A Detailed Study of Low-Frequency Noise Complaints

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ABSTRACT
From 203 cases of low-frequency complaints a random selection of twenty-one cases were investigated. The main aim was to answer the question whether the annoyance is caused by an external physical sound or by a perceived but physically non-existing sound, i.e. low-frequency tinnitus. Noise recordings were made in the homes of the complainants, and the complainants were exposed to these in blind test listening experiments. Furthermore, the low-frequency hearing function of the complainants was investigated, and characteristics of the annoying sound were matched. The results showed that some of the complainants are annoyed by a physical sound (20-180 Hz), while others suffer from low-frequency tinnitus (perceived frequency 40-100 Hz). Physical sound at frequencies below 20 Hz (infrasound) is not responsible for the annoyance - or at all audible - in any of the investigated cases, and none of the complainants has extraordinary hearing sensitivity at low frequencies. For comparable cases of low-frequency noise complaints in general, it is anticipated that physical sound is responsible in a substantial part of the cases, while low-frequency tinnitus is responsible in another substantial part of the cases.

1. INTRODUCTION

Many cases of noise annoyance deal with noise that has a significant content of low frequencies. The complainants typically describe the noise as "rumbling". Among the sources are compressors, ventilation systems, and slow-running or idling engines. The cases are often solved, either by use of traditional noise limits and measurement methods, or by use of special low-frequency procedures as introduced by some countries: Austria [1], Denmark [2] (explained in [3]), Germany [4], Poland [5] (explained in [6]), The Netherlands [7], Japan [8] (explained in [9]), Sweden [10] (criteria) and [11] (measurement procedure, translated and explained in [12]).

However, there is a group of cases where persons claim to be annoyed by rumbling noise, but where they are not helped in a way that they find satisfactory. This often leads to repeated complaints, anger at authorities, feeling of helplessness, and reports in the daily press. To a certain extent, these cases have some common characteristics. There is often no obvious noise source, and often only one or a few persons are annoyed. Many of the cases are in areas that are generally quiet, and, if measurements are made, they often show low values.

Because of these circumstances, it is often mistrusted that a real, physical sound is the cause of the annoyance. One explanation could be that the annoyed persons suffer from an internal sound. Such phenomenon is referred to as ***tinnitus*** (*"the sensation of sounds in the ears, head, or around the head in the absence of an external sound source"* [13]; "*the perception of a sound in the absence of any external sound applied to the ear"* [14]). Tinnitus may arise from abnormal activity at several different points in the auditory system, but the exact mechanisms are not fully understood, and tinnitus may occur in individuals with otherwise normal hearing [15], [16], [17], [18], [19], [20]. If the annoyance is caused by a real, physical sound, an explanation could be an unusually low hearing threshold of the annoyed person. The individual growth of loudness above threshold and/or the individual sensitivity to noise may also play a role.

It cannot be excluded that some cases are simply poorly investigated, and that they could have been solved by traditional means, if they had only been given proper attention. In that connection, it may play a role that some complainants use the term *infrasound* for the noise. Since it is usually believed that infrasound cannot be heard, the mere use of this term may have the effect that the complainant is considered less trustworthy, and that, as a consequence, the further handling of such cases is stopped or impeded. This seems to happen sometimes, even when it has been known for long that infrasound is audible, when it is sufficiently intense (review in [21]), and even when it cannot be taken for granted that the annoyed person will know, whether the frequency of a sound is below or above 20 Hz (20 Hz is usually taken as the upper limit of the infrasonic range [22]).

1.1 Previous studies

The literature has many reports of single or few cases of low-frequency noise problems (e.g. [23], [24], [25], [26], [27], [28], [29], [30], [31], [32], [33], [34], [35], [36], [37], [38], [39]). Some are of an anecdotal character, in particular those reported in the daily press. Only few systematic studies of many cases have been made.

For 48 complainants, Walford [40] distinguished between physical sound and internal sound by having the complainants listen to the annoying sound with and without earmuffs. No sound measurements were made. Prior to the test, each complainant had, in the laboratory, adjusted an artificial sound to have the same pitch as the annoying sound, and selected an earmuff that clearly attenuated the artificial sound. The matched sounds were in the 16-196 Hz range. Sargent [41] made a comprehensive study including questionnaires filled out by 295 complainants. Twenty-six of these were selected for further investigations, in which they adjusted an artificial sound to the best possible match of the annoying sound. In an attempt to identify the annoying sound, comparisons were made with noise measurements in their homes. Furthermore, ten of the selected complainants had audiological testing. Berg [42] made noise measurements in nineteen cases of low-frequency noise complaints and compared third-octave levels with national criteria of Sweden [43] and Germany [4], proposed criteria by Vercammen [44], and the normal hearing threshold for pure tones [45]. A German study (anonymous [46]) made noise measurements in thirteen cases of low-frequency noise complaints, and compared low-frequency third-octave levels with individual pure-tone hearing thresholds for the complainants. Moorhouse et al. [47] (also reported by Waddington et al. [48]) investigated eleven cases of low-frequency noise complaints by comparing logs of the occurrence of annoying sound as perceived by the complainants with certain noise events and the time course of certain frequencies as observed in noise recordings.

It is important to note the scope of a particular investigation and be aware of a pertinent interpretation of the results. Comparisons with existing criteria are adequate to show if noise abatement is justified with a legal background, while comparisons with the hearing threshold may tell whether there is an audible sound or not. However, due to loudness summation in critical bands, there is significant uncertainty connected to comparisons of third-octave levels with pure-tone hearing thresholds (normal or individual). Of the five larger studies, only the correlation study [47] tried to demonstrate a causal relationship between the measured noise and the annoyance. Except for an early study of two cases [23], none of the studies reproduced the measured sound to the complainants to get a direct confirmation that they were in fact measuring the annoying sound.

A special challenge to such studies relates to the method used for measuring the sound. Particularly at low frequencies, standing waves result in significant frequency dependent variation in sound level within a room, and, in a single measurement position, certain frequencies may be badly represented {Pedersen, Møller, et al. 2007 1780 /id} [49]. Only few of the investigations mentioned have dealt with the standing wave problem in a systematic way, e.g. by measuring in more than a single position.

1.2 Present study

In our department, we have previously registered about 200 cases of low-frequency noise annoyance [50], [51]. It was the objective of the present study to investigate a random sample of these thoroughly and, if possible, explain every single case. Since a variety of explanations might exist, it was considered important to include more than just a few cases, so that some general conclusions could possibly be deducted from the results. Despite the extensive resources needed in each case, it was decided to investigate 22 cases[1].

A key issue was to answer the questions, whether the annoyance was caused by a physical sound or not, and if it was, which frequencies were responsible. Recordings were made at the place, where the annoyance occurred, and played back to the complainants under controlled conditions in the laboratory. The frequency range covered was 2-350 Hz, and the tests made use of a special low-frequency exposure facility in our laboratory [52]. Blind tests were used to reveal, if the complainants could hear the sound from their home. For those who could, recognition tests were performed in order to show, if the recorded sounds were similar to the annoying sound. Based on the outcomes of these tests, complainants can be divided into the following three categories:

1. The complainant could hear the recorded sound and reported that it resembled the annoying sound.
2. The complainant could hear the recorded sound but reported that it did not resemble the annoying sound.
3. The complainant could not hear the recorded sound.

For the first and last categories, natural conclusions are that the annoyance felt at home is caused, or respectively not caused, by a physical sound. For complainants who fall into the second category, there is no obvious and straightforward conclusion, and it may not be possible to make a final conclusion.

For the sounds that were heard, blind tests and recognition tests were made for the sounds divided into four frequency sub-bands in order to reveal, which frequencies are audible and possibly responsible for the annoyance.

The laboratory tests of the complainants also comprised examination of their low-frequency hearing (thresholds and loudness function). In addition, attempts were made to identify characteristics of the annoying sound by playing artificial sounds (tones and noise bands) with various frequencies and levels.

The recordings were made at the place where the annoyance occurred, which in all cases means at home and indoors. Since measurements in single positions in general are insufficient and may virtually fail to reveal certain frequency components [49], recordings were made in many positions in the room. The recordings were not only used in the laboratory test, but also analyzed and compared to environmental criteria in Denmark and Sweden.

It was not within the scope of the study to point at a particular noise source or to enter the individual cases to obtain a reduction of the noise. However, the subjects were informed about the findings in their own case and given copies of the measurement results, which they can use for possible further initiatives.

The recordings were made in the period from August 2003 to December 2004. Due to an unfortunate error in the ventilation system of the exposure facility and even more unfortunate delays in the repairing of it, the laboratory tests had to be

[1] One subject withdrew before the laboratory tests, so the final study comprised 21 subjects.

postponed several times. They were finally carried out during the spring and summer of 2006, when all subjects were invited to Aalborg to participate, each for a full day.

2. METHODS

2.1 Subjects

Twenty-two subjects were selected from the group of 203 persons who had responded in our previous survey on low-frequency noise problems [50] (full report in Danish in [51]). Twenty subjects were selected randomly, while two were selected because of long-term contact with the university. Before the selection process, 69 persons were removed from the original group (30 persons who had already reported that the problem was solved by noise reduction, because they had moved or for other reasons, 30 persons with whom we had lost contact, and 9 persons for various other reasons). A substitute was selected, if a selected person was not annoyed any more (happened 12 times), or did not want to or was unable to participate (happened 22 times). Constraints were put to the random selection in order to keep the geographical and gender distributions close to those of the original group.

Unfortunately, one subject withdrew from participation just before the laboratory experiments. At that time, it was not possible to have a replacement, and the experiment ended up having only 21 subjects.

The final group of subjects had 38.1% men (34.8% in the original group), 52.4% were from places with zip codes below 3700 (roughly Copenhagen and North Zealand) (53.2% in the original group), and the average age (at the time of submitting the questionnaire) was 53.5 years (55.5 years in the original group). All subjects had reported in the questionnaire that they sense the sound with their ears (98% in the original group), five subjects had reported that they are the only person who can hear the noise, and 13 had asked authorities for help, most of them more than once.

All subjects were examined by an otolaryngologist on the same day as the laboratory experiments took place. These examinations included otomicroscopy, pure-tone and impedance audiometry and caloric testing. The subjects were found otoneurologically normal except for one case of preponderance, two cases of minor left side relative hearing loss, four cases with a dip at 6 kHz indicating a noise induced hearing loss and one case of presbyacusis. One subject (subject O) mentioned at the laboratory tests that the annoying sound had disappeared some time ago, possibly after some changes had been made at a suspected noise source.

2.2 Recordings

Recordings were made in the home of each subject in the room where the noise was most annoying, usually the living room or bedroom. The main power was turned off, the windows were closed, and all subjects confirmed that the sound was still present before the recordings were made. Many of the subjects reported that the noise was not always equally loud, and measurements were only made, if it was clearly audible to them. If possible, the subjects were present during the recordings or showed up now and then to confirm that the noise had not disappeared. All subjects except two (subjects K and Q) confirmed the presence of the sound again at least at the end of the measurements. The recording equipment and all persons were outside the room during the recordings.

In all cases, there were disturbing sounds like of passing cars, distant agriculture machinery etc., which were clearly audible. The subjects were asked to identify these sounds, and all subjects confirmed that they were not part of the annoying low-frequency noise. Recordings often had to be repeated or even postponed for hours, days, or even longer periods, if the annoying sound was not present or when there were too many disturbances. Many recordings had to be made in the evening or at night. Recordings were not made on days with rain or with disturbing wind (nearest official measurement < 7 m/s, usually much lower (open area 10 m height, 10-

minute average), much less at the place of measurement).

The problem with standing waves at low frequencies was addressed by recording in 20 microphone positions in each room. The microphone positions were chosen in such a way that it was possible to obtain several outcomes of the Danish [2] and Swedish [11] measurement methods. Measurement positions also comprised three-dimensional corners (3D corners), which reflect better the levels that persons in the room may be exposed to [49]. For details on the measurement methods, see Appendix A.

A four channel recording system (01 dB Harmonie with four GRAS type 40 EN one-inch microphones and type 26AK preamplifiers, combined -3-dB lower limiting frequency below 1 Hz, 6400 Hz sampling frequency) was used. Recordings were made in four positions at a time, thus all recordings were made in five recording periods. Each recording period was three minutes, and attempts were made to have as few disturbances as possible, so that shorter "clean" periods could be found later for use as stimuli and for analysis. This was a time consuming task, and very often recordings had to be repeated due to disturbances. Measurements in one home took from a few hours to more than a full day.

2.3 Analysis of recordings and selection of stimuli

Periods of the recordings without disturbing sounds like passing cars etc. were found by listening to the sound (often at higher than natural level) aided visually by spectrograms. These periods were analyzed further using spectrograms and third octave-band analyses as well as listening, and representative 5-second periods were selected for use as stimuli in the blind tests and recognition tests. Linear fade-in and fade-out ramps were applied over the first and last 0.5 s. The stimuli were chosen in such a way that prominent low-frequency components of the recorded noise were represented at the highest levels found in each home. At least two stimuli were chosen for each case, one from a 3D corner and one from another position, but in several cases, it was necessary to include more than two stimuli. The stimuli are denoted *Sl*, *S2* etc.

In addition, a single stimulus was used for all subjects. This stimulus was chosen by the experimenters as a stimulus that fitted well with typical descriptions of the annoying sound as given by complainants. The stimulus was from the home of subject B, and in the following, it is denoted *REF*.

Subjects P and Q were neighbours and believed to be annoyed by the same sound. They appointed rooms only separated by a common wall. However, the recorded sounds differed somewhat; there was a very clear 100 Hz tone in the recordings from subject P, while, in the recordings from subject Q, such component did exist, but it was not particularly prominent. Subject Q was one of the two who did not confirm the presence of the sound during or after the recordings, and a recording from subject P was therefore included in the blind test of subject Q (as S4).

An example of the analysis and the selection of a stimulus is given in the following. Figure 1 shows spectrograms of recordings in four different microphone positions in the same time interval. Since the hearing threshold varies considerably with frequency in the low-frequency range, the sound pressure level of each spectral component has been weighted relative to the normal hearing threshold. The threshold weighting of the spectrograms helps to identify frequency components that are potentially audible, but the spectrograms cannot directly show if they are audible or not, since that depends on, how the frequency components are summed by the hearing function (critical band concept).

The noise from a passing car is seen as a vertical line at about 90 seconds. From listening to the recordings assisted by the spectrograms, the period 0-52 seconds was found as relatively undisturbed. For this period, more detailed spectrograms and third-octave analyses were made; see Figure 2 and Figure 3. From these, as well as repeated listening, channel 1 in the period 15-20 seconds was selected - a period that was virtually undisturbed, and the position where the level of the pronounced frequency component at 100 Hz was highest. Higher harmonics can be seen as grey lines at 200, 300, and 400 Hz. The absence of this 100 Hz component in channel 3 clearly illustrates the problems with standing waves.

Figure 4 shows third-octave analyses of the 53 stimuli used in the blind tests.

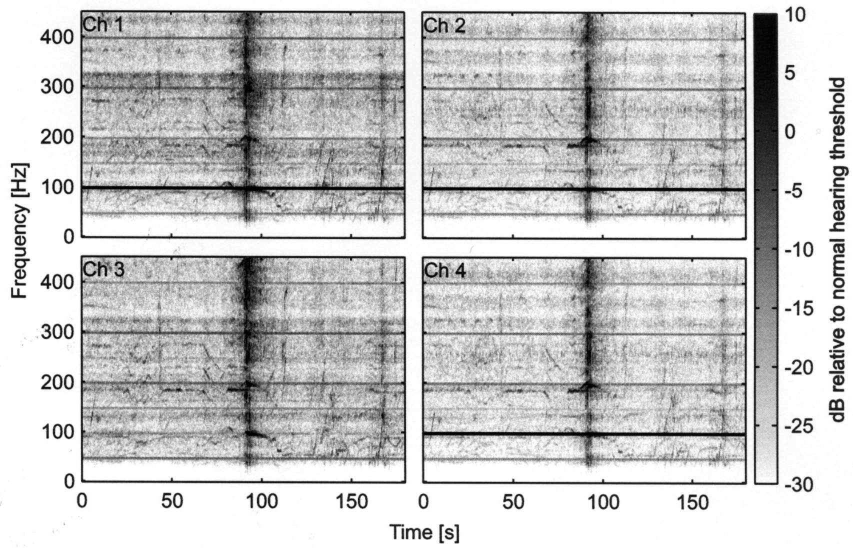

Figure 1: Example of threshold-weighted spectrograms of recordings from four microphone positions in one measurement period (3D corner positions, subject P). Levels more than 10 dB above and 30 dB below threshold are black and white respectively. Pure-tone thresholds from ISO 389-7 [45] and, for the infrasound region, based on Møller & Pedersen [21], with additional data from [53] [54] and [55].

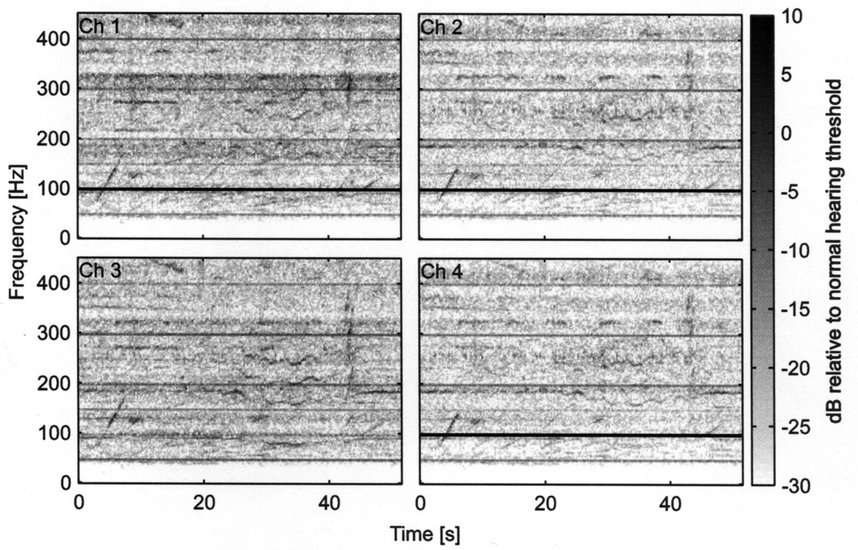

Figure 2: Zoom at the relatively undisturbed 0-52 s period of Figure 1.

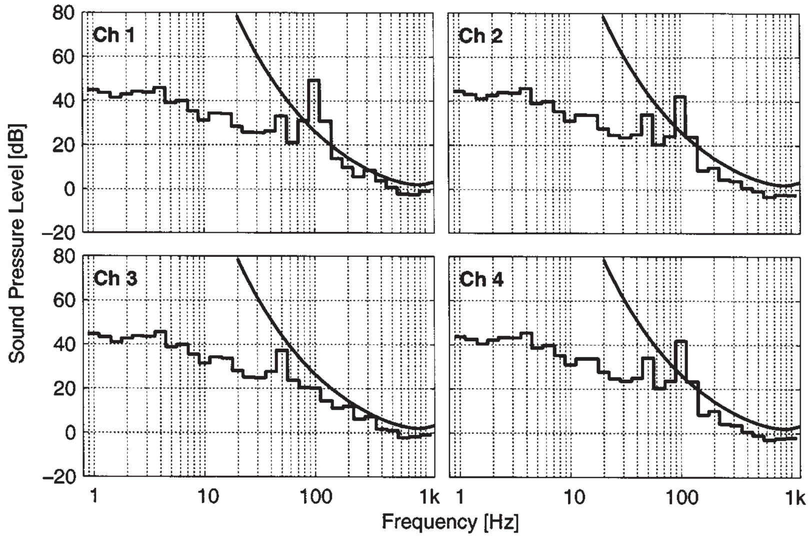

Figure 3: Third-octave analyses of the relatively undisturbed 0-52 s period from figure 1. Smooth curve shows the normal hearing threshold for pure tones (ISO 389-7 [45]).

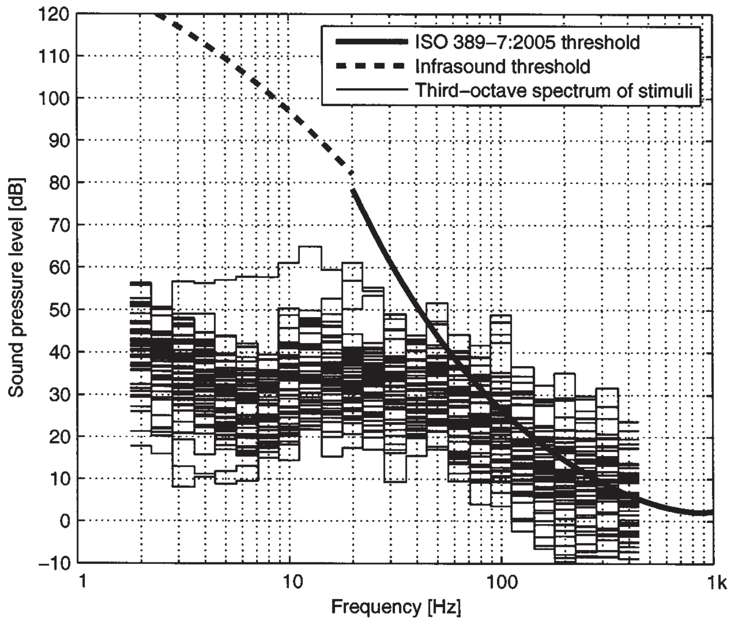

Figure 4: Third-octave analyses of all 53 stimuli plotted with the normal hearing threshold [45] and an infrasound threshold based on Møller & Pedersen [21], with additional data from [53], [54] and [55].

2.4 Test setup

A new low-frequency test facility [52] was used for the laboratory experiments. The facility uses advanced digital signal processing to control the signal to each of 40 loudspeakers and thereby creates a homogeneous sound field in a major part of the room. The facility covers the frequency range 2-350 Hz (-3 dB frequencies) thus it allows controlled reproduction of the infrasonic and low-frequency ranges with a fair overlap into middle frequencies. The facility is equipped with a ventilation system that gives sufficient airflow for continuous occupation of the room, while still maintaining a background noise level more than 10 dB below the normal pure-tone hearing threshold for all third-octave bands. The background noise level measured in the listening position is shown in Figure 5 for the condition with ventilation off, ventilation on, and ventilation plus cooling compressor on (the cooling compressor was rarely running). On five days of the experimental period, a broken bearing in a circulation pump resulted in a clearly audible noise from the ventilation system. During these days (experiments with subjects A, E, I, M and R), the ventilation system was turned off during the experiments, and fresh air was obtained by running the system during extended breaks.

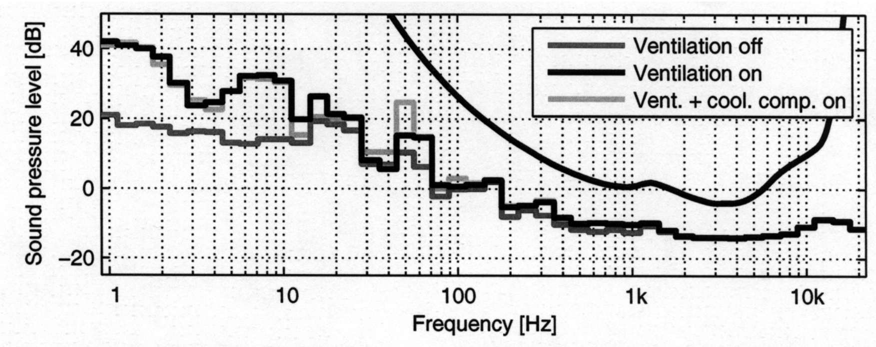

Figure 5: Third-octave analysis of the background noise measured at the listening position in the low-frequency test facility compared to the diffuse-field pure-tone hearing threshold [45]: Ventilation off, ventilation on, and ventilation and cooling compressor on. Values above approx. 2000 Hz reflect the noise-floor of the measurement microphone and preamplifier.

The subject was seated in an armchair facing one wall with 20 loudspeakers and with another wall with 20 loudspeakers behind him/her as shown in Figure 6. The loudspeaker walls were covered with a grey fabric so that the loudspeakers and the movements of the membranes were hidden. During the experiments, the subject was monitored through a camera, and an intercom was used so that the experimenter could communicate with the subject.

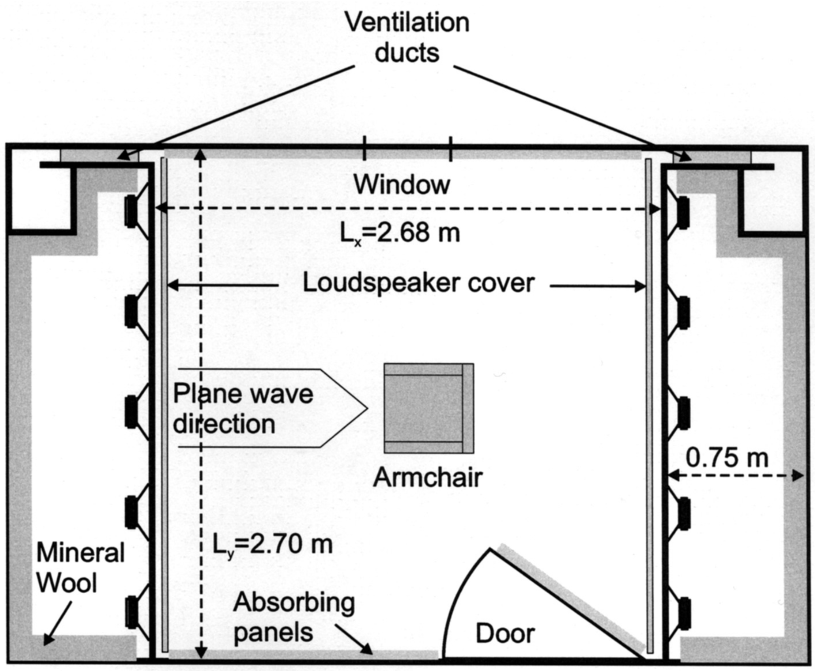

Figure 6: Diagram of the low-frequency test facility seen from above. The subject was seated in the armchair facing one loudspeaker wall.

2.5 Measurements of the low-frequency hearing function

The pure-tone low-frequency hearing threshold of each subject was measured at the octave frequencies from 8 Hz to 250 Hz using a slightly modified version of the standard ascending method [56]. The modification consisted of having level steps of -7.5 dB rather than -10 dB after each ascend, a modification that was proposed by Lydolf et al. [57] to give interlaced presentation levels and thus a higher resolution.

An equal-loudness contour was determined for each subject at the octave frequencies from 8 to 250 Hz using a two-alternative forced-choice maximum-likelihood procedure as described by Moller and Andresen [58]. A reference tone of 250 Hz at a level of 20 dB above the individual hearing threshold was used. Note that no specific value of loudness level can be assigned to the contour since that would require the comparisons to be made with a 1 kHz tone. However, for a person with average hearing, it would be close to a l9-phon contour [59].

The tone durations for both threshold and equal-loudness determinations were 2 seconds plus linear fade in/out ramps of 250 ms each. Responses were given using an answer box with lights and buttons.

2.6 Blind tests with original recordings

The blind tests were based on a three-interval forced-choice paradigm. The stimulus was presented in one five-second interval out of three that were indicated with lights on a small tablet. The interval with the stimulus was selected randomly, and there was silence during the other two intervals. The task of the subject was to indicate with push-buttons below the lights, which interval contained the stimulus. A fourth button could be used to indicate that the subject did not hear any sound. At natural level, the risk of false negatives and positives for heard is in the order of 1%. A detailed explanation of the complete procedure is given in Appendix B.

2.7 Recognition tests with original recordings

After the blind tests, those sounds that were heard at natural level or at +5 dB were played back in a sequence, and the subject was asked which, if any, that most resembled the annoying sound at home. If only one sound was audible, the subject was asked if that sound resembled the annoying sound. The subject was also asked, if the selected sound was louder or softer than the sound at home. The sequence of sounds could be repeated as many times as the subject wanted.

2.8 Blind tests with filtered recordings

Those of the sounds from the subject's home that were heard in the blind tests were filtered into four frequency ranges, and blind tests were carried out with the filtered sounds, using the same procedure as for the original sounds. The frequency ranges were: <20 Hz (infrasound), 20-60 Hz, 60-180 Hz and >180 Hz (denoted INF, LFl, LF2 and MF respectively). The involved high- and low-pass filters were digital 5th-order Chebychev filters with a pass-band ripple of 0.5 dB.

2.9 Recognition tests with filtered recordings

For each sound, the filtered versions that were heard at natural level or at +5 dB were used in a recognition test, similar to that for unfiltered sounds. Note that in this test, filtered versions of the same sound were compared, whereas in the first recognition test, unfiltered versions of different sounds were compared.

2.10 Matching of annoying sound

Some physical characteristics of the annoying sound in the home were estimated in a matching experiment. Assisted by responses from the subject, the experimenter adjusted the frequency and level of a tone, until the pitch and level matched as closely as possible that of the annoying sound in the home. In addition, third-doctave noise bands were presented in order to investigate, if the annoying sound was more of a noise-band nature than of a tonal nature. For both signals, a frequency resolution of a third octave was used, and the adjustment process always started with a pure tone at 250 Hz, 31.4 dB, which corresponds to a level 20 dB above the normal hearing threshold.

3. RESULTS

3.1 Observations in the quiet laboratory

Eight subjects reported of a low-frequency noise in the experimental room, even when no sound was emitted (subjects A, D, G, J, K, M, N and T). Some mentioned it as soon as they were seated, while others reported it later during the experiments. In some cases, it was reported as being similar to the annoying sound in the home, while in other cases, it was reported to be slightly different. In those occasions, the ventilation was turned off during the remainder of the experiment; however, this did generally not affect the subject's sensation of a sound. Fresh air was then obtained by running the ventilation system during extended breaks. The sensation of a low-frequency noise that is more or less constant - and in any case unrelated to the stimuli - might obviously influence the experiments, but the experiments were still carried out as well as possible also for these subjects.

3.2 Measurements of the low-frequency hearing function

Three subjects (A, J and N) gave highly inconsistent responses at some frequencies. This resulted in several attempts to meet the stop criteria of the threshold or equal loudness procedures, each time ending at a different level. For one subject (subject F), the equal loudness contour was below the measured threshold at several frequencies, even when responses in each of the procedures appeared reasonably consistent. The procedures worked well for the remaining subjects. Results for these are shown in Figure 7 (hearing thresholds) and Figure 8 (equal loudness contours). Figure 8 also shows (in grey) the equal loudness contours given relative to the individual threshold.

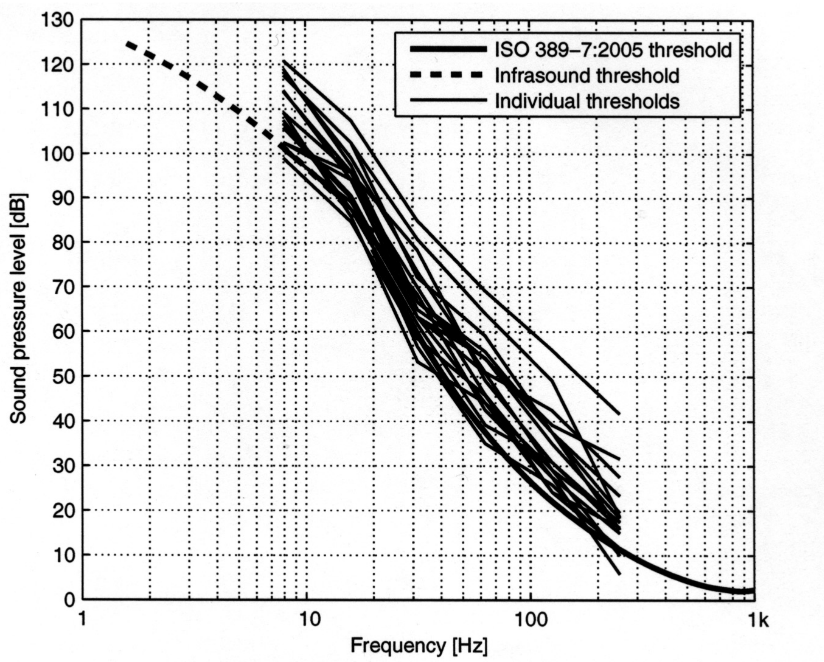

Figure 7: Individual hearing thresholds (thin lines), normal hearing threshold above 20 Hz [45] (heavy line), and infrasound threshold based on Møller & Pedersen [21], with additional data from [53], [54] and [55] (dashed line). (Subjects A, F, J, N not included).

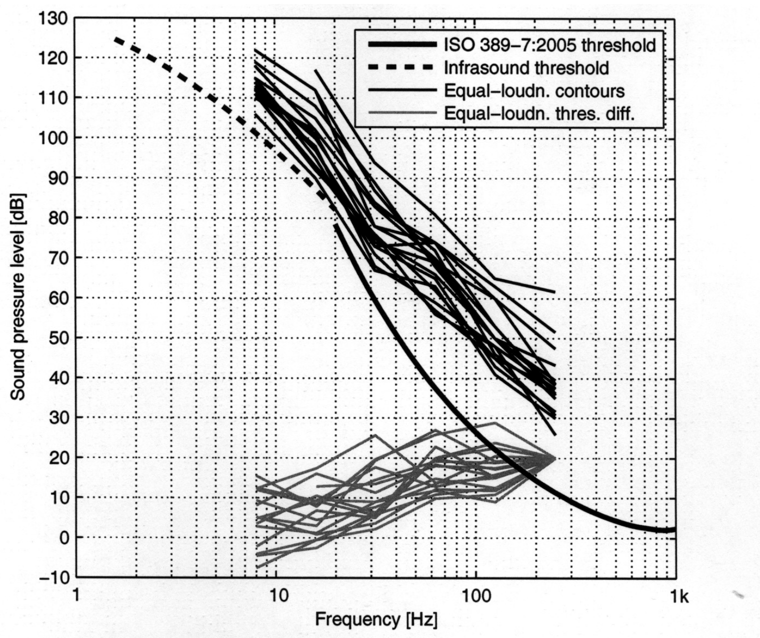

Figure 8: Individual equal-loudness contours (thin lines), the same given relative to individual hearing threshold (grey lines), normal hearing threshold above 20 Hz [45] (heavy line), and infrasound threshold based on Møller & Pedersen [21], with additional data from [53], [54] and [55] (dashed line). (Subjects A, F, J, N not included).

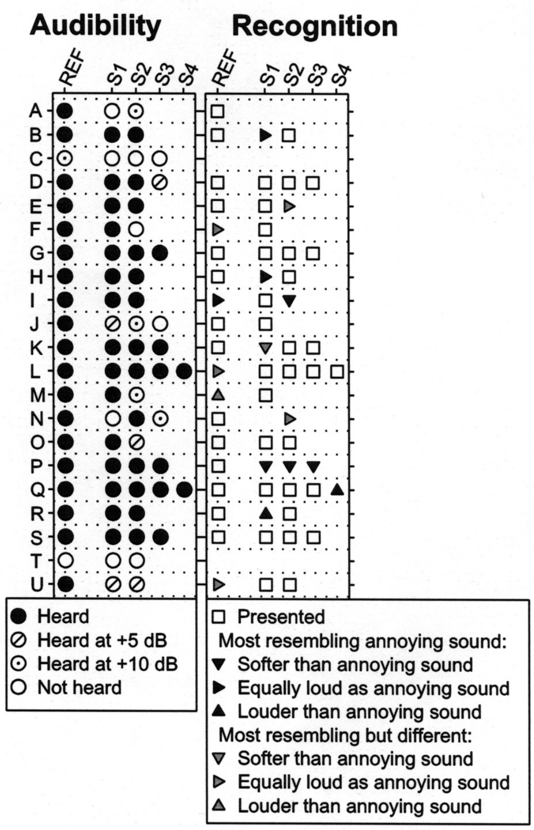

Figure 9: Results from blind tests (left) and recognition tests (right) with original recordings. Each row shows results for one subject. REF denotes the reference sound, while S1-S4 denotes sounds from that particular subject's home. Sounds that were played back but not appointed are denoted.

3.3 Blind tests and recognition tests with original recordings

The left frame of Figure 9 shows the results from the blind tests with original recordings.

Right frame of Figure 9 shows the results of the recognition tests with original recordings. The stimulus that resembled the annoying sound most is shown with filled triangles. The orientation of the triangle indicates how loud the subject perceived the stimulus compared to the annoying sound at home. If it was reported that two or more sounds resembled the annoying sound equally well, both (all) are indicated. Sometimes subjects spontaneously reported that although the stimulus resembled the annoying sound, it was qualitatively different (e.g., part of the annoying sound was missing in the stimulus or the stimulus was "not quite" like the annoying sound). In these cases, symbols are grey, otherwise they are black.

In Table I. the subjects are divided into the categories given in the introduction (Section 1.2). An extra category la has been introduced to accommodate for the spontaneous reports on qualitative differences. Subjects in this category are later moved to the main categories (Section 4.4).

Table I.

Division of subjects into categories based on the results from the blind and recognition tests with original recordings. Rightmost column gives subjects after adjustment in section 4.4, where those in category Ia are placed in the other categories.

Category	Description	Subjects	Subjects (adjusted)
I	Heard. Resembles annoying sound	B, H, I, P, Q, R	B, E, H, I, P, Q, R
Ia	Heard. Resembles annoying sound but different	E, K, N	
2	Heard. Does not resemble annoying sound	D, F, G, L, M, O, S	D, F, G, K, L, M, N, O, S
3	Not heard	A, C, J, T, U	A, C, J, T, U

3.4 Blind tests and recognition tests with filtered recordings

Figure 10 shows the results from the blind tests (left) and recognition tests (right) with filtered recordings. It is noted that all sounds that were heard in the original version were also heard in at least one of the filtered versions.

3.5 Matching of annoying sound

Figure 11 shows the results of the matching. Some subjects requested sounds with a combination of several tones or modulated tones but such sounds were not part of the matching stimuli that were available. The matched frequencies are in the 16-100 Hz frequency range.

3.6 Summary of individual results

A summary of the individual results is shown in Figure 12. Each frame shows data for one subject. Measured hearing thresholds and equal loudness contours are shown together with third-octave analyses of the stimuli, where frequency ranges that were audible at natural level in the blind tests are marked with thick lines in grey or black, where black represents a frequency range reported as most resembling the annoying sound. Results of the matching tests are also shown. The threshold and equal loudness data for subjects A, F, J and N that were excluded in Figure 7 and Figure 8 are included in their respective frames. For subject Q the stimulus with the highest 100 Hz level is stimulus S4, the stimulus recorded at the neighbour, subject P, see Section 2.3.

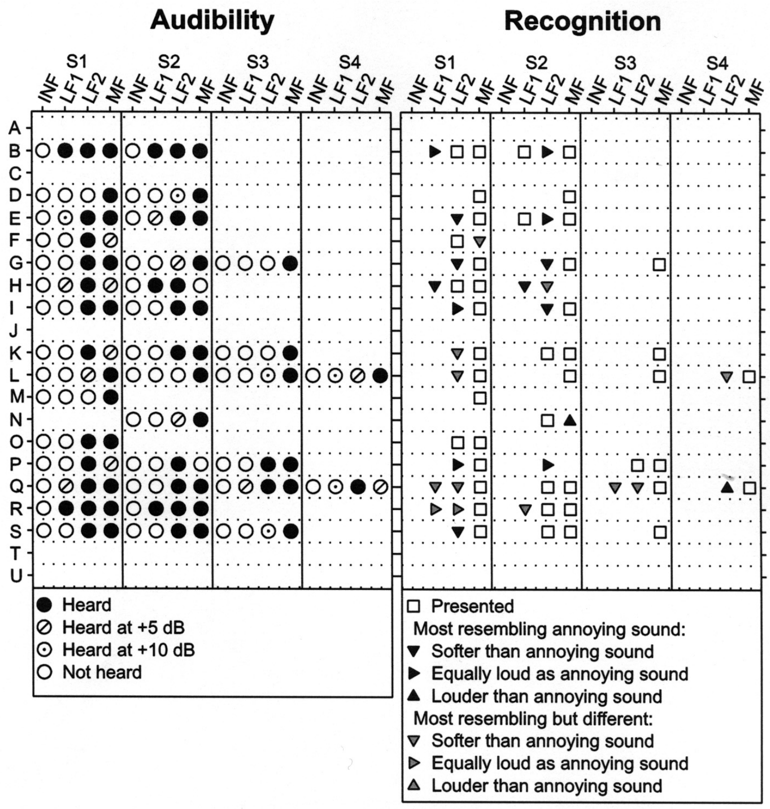

Figure 10: Results from blind tests (left) and recognition tests (right) with filtered recordings. Each row shows results for one subject. INF, LF1, LF2 and MF denote the frequency ranges <20 Hz, 20-60 Hz, 60-180 Hz and >180 Hz respectively. Sounds that were played back but not appointed are denoted.

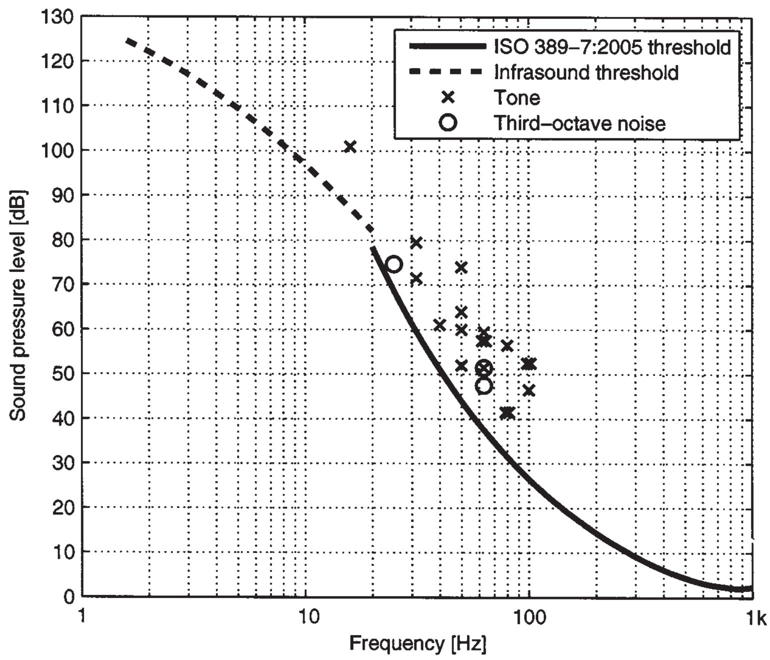

Figure 11: Results from matching experiment, normal hearing threshold [45] (full line) and an infrasound threshold (dashed line) based on Møller & Pedersen [21], with additional data from [53], [54] and [55]. If two results coincide, symbols have been moved slightly horizontally in order to make both visible.

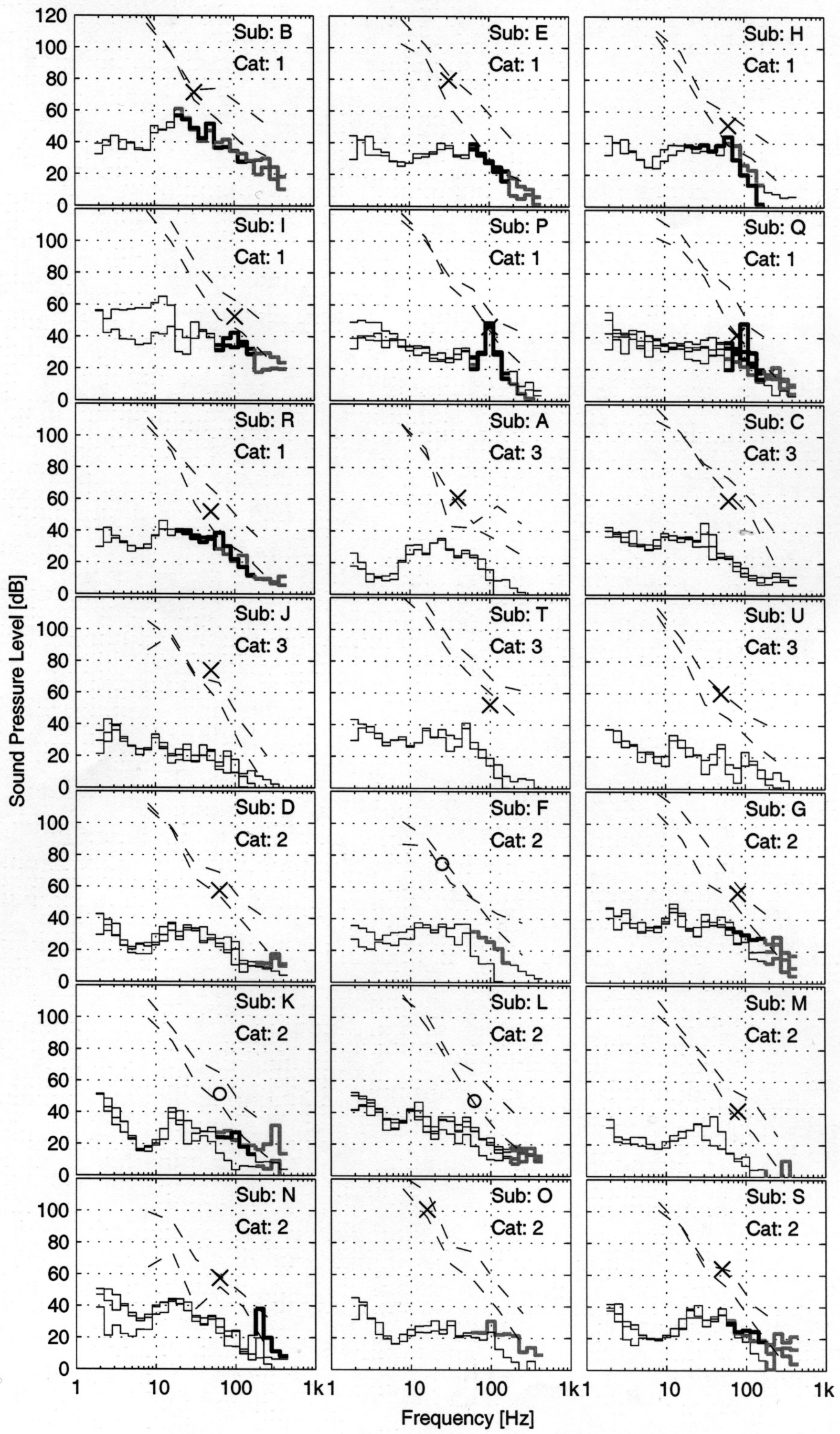

Figure 12: Individual data for each subject shown in the category order 1-3-2: Third-octave analysis of the stimuli, where the thick lines in grey and black represent a frequency range audible to the subject at natural level (from blind tests with filtered sounds) and black is the most resembling frequency range (from recognition tests with filtered sounds). Dashed lines show individual hearing thresholds and equal-loudness contours. Results from the matching experiment are shown as x for tones and circles for third-octave noise.

4. DISCUSSION

4.1 Measured noise levels

The measurements in the complainant's homes showed a large range of noise levels. As seen in Figure 4, the third-octave levels are all below the normal hearing threshold at frequencies below 50 Hz, while some exceed the threshold at higher frequencies. It was observed that the sound varied much between the different microphone positions in the individual case, which supports the findings by Pedersen et al. [49], and illustrates how important the microphone position is in indoor measurements at low frequencies (see section 4.8.1 for more details on the effect of measurement methods).

4.2 Hearing function

It is seen from Figure 7 that the subjects generally have a hearing threshold around or slightly above the normal hearing threshold in the low and infrasonic frequency ranges. This pattern seems to be in agreement with what could be expected for a group with the actual age distribution (maybe except for a single case, subject T, upper curve at all frequencies).

Extraordinary hearing sensitivity at low frequencies is often proposed as a possible explanation for low-frequency noise complaints. Examples of extraordinary sensitivity at low frequencies are reported in [60] and [61] (summarized in [21] with additional unpublished data from Lydolf (1997)). Such cases are however, not revealed in the present investigation. Also three previous studies failed to show extraordinary hearing sensitivity of complainants ([40] with 30 complainants measured, [62] with four complainants, [54] with ten complainants). In the German study [46], extremely low hearing thresholds were shown at some frequencies for a single complainant, but the method used was not described.

Microstructure of the hearing threshold is another phenomenon that has been mentioned as a possible explanation of low-frequency noise complaints [63]. If a microstructure is present, a narrow dip in the hearing threshold at the same frequency as a significant component of the noise may make the sound audible, even when this would not be expected from the spectrum and the general threshold. The present study did not investigate microstructures of the hearing threshold, but, when some critical-band summation is taken into account, all audible frequency ranges in Figure 12 are easily explained from the spectrum and the individual puretone hearing thresholds.

As reported, three subjects gave highly inconsistent responses at some frequencies during threshold determination. Since the ascending method is quite sensitive to this, it resulted in repeated runs and potentially unreliable data. In these cases, a forced choice procedure could have provided data that are more reliable. The inconsistent responses could very well be related to a more or less permanent sensation of sound, and it is observed that the three subjects are all among those who reported on sound in the experimental room even when no sound was emitted.

The measured low-frequency equal-loudness contours seen in Figure 8 follow the ''normal' trend of compression towards low frequencies (see e.g. [21] and [64]), meaning that the contours lie closer to the hearing threshold (particularly obvious from the grey curves). This implies that slight changes in level lead to considerable changes in the perceived loudness of a low-frequency sound.

Some subjects have a tendency of a sudden narrowing of the gap between their threshold and equal-loudness contour. However, the measurement uncertainty from both threshold and equal-loudness measurements is too large to conclude on this. Measurement uncertainty can also explain a few cases, where the hearing threshold and loudness curves intersect. Of course, such phenomenon may also be due to time varying hearing functions.

4.3 Audibility of various frequencies of recorded sound

An important result from the blind tests with filtered recordings (Figure 10) is that the frequencies below 20 Hz (infrasound) were not audible in any of the cases - not even at 10 dB above the recorded level. It is not known how wide the critical bandwidth is in this frequency region, but this result could be expected since the third-octave levels at these frequencies were considerably (>20 dB) below the hearing threshold as seen in Figure 4. Noise in the frequency range 20-60 Hz was audible at natural level in a few cases (5 out of 36 sounds that were presented in filtered versions), but in most cases, it was only the 60-180 Hz and/or the >180 Hz ranges that were audible at natural level.

4.4 Adjustment of categories

Before discussing, whether the annoyance is caused by physical sound or not for categories and individual cases, it is appropriate to make minor adjustments of the categories.

If the typical stimulus (REF) was comparable to the annoying sound in a subject's home, the subject could - by coincidence - have chosen this in the recognition test rather than a sound from the home. It is therefore necessary to consider, if there are subjects who have accidentally been placed in category 2 due to the existence of the typical stimulus. This is done by having a closer look at the relevant subjects' responses for the filtered sound. Three subjects of category 2 (subjects F, L, M) appointed the typical stimulus in the recognition test. Subjects F and L reported one respectively two filtered sounds being similar to the annoying sound, but none of these was audible at natural level. Subject M could only hear one frequency range of one recording, and that was not reported similar to the annoying sound. Thus, these observations do not suggest that any of the three subjects have been misplaced.

It is also relevant to have a closer look at the three subjects of category la, and if possible find arguments from the tests with filtered sounds for moving them to one of the main categories. In the tests with filtered sounds, subject E appointed the same frequency range for two sounds, both times without reservation, and there is ample reason to consider this as a positive recognition. Thus, it is justified to move this subject to category 1. Subject K appointed one filtered sound, again with reservation, and another sound with similar levels in that frequency range was not appointed. Furthermore, the reservation of this subject was substantial ("it resembles, but it is not at all the same"), and it is justified to move this subject to category 2. In the tests with filtered sounds, subject N only heard the >180 Hz frequency range and appointed this. The particular sound had a prominent tone around 200 Hz. A variety of low-level tones was present in all recording, but this exceptional tone was only found in one of five recording periods. No explanation of this is known. The sensation evoked by a 200 Hz tone would normally be less rumbling than what is often associated with low-frequency noise, and the subject reported that the tone was louder than the annoying sound. It is thus somewhat uncertain, if the annoyance is caused by this tone, and it is justified to move the subject to category 2. The categories after these adjustments are given in the right column of Table I.

4.5 Evaluation of individual cases

In the following, additional comments will be given to the categories and, in particular for category 2, to individual cases.

4.5.1 Category 1

The subjects in category 1 were able to hear the recorded sound, and they reported that the sound resembles the annoying sound at home. Furthermore, for all the subjects, a particular frequency range was successfully appointed in the tests with filtered sounds. For these subjects, it is therefore concluded that the annoyance is caused by a physical sound, and its frequency range has been identified.

Six of the seven subjects in this category matched the annoying sound to a frequency range, where significant energy was seen in the recordings, and they appointed the same frequency range(s) in the recognition test with filtered recordings. These observations further support that the recorded sound is the cause of annoyance. In the matching, two subjects (P and Q) hit even the level surprisingly well, while the others matched a level 7-17 dB above the third-octave levels in the particular frequency range. The somewhat higher level is easily justified by the critical-band loudness summation and the slope of the threshold/equal-loudness contours. None of the seven subjects in the category was among those who reported on sounds in the quiet experimental room.

4.5.2 Category 2

Basically, the lack of recognition of the recorded sound would propose that the annoyance is not caused by sound. On the other hand, the human ability to memorize sound is not perfect, and the sensation of a particular sound may be different when it is heard in the laboratory than under more relaxed conditions at home. The recorded sound was indeed audible, and it cannot be excluded that physical sound could be the reason for the annoyance.

Three subjects of the category call for special comments. As mentioned in section 2.1, subject O reported that the annoying sound had disappeared some time ago, and the recognition and matching tests are thus of limited value, and the data will be disregarded in the conclusion. For this subject, it is hardly possible - and of little importance - to clarify if the annoyance was caused by physical sound or not. Subject N appointed a recorded sound with a prominent tone around 200 Hz as resembling the annoying sound (see section 4.4). However, the tone only occurred in one of the five recording periods, and it cannot be unambiguously concluded that this is the annoying sound. If it is not, results imply that the annoyance is not caused by a physical sound (the subject reported on sounds in the quiet experimental room, could not hear other sounds or frequency ranges, and matched to a frequency much below the 200 Hz tone). Subject M had after the recordings found that the annoying sound does not change in level when moving around inside the house, while other low-frequency sounds do because of standing waves. The subject had realized that an internal tone is responsible and found the tone to be around 80 Hz. This was confirmed in the experiments, where the tone occurred in the quiet laboratory, and the matching test even verified the frequency.

For the remaining six subjects in category 2, various cues may suggest that the problem is caused by physical sound, or that is is not. Recognition of filtered recordings tends to propose physical sound. Five subjects (F, G, K, L and S) recognized filtered recordings, two of these (F and L) however only at +5 dB level, and for three of them (F, K and L) the recognition was with reservation. All five subjects reported that the recorded sound was lower than the annoying sound at home, which could be taken as a weakening of the recognition cue. Three subjects heard sound in the quiet laboratory (subjects D, G, K), which suggests that internal noise could be the cause of the annoyance. One subject (subject F) matched the annoying sound to a frequency far from the recognized frequency range, which speaks against physical sound. Adding these cues for the individual subjects does not give clear indications, and it is not considered possible to make conclusions for these six subjects. It is believed that a more interactive process with measuring and immediate playback of the sound can lead to the explanation also in these cases.

4.5.3 Category 3

Significant measures were undertaken to ensure that the annoying sound was present during the recordings[2], and that the stimuli presented to the subjects represented the highest levels found. It must therefore be assumed that in all cases, where the subject was unable to hear the stimuli at natural level, the annoyance has other reasons than a physical sound.

It is seen from Figure 12 that, for the subjects in this category, the matched annoying sounds are in general considerably above the levels found in their homes. It is noted that two of the five subjects in the category could hear the sound at +5

[2] It is noted that the two subjects, who did not reconfirm the presence of the sound after the recordings (see section 2.2), are not in this category.

dB (subjects J and U), but they did not find it similar to the annoying sound. It is further observed that three of these subjects (subject A, J and T) were among those who reported a low-frequency sensation while seated in the quiet experimental room. Two of the subjects (subjects A and J) were among those who gave inconsistent responses in the measurements of the hearing function.

It is observed from Figure 12 that for all cases in the category, the matched frequencies are at 100 Hz or below. Since the annoyance is not caused by physical sound, it would therefore be appropriate to use the term *low-frequency tinnitus*. The authors are aware that the term tinnitus is most often - and in particular by the layman - used for a high-pitched sensation ("tinnitus, *a sensation of ringing in the ears*", [65]), but nothing in the general definitions ([13], [14]) speaks against using the term in connection with a low-pitched sensation. This option is also mentioned in information material from professional organizations to the public, e.g. "Tinnitus, Ringing *Buzzing Roaring Whooshing Chirping Beating Humming*" [66] and "*Tinnitus noises are described variously as ringing, whistling, buzzing and humming*" [67].

In the medical literature, low-frequency tinnitus has been mentioned with specific medical conditions [68], [69], [70]. Low-frequency hearing loss and low-frequency tinnitus are characteristic symptoms of Meniere's disease [71], [72], but are by far too frequent to be taken (in isolation) as prodromal signs of this disease [73], [74].

In previous studies of low-frequency noise complaints, the term low-frequency tinnitus was also used by Walford [40] for those cases, where the annoying noise was shown to be internal. In addition to the options of external and internal sound, Walford operated with the hypothesis that a non-acoustic external field could evoke the sensation of sound and thus be responsible. He mentioned an electromagnetic field as a possibility in two cases, but this was never confirmed. Berg [33] also uses the term low-frequency tinnitus. Walford's study [40] also suggested that tinnitus percieved as a low-pitched sound is not unusual. In addition to the low-frequency-noise complainants, he also had a control group of 229 tinnitus patients from a neuro-otology clinic at a hospital. Of these, 55 (24%) matched their tinnitus to sound with a frequency below 200 Hz. Other studies (e.g. Konig et al. [75]) have no patients at all, who matched to frequencies below 1000 Hz, which suggests some kind of pre-screening, possibly connected to a more narrow definition of tinnitus. In clinical practice, lack of equipment for tinnitus matching at low frequencies may also play a role.

4.5.4 Summary of evaluations

For seven subjects (all subjects in category 1), physical sound is found to be responsible for the annoyance. For six subjects (all subjects in category 3 plus subject M), the annoyance it not caused by physical sound, and these cases are explained by low-frequency tinnitus. For one subject (subject N), a 200 Hz tone was found that is possibly responsible, but low frequency tinnitus cannot be excluded. For one subject (subject O), the noise had disappeared some time ago, and it is hardly feasible to find the reason for the annoyance. The remaining six subjects (subjects in category 2 except subjects M, N, and O) could hear one or more of the recorded sounds, but no specific physical sound could be appointed, and it is not possible to conclude, whether physical sound or low-frequency tinnitus is responsible for the annoyance.

4.6 Level of annoying sound

From Figure 12 it is observed that the levels of the matched sounds are generally close to the individual hearing threshold, both for cases with physical sound and cases with low-frequency tinnitus. There are many accounts in the literature that loudness and annoyance rise steeply above thresholds at low frequencies (e.g. [76], [64], [21], [77], [78]). In the present study, the steep rise of loudness is also reflected in the compression of the hearing thresholds and the loudness curves mentioned in section 4.2. The results from the present investigation are insufficient to determine if this steep rise of loudness and annoyance is more pronounced for low-frequency noise complainants than for others. If that is the case, it could be associated with a conditional response to the mere hearing of low-frequency sound that has emerged as a result of long-term annoying exposure (whether the source is physical or internal). As proposed by Persson Waye [79], this could be explained in the light of recent knowledge of the function of our sub cortical system with the amygdala and its unusual capacity to learn and react to adverse sounds and especially sounds that are connected with fear and danger [80], [81].

4.7 Generalization of the findings

Even when the present study is focused on clarification of individual cases, these were selected randomly[3] from a specified group, and it is possible to derive statistics that applies generally to similar cases.

The complainants in the group, from which the subjects were effectively[4] selected, can be characterized as *persons who, in their own understanding, have an unsolved problem of low-frequency noise annoyance*. It is obvious that the group is influenced by a large number of factors, e.g. the individual persons' understanding of their problem and motivation to get involved, the method of the previous investigation [50], its registration procedure and announcement, the perseverance of individuals and authorities in finding a solution etc. Some of these factors will appear likewise in any similar group, whereas others are distinct for the group, from which the subjects were selected. If the 30 complainants with whom we had lost contact differed from the group as a whole, this would also have biased our group of subjects. The same applies for the 22 selected complainants, who did not want to participate (see Section2.1). It should be emphasized, though, that participation was quite demanding for the subjects; it is fully understandable that complainants declined, and no-body is blamed for not participating.

For 33% of the subjects (seven out of 21) it was confirmed that the annoyance was caused by a physical sound. Assuming a binomial distribution, the corresponding 80% confidence interval is 20-49%. Low-frequency tinnitus was confirmed to be responsible in 29% of the cases (six out of 21), and for this, the 80% confidence interval is 16-44%. Unexplained cases are due to physical sound or tinnitus in an unknown proportion. With the reservations that follow from the circumstances mentioned in the previous paragraph, it can be concluded in general that physical sound is responsible in a substantial part of such cases (at least 20%), while low-frequency tinnitus is responsible in another substantial part of the cases (at least 16%).

4.8 Evaluation of cases by Danish and Swedish low-frequency noise guidelines

The seven cases in category 1, where the annoyance is explained by a specific physical sound, are evaluated using the Danish and Swedish guidelines. Figure 13 shows results of the two methods as well as the power average of the eight 3D-corners for the longest possible undisturbed periods. The requirement to the duration of the measurement period in the Swedish guidelines (30 seconds) is fulfilled in most cases, whereas that of the Danish guidelines (5 minutes) is not fulfilled in any of the cases. However, from spectrograms of all the recordings from subjects in this category, it is observed that the annoying sounds are of a quite steady nature, so the duration does not influence the result.

As reported in Appendix A, with the measurement positions used, three different outcomes exist of the Swedish method and 24 of the Danish method. For all measurement methods, third-octave levels are given as well as G-weighted levels

[3] Two cases were preselected, see Section 2.1; however, this was done without a priori knowledge of possible findings, and the inclusion of these cases is not supposed to compromise data by introducing bias. The two preselected cases turned out to be in each of the categories 1 and 3.

[4] Complainants for whom the problem had been solved, were removed either before or after the random selection, see Section 2.1.

(L_{PG}) and A-weighted levels for the 10-160 Hz frequency range ($L_{pA'LF}$ as defined by the Danish guidelines). The figure also shows the limits for third-octave levels given by the Swedish guidelines and the limit for dwellings given by the Danish guidelines to $L_{pA,LF}$ (25 dB at daytime, 20 dB evening and night). The Danish limit of 85 dB for L_{pG} is above the scale in the figure.

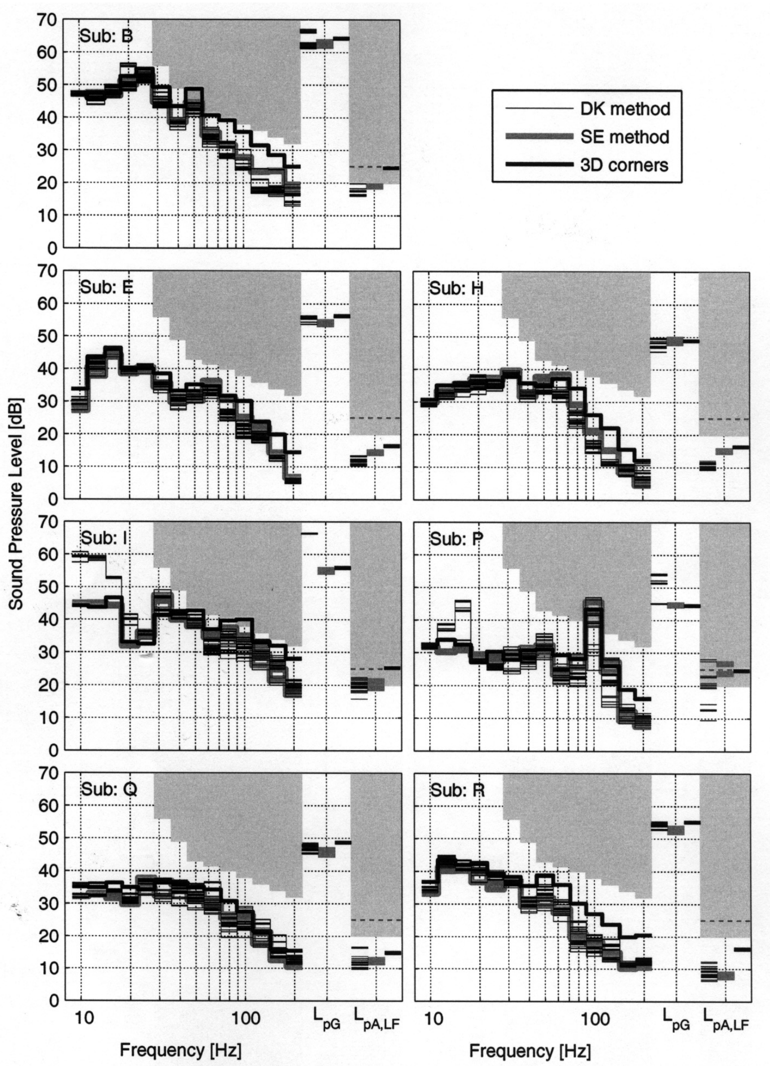

Figure 13: Comparison of all possible outcomes of the measurement methods compared to the Danish and Swedish limits. The grey areas represent the limits in Denmark (for $L_{pA,LF}$) and Sweden (for third-octave levels). The Danish L_{pG} limit of 85 dB is above the scale and not shown. For the L_{pG} and $L_{pA,LF}$ the lines are plotted in the order: DK method, SE method, and 3D corners.

4.8.1 Measurement methods

It is not within the scope of the present investigation to evaluate measurement methods, but a few comments are appropriate. At the lowest frequencies (<25-50 HZ, probably depending on room size), the third-octave levels generally demonstrate a good agreement between methods. This is natural, since at these frequencies, the wavelength is large compared to the room dimensions, and the level varies less within the room than at higher frequencies. Exceptions are seen in the results for subjects I and P, however, these are caused by differences in the sound between measurement periods rather than spatial variation. (The deviating spectra are from the same recording period). The agreement between methods at the lowest frequencies (and disagreement for subjects I and P) is reflected in the results for L_{pG}.

At higher frequencies, i.e. above 25-50 Hz, third-octave levels agree less well. There is even significant variation between different outcomes of the Danish method. The highest levels are usually obtained by the power average of 3D corners and the lowest by the Danish method. The variations above 25-50 Hz are also reflected in the results for $L_{pA,LF}$. The largest variation is seen for subject P, where levels obtained with the Danish method span a range of nearly 20 dB. In this case, the sound is dominated by a single third-octave band (actually a 100 Hz tone, see Section 4.9).

The findings are in line with the results by Pedersen et al. [49] who proposed the level that is exceeded in 10% of a room as a target for measurements of low-frequency noise in rooms. This level is close to the highest levels in the room, however avoiding levels being present in only small parts of the room. Thus, it serves as a good estimate of the level that people will normally be exposed to in the room. They showed that, particularly the Danish measurement method has large uncertainty and high risk of giving results below the target.

4.8.2 Comparisons with limits

Of the seven cases, two (subjects B and P) have levels that exceed the Swedish limit (using the Swedish measurement method), and two (subjects I and P) have levels that exceed the Danish limits (using the Danish measurement method). For the latter, though, only some of the outcomes of the Danish method exceed the limits. However, the power average of 3D corners is above both the Swedish and Danish limits for all three cases.

The large uncertainty in measurement results of particularly the Danish method is a major problem in the assessment of such cases. The extremely large variation in the case of subject P has already been mentioned, but also the case of subject B is an unfortunate example. Values of $L_{pA,LF}$ above the 20 dB limit were actually seen in several of the original measurements (range 16.6-23.2 dB), but the selection procedure for positions in the Danish measurement method made the result end up in the range 16.9-19.8 dB. These are all below the limit of 20 dB, even when there is no doubt that the 20 dB limit is exceeded at many places in the room.

It is not within the scope of the present investigation to evaluate the national limits of Denmark and Sweden. However, it is worth noting that, even when using the best available measurement method (power average of 3D corners), and even when none of the complainants had unusual hearing sensitivity, the limits only indicate low-frequency problems in three out of the seven low-frequency noise cases. There are evidences in the literature that noise below the Danish limits can be annoying even for people who do not complain from low-frequency noise (e.g. [62], [82], [83]).

4.9 Analyses of the annoying low-frequency sounds

It is not within the scope of this investigation to find the source of the annoying low-frequency sound; however, a detailed frequency analysis might reveal some information of the nature of the sound. For the cases, where physical sound was found to be responsible for the annoyance, power-averages of 0.1-Hz-resolution FFT-analyses from the eight 3D-corners are shown in Figure 14. These spectra will not be found in any specific position in the rooms, but they represent each frequency component at levels slightly below the highest levels that do exist in the rooms (see section 4.8.1).

A general observation is that the sounds in all cases are of a complex nature where multiple harmonic tones exist. This indicates that the source(s) in each case has rotating parts or pistons running at fixed (revolution) frequencies (e.g pumps/compressors, engines, fans and ventilation systems).

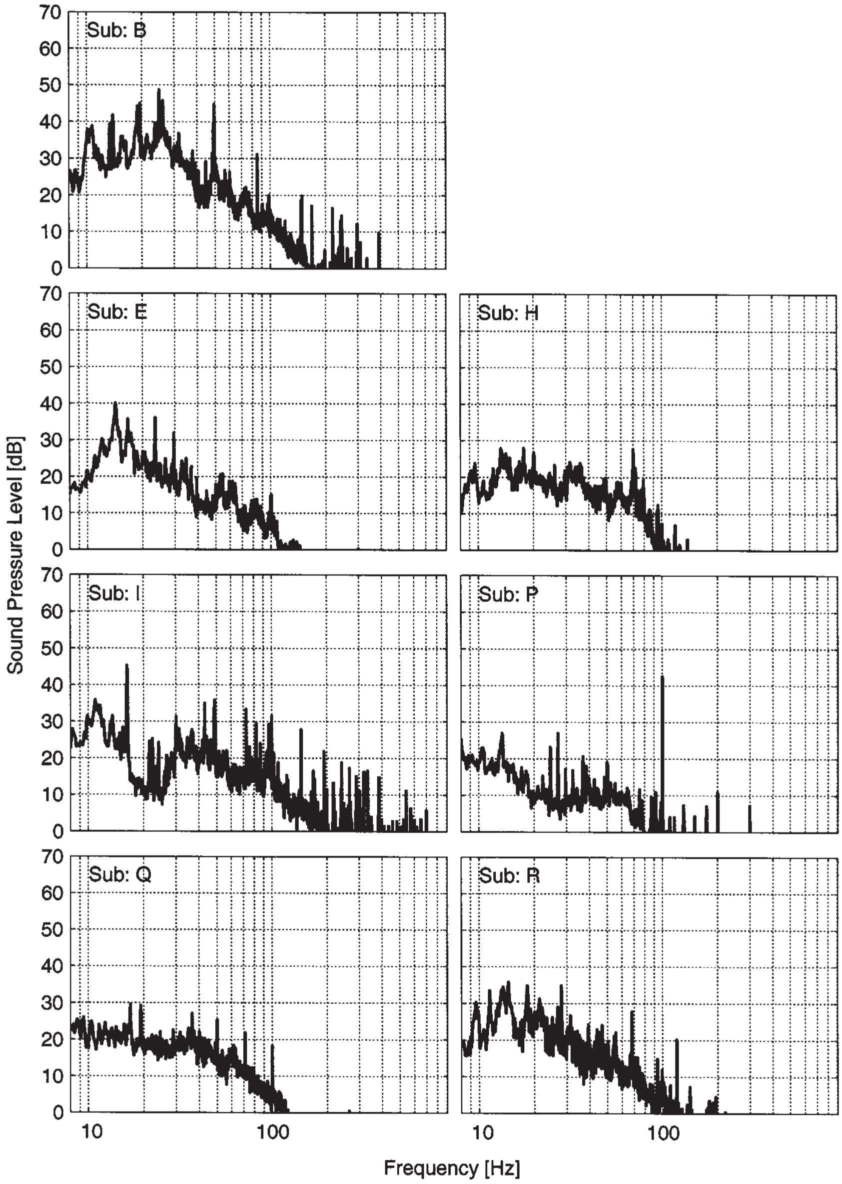

Figure 14: Power-average of FFT spectra with 0.1 Hz frequency resolution (50% overlap Hanning window) from the eight corner positions for each of the clear low-frequency noise cases.

4.10 Treatment of low-frequency noise complainants

For cases of low-frequency noise complainants, it is important to identify the nature of the problem before deciding on any actions. If the annoyance is not caused by a physical sound, no noise abatement or fight against potential sources will help. If physical noise is the problem, any mention of tinnitus is inappropriate. As this investigation shows, it is possible that inadequate measurements lead to failure in revealing a potentially annoying sound. On the other hand, since measurement systems are very sensitive, they will always measure some sound, and it is observed that tonal components can be found in all 21 cases of this study. The fact that a sound can be measured does not necessarily mean that it is audible and/or that it causes the annoyance.

The level variations within a room may sometimes serve as a simple mean to investigate if an annoying sound is internal or external. If moving slowly around inside changes the level and character of the sound, this is an indication of standing waves and a hint that an external sound is responsible. If not, it suggests an internal sound. However, the method requires significant cooperation and understanding of the annoyed person and may only be applicable in some cases. Furthermore, it may fail completely at the lowest frequencies. An earmuff test as used by Walford [40] may be useful in some cases, but it is uncertain, since the earmuff may fail to attenuate external low-frequency sound, and it may increase physiological noise [84]. If the sound is heard not only in a specific place but in any otherwise quiet environments and in other geographical locations this could also indicate an internal sound.

A recent study [85] showed that 25% of tinnitus sufferers initially believed (before diagnosed with tinnitus) that the sound was a real sound from e.g. domestic equipment or the neighbours. The study did not address low-frequency cases specifically, but there is no reason to believe that there are more cases of real sound among these than among cases of higher frequencies.

For the complainants where the annoyance is caused by a physical low-frequency noise, the natural solution is to reduce the noise. However, it is sometimes difficult to find the noise source, and, as seen in some of the cases in the present study, the noise may be annoying, even when the limits are not exceeded. In such cases, it can be difficult to convince the owner of the noise source to find a solution. Probably, an evaluation of limits is appropriate.

For the complainants with low-frequency tinnitus, it is possible that the knowledge that the sound is internally generated will help coping with the problem in various ways. Tinnitus can be symptoms of a variety of diseases related to the ears, the cardiovascular system, the metabolism, hormone balance, stress, medication, grinding teeth, etc., and identifying and curing the disease might attenuate or even remove the tinnitus. However, in many cases the cause of a tinnitus is not possible to diagnose. Mental relaxing therapy and hypnosis seems to help in some cases, but scientific proofs for these methods are still lacking. The mere acknowledgement of tinnitus as an official (and not uncommon) diagnosis may help.

The use of higher frequency masking sounds can be used as a last resort if no other cure is found. Here it might be a problem to live in quiet surroundings with a good insulated house or to have hearing loss at higher frequencies since these factors lower the possible masking from higher frequency sounds.

5. CONCLUSION

Twenty-one cases of complaints of low-frequency noise have been investigated. In seven cases (33%), the annoyance is caused by physical sound, while in six cases (29%) the complainants suffer from low-frequency tinnitus. In one case, a specific tone is possibly responsible, but low-frequency tinnitus cannot be excluded. In one case, the noise has disappeared some time ago, and it is hardly feasible to find the reason for the annoyance. In the remaining six cases, it is not possible to conclude from the present study, whether the annoyance is caused by physical sound or not, but it is believed that a more interactive process with measuring and immediate playback of the sound can lead to the explanation also in these cases.

Even if the exact proportions of categories may not hold for low-frequency noise complaints in general, it is anticipated that physical sound is responsible in a substantial part of the cases, while low-frequency tinnitus is responsible in another substantial part of the cases.

Frequencies below 20 Hz (infrasound) are not responsible for the annoyance or at all audible - in any of the investigated cases, and none of the complainants has extraordinary hearing sensitivity at low frequencies. For the confirmed cases of physical sound, the annoying components are tones, or combination of tones, in the frequency range 20-180 Hz. In the cases of confirmed or possible low-frequency tinnitus, the frequencies of the perceived sounds are in the frequency range 16-100 Hz. Whether the annoying sound is physical or internally generated, its level or matched level is not much above the individual hearing threshold. This confirms the often-reported rapid increase of annoyance with level above threshold at these frequencies. It is not possible from the material to see if low-frequency-noise complainants differ from other people at this point.

It was not within the scope of the study to point at a particular noise source or to enter the individual cases to obtain a reduction of the noise. However, in all cases, where physical sound is responsible for the annoyance, analyses reveal sound of a complex nature with multiple harmonic tones. This indicates that the source(s) in each case has rotating parts or pistons running at fixed (revolution) frequencies (e.g. pumps/compressors, engines, fans and ventilation systems).

Microphone positions are critical in indoor low-frequency noise measurements. This problem is insufficiently addressed in the Danish guidelines for low-frequency noise measurements, and results obtained with these may be encumbered with significant uncertainty. When appropriate measurement methods are used, the Danish limits are exceeded in three out of the seven cases caused by physical low-frequency noise.

ACKNOWLEDGEMENT

The authors would like to thank the subjects for their participation in the experiments and oto-rhino-laryngologist Peder Christian Frandsen and his colleagues for examining the subjects at the clinic. The study was financially supported by Marie & M. B. Richters Fond, The Danish Research Council for Technology and Production Sciences, and Aalborg University.

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APPENDIX A - Measurement procedure

If the subjects could point to areas, where the sound was particularly annoying, three positions were chosen within these areas. If not - and that was very often the case - three positions were chosen in representative living areas in such a way that they fulfilled the Danish guidelines [2] (explained in English in [3]), i.e. height 1-1.5 m, at least 0.5 m from walls and larger furniture, and not in the middle of the room. One microphone position was the "corner" position according to the Swedish guidelines [11], (see [86] for the English version with added explanation and data examples), i.e. the position with the highest C-weighted level near corners of the two-dimensional floor plane (0.5 m from the walls) and at a height between 0.5 and 1.5 m. In the following, this is referred to as the *SE corner*. Often it was not possible or difficult to find a clear maximum, either because the C-weighted level fluctuated much with time, or because the level did not vary much with position. Measurement positions were also chosen as "corner" positions according to the Danish guidelines, i.e. near corners of the two-dimensional floor plane (0.5-1.0 m from the walls) at a height of 1.0-1.5 m. Eight such *DK corner* positions were chosen, four with distances of 0.5 m and four with distances of 1.0 m to adjacent walls, all at a height of 1.25 m. Finally, eight positions were chosen in three-dimensional corners (distance to walls, floor or ceiling of few centimetres), in the following referred to as 3D corners. A recent study [49] showed that *3D corners* are useful positions for measuring low-frequency sound in rooms.

Both the Swedish and Danish guidelines use the power average of one corner (respectively SE or DK corner) and two positions in representative living areas. With the present measurements, it is thus possible to calculate three different outcomes of the Swedish measurement procedure (three options for choosing two positions in representative areas) and 24 different outcomes of the Danish measurement procedure (eight choices of corners times three choices of two other positions)[5]. For small rooms though (<20 m^2), the Danish method allows use of the power average of two DK corner positions in each of their floor-plane corner, in which case the present recording positions allow calculation of 24 different outcomes (relevant and used for subjects G, I, J, P and T). In addition, the power average of all 3D corners can be calculated as proposed in [49].

[5] Differences exist in the Swedish and Danish rules for positions in representative living areas, and only the Danish rules are strictly obeyed. In the Swedish rules, appointment by the complainant is not mentioned, areas to be avoided comprise not only the middle of the room but also areas around 1/4 and 3/4 along length and width of the room, heights should be 0.6, 1.2 or 1.6 m.

APPENDIX B - Blind test procedure

A test of, whether a subject can hear a given sound, consisted of a pattern of *sub-tests*. In a sub-test, consecutive presentations were given, until either three correct responses in a row ("passed") or two wrong responses ("failed") were obtained. A sub-test thus consisted of 2-6 presentations. In the full test, consecutive sub-tests were given. Although the key issue was to determine, whether the subject could hear the sound at its natural level, presentations at 5 and 10 dB above natural level were also included, when the natural level was not heard at first.

A complex pattern of presentations was used in order to achieve good statistical certainty, while keeping the number of presentations low. The complete flow-chart is shown in Figure 15. For each sound, the test started at natural level, and if a sub-test pattern of *pass-pass* or *pass-fail-pass* was obtained, the natural level was accepted as heard. If not, sub-tests were carried out at higher levels, and if both +10 dB and +5 dB were passed, a second attempt was given to obtain a pass-pass or pass-fail-pass pattern at natural level. If this failed, options were given to have +5 dB or +10 dB accepted as heard. Hence, two subtest passes were required for natural and +5 dB, while one pass was required for +10 dB.

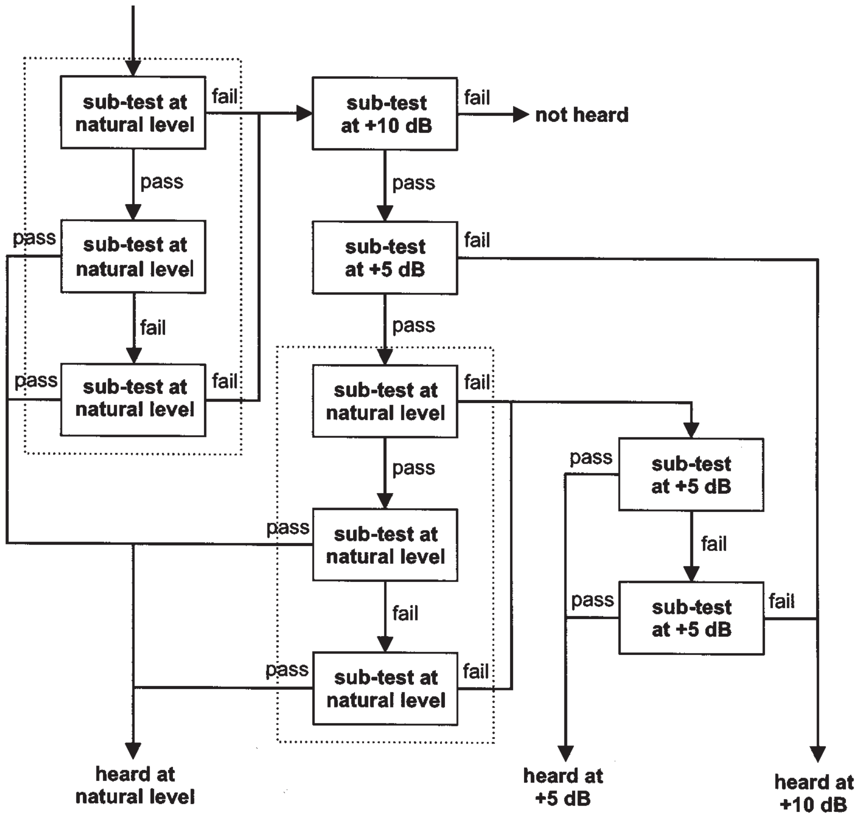

Figure 15: Flow chart of the blind test procedure. One sub-test holds consecutive presentations, until either three correct responses in a row ("passed") or two wrong responses ("failed") are obtained (2-6 presentations). The two options for pass-pass or pass-fail-pass patterns at natural level are shown in the dotted rectangles.

If the stimulus was in fact the annoying sound, wrong responses were not to be expected, in particular not since the stimuli had been chosen among the highest levels within the room. A false negative result, i.e. getting a "cannot hear", when the subject can actually hear the stimulus (type 2 error), was thus, in principle, unlikely. Nevertheless, the test allowed for several accidental wrong responses or for a detection probability lower than 100%. The right column of Table II shows the risk of false negative results, assuming a detection probability of 90%. The left column of the table shows the risk of false positive results, i.e. the risk of getting a "can hear" result from pure guessing (type 1 error).

Table II.

Probability of false positive results (type I errors) and false negative results (type 2 errors). A detection probability of 33% (pure chance) is assumed for false positive results, 90% for false negative results. Assumed probability for other levels than given by the row are given in notes.

	false positive	false negative
natural level	1.0% [1] 2.0 % [2]	0.6%[5]
+5 dB	0.1%[3] 1.0%[4]	9.7%[6]
+10 dB	7.1%	9.3%[7]

Notes: [1]33% detection at +5 and +10 dB, [2]100% detection at +5 and +10 dB [3]33% detection at +10 dB. [4]100% detection at +10 dB, [5]100% detection at +5 and +10 dB, [6]100% detection at +10 dB, 33% at natural level, [7]33% detection at natural level and +5 dB.

The method was fairly fast for a single sound, but a number of presentations were needed for the test of several sounds. In particular, presentations where the sound is not heard are tiring, and it is confusing for the subject repeatedly to have to select an interval, even when nothing is heard. In order to reduce the number of such presentations, a fourth button, “could-not-hear”, was also provided. A “could-not-hear” reply counted as a single wrong response, not as a failed sub-test. This fourth button might interfere with the statistics by lowering the risk of false positive results and raising the risk of false negative results (which is good and bad, respectively). However, with the present group of subjects it was considered more important to keep the experiment short than to strictly obey all preconditions for the statistics. Furthermore, all subjects were highly motivated towards hearing the sound, and the risk that they would use the fourth button, if they had just the slightest idea of which interval contained the stimulus, was considered low.