Rajala, Ville; Hakala, Jarkko; Alakoivu, Reijo; Koskela, Ville; Hongisto, Valtteri

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Hearing threshold, loudness, and annoyance of infrasonic versus non-infrasonic frequencies

Ville Rajala [a,b], Jarkko Hakala [a], Reijo Alakoivu [a], Ville Koskela [c,d], Valtteri Hongisto [a,c,*]

[a] Turku University of Applied Sciences, Acoustics Laboratory, Joukahaisenkatu 7, FI-20520 Turku, Finland
[b] Patria plc., Hatanpään valtatie 30, FI-33100 Tampere, Finland
[c] Aalto University, Acoustics Lab, Otakaari 5E, FI-00076 Espoo, Finland
[d] LK-Paloinsinöörit Ltd., Lemminkäisenkatu 14–18 A, FI-20520 Turku, Finland

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ABSTRACT

Research related to perception, loudness, and annoyance of infrasound (frequency below 20 Hz) is limited compared to non-infrasound (20–20000 Hz). The purpose was to determine hearing threshold, equal loudness contours, equal annoyance contours, and other sensations apart from hearing. The laboratory experiment involved 19 normal hearing participants. Observed hearing thresholds within 4–8000 Hz agreed with previous findings supporting the adequacy of our methods. Equal-loudness contours for 20, 40, and 60 phon were determined within 4–1000 Hz. They emphasized the non-linear nature of hearing. The dynamic range of hearing is extremely suppressed at infrasonic frequencies: an increment of 5 dB at 4 Hz feels like an increment of 10 dB at 20 Hz and an increment of 20 dB at 1 kHz. Equal-annoyance contours were derived for 20, 40, and 50 phon within 4–1000 Hz. Because individual hearing thresholds varied up to 20 dB, an infrasonic tone still being inaudible for one participant could be loud or annoying for another participant. The finding may explain why some people perceive low frequency sound more annoying than the others. Other sensations apart from hearing (such as pressure in the ear, headache, and vibration sensation) were reported both for infrasound and non-infrasound. Thus, other sensations apart from hearing are not limited to infrasonic frequencies. The study findings emphasize that sound below 20 Hz should be treated similarly as sounds within 20–20000 Hz. Health effect assessment procedures would benefit from standardized hearing threshold below 20 Hz.

1. Introduction

Sound with frequency under 20 Hz is called infrasound. Broner [2], Møller & Pedersen [15], Leventhall [12], and HPA [3] have published valuable reviews concerning the evidence-based knowledge related to the perception and health effects of infrasound. They support the view that infrasound perception and health effects do not differ from those of non-infrasound. There is strong evidence about the existence of hearing threshold (HT) in decibels also for infrasound down to 2 Hz [15]. Infrasound does not seem to cause adverse health effects unless hearing perception has been taken place [12]. Adverse effects of noise, including infrasound, are primarily caused via hearing sensation. In other words, there is no evidence that inaudible infrasound had adverse health effects on humans. For example, tactile perception and body resonances, which are often associated with infrasound among big audience, exist at low frequencies more easily than at high frequencies. However, these perceptions begin at 20–30 dB higher sound pressure levels (SPL) than the SPL of hearing threshold [27]. Thus, hearing sensation precedes tactile perception and body resonances and remains as the most sensitive path of infrasound and non-infrasound perception.

The main reason for a special name "infrasound" for sound frequencies below 20 Hz is that the pitch of infrasonic tone may not be recognized [15]. Musical instruments do not produce frequencies below 17 Hz. The frequency of tones under 10 Hz can be subjectively identified by counting the pressure maxima (beats) per second [15].

The most fundamental sound perception concepts are HT, loudness, and annoyance. HT describes the lowest SPL as a function of frequency, which 50 % of young, otologically normal adults can hear in silent laboratory conditions. HT is usually determined by using sine tones [4,6]. The SPL of HT varies from 122 dB at 2 Hz [15] to −5 dB at 4000 Hz [4]. HTs in the frequencies

* Corresponding author at: Turku University of Applied Sciences, Joukahaisenkatu 7, FI-20520 Turku, Finland.
E-mail address: valtteri.hongisto@turkuamk.fi (V. Hongisto).

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20–18000 Hz have been standardized because a sufficient agreement between studies has been achieved amongst the member countries of International Organization of Standardization, ISO [4,6]. The process of the standardization was explained by Møller and Pedersen [15]. Insufficient data and some disagreement between them were found to be important reasons why the above-mentioned standards excluded infrasonic frequencies. Therefore, further research is warranted to provide stronger scientific evidence about the HT of infrasonic frequencies.

Equal loudness contours (ELCs) in the frequencies 20–12500 Hz are also standardized [4]. ELC describes the SPL as a function of frequency where the perceived loudness is constant. ISO [4] involves a graphic presentation of the ELCs in 10 dB steps from 10 to 100 dB. The SPLs on each ELC have the same perceived loudness level [phon]. The ELCs of ISO [4] are much closer to each other at low frequencies than at high frequencies meaning that the sensation of loudness is strongly frequency dependent: a 5-dB increment of SPL at 20 Hz is perceived similarly as a 10-dB increment of SPL at 1 kHz. Only few studies have published ELCs below 20 Hz. Based on the existing experimental data, Møller & Pedersen [15] presented a proposal for ELCs in the infrasonic range. However, they admitted that uncertainty of data behind the proposal was still high. This is an important reason why ELCs for infrasound are not standardized along with the fact that the HTs of infrasonic frequencies have not been standardized. They concluded that there is a need for further research both for HTs and ELCs of infrasonic frequencies to promote their standardization. ELCs are important since they can be used, e.g., for the calculation of objective loudness of sounds having a specific spectrum [8,9].

It is important to make a difference between the concepts of loudness and annoyance. There is evidence that annoyance responses are much higher than loudness responses for, e.g., tonal [16] and amplitude modulated [24] sounds, although the same response scale from 0 to 10 was used. Because annoyance is a psychological attribute describing the *spontaneous adverse reaction* to sound, it depends not only on objective loudness. For example, Radun et al. [17] showed that noise annoyance of wind turbine noise in habitats was very little associated with the SPL of wind turbines. It was stronger associated with non-acoustic factors, such as concerns about health effects, living area, and noise sensitivity. Therefore, loudness may not be a sufficient psychometric variable to describe human responses to sounds. It is justified to investigate both loudness and annoyance.

The concept of equal annoyance contours (EAC) seldom appears in scientific literature. The concept is analogue to ELCs: they describe the SPL for frequencies to be perceived equally annoying. For example, EAC_{20} indicates the SPLs as a function of frequency that are equally annoying as a 1 kHz tone having SPL of 20 dB. EACs have been studied much less than ELCs. We are only aware of one study which has defined EACs extending to infrasonic frequencies [1]. For comparison, Kurakata et al. [11] and Subedi et al. [21] developed EACs within 1000–18000 Hz and 31.5–80 Hz, respectively. It should be emphasized that high noise annoyance is a predictor of many adverse health effects [26]. It is highly justified to further explore the EACs of infrasound since a single study is not sufficient to draw definitive conclusions in health effect research.

The determination of the EACs of infrasonic frequencies is relevant because infrasound is often tonal. Literature suggests that infrasound may become annoying almost immediately when it is audible, that is, when the SPL exceeds the HT [15]. Increasing knowledge about the annoyance of infrasound is essentially important since many countries consider developing regulations for infrasound. Some countries already have already published target values for frequencies under 20 Hz [23].

Infrasound has been found to cause also other sensations except audible sensation [15]. However, experimental research on the other sensations of audible infrasonic tones is very limited [1]. Very few studies have investigated other sensations apart from hearing for infrasound. It is important to study whether other sensations are limited below 20 Hz or do they appear also above it.

Our purpose is to increase the knowledge related to infrasound and non-infrasound perception from four viewpoints:

1. Determine normal hearing threshold (HT) in frequency range 4–8000 Hz.
2. Determine equal loudness contours (ELCs) in the frequency range 4–1000 Hz.
3. Determine equal annoyance curves (ELCs) in the frequency range 4–1000 Hz.
4. Survey other sensations apart from hearing associated to sound within 4–1000 Hz.

2. Materials and methods

2.1. Participants

We limit our research to normal hearing young adults and into a laboratory setting, as they are the normal constricts for psychoacoustical standards [4,6]. The participants were recruited through Turku University of Applied Sciences mailing lists. We invited participants having age in range 19–26 years, normal hearing, native Finnish language, and ability to read computer display without eyeglasses. Wearing eyeglasses was excluded to guarantee similar attenuation of the headphones between participants. We instructed that one should not participate the experiment during a flu or any other illness. The participants were told in the recruitment letter that the purpose of the experiment is to determine how sounds with different frequency are heard and perceived. Inclusion of infrasonic frequencies were not specifically mentioned.

Nineteen voluntary persons (15 female, 4 male) participated in the experiment. The participants were native Finnish speakers and their age ranged from 19 to 26 years (mean 23, standard deviation 2). The participants received a 30 € gift token as a compensation for their participation. The research plan was supported by the ethic committee of Turku University of Applied Sciences (25th Feb 2019, No. 2019–018).

2.2. Sounds

All experimental sounds were synthetic sine tones in frequency range 4–8000 Hz or in the range 4–1000 Hz. The frequencies are listed in Table 1. The sounds were generated by using MATLAB R2017b and they were saved in standard audio file format (.wav, 24-bit, f_s = 48 kHz). The sounds included linear fade-in fade-out to avoid chirps in the beginning or in the end of the playback. The fade duration varied between frequencies (F in Table 1**)** and was selected based on subjective evaluation to be as short as possible without audible chirps.

2.3. Production of acoustic stimuli

The experiment was conducted inside a chamber, which was designed and built for this experiment. It was necessary to use a chamber to produce sufficiently high SPLs at low frequencies. The chamber is described in Fig. 1**.** Photographs are shown in **Fig. S1** in Supplementary material. The lowest mode inside the chamber is vertical and it has a frequency of 80 Hz. In general, all rooms, including our chamber, behave as constant pressure chambers below the lowest mode since modal behavior of sound field can no longer exist. For example, Keränen et al. [10] have provided experimental evidence about the constancy of SPL from many living rooms, which have much larger dimensions than the

Table 1
The assumed HT, $L_{p,start}$ (see **Secs. 2.6–2.7**), the unweighted SPLs corresponding to loudness levels 20, 40, and 60 phon [4], the dynamic range of the tone in equal loudness test, *DR* (see ***Sec.* 2.6**), size of pseudorandom step in the loudness test, *S* (see ***Sec.* 2.6**), the fade duration, *F*, the headphone sound attenuation, *A* (see ***Sec.* 2.4**), and the SPL of background noise inside the headphones, *B* (see ***Sec.* 2.3**), as a function of frequency, *f*.

f [Hz]	$L_{p,start}$ [dB]	20 phon [dB]	40 phon [dB]	60 phon [dB]	*DR* [dB]	*S* [dB]	*F* [ms]	*A* [dB]	*B* [dB]
4	107.0	120.7	124.8	127.4	10.0	1.0	300	0.1	52
5	105.0	118.0	122.0	126.0	10.0	1.0	300	0.2	52
6.3	102.5	115.0	120.0	125.0	10.0	1.0	250	0.2	47
8	100.0	109.4	114.3	118.1	10.0	1.0	250	0.2	46
10	97.0	107.0	112.0	116.0	10.0	1.0	200	0.3	43
12.5	92.0	103.0	108.0	115.0	10.0	1.0	200	0.3	38
16	88.0	95.1	101.3	106.9	10.0	1.0	200	0.4	34
20.8	78.5	89.6	99.9	109.5	20.0	2.0	150	0.6	29
25	68.7	82.7	93.9	104.2	20.0	2.0	150	1.2	27
31.3	59.5	76.0	88.2	–	20.0	2.0	100	2.2	22
63	37.5	58.6	73.1	85.9	20.0	2.0	50	12.5	11
125	22.1	43.9	60.6	75.6	–	–	50	12.4	17
250	11.4	32.0	50.4	67.5	30.0	3.0	50	12.7	2
500	4.4	23.4	43.1	62.1	30.0	3.0	50	9.4	7
1000	2.4	20.0	40.0	60.0	30.0	3.0	50	12.8	−7
1500	1.7	21.4	42.5	63.2	–	–	50	12.3	−9
2000	−1.3	18.2	39.2	60	–	–	50	15.1	−9
3000	−6.0	14.3	35.6	56.4	–	–	50	29.5	−17
4000	−5.4	15.1	36.6	57.6	–	–	50	28.8	−22
8000	12.6	31.5	51.8	71.7	–	–	50	26.2	−18

chamber of our study. The chamber of our study behaves as a constant pressure chamber at 63 Hz test tone and below it. The chamber was installed on a wire rope floor in the middle of a fully anechoic room in Salo, Finland. The indoor dimensions of the anechoic room (from wedge tips) were 3.4x3.4x3.4 m.

The extensive frequency and dynamic range (120 dB) made it impossible to produce all sounds either by loudspeakers or headphones. Therefore, we had to use two methods at different frequencies. Stimuli within 125–8000 Hz were produced by headphones. Stimuli within 4–63 Hz were produced by loudspeakers of the chamber. The participants wore headphones throughout the experiment. The attenuation of the headphones was considered as explained later.

Four subwoofer elements (Eighteen sound 21LW1400, Italia) were mounted to the walls of the chamber. The chamber acted as an enclosure for the elements: backside of the elements was not covered but they also produced sound outside the chamber. The elements were covered by grilles so that the participant could not see them during the experiment nor during entering the room. The elements were driven by using a power amplifier (Behringer EP4000, Music Tribe, Metro Manila, Philippines). Closed type headphones (Sennheiser HDA 300, Sennheiser electronic GmbH & Co. KG, Wedemark, Germany) were connected to a power amplifier (MADSEN OB 822, Madsen Electronics ltd., USA). The devices received signal from a sound card (D-audio USB Pre-Amp, Duran Audio ltd., The Netherlands) connected to a computer.

The headphones were selected due to their ability to attenuate background noise inside the chamber below HT. However, the headphones also attenuated the loudspeaker sound. The attenuations *A* in Table 1 are based on manufacturer (63–8000 Hz, [20]) and our measurements (below 63 Hz). The attenuation at and below 63 Hz was compensated by increasing the SPL of the loudspeakers accordingly. The attenuation of headphones was measured using two methods: objective method and subjective method. These measurements are described in *Sec.* S2 of Supplementary material.

The chamber was equipped with two ducts, which acted as reflex tubes making the pressure chamber to behave as a Helmholz resonator. To avoid the escape of infrasound via the ducts, the resonator was tuned to 1 Hz. One of the ducts involved a fan to provide acceptable air quality and constant temperature inside the chamber throughout the long experiment.

The computer requesting the participant's responses was located outside the chamber to avoid the elevation of background noise inside the chamber. The display was outside the chamber behind a glazing to minimize the thermal load inside the chamber. Thus, the participant had a mouse and a keyboard on the table inside the chamber.

The background noise level inside the chamber (without headphones) was 23 dB L_{Aeq} during the experiment. The only audible background noise occurred at 500 Hz was produced by the fan. The participant wore sound attenuating headphones throughout the experiment, so that the SPL of background noise inside headphones fell below the HT in the ear channel also at 500 Hz (see *B* of Table 1).

2.4. Verification measurement and SPL adjustment

The SPL was measured individually for every experimental sound used in every phase of the experiment. We measured the 20-second equivalent SPL, $L_{eq,20s}$, for each tone.

The SPL was verified in the range 4–63 Hz by using a precision sound level meter (Norsonic NOR150, Norsonic AS, Tranby, Norway), a microphone preamplifier (G.R.A.S. 26CI, G.R.A.S Sound & Vibration, Holte, Denmark), and a condenser microphone (G.R.A.S. 46AZ). Because the chamber acts as a constant pressure chamber within this range, a single measurement position was used at the expected position of the participant's head.

In the range 125–8000 Hz, the SPL was verified with a head-and-torso simulator (Brüel&Kjær 4100), a microphone power supply (Brüel&Kjaer 2804), and a portable multitrack recorder (TASCAM DR-680MKII, Teac Co., Tokyo, Japan). MATLAB programming software (MathWorks Inc., Natick, MA, USA) was used to measure and adjust the SPL to match the target values in 125–8000 Hz. The frequency dependent diffuse-field correction was applied (Brüel&Kjær Pulse Sound Quality 15.1.0), which compensates the amplification of SPL at high frequencies caused by the artificial ear of the head-and-torso simulator. The head-and-torso simulator was not used for infrasound since the microphones are not capable of measuring the absolute SPLs of infrasonic frequencies precisely.

All loudspeaker elements produce undesirable harmonics (nonlinear distortion) if the excursion of the element exceeds the linear dynamic range. For example, the second and the third harmonics of

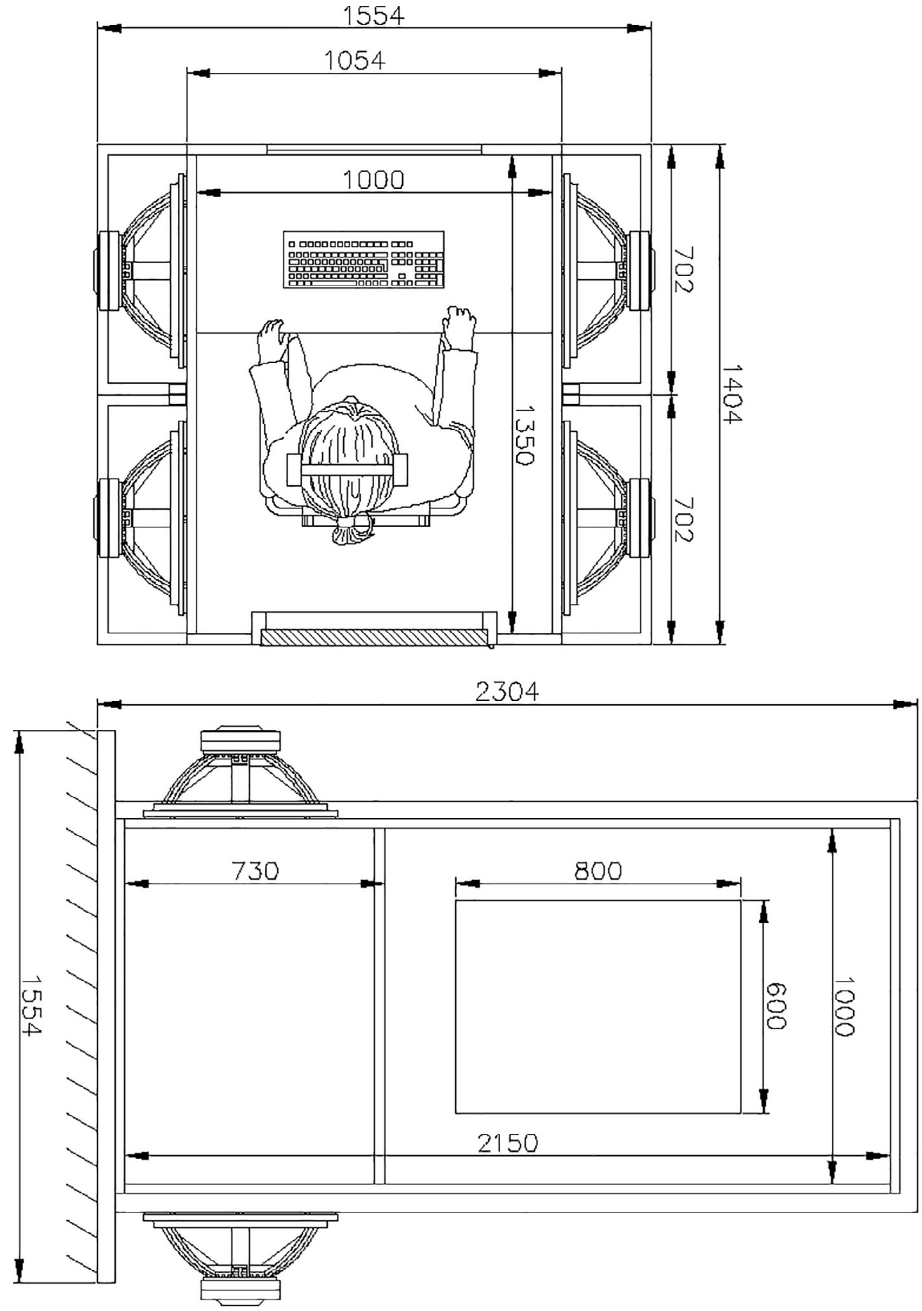

Fig. 1. Layout and frontal section of the chamber. Dimensions are in millimeters. Grilles covering hiding the loudspeakers are not shown. (One-column-wide).

a 4 Hz tone are 8 Hz and 12 Hz. Harmonics may bias subjective responses of infrasonic tones since the HT reduces rapidly with increasing frequency: tone's harmonics may be better audible than the tone itself. The SPL of harmonics was minimized by choosing loudspeakers enabling largest possible excursion. Takeshima et al. [22] applied a principle that the SPL of second, third, and fourth harmonic component should be 30, 40, and 50 dB below the SPL of fundamental tone, respectively. We examined possible distortion generated by the four loudspeaker elements in the frequency range 4–63 Hz using the full dynamic range of each experimental frequency although distortion typically increases with level and only testing the largest SPL would suffice. The distortion measurement was made by using a microphone preamplifier (G.R.A.S. 26CI), a microphone (G.R.A.S. 46AZ), and a portable multitrack recorder (RION DA-21, Rion Co., Japan). The harmonic components were achieved from FFT-spectrum by using MATLAB. The harmonic distortions at the highest SPLs of the experiment are reported in **Table S1** in Supplementary material. The SPLs of the harmonics agreed with the principles of Takeshima et al. [22] within 5–63 Hz. Violation at 4 Hz is not meaningful since the SPLs of the harmonics are below the HT. Therefore, the SPL of harmonics are not expected to bias our findings.

2.5. Overview of the experimental procedure

The experimental materials were collected in March–November 2019. One participant at a time conducted the experiment. The responses were collected using a computer and MATLAB based software with a graphical user interface.

Table 2
The 12 phases of the experiment and their typical durations.

Phase	Duration [min]	Description
1	5	Information consent form
2	10	Loudness rehearsal
3	30	Loudness test, part 1
4	5	Break
5	30	Loudness test, part 2
6	5	Break
7	30	Hearing threshold test
8	5	Break
9	5	Annoyance rehearsal
10	17	Annoyance test
11	10	Reporting other sensations
12	5	Feedback and gift token

The experiment involved 12 phases (Table 2). Each participant stayed in the laboratory on average 2.5 h. Although the duration of the whole experiment was long, we do not expect that it biased the results, since the experiment contained three breaks and each experimental phase involved different tasks.

First, the subjects read and signed an information consent form (phase 1). The phase 2 was a rehearsal for loudness test. We allowed participants to ask any questions regarding the rating procedure. They rated 15 pairs of tones (500 Hz, 60 phon) and these ratings were not analyzed. Phases 3 and 5 included the loudness test (***Sec.* 2.6**). Phase 7 was the hearing threshold test (***Sec.* 2.7**).

Phase 9 was a rehearsal for the annoyance test. The participant rated six sounds in order 8000, 25, 4, 125, 500, and 31.3 Hz. The corresponding SPLs were 71.7, 104.2, 127.4, 43.9, 43.1, and 88.2 dB. We allowed participants to ask any questions regarding the rating procedure. The ratings were not analyzed. Phase 10 was the annoyance test (***Sec.* 2.8**). Phase 11 concerned the verbal reporting of possible other sensations associated to the sounds that caused other sensations apart from hearing in annoyance test (***Sec.* 2.9**).

Phases 4, 6, and 8 were short breaks. They were included to refresh the participant and to maintain adequate temperature and carbon dioxide levels in the chamber (door was left open).

After the experiment, the participants received a gift token and a short introduction of the goals and expected scientific impacts of the experiment. The participants had a change to ask any questions related to the experiment.

2.6. Loudness test (phases 3 and 5)

The purpose of the loudness test was to determine the ELCs based on subjective ratings of the participants. The test utilized the Randomized Maximum Likelihood Sequential Procedure (RMLSP) yielding reliable and unbiased Point of Subjective Equality (PSE) estimates [22]. In RMLSP experiment the participant judges which one of two sounds is louder. This is also known as two-alternative forced choice method. Each sound pair always involved a *reference sound* and a *test sound*. Reference sound of an ELC is a tone having a fixed frequency and SPL, e.g., 1 kHz tone presented at 20 dB, if 20 phon ELC is under investigation. The frequency of the test sound is varying and the SPL that produces the same loudness perception than the reference sound is under investigation. PSE describes the SPL of the test sound resulting in equal loudness perception as a reference sound. PSE is achieved from a psychometric function as a point where the probability of the test sound to be perceived louder than the reference sound is 50 %. **Fig. S2** in Supplementary material demonstrates a psychometric function. **Fig. S3** in Supplementary material visualizes the conduct of two sound pairs and shows the timings we used in the experiment. Four pseudorandom orders of frequencies and loudness levels were created.

The setting of the test sound's SPL followed a strict procedure. The first SPL of the test sound, $L_{p,start}$, was chosen to correspond to 20, 40, or 60 phon loudness levels (Table 1) based on existing knowledge [4,13]. If the participant responded that the first test sound was louder than the reference sound, then the SPL of the next test sound was decreased with amount of dynamic range (*DR* of Table 1) divided by two. If the situation was opposite, the SPL of the next test sound was increased with the same amount. The dynamic ranges were frequency dependent (Table 1**)**. They were found suitable and efficient in pilot tests. For the following sound pair, the test sound SPL was the sum of the PSE and a pseudorandom value. The pseudorandom value was one of the values within the dynamic range separated by step size (see *S* of Table 1**)**. The PSE was re-calculated after every sound pair by fitting a psychometric function to the achieved data.

The achievement of one loudness level for a single frequency constituted 15 successively played sound pairs. A visual cue was always given when a test sound was played (a red sign was shown either below sentence "*First sound is played*" or below "*Latter sound is played*") so that the participant did not need to hesitate about the existence of sounds when an unfamiliar infrasonic frequency appeared. The question presented for the participant was: *"Which one of the sounds is louder or more audible?*" Response alternatives were "*First*" and "*Latter*". We instructed that the participant should guess if sounds seemed equally loud.

The experiment consisted of 14 test frequencies within frequency range 4–1000 Hz (Table 1) and one reference frequency. The reference frequency was chosen to be 125 Hz instead of conventional 1 kHz, because it has been argued that comparison of loudness may be difficult if the frequencies of two compared sounds drastically differ [13]. Three loudness levels 20, 40, and 60 phon were tested for all test frequencies except 31.3 Hz. For 31.3 Hz, only 20 and 40 phon tests were conducted due to unavoidable rattle of the door handle of the chamber at 60 phon level. Thus, the total number of stimuli pairs was 629.

The psychometric function fitting was made by using *psignifit* toolbox available for MATLAB [19]. We used cumulative gaussian function to fit the data. During the experiment the PSE calculation was made by using *psignifitfast* function also available for MATLAB. During the final calculation of PSEs *psignifitfast* function was not used.

The duration of test sound was 1500 ms including a rise and decay time of 50 ms used by Takeshima et al. [22]. There was a 700 ms break between the two sounds to be compared. The response time was 1500 ms. If no response was given, the same pair of sounds were repeatedly presented.

2.7. Hearing threshold test (phase 7)

The purpose of this test was to determine the exact HT level of the participants. The test was placed after the loudness test and not before it because we wanted to be sure that the participants are familiar with the sounds, especially the unfamiliar infrasonic tones.

The HT level was determined by using a modified staircase method. It resembles the ascending method of ISO 8253-1 standard [7]. However, we modified it to some extent to reduce the duration of the test and to improve the accuracy of results. The HT level was determined with an accuracy of 2 dB (step size) instead of 5 dB proposed in the standard. **Fig. S4** in Supplementary material shows the block diagram that was followed for each frequency. The order of test frequencies was 3000, 1000, 63, 2000, 1500, 20.8, 16, 31.3, 12.5, 500, 4000, 8000, 10, 25, 125, 8, 6.3, 250, 5, 4, and 3000 Hz for all participants. One frequency

(3000 Hz) was presented both as the first and the last to test the repeatability of responses.

The participant was instructed to report a hearing sensation by pressing with mouse a button on the screen. Each sound was played at least 5 s or so long that the participant pressed the button. The rise and decay time of the tone was 50 ms. There was a quiet period between two suggestive sounds. The duration of the quietness was randomly chosen between 1 and 4 s. It was followed if the participant pressed the button also during the quiet period. The experimental procedure required that the participant responded twice to the HT level.

The SPL of the first sound was chosen to be quite low ($L_{p,start}$ of Table 1), because of three reasons: exceptionally large number of frequencies, participants were expected to have normal hearing, and the participants were already familiar with the infrasound. $L_{p,start}$ represents the presumed HT of ISO 389–7 [6] for frequencies 20–8000 Hz and from Watanabe and Møller [25] for frequencies 4–16 Hz. The lowest SPL of the test sound was 14 dB below $L_{p,start}$ and the highest SPL of the test sound was 16 dB above it.

The number of stimuli in HT test varied between participants since they had different HT levels and different response consistencies close to the HT level. The median number of audible stimuli for a participant having a normal HT level was 252.

2.8. Annyance test (phase 10)

The purpose of this test was to determine the subjective annoyance rating for different frequencies of sound and derive equal annoyance contours (EACs). The sounds consisted of 60 sine tones in frequency range 4–8000 Hz. Each frequency was played using the SPLs of loudness levels 20, 40, and 60 phon (Table 1). Each sound was played once. We used four predetermined pseudorandom orders to avoid carry-over effects.

We applied two-alternative forced choice method for measuring noise annoyance, because noise annoyance is significantly more complex attribute of a sound than loudness. Noise annoyance was measured according to ISO/TS 15666 [5] by question: "*How much does the sound bother, disturb, or annoy you?*" The 11-step response scale was from 0 to 10, where 10 was labeled as "*Extremely annoying*" and 0 as "*Not at all*". The participants were instructed to use the full scale and try to make their responses as consistent as possible. As some of the sounds were close to the hearing threshold, the participants could also report inaudibility: "*I do not hear a sound.*".

If the participant felt that the sound was associated with other sensations apart from hearing sensation, they could express it by selecting a button labeled "*I have also other sensations apart from hearing sensation.*" The precise sensation was asked later in Phase 11. The participants had to listen the sound for 5 s before the response scale became visible and available. The rise and decay time of the tone was 50 ms. The sound was played at most 15 s. The participant was instructed to use as much time for the judgement process as needed. Furthermore, it was instructed that the quiet period after the end of the sound should be ignored in the judgement. We had to use a relatively short listening time since the whole experiment was already very long. Møller [14] studied the annoyance of infrasonic tones using three exposure times (0.5, 3, and 15 min) and the exposure time did not affect the outcomes. Therefore, it was justified to expect that short exposure time did not significantly affect the annoyance ratings.

2.9. Reporting other sensations (Phase 11)

The purpose of this test was to collect detailed verbal information about participants' other sensations apart from hearing, if they reported any existence of other sensations in phase 10. The phase 11 was customized according to individual responses in phase 10: we presented only those individual sounds, for which the participants reported other sensations.

The sounds were played once and in the same order as they occurred in the annoyance test. The participants had to listen the sound for 5 s before responding became available. The sound stopped after 15 s. The participant described freely in an open form the other sensations that were associated with the sound. The responses were given using computer keyboard and there was no time pressure. The participant could also select one of the buttons "*I hear sound, but it is not associated with other sensations apart from hearing.*" or "*I do not hear a sound.*".

2.10. Outlier analyses

Loudness test. All individual psychometric functions during ELC test were visually examined for bad fitting. We excluded 27 fits out of 779 due to strong deviation. Such PSEs could be ignored if a participant responded (nearly) always that the test sound was quieter than the reference sound. It is impossible to determine PSE from that kind of responses by using a psychometric function or any other method. All excluded PSEs occurred for the highest SPLs of infrasonic range.

Hearing threshold test. The lowest played SPL of the HT phase was 14 dB below $L_{p,start}$. $L_{p,start}$ −14 dB was reported to be the HT for participant 3 at 4 Hz (93 dB) and for participant 19 at 63 Hz (23.5 dB). Thus, we had chosen the lowest played SPL quite appropriately since it was inaudible in most cases. Both participants had zero button presses during the silence between the sounds for those frequencies, suggesting that the participants genuinely heard these SPLs. Previous literature has reported about people with exceptionally low HT in infrasound [15]. These two achieved HTs at $L_{p,start}$ −14 dB are probably overestimates for these two participants since they heard that sound. Therefore, these two individual observations were excluded from further analyzes. The exclusion had no significant impact on the mean HT.

Annoyance test. Annoyance responses were compared to the mean of all responses. The procedure is described in Rajala and Hongisto [18]. For example, values deviating more than 2.7·SD (standard deviation) from the mean were considered as outliers. Such cases were not observed. Furthermore, the annoyance responses of each participant had a good correlation with the mean annoyance of all participants. Thus, no outliers were reported, and all annoyance data could be used in further analyses.

2.11. Data analyses

Equal-loudness contours. PSE was calculated for all frequencies and loudness levels presented in the loudness experiment. PSE was calculated by fitting a psychometric function to the data. *Psignifit* toolbox [19] was again utilized. The cumulative normal function was used for fitting and maximum a posteriori estimation was as the estimate for PSE. All values in vicinity of 0.5 dB were pooled as pooling increases the reliability of fitting of data with few trials [19]. The final ELC was formed by calculating mean from the PSEs after removal of the outliers. The ELCs were formed for loudness levels 20, 40, and 60 phon.

Hearing threshold. The HT curve was achieved by calculating the mean HT for each frequency from all data after removal of outliers.

Equal annoyance contours. The EACs were determined by applying the following method for every frequency (Fig. 2). Similar method was applied by Andresen and Møller [1]. First, the mean annoyance of all participants was determined for every sound. Second, a linear fit was determined over the three mean annoyance values and their corresponding SPL by using equation.

$$A = kL + b, \quad (1)$$

where A is annoyance, k and b are the coefficients of the linear fit and L is the SPL. Third, mean annoyance of 1000 Hz at SPLs 20, 40, and 50 dB was selected to be the basic points of the EAC20, EAC40, and EAC50, respectively. The annoyance values corresponding to these levels (A_{20}, A_{40}, A_{50}) were calculated by using Eq. (1). Fourth, the SPL corresponding to annoyance $A_{20,}$ A_{40}, and A_{50} was calculated in all frequencies by using equation.

$$L = (A_i - b)/k, \quad (2)$$

where b and k are the linear fit coefficient of the frequency and A_i= (A_{20}, A_{40}, A_{50}).

Because the sounds were presented in the annoyance test at the SPLs of 20, 40, and 60 phon (Table 1), our original aim was to determine EAC_{20}, EAC_{40}, and EAC_{60}. However, the determination of EAC_{60} required very strong extrapolation in infrasonic region. This can be imagined by the example of Fig. 2. To avoid increased

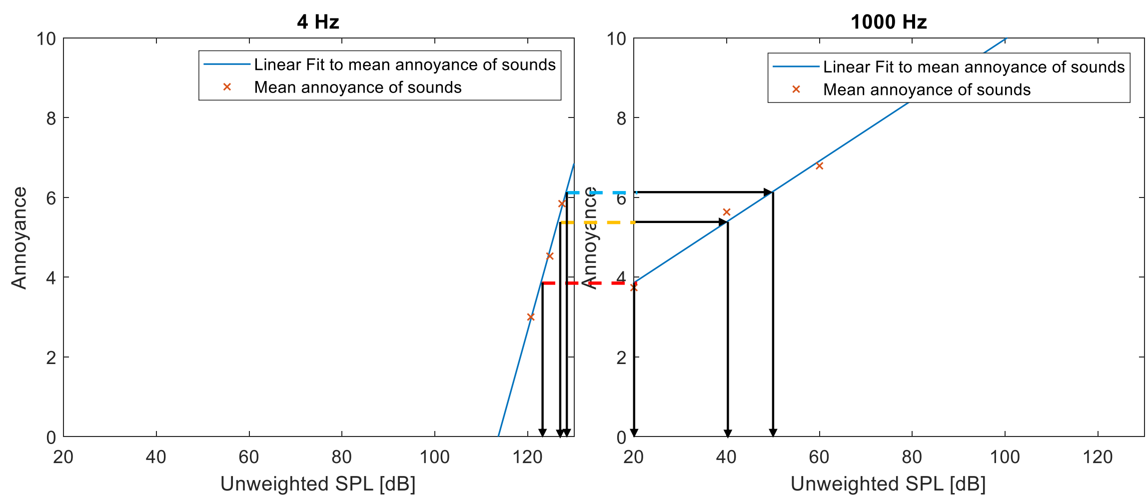

Fig. 2. An example of determining the equal annoyance level for 4 Hz. In the left, a linear fit is determined for the three tested loudness levels (20, 40, and 60 phon). In the right, the corresponding equal annoyance level for 4 Hz is determined from the corresponding SPLs of 1000 Hz.

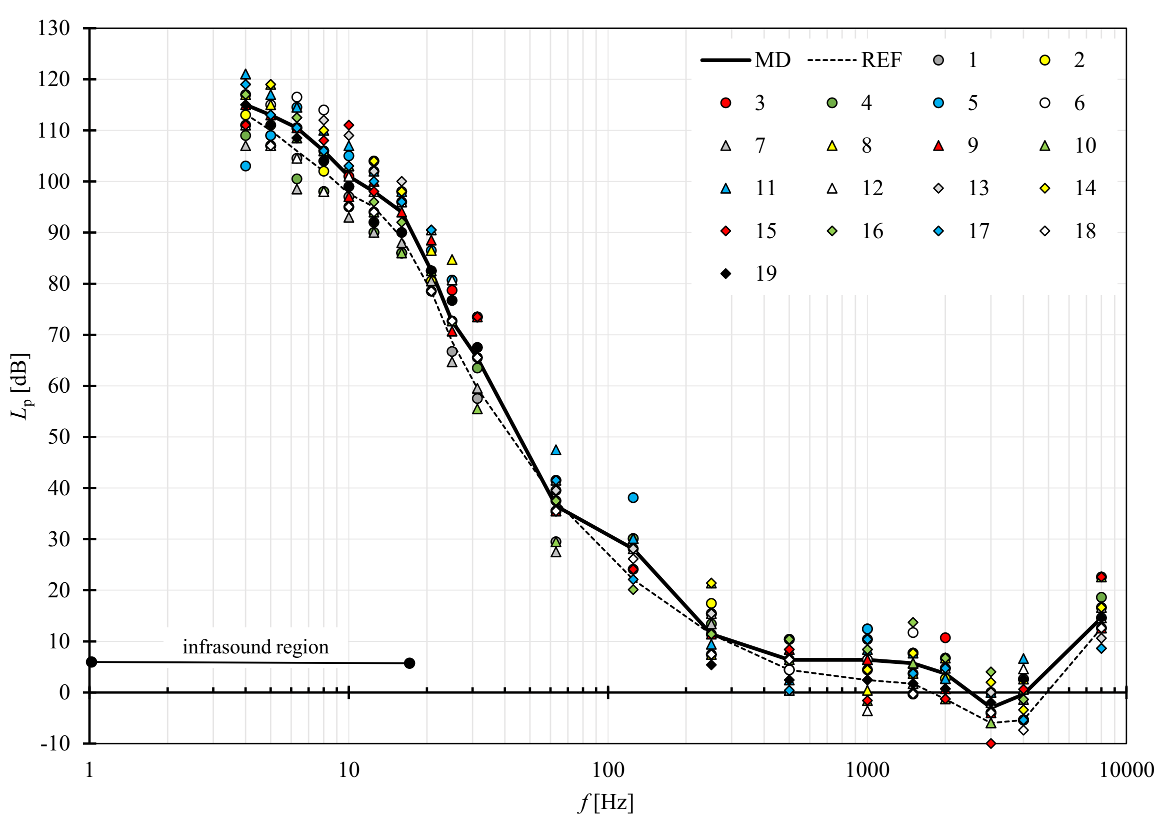

Fig. 3. The unweighted SPL, L_p, of the hearing threshold (HT) as a function of frequency, f. MD is the median of 19 participants. REF is a combination of the standardized HT of ISO 226 [4] within 20–8000 Hz and the proposal of infrasonic HT presented by Møller and Pedersen [15] within 4–16 Hz. Symbols named from 1 to 19 represent the individual HTs of the 19 participants.

uncertainty due to extrapolation, we contented ourselves to report EAC_{50}.

3. Results

The results of HT test are shown in Fig. 3. Numerical values of mean and standard deviation are shown in **Table S2** in Supplementary material.

The ELCs for 20, 40, and 60 phon derived from loudness test data are shown in Fig. 4**.** Numerical values of mean and standard deviation are shown in **Table S2** in Supplementary material.

The mean *annoyance* as a function SPL is shown in Fig. 5. The means and 68 % confidence intervals of the *annoyance* ratings are shown in **Fig. S5** of Supplementary material. Fig. 6 reports the SPLs of the equal annoyance contours (EAC_{20}, EAC_{40}, and EAC_{50}) derived from *annoyance* ratings. Comparison to a previous study is also presented. **Table S3** in Supplementary material gives the exact SPLs and related 95 % confidence intervals of the EACs.

Three participants did not report any other sensations apart from hearing during phase 10. Table 3 describes the distribution of existence of other sensations during the annoyance test (phase 10) to different frequencies and loudness levels. The number of reports was 257. That is, 22.3 % of all presented sounds were associated with other sensation apart from hearing.

Those sounds were played again in phase 11, for which the participant reported other sensations apart from hearing during phase 10. The themes of physiological sensations reported in written form are summarized in Table 4. Altogether 22 sounds (8.6 %) were no longer producing other sensation than hearing which suggests that the other sensations in phase 10 were weak, temporary, or falsely reported. One participant reported four sounds to be inaudible while all other participants could still hear their dedicated sounds. Thus, verbal description was given for 231 sounds presented. A large share of those 231 responses were associations to certain real-life sounds or living environments rather than real physiological sensations that we were primarily interested upon. We prompted the participants to tell everything that appears in their mind to receive as much comments as possible. However, did not report associations which are not dealing with bodily sensations.

Graphic comparison of our ELCs and EACs is shown Fig. 7 to assess the differences between the two subjective variables *loudness* and *annoyance*.

4. Discussion

4.1. Hearing threshold

Our HTs agree reasonably well with the previous work (Fig. 3). We could determine the HTs for nearly all participant in infrasonic range confirming that our SPL coverage for infrasound was suitable for the HT experiment. Individual variations in HT were rather high for all frequencies, approximately 20 dB. Our SDs in the infrasonic range were 4–5 dB (**Table S2**). The values agreed with the SD of the previous studies [15] and for frequencies above 20 Hz [11].

HT at 3000 Hz was determined twice. The mean HTs differed less than 1.0 dB. This suggests that the group level repeatability of our experiment is very good. It should be noted that 1 dB difference in SPL is almost unnoticeable.

Our HTs in the infrasonic range were 2–5 dB higher than the proposal of Møller & Pedersen [15], which was based on several studies. The exceedance was small and not alarming, since the precision of SPL measurements are typically in similar range, ±2 dB. In addition, different participants may also explain minor differences between independent experiments.

Our HTs were somewhat higher than the standardized HTs in 20–8000 Hz [6]. ISO 389–7 standard [6] defines the HTs in free field

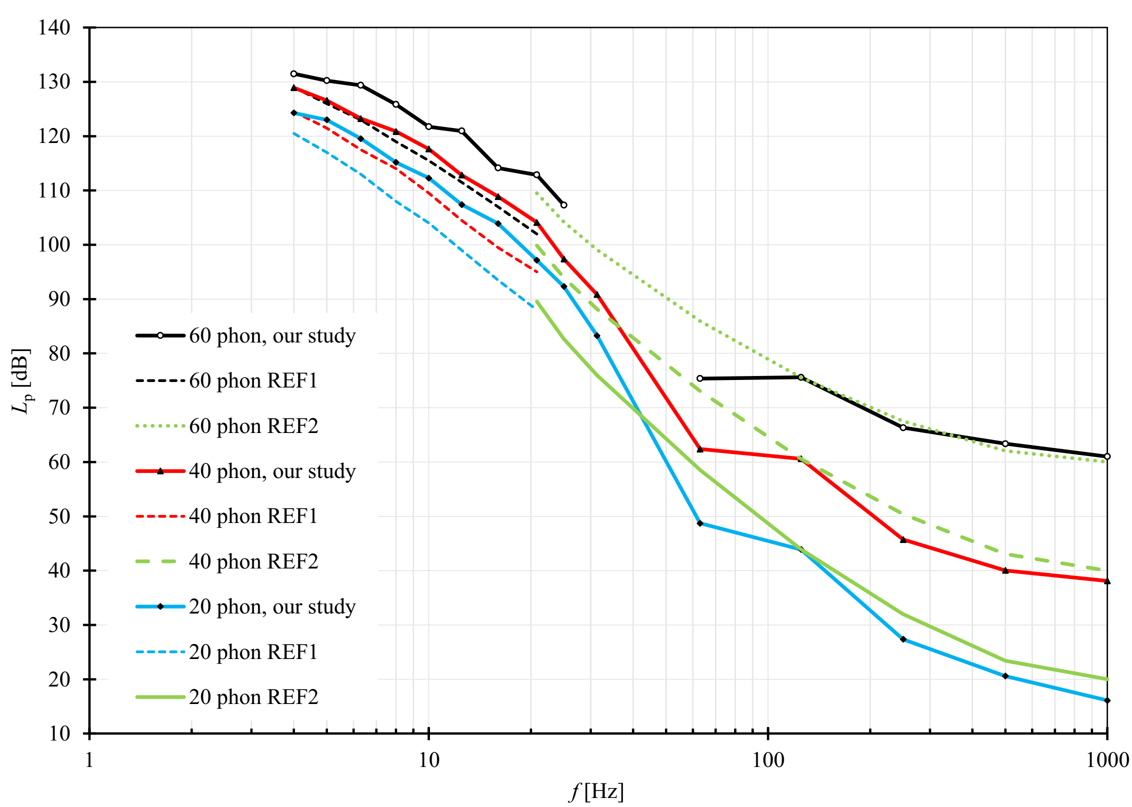

Fig. 4. The unweighted SPL, L_p, as a function of frequency, f, for the mean ELCs obtained in "our study" and in the literature. REF1 represents the proposed ELC of Fig. 21 of Møller and Pedersen [15] within 4–20 Hz and REF2 represents the standardized ELCs of ISO 226 [4].

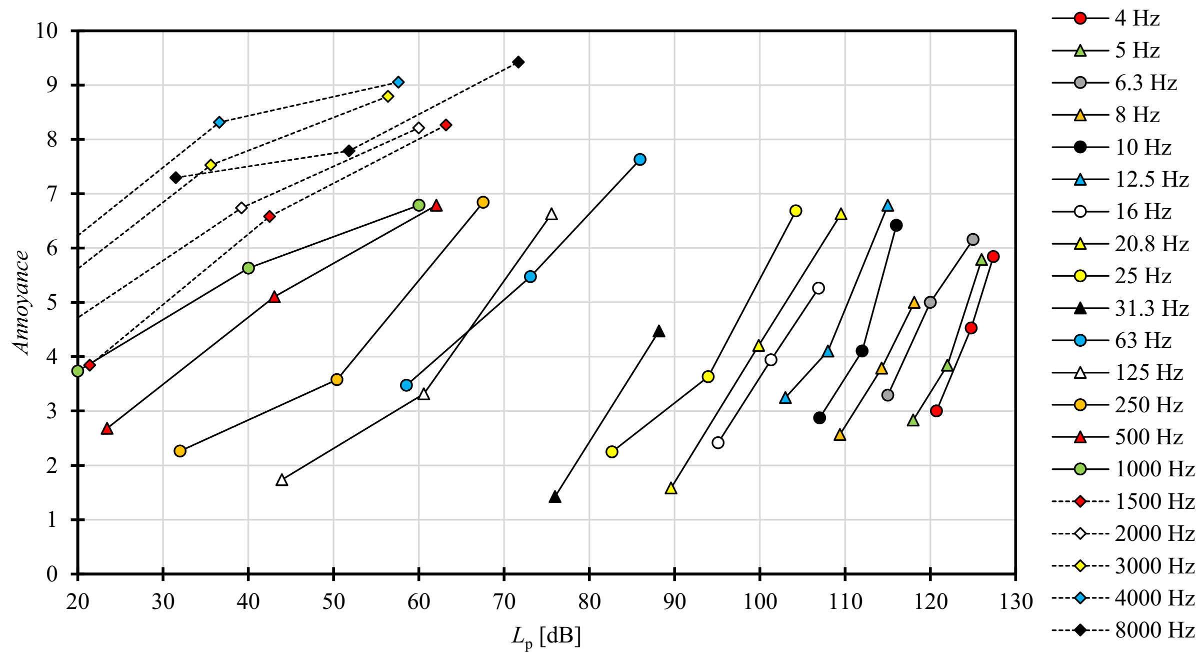

Fig. 5. The mean *annoyance* as a function of unweighted SPL, L_p, for the 20 studied frequencies from 4 to 8000 Hz. For each frequency, the three SPLs conformed with the ELC 20 phon (lowest point), 40 phon (middle point), and 60 phon (highest point) indicated in Table 1. The response range was from 0 (Not at all) to 10 (Extremely annoying).

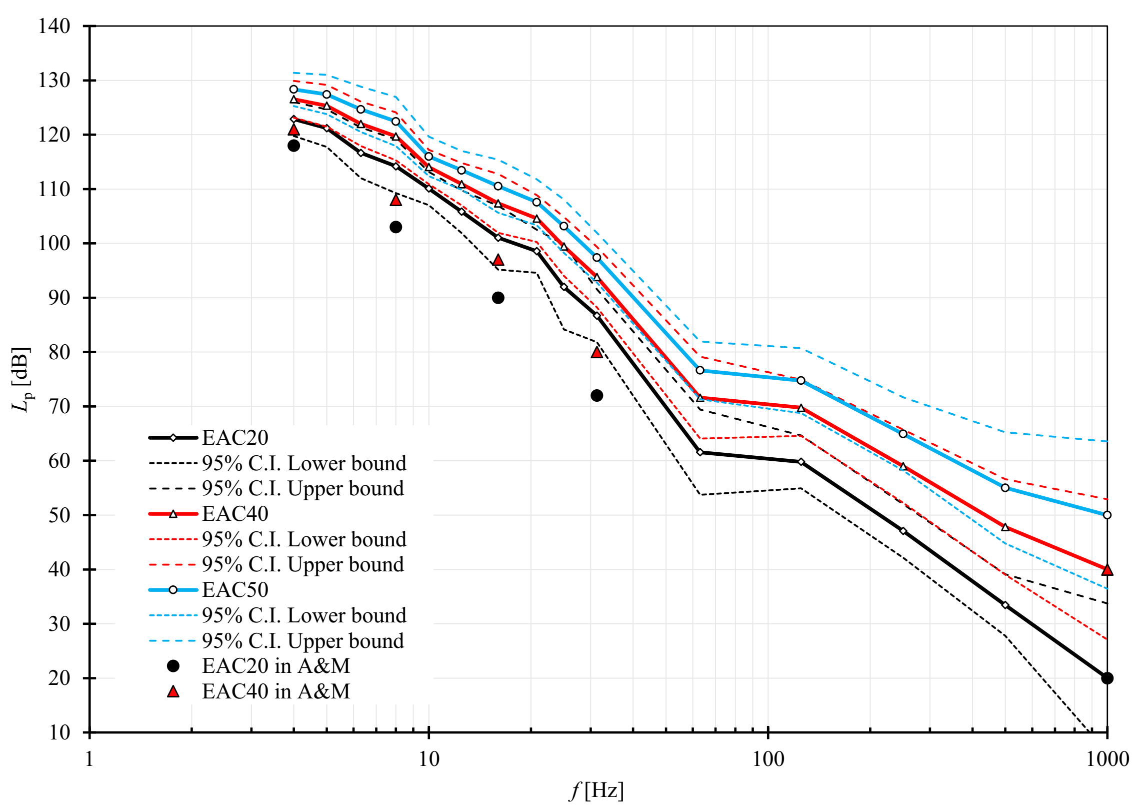

Fig. 6. The equal annoyance contours (EACs) as a function of frequency, f. Curve EACx0 depicts the SPLs which were perceived equally annoying as 1 kHz tone at SPL of x0 dB. EAC20 and EAC40 reported by Andresen and Møller [1] is abbreviated by A&M.

by using a loudspeaker in front of the participant while we used headphones within 125–8000 Hz. This methodological difference may explain the minor difference. The methodology of our hearing threshold experiment was not especially designed to follow any standard. However, as our results did not majorly deviate from standardized HT [6], our methodology seems to be sufficient. T.

The SD of all participants was 4.3–5.0 dB at individual infrasonic frequencies. However, the HT of certain participants (4, 5,

Table 3
The number of participants reporting other sensations apart from hearing during the annoyance test (Phase 10, P10) and other sensations test (Phase 11, P11) for different frequencies, *f*, and loudness levels. The total number was 257 and 235 in phases 10 and 11, respectively.

f	Loudness level					
	20 Phon		40 Phon		60 Phon	
[Hz]	P10	P11	P10	P11	P10	P11
4	5	4	8	7	11	11
5	5	4	5	5	10	10
6.3	8	8	11	11	11	11
8	5	4	6	4	10	10
10	5	4	6	5	7	6
12.5	9	8	7	7	9	9
16	2	2	5	3	9	9
20.8	2	2	8	8	13	13
25	3	3	6	6	10	10
31.3	2	2	10	9	10	10
63	7	6	8	7	14	12
125	0	0	1	1	1	0
250	0	0	0	0	0	0
500	0	0	0	0	0	0
1000	0	0	0	0	1	0
1500	0	0	0	0	0	0
2000	0	0	0	0	0	0
3000	0	0	0	0	1	0
4000	0	0	0	0	1	1
8000	1	0	0	0	4	3

7, 10, 12) was even 10–12 dB lower than the mean of all participants. On the other hand, the opposite situation occurred for certain participants (5, 8, 14, 15). Because the procedure of determining HT is extremely disciplined, these findings are probably not accidental. Our findings support the existence of individual microstructure in HTs. This agrees with Møller & Pedersen [15]. Interestingly, the mean HT over all studied infrasonic frequencies of three participants (1, 4, and 7) was at least 6 dB lower than the mean of all participants. This suggests that some individuals may hear all infrasonic frequencies better than the others. Because we tested only 19 normal hearing people, it is probable that larger deviations from the mean HT appear in the whole population. This is supported by our own findings since we excluded two individual HT data which deviated more than 12 dB from the mean (***Sec.* 2.10**).

Many regulations of low frequency noise are located very close to HT [23]. Because individual differences in HT may differ more than 12 dB from the mean HT, the use of mean HT as a basis of noise regulations may contain risks. Such noise regulations, which are based on HT, should consider the natural distribution of HT among the population.

Because the task in HT test is extremely simple (response after perception), we did not randomize the order of test frequencies between the participants. It is possible that some error was caused due to the lack of randomization. However, the difference of mean

Table 4
The themes of physiological sensation other than hearing that were reported during phase 11 for different frequencies, *f*, and loudness levels (phon).

f [Hz]	20 Phon	40 Phon	60 Phon
4	Pressure in the ear Vibration sensation (light)	Pressure in the ear The feeling of airflow **Irritant sound, makes me nervous	Pressure in the ear Vibration sensation The feeling of airflow Ear pain and headache
5	Pressure in the ear Vibration sensation (body and lower limb)	Pulsating pressure in the ear and head	Pulsating pressure in the ear and head Vibration sensation The feeling of airflow Ear pain
6.3	Pressure in the ear and head Vibration sensation (throughout the body) Headache	Pressure in the ear and head Vibration sensation (upper body) Everything vibrates Headache	Pulsating pressure in the ear and head Vibration sensation (body, lower limb) Ear pain and headache Everything vibrates Gets irritated
8	Pulsating pressure in the ear Vibration sensation (throughout the body) Just like someone sniffing	Pulsating pressure in the ear Everything vibrates **Irritant sound, makes me nervous	Pulsating pressure in the ear and head Vibration sensation (thigh, upper arm, body) Ear pain and headache
10	Pulsating pressure in the ear Vibration sensation (chest, guts) Vibration in body	Pulsating pressure in the ear Vibration Sensation (thigh and middle)	Pulsating pressure in the ear and head Ear pain and headache
12.5	Pulsating pressure in the ear and head Vibration sensation Headache	Pulsating pressure in the ear and head Vibration sensation (lungs and chest)	Pulsating pressure in the ear and head Vibration sensation (throughout the body) Ear pain and headache
16	Pulsating pressure in the ear Vibration sensation (throughout the body)	Pressure in the ear and head Vibration sensation (neck, head, guts)	Pulsating pressure in the ear Vibration sensation (body and brain)
20.8	Vibration sensation (throughout the body)	Pressure in the ear and head Vibration sensation (throughout the body) Feeling of airflow	Pulsating pressure in the ear and head Vibration sensation (throughout the body) Everything vibrates (desk and booth) Ear pain
25	Pressure in the ear Irritant sound, makes me nervous	Pressure in the ear and head Vibration sensation (throughout the body) Everything vibrates (desk and booth)	Pressure in the ear Vibration sensation (throughout the body) Everything vibrates (desk and booth)
31.3	Vibration sensation Irritant sound, makes me nervous and anxious	Vibration sensation (throughout the body) Everything vibrates (desk and booth)	Vibration sensation (throughout the body) Everything vibrates (desk and booth) Ear pain
63	Vibration sensation (throughout the body) Everything vibrates (desk and booth)	Vibration sensation (throughout the body) Everything vibrates (desk and booth)	Vibration sensation (throughout the body) Everything vibrates (desk and booth)
1500			Ear pain
4000			Headache
8000			Sense of pain (head)

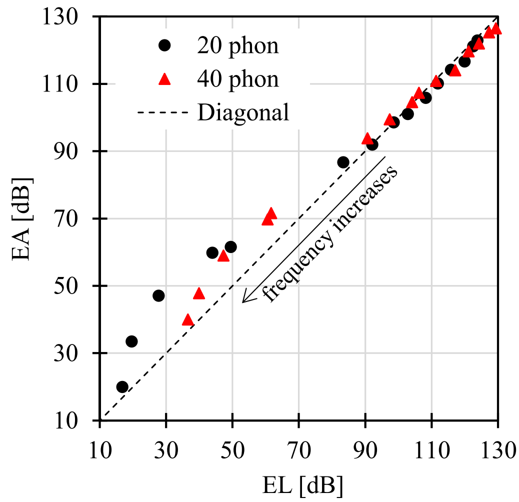

Fig. 7. The association between the SPL of equal loudness, EL (Fig. 4), and the SPL of equal annoyance, EA (Fig. 6), for frequencies 4–1000 Hz. Data point at diagonal means that annoyance and loudness are perfectly associated.

HT at the repeated tone of 3000 Hz was only 0.6 dB. This supports that the error of our HT result is small.

4.2. Equal loudness contours

Our results confirmed earlier findings that the equal loudness contours (ELCs) increased nearly monotonically with decreasing frequency and that the dynamic range of hearing compressed with reducing frequency [15]. An increase of SPL by 5 dB below 10 Hz increased subjective loudness as much as an increase of SPL by 20 dB at 1 kHz.

Between 125 and 1000 Hz, our ELCs were very close to the standardized ELCs of ISO [4] as shown in Fig. 4. Between 20 and 63 Hz, the standardized ELCs and our ELCs differed to some extent. In infrasonic range (4–16 Hz), our ELCs were higher than those proposed by Møller & Pedersen [15]. Part of this could be caused by the previous observation that our HT was somewhat higher than the HT of Møller & Pedersen [15]. However, this difference does not fully explain the observed difference in ELCs. Their proposed ELCs showed a discontinuity in 20 Hz compared to the standardized ELCs [4] at 20 and 40 phon, while our ELCs were continuous around 20 Hz range. This rises an overall doubt that the infrasonic ELCs of Møller and Pedersen [15] might be too low. Furthermore, Møller and Pedersen [15] stated that there is considerable uncertainty in ELCs, as the preceding few studies of infrasonic ELCs showed large variability.

Our ELC at 20 phon deviated from ISO 226 [4] in two ways. First, our values were higher at 20–31 Hz. Second, our values were lower at 63 Hz. Because our HT curve in Fig. 3 did not show similar deviation from the standardized HT, it is difficult to explain the difference at 63 Hz by an error in the SPL setting. It is possible that the chamber produced a resonance or another sensation at 63 Hz tones at 20, 40, and 50 phon levels, which we could not control. We believe that our ELC results at 63 Hz contains a larger uncertainty than at the other frequencies.

The SDs obtained for PSEs were close to the SDs of the HT (**Table S2**). Thus, individual variations in perception of loudness were in the same range as individual variations in HT. This is interesting observation for infrasonic region, where a small change in SPL significantly affects loudness. In other words, an infrasonic tone which is inaudible for one person can be perceived as loud for another person.

4.3. Equal annoyance contours

Fig. 5 showed that high frequency tones (f > 1500–2000 Hz) were more annoying than low frequency tones with same loudness level (20–60 phon). This agrees with Oliva et al. [16], who studied the annoyance of low-level tonal sounds having the same A-weighted SPL. They found that low-frequency tones were less annoying than high-frequency tones when the overall levels are within 25–35 dB L_{Aeq}.

The three EACs are much closer to each other below 31.5 Hz than within 125–1000 Hz. This suggest that a small increment in SPL in low frequencies could drastically increase the perceived annoyance. Despite of this, high frequency tones were perceived much more annoying than infrasonic tones within 20–60 phon. Therefore, our results do not suggest that infrasound is more annoying than sound above 16 Hz: human is just more sensitive to SPL changes in infrasonic frequencies.

Although the annoyance test included frequencies within an extremely broad frequency range, 4–8000 Hz, we only reported the EACs in frequency range 4–1000 Hz. This was justified because the mean annoyance values were always high above 1000 Hz: reliable extrapolation of the EAC SPL values at 20, 40, and 50 phon according to the method of Fig. 2 was no longer possible.

Andresen and Møller [1] published EACs in frequency range 4–1000 Hz in frequencies 4, 8, 16, 31.5, and 1000 Hz. We studied much larger number of frequencies (15 tones, 7 in the infrasonic range). Therefore, our study provides significant new contribution in the research of infrasonic annoyance. Their EACs with base point at 20 dB and 40 dB in 1000 Hz were compared to our contours (Fig. 6**)**. They found a similar relationship that smaller frequencies require higher SPL to be perceived equally annoying as high frequencies. Furthermore, they also described the EACs to be very close to each other in infrasonic range. However, our EACs usually located higher than they observed. The difference is more than 10 dB for some frequencies. Interestingly, at 12.5 Hz their 20 dB ref 1 kHz EAC slightly falls below HT proposed by Møller and Pedersen [15], which raises a doubt if their curves are too low in overall.

Based on visual assessment, there seems to be a dip at 63 Hz in Fig. 6. Previous studies have not published EACs at around this frequency range which prevents comparative analysis. Because our ELCs of Fig. 4 also revealed a dip at 63 Hz when compared to current literature, it is justified to speculate that the dip at 63 Hz in our EACs is actual. It is possible that the chamber produced a resonance or another sensation at 63 Hz tones at 20 and 40phon levels, which we could not control. We believe that our EAC results at 63 Hz contains a larger uncertainty than at the other frequencies.

The absolute values of EACs should be interpreted with caution because individual variations in infrasonic HT are high. However, the trends of the EACs should still be valid even if individual annoyance perception differs much. Thus, we state that the trends we observed are more important than the absolute SPLs in our EACs. Infrasound, which is inaudible for one person, can be annoying for another person. This kind of extreme difference in perception cannot be observed for high frequency sound. Møller and Pedersen [15] came to the same conclusion.

4.4. Annoyance vs Loudness

Fig. 7 suggests that *annoyance* and *loudness* are not equivalent concepts at least in a focused laboratory experiment. EACs were below ELCs at infrasonic frequencies, but the opposite situation was found above 20 Hz. This suggests that when infrasound is audible for a person, it might trigger annoyance very fast although the infrasound is not perceived to be loud. This agrees with Oliva et al. [16] and Virjonen et al. [24] who also found annoyance ratings to be higher than loudness ratings in laboratory environment. The finding calls for further systematic research on the differences of loudness and annoyance.

4.5. Other sensations

Participants reported other sensations to exist in the whole frequency range (Tables 3-4). Altogether 296 other sensations appeared in the infrasonic range (approximately-three octaves) and 196 of them appeared in the non-infrasonic range. The sum of reported other sensations over all frequencies were 47, 73, and 115 for 20, 40, and 60 phon loudness levels, respectively. That is, other sensations were more usual when the SPL was higher.

The themes of reported other sensations did not dramatically differ at the limit frequency of infrasound (16 Hz). Thus, our results do not support that infrasound causes completely different sensations than non-infrasound. However, it was obvious that other sensations were more frequently reported for infrasound than for non-infrasound. It is worth mentioning that most of the participants had probably never heard such loud tonal infrasonic stimuli before in such a focused situation. The infrasonic stimuli were probably very strange for the participants. The peculiarity of sound may have biased the reporting sensitivity to some extent. This was supported by the fact that almost 10 % of reporting in phase 10 did no longer cause reporting in phase 11.

The strength of our experiment was that we did not pursue any specific sensations by offering a list of sensations reported in the literature, but we let the participants describe their feelings spontaneously. Therefore, we believe that these sensations could be observed among the whole population if they are similarly tested a focused laboratory experiment.

It should be noticed that we did not study inaudible infrasound. Therefore, these sensations cannot be generalized to concern inaudible infrasound which is exists in our everyday living environments due to numerous sources [12].

Andresen and Møller [1] let the participants to write free comments once after the whole annoyance experiment involving five tonal frequencies (4, 8, 16, 31.5, and 1000 Hz). The comments involved physiological sensations such as pressure in the ears, at the eardrum or head, headache, or a tendency to it, and interference with breathing. Other sensations involved vibrations of clothes, and newspapers. Our findings agree with many of them but provide much broader range of other sensations. Furthermore, their responses concerned all studied tones in general and the responses could not be associated to any specific frequency. Therefore, our results provide important new contribution since we inquired to describe other sensations for specific frequencies.

4.6. Other considerations

In the loudness experiment we had 15 trials in one PSE test. This is rather small number, as less than 200–300 trials are usually considered small for psychometric function fitting [19]. Furthermore, every SPL was usually presented only once in each test. However, this hindrance was partially solved by pooling the data. We visually examined all psychometric functions and they showed good fit with the data despite the suboptimalities. Even if bigger number of trials would increase the precision of individual PSEs, the effect on mean ELC is probably small.

Our study involved only pure tones which represent narrowband noise. Real-life audible infrasound can also have wideband character. Møller [14] found in a controlled experiment that the 8, 16, and 31.5 Hz tones and one-third octave band noise centered on the same three frequencies had equivalent EACs. Therefore, it is justified to expect that our EACs could be applied also for the evaluation of wide-band noises. The finding of Møller [14] may also indicate that HTs may be the same for one-third octave band noise and pure tone. Because many countries base their low-frequency noise limits to HT [23], and measurements are conducted in one-third octave bands, further research involving non-tonal sounds, such as third-octave or octave band noise, is warranted.

Møller and Pedersen [15] concluded that there is a need for further research of both HTs and ELCs in the infrasonic range. This is necessary before sufficient international agreement and standardization would be possible. It seems that the agreement about infrasonic HTs is relatively good down to 4 Hz. It could be realistic to consider the standardization of infrasonic HT. This is important since many legislations of low-frequency noise stand upon the standardized HT down to 20 Hz but standardized HT is lacking below 20 Hz. Instead, the number of ELC studies covering the infrasonic range is still insufficient and more research is needed.

Our results may have been affected to some extent by the fact that the order of tests (ELC, HT, EAC, other sensations) was not randomized: the same test order was applied for every participant (Table 2). We had strong reasons for that. First, the HT test could not appear first since our preliminary tests showed that infrasonic frequencies could be unfamiliar for the participants. It was justified to begin with loudness test where the participant was visually informed when a test sound was played and this way all participants became familiar with infrasonic frequencies. We believe that this is a strength with respect to the reliability of the later tests (HT test, annoyance test, other sensations test). Second, Other sensations -test could not appear before Annoyance test. Because of these edge conditions, there was only limited possibilities to randomize the test orders.

5. Conclusions

This experimental audiological study inspected the hearing threshold, loudness, annoyance, and other sensations apart from hearing among 19 normal-hearing people in a wide frequency range.

Equal loudness contours 20 phon and 60 phon were very close to each other in the infrasonic range, within 20 dB. That is, even a small change in SPL significantly affects perceived loudness. Because the differences in individual hearing thresholds varied even by 20 dB, an infrasonic tone which is inaudible for one person can be perceived as loud for another person. The finding may explain why some people perceive low frequency sound louder than the other people.

Annoyance experiment confirmed that even a small increment in SPL in low frequencies could drastically increase the perceived annoyance. However, this does not mean that audible infrasound is automatically more annoying than audible non-infrasound. Tones above 16 Hz presented at 60 phon were systematically more annoying than infrasonic tones presented at 60 phon. This suggests that infrasound is not necessarily more annoying than sound above 16 Hz: human is just more sensitive to SPL changes in the infrasonic range. Because the difference in individual hearing thresholds vary up to 20 dB, an infrasonic tone which is inaudible for one person can be perceived as annoying for another person. The finding may explain why some people perceive low frequency noise more annoying than the others.

Other sensations (apart from hearing) were reported both for infrasound (below 20 Hz) and non-infrasound (20–63 Hz). That is, other sensations were not limited to infrasonic frequencies.

The current evidence seems to be sufficiently strong to consider the standardization of hearing threshold level within 5–20 Hz. Standardization is important because concerns about the impacts of environmental infrasound on humans are increasing. The lack of a standardized hearing threshold level prevents many nations to establish target levels for infrasound. The lack of target levels can increase the misunderstanding that infrasound would be inaudible. More experimental evidence about hearing threshold is needed below 5 Hz.

CRediT authorship contribution statement

Ville Rajala: Methodology, Investigation, Writing – original draft. **Jarkko Hakala:** Methodology, Investigation, Visualization. **Reijo Alakoivu:** Methodology, Investigation. **Ville Koskela:** Methodology, Investigation, Validation. **Valtteri Hongisto:** Conceptualization, Methodology, Validation, Formal analysis, Resources, Writing – original draft, Visualization, Supervision, Project administration, Funding acquisition.

Data availability

The authors do not have permission to share data.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.apacoust.2022.108981.

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