be used in this article. For sound in the frequency range 20-200 Hz, the term *low-frequency sound* is used. Since there is no sharp change in hearing at 20 Hz, the dividing into infrasound and low-frequency sound should only be considered as practical and conventional.

Sensation of sound at low and infrasonic frequencies

Everyone knows from his everyday environment the feeling of hearing sound at low and infrasonic frequencies. The following are examples of typical low-frequency sound sources: ventilation systems, compressors, idling trucks and the neighbour's stereo. Infrasound at an audible level is usually found on the car deck of a ferry and when driving a car with an open window. However, infrasound is most often accompanied by sound at other frequencies, so the experience of listening to pure infrasound is not common.

The subjective quality of the sound varies with frequency. In the low-frequency range pure tones still result in a tonal sensation, and - like at higher frequencies - a sensation of pitch is connected to the sensation. If the frequency is gradually lowered from 20 Hz, the tonal sensation disappears, the sound becomes discontinuous in character and it changes into a sensation of pressure at the eardrums. At even lower frequencies it turns into a sensation of discontinuous, separate puffs, and it is possible to follow and count the single cycles of the tone. Some early descriptions of these phenomena were given by Brecher (1934) and by Wever and Bray (1936). However, the lower limit of tonality has been known much longer, e.g. it has influenced the building of musical instruments, where the largest organ pipes are tuned to a frequency around 17 Hz.

Yeowart et al. (1967) described pure tones above 20 Hz as smooth and tonal, at 5-15 Hz a rough sound with a popping effect was reported, and tones below 5 Hz were described as chugging and whooshing. Below 5 Hz a sensation like "motion of tympanic membrane itself" was reported. The perception of noise bands was investigated by Yeowart et al. (1969). For an octave band around 125 Hz the random noise was perceived as banded noise, while at 63 Hz the character changed into a sensation of a fluctuating tone. The octave bands around 32 Hz and 16 Hz were described as traffic rumble, at 16 Hz with a fluctuating flutter, while the band at 8 Hz was described as a rough peaky tone. For the octave-band noise around 4 Hz separate random peaks were perceived.

The early qualitative descriptions are well in line with later descriptions in the literature as well as with reports from numerous experimental subjects in the authors' laboratory and with the authors' experience from exposure of themselves.

It is mentioned by many authors and easily verified in a laboratory with suitable equipment that the loudness of low-frequency and infrasonic sound grows considerably faster above threshold than sound at higher frequencies. Yeowart et al. (1967) mentioned that at 4 Hz a 1 dB change in level was sufficient to cover the whole range from inaudible to definitely detectable. The faster growth of loudness is reflected in the equal-loudness-level contours, where the distance between the curves decreases with decreasing frequency (see separate section 'Studies of equal-loudness-level contours'). An implication of this compression is that if a low-frequency sound is just audible, then a relatively small increase in level will result in a much louder sound.

The sensation mechanism
It has been a matter of interest, how we sense the lowest frequencies, and the key question is, if we sense them with our ears and in the same way as we sense higher frequencies.

There is no doubt that the ear is the organ that is most sensitive to sound at these frequencies. This is seen from the fact that hearing thresholds are the same, whether the whole body or only the ears are exposed (see the section 'Do we sense with our ears'). It is more difficult to determine whether the sensory pathway belongs to the auditory system or not. Békésy (1936) noted that it is difficult to distinguish whether the sensation is of a pressure or tactile nature, or of an auditory nature. He argued, though, that touching two symmetrical places on for example the entrance to the external meatus results in two separate sensations, while binaural exposure to infrasound fuses into a single impression localized in the middle of the head. Therefore he concluded that it is in fact an auditory sensation. However, he also observed that at higher sound pressure levels the auditory sensation is accompanied by a "true" sensation of touch at each of the ears. If the level of the sound is increased even further, a sense of tickling or prickling is observed. That the sensation at low levels is auditory is further supported by the fact that perception thresholds for deaf people are much higher than for people with normal hearing (see section 'Non-auditory perception').

It seems fair to conclude that the sense of hearing is the primary sense for detecting sound at low and infrasonic frequencies. However, it has often been proposed that we do not sense infrasound directly, but that we simply hear higher harmonics produced by distortion in the middle and the inner ear (see e.g. Johnson (1980)). If this were true, it would then be reasonable to assume that the subjective quality of a 15-Hz tone would be comparable to that of a tone or a combination of tones at higher harmonics like 30 and 45 Hz. However, to the authors' knowledge such similarity has not been reported, and in an informal listening test with the authors and colleagues as listeners, such sounds were perceived as clearly different in timbre, pitch and general quality. Thus, the theory is not supported.

Modulation of hearing
One way in which the presence of infrasonic sound can be detected at levels around or possibly below the hearing threshold is by modulation of higher frequencies. The infrasound moves the eardrum and the middle ear bones, and the displacement may be so large that their mechanical properties and the transmission change. As a consequence, sounds at higher frequencies are amplitude-modulated with the infrasound. This effect is easily demonstrated in a suitable laboratory, and it emphasises the need of very quiet conditions, when perception of infrasound is studied.

Speech modulation
Another modulation effect is sometimes mentioned in connection with infrasound, namely modulation of speech. Whereas the effect mentioned in the previous paragraph relates to a person as a sound detector, this effect relates to a person's generation of sound. When a person speaks in the presence of infrasound, the pressure from the infrasound may create a small pulsating airflow in the throat. This flow adds to the natural flow from breathing and speaking, and it modulates the speech. The effect is only noticed at high levels of infrasound.

Studies of hearing threshold
The threshold is most likely the single characteristic of the hearing that is investigated most and best known. However, it is not trivial to produce a well-controlled exposure at low frequencies, and many original investigations have a bad coverage of this frequency region. The number of investigations in the infrasonic region is even more limited.

Thresholds are usually given in terms of the pressure of a free plane wave, in which the listener is exposed horizontally and from the front. The pressure is measured without the listener being present in the sound field. A threshold given this way is called the *minimum audible field*, or the MAF. Another possibility is to specify the threshold in terms of the actual pressure at the eardrum during exposure - in principle without specific requirements to the nature of the sound field. This is called the *minimum audible pressure*, or the MAP.

At high frequencies the presence or absence of a person has a substantial impact on the sound field, and there is a significant difference between the MAF and the MAP. Furthermore, the difference depends on the nature of the sound field (e.g. free or diffuse), direction to sound source(s) etc. At low frequencies, however, the listener's head and body have little or no impact on a free plane wave, and it is expected that MAP and MAF will have the same value.

Measurements of MAP may in principle be carried out in any sound field. However, they are usually done either in a pressure-field chamber that encloses the entire body of the listener, or with the sound created in a cavity that is coupled to the ear (or to both ears). If, in the latter case, the cavity is very small, e.g. like that of a supra-aural audiometric earphone, physiological activity around the ear seems to result in noise under the earphone that elevates the threshold, in particular at low frequencies (see e.g. Anderson and Whittle (1971)). Therefore MAP measurements with sound applied in very small volumes have not been included in the following.

Sivian and White (1933) gave a review of earlier studies of hearing thresholds. These investigations differ much in means of exposure and calibration as well as experimental method, and they are now mainly of historical interest. Nevertheless it is interesting to see how close the results of at least some of these studies are to threshold data obtained in more recent years. These early studies will not be further reported here.

Common to all studies mentioned in the following is that they have been made with sinusoidal tones, and that the duration of the tones has been so long that the temporal integration of the ear is expected not to have any impact on the result (usually a duration of 0.5-2 s or longer).

Most studies have been made in a free or an approximately free sound field (e.g. an anechoic room) using an electrodynamic transducer (usually a loudspeaker) as sound source. Data obtained under such conditions have been presented by Sivian and White (1933) (100 Hz-15 kHz, 14 subjects monaural, five subjects binaural), Fletcher and Munson (1933) (60 Hz-15 kHz, 11 subjects), Churcher et al. (1934) (100 Hz-6.4 kHz, 48 subjects), Churcher and King (1937) (54 Hz-6.4 kHz, 10 subjects), Robinson and Dadson (1956) (25 Hz-15 kHz, up to 120 subjects depending on frequency, lowest frequencies measured in a duct), Teranishi (1965) (63 Hz-10 kHz, 51 subjects), Anderson and Whittle (1971) (50-1000 Hz, ten subjects), Brinkmann (1973) (63 Hz-8 kHz, up to 58 subjects depending on frequency), Betke and Mellert (1989) (40 Hz-15 kHz, up to 44 subjects depending on frequency) (reported in more detail by Betke (1991)), Fastl et al. (1990) (100-1000 Hz, 12 subjects), Watanabe and Møller (1990a) (25-1000 Hz, 12 subjects), Takeshima et al. (1994) (31.5 Hz-20 kHz, below 1 kHz: 17-69 subjects depending on frequency) (partly reported on earlier occasions, e.g. by Suzuki et al. (1989)), Lydolf and Møller (1997) (50 Hz-8 kHz, 27 subjects), Poulsen and Han (2000) (125 Hz-16 kHz, 31 subjects) and Takeshima et al. (2001) (31.5 Hz-16 kHz, below 1 kHz: seven to eight subjects). Most likely the study by Bellmann et al. (1999) (40-160 Hz, 12 subjects) was also carried out in a free-field, although it was not specifically reported.

Especially at the lowest frequencies it is difficult to produce sufficiently high sound pressure levels in a free field, and the walls of even the best anechoic room become reflective. As a consequence no free-field data were reported below 25 Hz, and most investigations did not even go down as far as that.

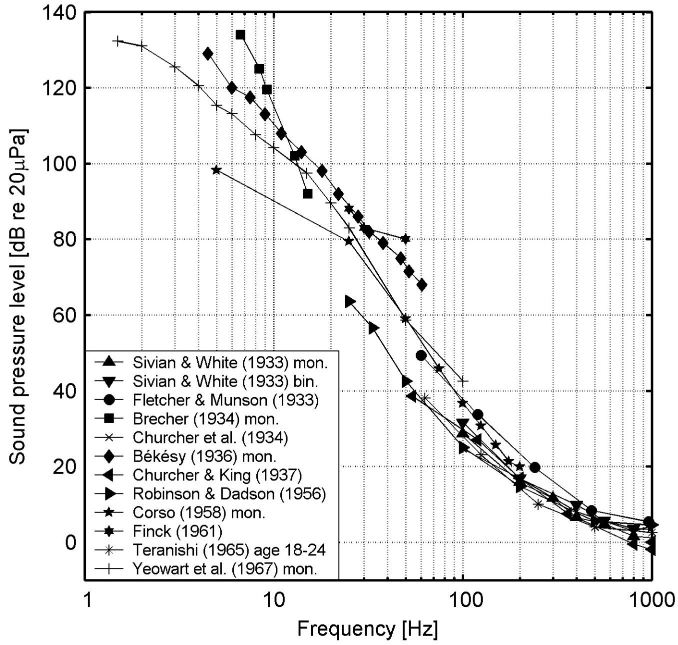

Figure 1. Low-frequency hearing thresholds measured in the period from 1933 to 1967.

Some investigators have produced the sound in a pressure chamber connected to the outer ear(s) either directly or by means of tubes. Data obtained under such conditions have been reported by Brecher (1934) (6.7-15.1 Hz, one subject, monaural), Békésy (1936) (4.5-61 Hz, one subject, monaural), Corso (1958) (5-200 Hz, 15 subjects), Finck (1961) (25-50 Hz, five subjects, binaural), Yeowart et al. (1967) (1.5-100 Hz, six to ten subjects depending on frequency, monaural) and Yeowart and Evans (1974) (5-100 Hz, five subjects, binaural). In the study by Brecher (1934) the sound was generated by a membrane driven by an eccentric wheel. Unlike other investigators, Brecher kept the level constant and varied the frequency to obtain the threshold. Békésy (1936) excited the pressure chamber by either a thermophone or a pistonphone. (A thermophone uses an amplitude-modulated alternating current to produce temperature variations in a conducting wire or foil. The surrounding air expands and contracts with the modulation, thereby creating pressure variations at the modulation frequency). The later studies used electrodynamic transducers to generate the sound.

Another group of studies used a larger pressure-field chamber that covered the entire body of the subjects. This applies to studies by Whittle et al. (1972) (3.15-50 Hz, up to 58 subjects depending on frequency), Yeowart and Evans (1974) (2-20 Hz, 12 subjects), Okai et al. (1980) (8-50 Hz, 28 subjects), Yamada et al. (1980) (8-63 Hz, 24 subjects), Nagai et al. (1982) (2-40 Hz, 62 subjects), Landström et al. (1983) (4-25 Hz, ten subjects), Watanabe and Møller (1990b) (4-125 Hz, 12 subjects), Watanabe et al. (1993) (5-40 Hz, 20 subjects) and Lydolf and Møller (1997) (20-100 Hz, 14 subjects plus nine added after publication). All studies made in whole-body pressure-field chambers used electrodynamic loudspeakers to generate the sound. Most studies had the loudspeakers mounted directly in the chamber, while in two (Whittle et al. (1972) and Yamada et al. (1980)) the sound was generated in one box that was connected to the exposure chamber by a tube. The two-box construction was used to reduce high-frequency noise from the amplifier by acoustic filtering. The exposure chamber used by Landström et al. (1983) had an opening to the outside, thereby forming a Helmholtz resonator that was tuned to the exposure frequency.

Figures 1-3 show all the thresholds that have been reported above. Although mainly frequencies below 200 Hz are considered in the present article, data up to 1 kHz are shown. Monaural and binaural data are shown as observed (i.e. with no correction), no distinction is made between data for men and women, and no distinction is made between MAF and MAP. For studies that have reported data for different

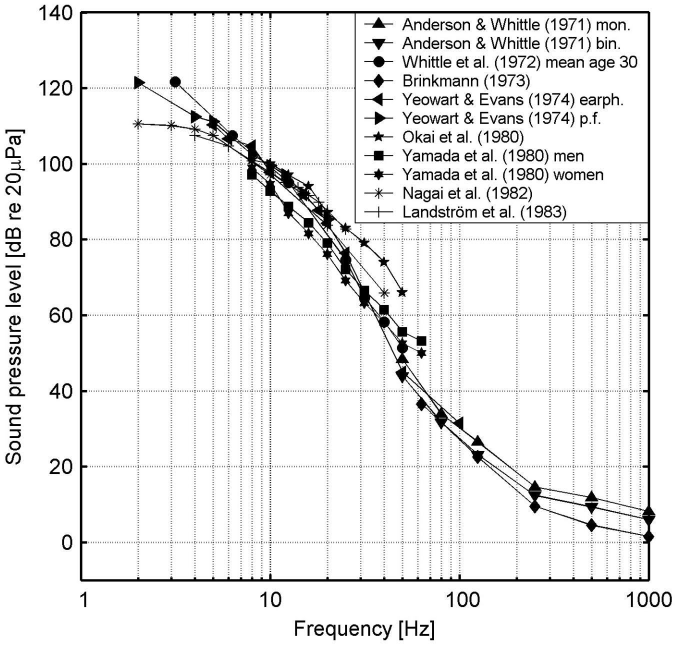

Figure 2. Low-frequency hearing thresholds measured in the period from 1971 to 1983.

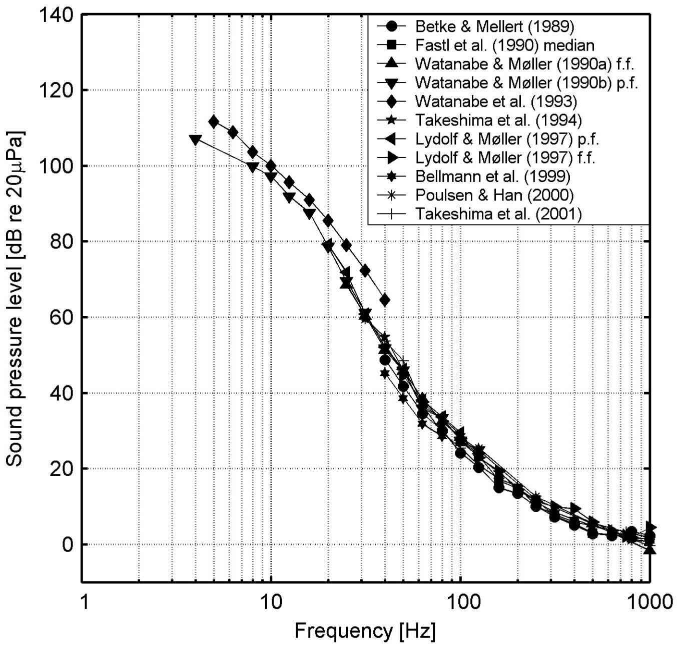

Figure 3. Low-frequency hearing thresholds measured in the period from 1989 to 2001.

age groups, the youngest group is shown (Teranishi et al. (1965), Whittle et al. (1972)).

It is obvious from Figures 1-3 that differences between investigations exist. However, one should have in mind that the data are obtained in a period of 70 years with very different techniques. Not surprisingly the largest discrepancies are found in the low and infrasonic frequency region, because it is much more difficult to produce the stimuli needed for this region. The demand on higher sound pressure levels with less harmonic distortion (due to the steep slope of the threshold curve) are difficult to meet as the production of higher sound pressure levels usually causes more harmonic distortion. Other differences between investigations can be found, e.g. in background noise level, sound field, subjects (number, age, selection process), psychometric method, instruction of the subjects, whether mean or median threshold is reported, and number of repetitions.

The differences between the investigations are so large that comparisons across investigations of the results cannot give answers to questions like

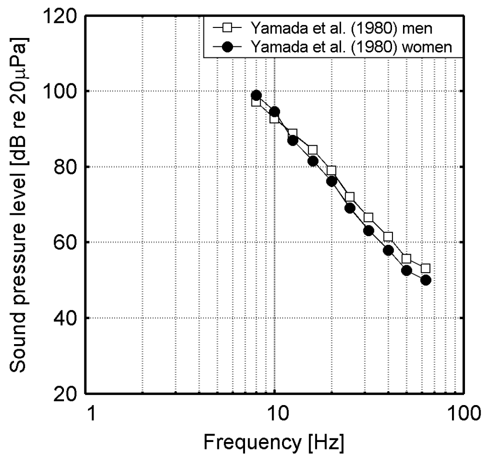

Figure 4. Low-frequency hearing thresholds for men and women.

the effect of gender, effect of age, monaural versus binaural exposure, effect of sound-field, and differences between persons. Therefore the following sections will deal with single investigations that focus on these specific issues.

Significance of gender

Most investigations have included both male and female subjects. Robinson and Dadson (1956) noted that there was no systematic difference between thresholds of men and women, but they did not show data separately for the two genders. Only Yamada et al. (1980) reported data separately. Figure 4 shows their data for the two genders. Women seem to be around 3 dB more sensitive than men except at 8 and 10 Hz, where men are around 2dB more sensitive. The standard deviation between subjects is not specified, so a statistical test cannot be performed on these data. However, large differences between persons are mentioned in the study, and when the relatively low number of subjects (16 men and eight women) is recalled, it is most likely that the differences between genders are not statistically significant.

Significance of age

Several investigations have studied thresholds for different age groups. Robinson and Dadson (1956) had many subjects in a wide age range (16-63 years), and they concluded that there was no effect of age at frequencies below 1 kHz. Consequently only data above this frequency were reported separately for different age groups. Yamada et al. (1980) mentioned threshold differences of 2-6 dB between people below and above 30 years, but he did not mention details about group sizes and age ranges, and the only original data reported are for subjects around 20 years.

Teranishi (1965) reported data separately for five age groups with 10 or 11 subjects in each group. Whittle et al. (1972) reported data for two groups, one with mean age 30 years (23 subjects) and one with mean age 47 years (35 subjects). The data from these two investigations are seen in Figure 5. This data suggests that up to 1000

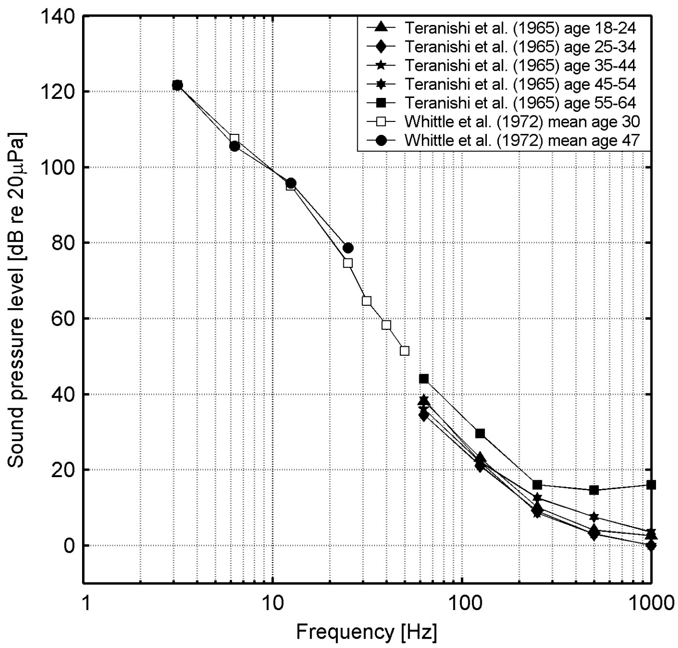

Figure 5. Low-frequency hearing thresholds for different age groups.

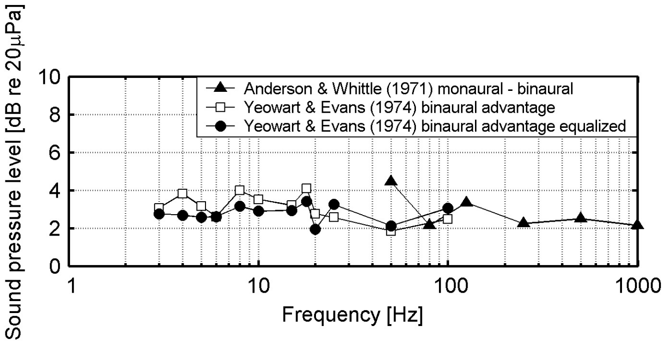

Figure 6. The difference in thresholds between monaural and binaural exposure. (The data by Yeowart and Evans (1974) marked "equalized" refer to the condition, where signals have been adjusted to obtain equal sensation at the two ears during the binaural exposure).

Hz there is no effect of age up to about 55 years.

Monaural versus binaural hearing

It is well accepted that binaural thresholds are slightly lower than monaural thresholds. The difference is called the binaural advantage, and it is said to be in the order of a few decibels, quite often around 3 dB. Some of the investigations already reported have studied the binaural advantage at low and infrasonic frequencies.

Sivian and White (1933) simply concluded that binaural thresholds were similar to monaural thresholds for the person's best ear. This was observed for only two subjects, and it was most likely too general and inaccurate. Anderson and Whittle (1971) measured for the same 10 subjects both monaural and binaural thresholds. Yeowart and Evans (1974) measured also monaural and binaural thresholds for the same group of subjects (3-4 depending on frequency). The binaural thresholds were measured in two situations, one with equal sound pressure at each of the two ears, and one where a level difference was applied between the two ears corresponding to the difference between ears in the monaural thresholds. The binaural advantage as observed in these two investigations is displayed in Figure 6 (for Anderson and Whittle (1974) calculated by the present authors as the difference between mean monaural and mean binaural thresholds). It is seen that a binaural advantage around 3 dB is probably applicable also at low and infrasonic frequencies.

Significance of sound field

Whittle et al. (1972) observed a large difference between their thresholds obtained in a whole-body pressure-field chamber and thresholds for free-field exposure given in ISO R226:1961. In order to see whether this was an effect of the sound field they also measured free-field thresholds for their own subjects. Measurements were made in four series, where the psychometric method and the set of included frequencies varied. A difference of several decibels was seen between thresholds obtained in the two sound fields. However, differences of the same order of magnitude were seen between different series in the same sound field, and no conclusion could be drawn about the effect of sound field.

Watanabe and Møller (1990b) studied for a group of 12 subjects thresholds with exposure in a free field and in a whole-body pressure-field chamber, keeping all other conditions constant. The results are shown in Figure 7. It is seen that there is a very good agreement between the two data sets in the overlapping frequency region. Thus, the data give no reason to suspect any effect of the sound field.

Do we sense with our ears?

Connected to the issue of the perception pathway is the question, whether the same thresholds are obtained if the whole body or only the ears are exposed. Yeowart and Evans (1974) measured thresholds in a whole-body chamber and with a binaural earphone. The number of subjects was not the same (12 and five respectively), and it is not stated whether there is overlap between the groups. Nevertheless, psychometric method and conditions in general were probably very similar. The data are seen in Figure 8. It is seen that the agreement between the two data sets is very

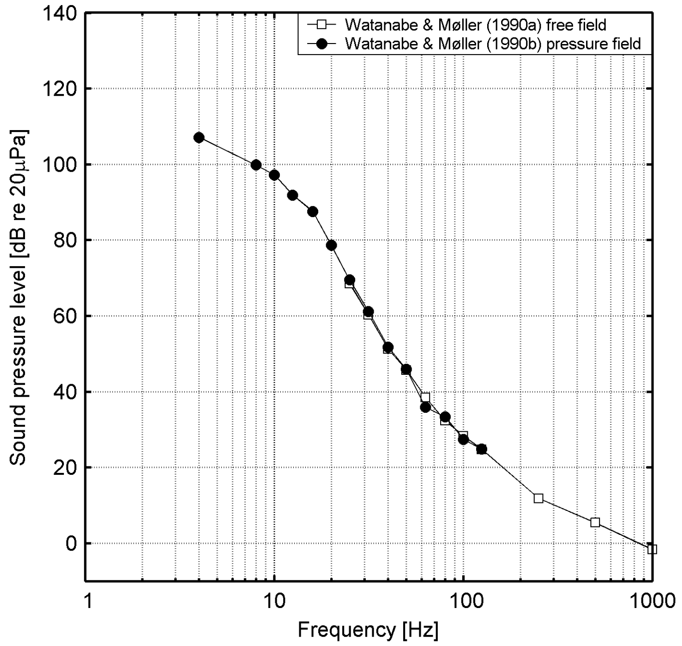

Figure 7. Low-frequency hearing thresholds measured in free-field and pressure-field conditions.

good. This supports the assumption that also these low frequencies are actually sensed by the ears.

Standardization of hearing thresholds

The first document that expresses an international agreement about the human hearing threshold is ISO R226:1961. The document covered not only the hearing threshold but also equal-loudness-level contours. Like all later standards it does not cover frequencies below 20 Hz. The bibliography of the document includes all relevant studies available at that time (Sivian and White (1933), Fletcher and Munson (1933), Churcher and King (1937), Robinson and Dadson (1956)), but data reflect only the study by Robinson and Dadson (1956).

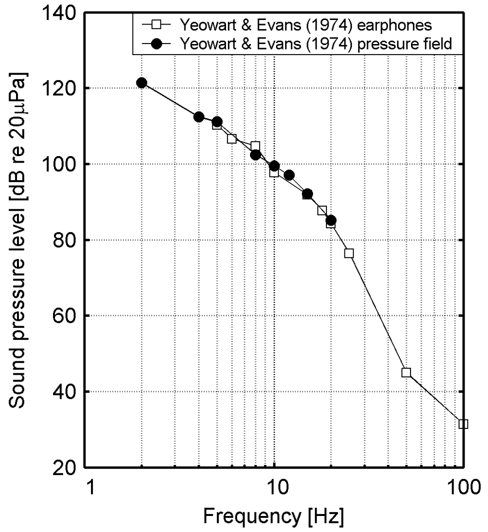

Figure 8. Low-frequency hearing thresholds measured in ear-only exposure (earphone) and whole-body pressure-field conditions.

In 1987 ISO R226:1961 was revised and issued as ISO 226:1987. The revision was a major editorial renewal, but the data were unchanged, except that they were specified at slightly different frequencies (the then new standard third-octave frequencies), and the highest frequency had been lowered from 15 kHz to 12.5 kHz. The unused studies had been removed from the bibliography.

In 1996 a standard was issued that covered only the hearing threshold and not the equal-loudness-level contours (ISO 389-7:1996). This was based on data from Robinson and Dadson (1956), Brinkmann (1973), Betke and Mellert (1989), Suzuki et al. (1989), Fastl et al. (1990), Vorländer (1991) (only frequencies above 8 kHz), Watanabe and Møller (1990a) and Watanabe and Møller (1990b). Deviations from previous standards were small (max. 3.9 dB at 20 Hz). An explanatory overview of the aggregation and processing of the data for the standard is given by Brinkmann et al. (1994).

Most recently agreement has been obtained for a complete set of hearing thresholds and equal-loudness-level contours, and a revised ISO 226

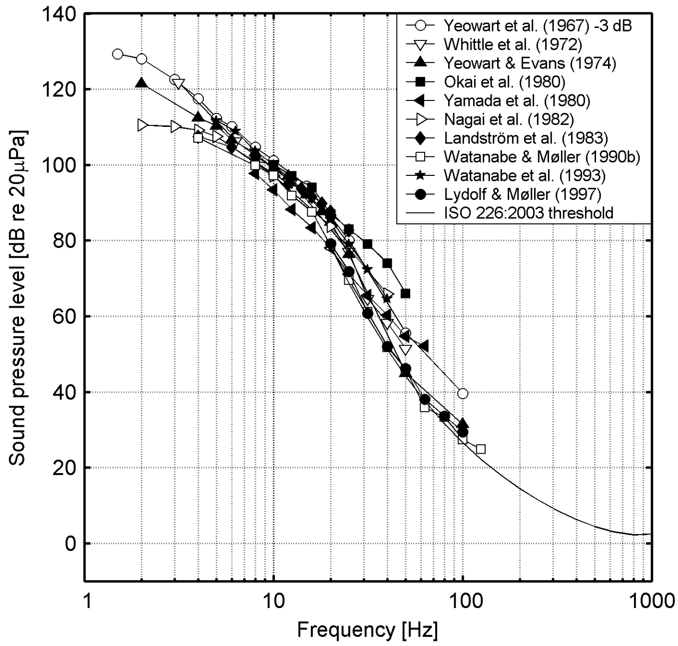

Figure 9. Standardized hearing threshold above 20 Hz (ISO 226:2003) and results from recent investigations covering frequencies at and below 20 Hz. (Whittle et al. (1972): weighted average of 30- and 43-year groups; Yeowart and Evans (1974): weighted average of ear and full-body exposures; Yamada et al. (1980): weighted average of men and women).

was issued in 2003 (ISO 226:2003). The hearing threshold is based on the same investigations as ISO 389-7:1996 with the addition of Teranishi (1965), Takeshima (1994), Poulsen and Thøgersen (1994) (only above 1 kHz), Takeshima et al. (2002) (only above 1 kHz), Lydolf and Møller (1997), Poulsen and Han (2000) and Takeshima et al. (2001). There are only small differences (max. 2.1 dB, at low frequencies max. 0.6 dB) between the threshold in this document and in ISO 389-7:1996. In order to avoid two different thresholds being standardized (although they are close), a formal revision has been initiated to make the thresholds of ISO 389-7 identical to those of ISO 226:2003.

The threshold of the most recent standard (ISO 226:2003) is included for reference in the following figures.

Proposed normal hearing threshold below 20 Hz

As no standardized hearing threshold exists for frequencies below 20 Hz, it is adequate at this place to propose a normal threshold for the lower frequencies, based on the existing data. Figure 9

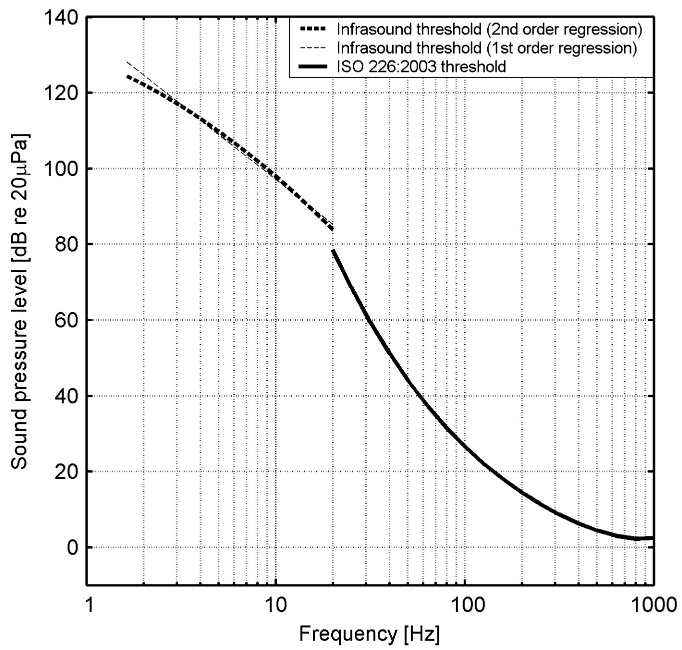

Figure 10. Standardized hearing threshold above 20 Hz (ISO 226:2003) and proposed normal hearing thresholds for frequencies below 20 Hz.

shows the most recent investigations of hearing thresholds that have data in the infrasonic frequency range, together with the hearing threshold of ISO 226:2003. (The monaural data from Yeowart et al. (1967) have been adjusted to binaural conditions by subtraction of 3 dB).

Some investigations have obtained values that are clearly too high in the 30-100 Hz range, but there is a remarkably good agreement between investigations in the 5-20 Hz range. Below 5 Hz there are very few investigations, and unfortunately they differ somewhat.

In Figure 10 the bold dashed line shows a second-order polynomial regression curve as an approximation to the data of Figure 9. As seen it does not connect precisely to the curve of ISO 226:2003. There are data that agree well with the standard (Yamada et al. (1980) and Watanabe and Møller (1990)), but other data are higher. It is not possible from the existing data material to give a definitive solution in the area around 20 Hz. The proposed curve is also somewhat uncertain below 5 Hz, where more data would be needed to give more conclusive values. Despite these uncertainties, the curve is probably correct within a few decibels, at least in most of the frequency range.

The thin dashed line gives the more coarse linear regression (approximation of a straight line). The slope of the line is 11.9 dB per octave which is very close to the 12-dB-per-octave slope of the G-weighting filter for infrasound (ISO 7196:1995). The thin dashed line corresponds to a G-weighted sound pressure level of approximately 97 dB.

Individual differences

Several hearing threshold studies have reported standard deviations between subjects. A summary of these is given in Figure 11.

In general the standard deviations between subjects are in the order of 5 dB nearly independent of frequency, maybe with a slight increase at 20-50 Hz. Only the study by Sivian and White (1933) shows considerably higher values (in the range 200-1000 Hz), a result that is most likely due to the experimental conditions in this early study.

Nagai et al. (1982) reported that out of 62 subjects 39 had a threshold that followed the general trend with increasing threshold for decreasing frequency, whereas the threshold of the remaining 23 subjects did not increase further below 5 Hz. For the latter group the threshold was claimed to flatten out or even decrease with decreasing frequency. For the same subjects no flattening was observed in

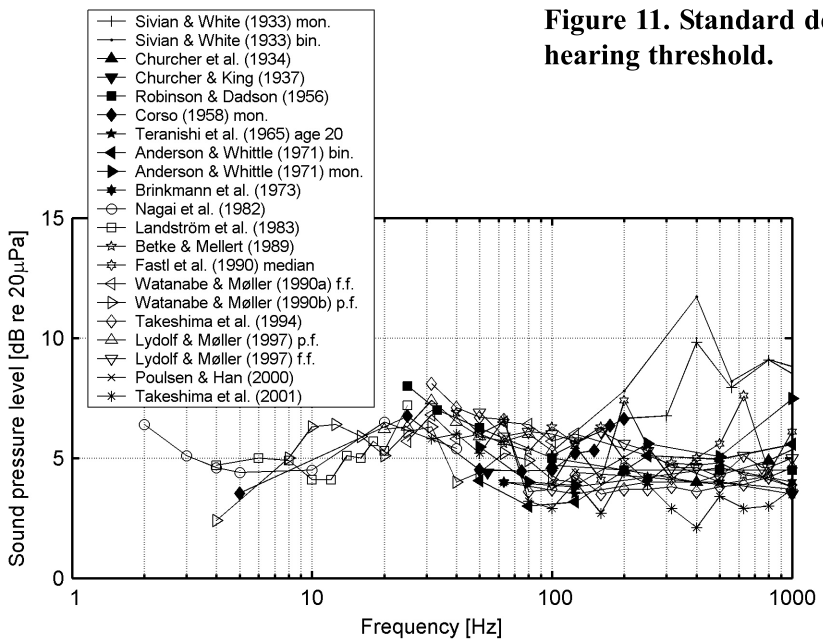

Figure 11. Standard deviations between subjects of the hearing threshold.

hearing thresholds for low-pass-filtered white noise, where data were similar to those of the rest of the subjects.

Especially sensitive persons

A few studies mention persons with extraordinary high hearing sensitivity at low frequencies. Okai et al. (1980) report of two subjects being especially sensitive to low-frequency sound, and Yamada et al. (1980) report of one subject. In addition, a subject has been observed in our laboratory with a repeatable, very low threshold (Lydolf, unpublished 1997). Figure 12 shows three of these cases compared to the ISO 226:2003 and the proposed normal threshold at infrasonic frequencies from above. (One of Okai's two subjects seems normal when compared to these data and is not shown in the figure). Assuming that the hearing threshold is normal distributed around the mean with a standard deviation of 5 dB, then the probability for a person to have a threshold around 20 dB below the mean - as seen in this figure - is extremely low, and most likely another explanation than the natural spread should be sought.

Extraordinary sensitivity to low-frequency sound might be explained by abnormalities in the person's hearing organs. A theoretical example could be an abnormally small aperture in the helicotrema at the apex of the cochlea. For low-frequency sound the helicotrema acts like a kind of pressure equalization vent for the perilymph in the cochlea, equalizing the pressure between the scala tympani and the scala vestibuli. If the helicotrema is unusually narrow or blocked, it cannot equalize the pressure fast enough, and an unusually high pressure will build up between the scala tympani and the scala vestibuli. The result is a greater mechanical excitation of the basilar membrane, and thus a higher sensitivity to these sounds is expected. For examples of simulations of the effect of the size of helicotrema see e.g. Schick (1994).

Hearing threshold microstructures

Another explanation for an apparently high sensitivity to low-frequency sound might be found in so-called microstructures in the individual hearing threshold. Frost (1987) showed that the hearing threshold as a function of frequency is not a smooth continuous line, but has peaks and dips of sometimes several decibels spread over the frequency spectrum. The irregularities were reported to be repeatable and not the result of experimental spread. An example showing microstructures in two persons' hearing thresholds is given in Figure 13. Although these particular persons do not have an especially good hearing, the microstructure is clearly seen. It is evident that for some persons the phenomenon of microstructures may lead to an extreme sensitivity at particular frequencies.

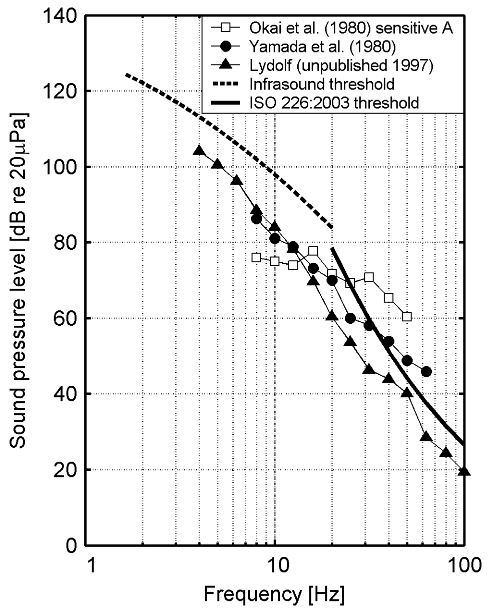

Figure 12. Hearing thresholds of three especially sensitive persons.

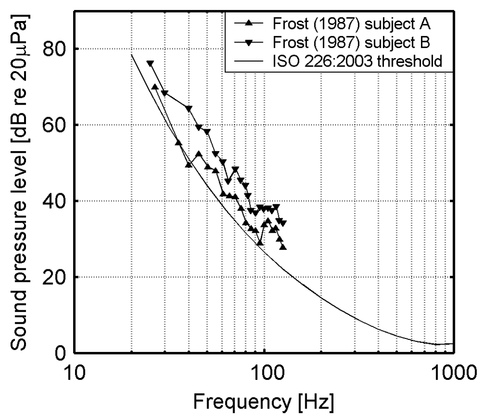

Figure 13. Example of microstructures in the hearing threshold for two persons.

Thresholds for non-sinusoidal sound

Only few threshold measurements exist for low-frequency non-sinusoidal sound. Yeowart et al. (1969) measured thresholds for octave-band-filtered random noise with center frequencies in the range 4-125 Hz and pure-tone thresholds for the same subjects. For center frequencies down to 32 Hz they found no significant difference between pure-tone thresholds and octave-band noise thresholds. In the range 4-16 Hz they found a significantly lower threshold for octave-band noise in the order of 4 dB. An explanation could have been that it is the higher frequency end of an octave band that is most audible, and comparison is then to be made with the threshold at that frequency rather than at the centre frequency of the noise band. With this explanation, the difference will be largest in the frequency range with the highest slope of the hearing threshold, i.e. 20-63 Hz. This was however not the range where the difference was seen, and the theory was thus not supported. This led to the idea, that for frequencies from 16 Hz and down, it might be the individual peaks in the sound pressure that we detect. Yeowart et al. (1969) modelled the hearing with appropriate time constants of the loudness perception and showed that the peak-detection theory could explain the 4 dB lower noise thresholds. The theory is in agreement with the subjective impression of sensing the individual oscillations at the lowest frequencies.

Nagai et al. (1982) made measurements with lowpass-filtered white noise with a lower limit of 2 Hz and upper limits of 5, 10, 20 and 40 Hz. Furthermore pure-tone thresholds were found for the same subjects. These measurements show the opposite pattern as that observed by Yeowart et al. (1969). For the random noise with upper limits of 20 and 40 Hz the threshold was lower than the pure-tone threshold (7-10 dB), but for the 2-5 Hz random noise the threshold was higher than the pure-tone threshold (about 6 dB).

Generally low-frequency and infrasonic sounds from everyday life are not pure tones alone, but rather combinations of different random noises and tonal components. It is however, impossible to make thresholds for all imaginable combinations of sounds that exist, and as seen above there is no final conclusion about possible higher or lower sensitivity to noise bands than to pure tones. Anyway, differences seem to be relatively modest, and the pure-tone threshold can with a reasonable approximation be used as a guideline for the thresholds also for non-sinusoidal sounds.

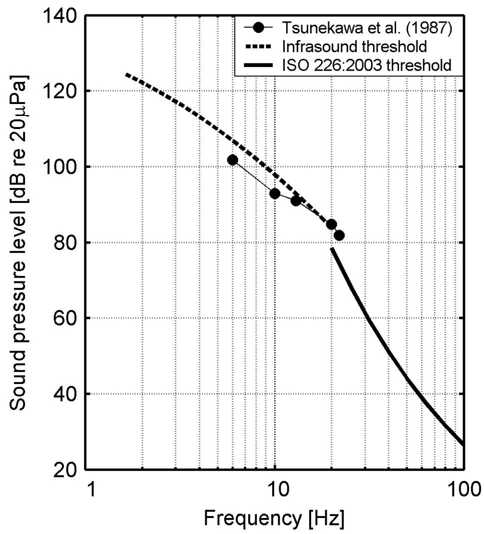

Figure 14. Hearing thresholds measured in the field by Tsunekawa et al. (1987).

Field measurements of hearing thresholds

All the investigations reported in the section 'Studies of hearing threshold' have been carried out in the laboratory. Tsunekawa et al. (1997) carried out an interesting study, where they found hearing thresholds using sound that occurred naturally in the field. They used the sound under two bridges, inside an automobile and beside some cooling towers. Of course, their resolution in frequency was determined by the frequencies that occurred naturally. While they recorded the sound they asked subjects to indicate, when the sound was audible and when it was not. They only used responses, when later analyses showed that the sound was sufficiently pure.

The results are given in Figure 14 together with the standardized threshold for frequencies above 20 Hz and the proposed normal hearing threshold for frequencies below 20 Hz. It is interesting to see how close their results are to the results obtained in the laboratory.

Non-auditory perception

As mentioned in the section 'The sensation mechanism', various attempts have been made to determine the way we sense the low and infrasonic frequencies. An investigation by Landström et al. (1983) deserves special attention. Hearing thresholds were measured for 10 normal-hearing subjects (five of each gender). Furthermore vibrotactile thresholds were measured for the same subjects and for 10 subjects with complete perceptive or sensory-neural deafness. The vibrotactile sensation was described as soft vibrations in different parts of the body, mostly in the lumbar, buttock, thigh and calf regions.

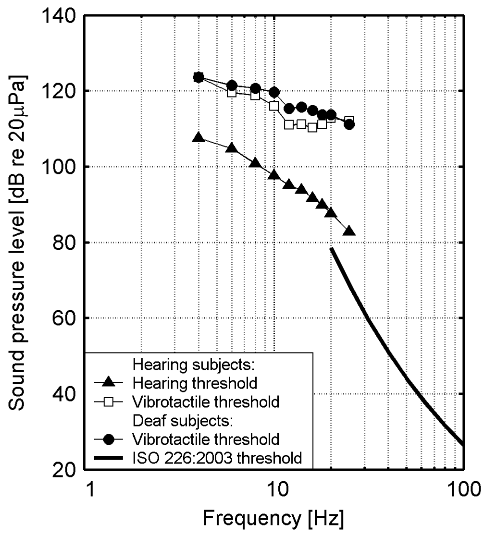

Figure 15. Hearing and vibrotactile thresholds as measured for hearing and deaf subjects by Landström et al. (1983).

The results from Landström et al. are given in Figure 15. It is seen that the vibrotactile thresholds are very similar for the hearing and the non-hearing groups. This suggests that the hearing subjects were really able to distinguish between the two sensations. The findings also support the idea that the sense of hearing is the primary sense for detecting the presence of sound at low and infrasonic frequencies. On the other hand, the results suggest that an additional way of sensation connected to vibration occurs at levels that are only 20-25 dB above the hearing threshold.

Spontaneous reactions from subjects and visitors in the authors' laboratory as well as their own experience suggest that vibrotactile sensations and a feeling of pressure may also occur in the upper part of the chest and in the throat region.

Studies of equal-loudness-level contours

Loudness is a measure of the subjectively percieved intensity of sound. The unit of *loudness level* is phon, and for a given sound it has the same numerical value as the sound pressure level (in dB relative to 20 µPa) of an equally loud reference sound. The reference sound consists of a frontally incident, sinusoidal plane wave at a frequency of 1 kHz. An equal-loudness-level contour is a curve in the sound pressure level versus frequency plane that represents tones of the same loudness level. Most studies are made with the reference tone held at a constant level, while some psychometric procedure is used to find the level of the test tone that makes the two tones appear equally loud to the subject. A few studies have used fixed levels of the test tone and varied the level of the reference tone, in which case interpolation is needed to obtain equal-loudness-level contours.

Initially, it should be mentioned that Kingsbury (1927) was one of the first to attempt measurements of equal-loudness-level contours. However, he used a monaural earphone, and no attempt was made to calibrate it to free-field conditions, thus his results will not be further reported here. Churcher et al. (1934) also made some early studies of loudness, but they used a reference tone of 800 Hz and a mixture of free-field and earphone exposures, thus their results will also not be reported further.

One of the best known studies of equal-loudness-level contours is the early one by Fletcher and Munson (1933). They reported data for the frequency range 62 Hz-16 kHz and loudness range 10-120 phon, based on measurements with 11 subjects. The measurements were performed using earphones, but since these were calibrated to free-field conditions, their data are considered relevant and will be included in the following. (In the review of hearing thresholds given above, studies that used audiometric earphones were excluded due to the risk of interference from physiological noise. This is not considered a problem for loudness comparisons, which take place at levels somewhat above threshold).

Most studies have determined points of equal-loudness-level directly according to the definition, i.e. through comparisons of the test tone and the reference tone in a free or an approximately free field. This applies to the studies of Churcher and King (1937) (54 Hz-9 kHz, 10-90 phon, up to 30 subjects depending on frequency and level), Betke and Mellert (1989) (100 Hz-1 kHz, 30 phon; 50 Hz-12.5 kHz, 40, 50 and 60 phon, 28 subjects), Suzuki et al. (1989) (125 Hz-8 kHz, 40 and 70 phon, 23 subjects; 63 Hz-12,5 kHz, 20 phon, ten subject), Fastl et al. (1990) (100 Hz-1 kHz, 30, 50 and 70 phon, 12 subjects), Watanabe and Møller (1990a) (25 Hz-1 kHz, 20, 40, 60 and 80 phon, 12 subjects), Lydolf and Møller (1997) (50 Hz-1 kHz, 20, 40, 60, 80, 90 and 100 phon, 27 subjects), Takeshima et al. (1997) (31.5-12.5 kHz, 20, 40, 50, 60, 70 and 90 phon, 9-30 subject depending on frequency and loudness level), Bellmann et al. (1999) (100 Hz-1 kHz, 60 phon, 12 subjects) and Takeshima et al. (2001) (50 Hz-16 kHz, 20, 40 and 70 phon, eight subjects).

For the lowest frequencies it is a practical problem to create sound in the same room as the reference tone (anechoic room) at sufficiently high level without significant harmonic distortion. It will be noted that none of the free-field studies mentioned in the previous paragraph had frequencies below 25 Hz, and most studies did not even go that far down. Furthermore, it is often mentioned that it is difficult for subjects to compare tones that are very distant in frequency. Some investigators have overcome these problems by making indirect loudness matches to the 1 kHz reference tone. Points of equal loudness are determined at a low-frequency anchor point of for example 100 Hz through direct comparisons with 1 kHz in an anechoic room. Then the 100 Hz points are used as new references for loudness matches in a pressure-field chamber, where large sound pressure levels can be produced at the lowest frequencies.

Studies that used exposures in pressure field in combination with individual anchor points determined in free field comprise those of Kirk (1983) (2-63 Hz, 20, 40, 60, 80 and 100 phon, anchor points at 63 Hz, 14 subjects), Møller and Andresen (1984) (2-63 Hz, 20, 40, 60, 80 and 100 phon, anchor points at 63 Hz, 20 subjects), Lydolf and Møller (1997) (20-100 Hz, 20, 40, 60, 80 and 100 phon, anchor points at 100 Hz, 14 subjects plus three added after publication) and Bellmann et al. (1999) (16-160 Hz, 60 phon, anchor points at 100 Hz, 12 subjects).

Two studies used experimental designs equivalent of using non-individual anchor points. Robinson and Dadson (1956) measured equal-loudness relations for the frequency range 25 Hz-15 kHz (up to approximately 130 phon and up to 120 subjects depending on frequency). Free-field conditions were used for the higher frequencies, while a suitably terminated duct was used for the lowest frequencies. At the lowest frequencies they used reference tones of 50 or 200 Hz that were converted into phon by means of interpolation in the data material from the free field. Whittle et al. (1972) used a pressure field for their experiments (3.15-50 Hz, up to 32 subjects depending on frequency). They used a reference tone at 50 Hz at three levels (60, 73 and 86 dB) without measuring the connection to 1 kHz. Subsequently they used ISO 226:1961 to find the standardized loudness levels of their reference tones and labelled the contours accordingly (33.5, 53 and 70.5 phon).

Figures 16-18 show the equal-loudness-level contours measured in the investigations mentioned above. It should be noted that the data from Fletcher and Munson (1933) and Robinson and Dadson (1956) are not original data, but data interpolated between original data points. For the data by Whittle et al. (1972) the authors have taken the liberty of plotting them as 20, 40 and 60 phon, respectively, since these loudness levels seem more reasonable than the original labels of 33.5, 53 and 70.5 phon when comparing with the other data in the same frequency area.

The figures clearly show large differences between equal-loudness-level contours from

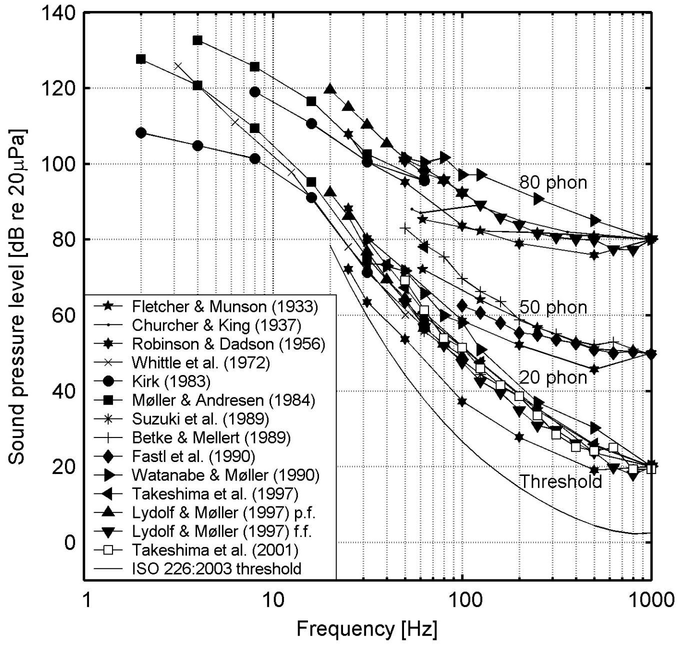

Figure 16. Low-frequency equal-loudness-level contours for 20, 50 and 80 phon.

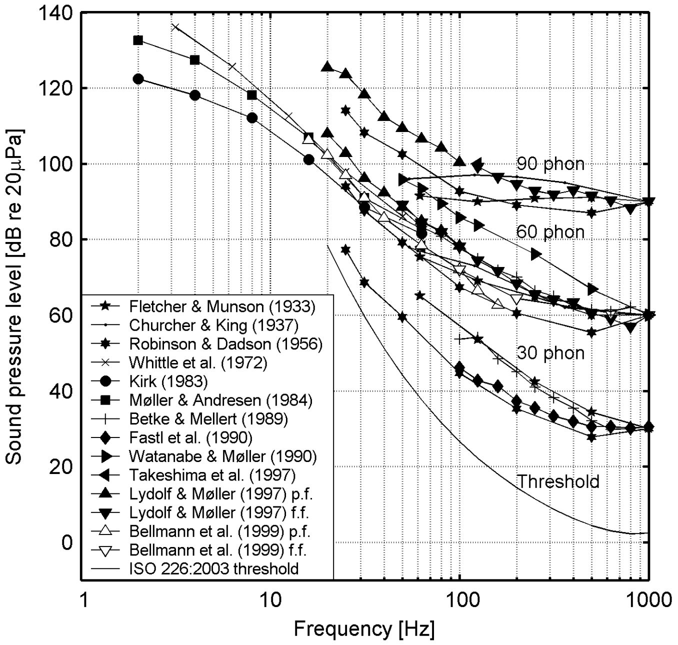

Figure 17. Low-frequency equal-loudness-level contours for 30, 60 and 90 phon.

different investigations. These differences are not only in the low-frequency region but also at higher frequencies.

Standardization of equal-loudness-level contours

The first international standard about equal-loudness-level contours is ISO R226:1961. The contours in this were solely based on the study by Robinson and Dadson (1956), despite the fact that also other studies were present at that time. As already mentioned in the section on standardization of hearing thresholds, the document was revised and issued as ISO 226:1987, however without changes in data.

Virtually all other investigations show data that are significantly higher than those of Robinson and Dadson (1956) in the frequency area below 1 kHz. The difference has been ascribed to the different psychometric methods used. The data from Robinson and Dadson seem significantly biased towards lower levels. Awareness of bias problems and the use of computerized adaptive psychometric methods in later studies have provided data that are believed to be more reliable.

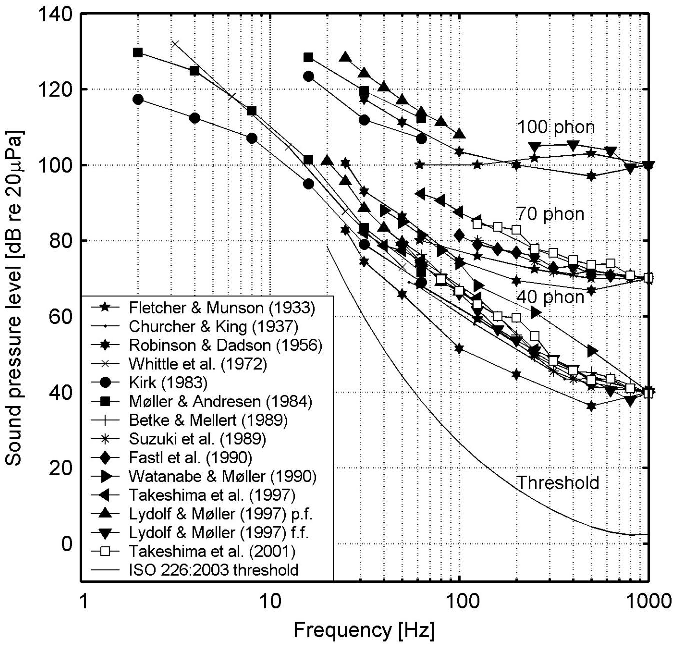

Figure 18. Low-frequency equal-loudness-level contours for 40, 70 and 100 phon.

Most recently agreement has been obtained for a complete set of hearing thresholds and equal-loudness-level contours, and a revised standard has been issued (ISO 226:2003). Below 1 kHz the equal-loudness-level contours are based on the investigations by Kirk (1983), Møller and Andresen (1984), Betke and Mellert (1989), Suzuki et al. (1989), Fastl et al. (1990), Watanabe and Møller (1990), Lydolf and Møller (1997), Takeshima et al. (1997), Bellmann et al. (1999) and Takeshima et al. (2001).

Figure 19 shows the standardized equal-loudness-level contours for the frequency range below 1 kHz, and the difference between the two old and the new standard is obvious.

Proposed normal equal-loudness-level contours below 20 Hz

No standardized equal-loudness-level contours exist for frequencies below 20 Hz, and only four investigations provide data in this frequency region. Whittle et al. (1972) and Møller and Andresen (1984) produce quite similar contours, and the two points provided by Bellmann et al. (1999) at 60 phon, 16 and 20 Hz, fit well with these. The contours by Kirk (1983) deviate considerably, and the authors take the liberty of disregarding these data in the following. The contours from the three other investigations are shown in Figure 20. Based on these data the authors have presented their best guess of general contours of 20, 40, 60 and 80 phon for frequencies below 20 Hz in Figure 21. However, these contours should be taken with great reservation because of the sparse amount of data and the uncertainty connected to the exact phon values they should be labelled with. On the other hand it seems beyond any doubt that the contours are very close in this frequency region.

More definite contours at low and infrasonic frequencies - in particular at high loudness levels - require that more experimental data become

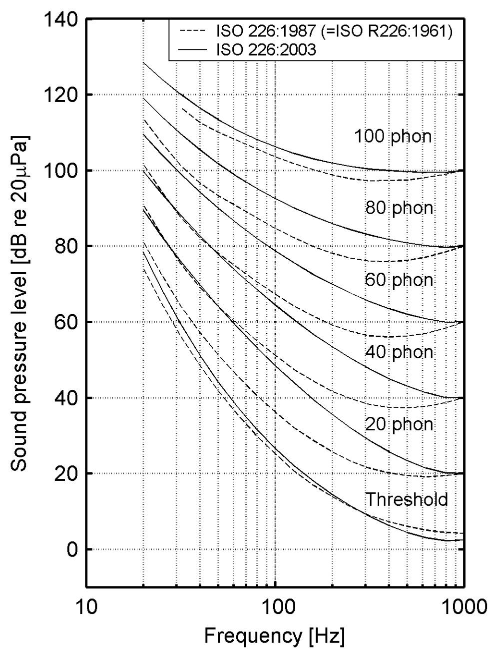

Figure 19. Standardized equal-loudness-level contours.

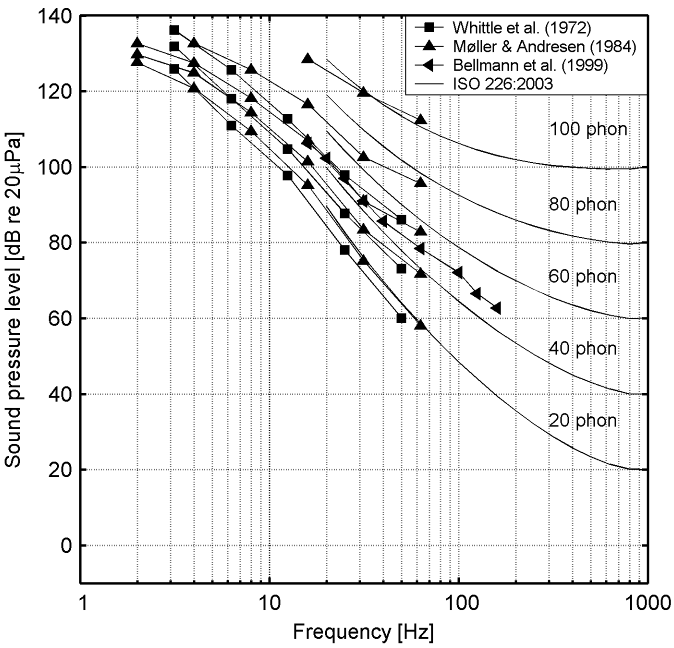

Figure 20. Standardized equal-loudness-level contours above 20 Hz and results from investigations covering frequencies at and below 20 Hz.

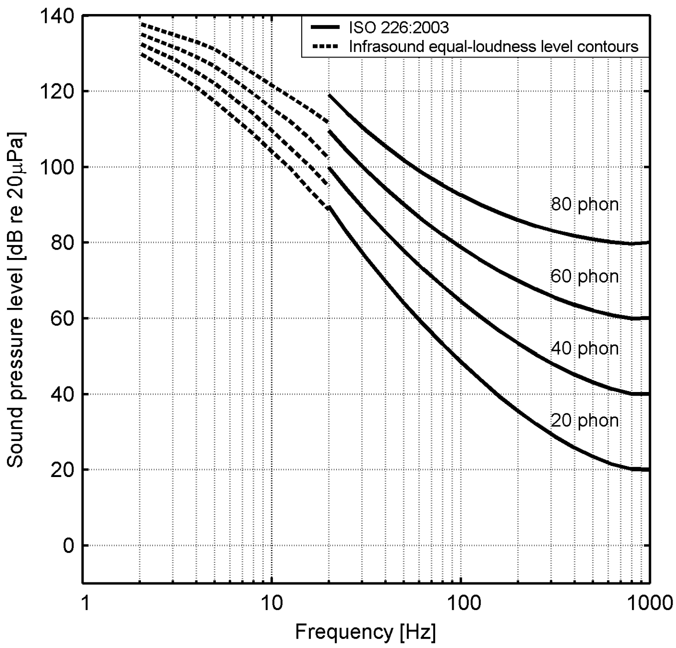

Figure 21. Proposal of equal-loudness-level contours for the infrasonic region together with standardized contours above 20 Hz.

available. Unfortunately, it is not a trivial task to produce the high sound pressure levels needed without significant harmonic distortion.

Conclusion

The human perception of sound below 200 Hz has been reviewed, and on the basis of results from various investigations it is possible to draw some general conclusions.

The hearing becomes gradually less sensitive for decreasing frequency, but there is no specific frequency at which the hearing stops. Despite the general understanding that infrasound is inaudible, humans can perceive sound also below 20 Hz. This applies to all humans with a normal hearing organ, and not just to a few persons. The perceived character of the sound changes gradually with frequency. For pure tones the tonal character and the sensation of pitch decrease with decreasing frequency, and they both cease around 20 Hz. Below this frequency tones are perceived as discontinuous. From around 10 Hz and lower it is possible to follow and count the single cycles of the tone, and the perception changes into a sensation of pressure at the ears. At levels 20-25 dB above threshold it is possible to feel vibrations in various parts of the body, e.g. the lumbar, buttock, thigh and calf regions. A feeling of pressure may occur in the upper part of the chest and the throat region.

There is a reasonable agreement between studies of hearing thresholds. For frequencies down to 20 Hz, a normal threshold has been standardized by ISO, and the present article presents a proposed normal threshold one decade further down in frequency. The proposed curve corresponds roughly to a G-weighted sound pressure level of 97 dB. More data are needed to give a more conclusive curve.

It cannot be finally concluded whether thresholds for noise bands are the same as pure-tone thresholds. Below 20 Hz it is possible that the peak sound pressure determines the sensation. The differences are small, though, and it seems reasonable to use the pure-tone threshold as a guideline also for non-sinusoidal sound.

The hearing threshold is the same for men and women. Degradation with age takes place only above 50 years. The threshold is the same in free and pressure field. Like at higher frequencies, the binaural advantage is around 3 dB, and the standard deviation between individuals is around 5 dB. However, there is evidence of individuals that have a hearing that is much better than normal (several times the standard deviation away from the mean). It has also been shown that the hearing threshold may have a microstructure that causes a person to be especially sensitive at certain frequencies. These two phenomena may explain observations from case studies, where individuals seem to be annoyed by sound that is far below the normal threshold of hearing. It should be stressed that the explanation has not been confirmed in specific cases.

Thresholds are the same, whether the whole body or just the ears are exposed, thus is can be concluded that the sensation takes place in the ears even at frequencies below 20 Hz. However, it is not totally clear, whether the sensory pathway for infrasound is the normal pathway for hearing. The observation that deaf people can only detect infrasound through vibrotactile sensation - and for that they have the same threshold as normal-hearing persons - suggests that the normal auditory system is used. A hypothesis that these frequencies are heard in terms of harmonic distortion in the ear is not supported.

In addition to direct detection, infrasound may be detected through amplitude modulation of sound at higher frequencies. This modulation is caused by the movement of the eardrum and middle-ear bones induced by the infrasound, which results in changes of transmission properties. At very high levels, modulation of speech can occur due to a pulsating airflow in the throat caused by the sound.

The perceived intensity of the sound rises more steeply above threshold than at higher frequencies. This is especially pronounced for frequencies below 20 Hz, where a sound only few decibels above threshold may be perceived as quite intense. Combined with the natural spread in thresholds, this may have the effect that a sound, which is inaudible to some people, may be loud to others. The compression of the dynamic range of the auditory system is reflected in the equal-loudness-level contours. Such contours have been standardized for frequencies down to 20 Hz, but there is a reasonable agreement between data also below this frequency, and contours have been proposed down to 2 Hz. However, this is based on only few investigations and more data are needed.

Acknowledgements
The authors want to thank their local and international colleagues for fruitful discussions about our perception of low frequency sound. Many discussions have taken place in an international collaboration on the loudness function, the NEDO project, which was only made possible thanks to the effort of Professor Yoiti Suzuki, Tohoku University, Japan. We also want to thank our former colleague, Morten Lydolf, who started the aggregation of the large amount of data and made it available to us. The work was supported by the Danish Technical Research Council and Aalborg University.

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