On the potential sources of a low-frequency sound percept only a few can hear

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Abstract

A small percentage of the general population reports almost constant humming or pulsing low-frequency sound percepts (LFSPs) while others in their vicinity, such as family members, often do not perceive these sounds. The origin of these LFSPs remains to be elucidated and may or may not be related to external sound sources. The underlying causes of these perceptions could also be subjective and belong to the tinnitus family, especially in cases where no external sound source sufficiently explaining the LFSP can be found. The present study puts forth two hypotheses to explain the phenomenon, based on both subjective and objective auditory phenomena: an unusually high auditory sensitivity to low-frequency sound, and hearing one's own low-frequency spontaneous otoacoustic emissions (SOAEs), sounds actively produced by the inner ear as a normal, physiological by-product of cochlear amplification. The present study employed high-resolution, low-frequency hearing threshold measurements and SOAE measurements in 28 individuals with LFSPs, and in control groups devoid of LFSPs. LFSP complainants self-reported hearing a LFSP at a median frequency of 50 Hz obtained with a frequency-matching procedure. With a few clear exceptions, complainants most often did not present unusually sensitive low-frequency hearing thresholds. Furthermore, hearing threshold fine structure was comparable to the control group. In addition, no SOAEs in the low-frequency range could be measured. Based on our results, while cases of hearing physical external sound sources are not ruled out, we suggest that a subjective tinnitus-like phenomenon in the low-frequency range is often the reason behind hearing these LFSPs.

Introduction

A small percentage of the general population, estimated to be between 2% and 4%, report an almost constant perception of a low-frequency sound. The acoustic quality of this auditory phenomenon is often compared to the sound of an idling diesel engine [1]. The characteristics of these low frequency sound perceptions (LFSP), frequently referred to as the "hum phenomenon", vary considerably between individuals and can be described as pulsing, humming, rumbling, or throbbing [1, 2]. A distinctive attribute of the hum is its tendency to be perceived exclusively by specific individuals, while others within the same familial unit or geographical vicinity often may not be able to hear it. The hum phenomenon has in the past years gained attention due to an increase in reports of LFSPs in the daily press in specific geographical regions, such as Oslo, Norway [3], Darmstadt, Germany [4], or Windsor, Canada [5], and others. LFSPs have been reported on various continents, and a map collecting the geographical distribution and characteristics of reported LFSPs is available on a dedicated website [6]. It is important to consider the possibility of reporting bias when drawing conclusions from the reported cases, which appear to show clear geographical clusters. Several studies have attempted to identify external sound sources as the cause of LFSP. However, potential external sound sources (ESS) were only reported in a few studies [7, 8]. Despite the absence of a definitive explanation for this phenomenon, three attempts to elucidate its relation to the auditory system are reviewed briefly below:

1. The perception of external low-frequency sounds in subjects with unusually sensitive low-frequency hearing thresholds.

LFSPs were reported in both the low-frequency and infrasound ranges, but typically with frequencies ranging from about 30 to 80 Hz [1]. Low-frequency sound (LFS) is loosely defined as sound with frequencies below 100-200 Hz [9, 10], while infrasound is typically defined as sound with frequencies below 16-20 Hz [9, 10], a frequency range which was originally considered to be inaudible to humans. However, several studies have shown that these frequencies can be heard when sound levels are sufficiently high, and that there is no sudden perceptual transition between LFS and infrasound [10]. Nevertheless, *normal* low-frequency and infrasound hearing thresholds (LFHTs) are much higher than those in the normal human hearing frequency range [10]. Most people seem to not experience annoying LFSPs, despite abundant low-frequency noise pollution in the industrialised world [e.g. 11]. However, a small percentage of the general population appears to have unusually low LFHTs, and considerable individual differences in hearing sensitivity, especially in the low-frequency range, exist [12], a result of the estimated normal distribution of normal hearing thresholds. At 31.5 Hz, for example, there is an approximately 17-dB difference between the first percentile and the median of hearing thresholds from a normal-hearing cohort [13]. As an example, for a place like Trondheim,

Norway with its ca. 250,000 inhabitants, this means that 2500 people will hear a 31.5 Hz sound with a sound pressure level of 43 dB SPL (ca. 17 dB lower than the ISO389-7:2019 threshold for that frequency), and 247,500 people will not. Consequently, it can be speculated that low-frequency sound hearers (LFSHs), a term we use here to refer to subjects hearing a LFSP, have hearing thresholds belonging to at least the lower half of the distribution of normal hearing thresholds. It has long been known that normal hearing thresholds show also a prominent microstructure, characterised by considerable threshold changes (up to 20 dB) associated with very small changes of test tone frequency [14, review: 15]. Such local hearing threshold maxima and minima go often unnoticed during routine clinical hearing tests due to the limited number of frequencies tested and the large spacing between, and threshold microstructures might represent another explanation for LFSPs [16, 17].

2. Sounds actively produced by the inner ear, so-called spontaneous otoacoustic emissions (SOAEs), which are heard by their owners

SOAEs are sounds produced by the inner ear as a by-product of physiological processes [see 18 for review]. The exact mechanisms behind SOAEs are still unclear, but two prevailing theories regarding their origin exist, both involving active outer hair cell (OHC) motility in the Organ of Corti of the inner ear [see 19 for review]. It has been estimated that approximately half of the population exhibits measurable SOAEs, with a trend of higher prevalence among female subjects [18, 20, 21]. SOAE frequencies are typically situated between around 0.5 and 6 kHz [18] and, to the best of our knowledge, low-frequency SOAEs have not been reported in humans. SOAE sound levels measured in the closed ear canal typically range from about -10 to about 20 dB SPL [18]. Consequently, a considerable proportion of SOAE levels may exceed the hearing threshold of their owners. This assertion is particularly valid considering the expectation that the intracochlear sound energy is greater than that measured in the ear canal as SOAE sound pressure levels [22]. SOAEs demonstrate often notable stability in terms of both frequency and level over a considerable part of their owners' lives, as evidenced by longitudinal studies [23, 24]. However, SOAES are mostly not perceptible to their owners [20, 25], as the auditory system appears to be able to adapt to, and filter out, these persistent sounds [22, 26]. However, SOAEs may be heard temporarily when transient changes in their frequency or level occur [22]. Reports of annoying, long-term perception of, albeit not low-frequency, SOAEs can be found in the literature [26] . Consequently, the experience of perceiving one's own low-frequency SOAE could offer an alternative explanation for the percepts LFSHs hear, which could be regarded as objective tinnitus (see below).

3. Low-frequency tinnitus

Tinnitus is a generic term that includes objective tinnitus, i.e. the perception of sounds generated within the human body, and subjective tinnitus, which is the perception of a sound in the absence of a physical sound source [27, 28]. Possible explanations for objective tinnitus include myoclonus of the middle ear muscles (i.e. brief involuntary twitching or jerking of the muscles of the middle ear or Eustachian tube), and vascular or tube malformations. These conditions are typically described by sound characteristics that are quite different from typical LFSP reports, such as being synchronous with breathing or heartbeat, or, in the case of myoclonus, manifesting as a clicking or fluttering sound [28, 29]. The underlying pathophysiology of subjective tinnitus, however, is far from being fully understood. The prevailing view is that it involves intricate interactions at all levels of the auditory system, including the cochlea, auditory nerve, and auditory cortex, as well as non-auditory systems [30, 31]. The onset of tinnitus is often preceded by peripheral, cochlear damage, but this is not necessarily the case. Tinnitus can also be triggered by stress and is influenced by the somatosensory system [31, 32]. Tinnitus is commonly thought of as a continuous, high-pitched sound, but a variety of spectral and temporal shapes have been described [33]. Those experiencing typical subjective tinnitus phenomena localise the sounds they hear mostly to the inside of their head, they internalise the sound [33], indicating that the sounds they perceive are not realistic. Some evidence in the literature reporting cases of tinnitus matched with quite low frequencies can be found [33, 34], and LFSPs and tinnitus are thus not mutually exclusive.

Scope of this study

The present study is concerned with the origins of LFSPs, employing widely accepted biomedical methodologies. Hypotheses that do not originate in the auditory system were not evaluated or taken into consideration in this study. Consequently, the term LFSP is employed in lieu of "the hum phenomenon" due to the absence of a definitive and well-defined definition. In this context, LFSP signifies the perception of low-frequency sounds that are not audible to most individuals, irrespective of the presence of a discernible physical sound source.

Methods

A total of 28 LFSHs were included in the study, with 13 males, 14 females, and one LFSH identifying as gender diverse. The median age of the participants was found to be 53.5 years. These participants were recruited from a social media group, where LFSHs self-organised. Additionally, 38 young, normal-

147 hearing adults, recruited from a poll of the department's students, without any dependencies related
148 to the authors of this study, were divided into two control groups (CG1 and CG2).

149 The study was approved by the local Ethics Committee of the University Hospital Munich, Ludwig-
150 Maximilians-Universität München, Germany (project number 19-107), in agreement with the latest
151 revision of the Code of Ethics of the World Medical Association (Declaration of Helsinki). All
152 participants were provided with written information about the study and its procedures and gave their
153 written informed consent. The recruitment period lasted from 1st of April 2019 until 31st of May 2019.

154 Control group participants did not report hearing LFSPs and had no self-reported history of neuro-
155 otological diseases. CG1 consisted of 31 participants (23 females, 8 males, median age 24 years,
156 whereas CG2 included 7 participants (3 females, 4 males, median age 22 years). All participants were
157 seated in a recliner placed in a sound-attenuated chamber while taking part in a set of experiments,
158 which took in total around three hours. Breaks were given as needed. All participants underwent
159 conventional audiometry to assess their hearing thresholds in the frequency range between 125 Hz
160 and 8 kHz before the actual experiments. The controls groups were comprised exclusively of individuals
161 with normal hearing, defined as hearing thresholds at each tested frequency that were at least 20 dB
162 HL, or better, but LFSHs included in the study regardless their hearing status. Conventional audiometry
163 was conducted using commercial software (Automatic Pure Tone Audiometry V2.28, Hörtech,
164 Oldenburg, Germany) and a gamepad (Bigben Interactive, Lesquin, France) as a feedback device,
165 testing both ears in all participants. Test tones were presented using circumaural headphones (HDA
166 200, Sennheiser Electronic GmbH & Co. KG, Wedemark, Germany), and an external soundcard (Fireface
167 UC, RME, Haimhausen, Germany) connected to a laptop (ASUS, G60VX, Taipei, Taiwan) was employed
168 for D/A conversion, set to a sampling rate of 44.1 kHz and a word length of 24 bits. The sound system
169 was calibrated using the software's built-in calibration routine, employing an ear simulator (Type 4153,
170 Brüel & Kjær, Nærum, Denmark) connected to a calibrated measuring amplifier (type 2636, Brüel &
171 Kjær, Nærum, Denmark), to ensure correct sound pressure level over the frequency range used.

172

173 1. Questionnaire and self-testing of low-frequency sound percept frequency

174 Prior to the measurements in our laboratory facilities, LFSHs were asked to complete a questionnaire.
175 The questionnaire consisted of 22 questions, including numerical analogue scales, multiple choice
176 questions, and individual response questions. The questionnaire was designed to collect demographic
177 data about the participants, the characteristics of the LFSP, and the factors influencing it. LFSHs were
178 also instructed to determine their sound percept frequency (SPF) at home by undertaking a frequency
179 matching procedure using a freely available online pure tone generator. The participants were asked

180 to adjust the frequency of a pure tone stimulus so that it would best match their SPF. They were also
181 encouraged to use circumaural headphones if possible. LFSHs were informed of the possibility of
182 binaural beats (that might occur when the generated tone frequency is close to their SPF), which is a
183 spatial hearing sensation that can occur when listening to a dichotic signal that differs slightly in
184 frequency between the ears, and they were asked to repeat the SPF matching process several times.
185 Whilst this procedure is undoubtedly less controlled than those conducted in the laboratory, it avoids
186 the problem that LFSPs can wax and wane and therefore may not be perceived while participants are
187 in the laboratory facilities, rendering a frequency-matching procedure impossible. Estimated SPFs
188 below 15 Hz were considered unlikely to be accurate due to potential equipment distortions. This is
189 because considerable high sound pressure levels (SPLs) are required for the stimuli to be audible at
190 such low frequencies. These are difficult to reproduce without significant distortions with consumer-
191 grade equipment. All participants were asked if they could perceive the hum while they were in our
192 laboratory facilities (for the most, located away from their hometown), which was confirmed by 11
193 participants (39% of all LFSHs).

194

195 2. Measuring low-frequency hearing thresholds

196 *Average LFHT from a normal-hearing cohort and high-frequency resolution LFHTs*

197 High-frequency resolution LFHTs were measured with the intention to assess low-frequency hearing
198 and threshold microstructure in the LFSH group with pure tones in a 16-Hz range symmetrically
199 distributed around the SPF as a centre frequency. LFHT measurements were carried out at nine
200 individual pure tone frequencies corresponding to the SPF, SPF ±1 Hz, SPF±2 Hz, SPF±4 Hz, and SPF±8
201 Hz, respectively. If participants were unable to match their SPF or if matching it required frequencies
202 below 15 Hz, thresholds were measured at seven default frequencies of 16, 20, 40, 63, 70, 80 and 125
203 Hz, which means that threshold microstructure could not be assessed. Threshold measurements were
204 carried out in one ear only. If the participants indicated that the LFSP could be lateralised to one ear,
205 that ear was measured, and if not, one ear was randomly chosen. 14 left ears and 14 right ears were
206 measured. The same seven default frequencies were also used for threshold measurements in CG1
207 participants (from one randomly selected ear only (20 right ears and 11 left ears). The data from CG1
208 was used to develop an average LFHT from a normal-hearing cohort, not reporting LFSPs. To be able
209 to compare the LFSH thresholds obtained with individually varying test tone frequencies (which
210 depended on the self-reported SPF) to the normal-hearing average LFHTs (obtained with default test
211 tone frequencies), a threshold value for each frequency point used in the LFSH group measurements
212 was required. To achieve this, the CG1 hearing thresholds were fitted with a polynomial function (3rd
213 order, red line in fig. 2; MatLab's "polyfit" function was used) to obtain an extra- and interpolated

214 LFHT. A reference range (RR) of normal LFHTs was obtained by calculating the 2.5th and 97.5th
215 percentile of the differences between the estimated, mean hearing thresholds (from interpolation)
216 and the measured hearing thresholds, at each measured frequency. The upper limit (97.5th percentile)
217 of this RR was accordingly calculated to be 11 dB above the fitted LFHT, while the lower limit (2.5th
218 percentile) was 12.2 dB below, resulting in a total RR of 23.2 dB around the fitted LFHT. In addition,
219 high-frequency resolution LFHTs were also measured in seven participants of CG2 with randomly
220 selected, individual sets of frequencies used for participants in the LFSHs group. Those participants
221 were measured several times and contributed 20 high-frequency resolution LFHTs in total.
222

223 *Technical setup and stimulation*

224 All stimuli were time-windowed with $\cos^2$ ramps to avoid onset-offset transients, and the stimulation
225 parameters were adjusted as a function of frequency. Stimulus parameters were adapted from
226 Kuehler, Fedtke (35) and are summarised in Tab. 1. Since LFSHs were tested at individual frequencies,
227 depending on their SPF, stimulus parameters were interpolated or extrapolated where needed, based
228 on the parameters shown in Tab. 1.
229

230 Table 1: Stimulus parameters for measurements of low-frequency hearing thresholds adapted from
231 [35]. Stimulus parameters were extra- or interpolated if not reported here.

Frequency (Hz)	Total Number of periods	Number of periods per ramp	Number of periods with full-scale amplitude	Period duration (ms)	Total signal Duration (ms)
125	75	4	67	8	600
80	48	4	40	12.5	600
63	38	4	30	15.9	604
40	30	4	22	25	750
20	20	3	14	50	1000
16	16	3	10	62.5	1000

232

233 The experimental procedures were controlled, and the signals used were generated using scripts
234 custom-written in MATLAB 2015a (The MathWorks, Inc., Natick, Massachusetts, USA) with the

SoundMexPro toolbox [36]. Experiments were run on a laptop (ASUS, G60VX, Taipei, Taiwan) connected to an external soundcard (Fireface UC, RME, Haimhausen, Germany). The generated analogue signals, required also for calibration, were amplified using an AV receiver (RB-971, Rotel, Tokyo, Japan) and sent to a modified aluminium diaphragm loudspeaker (Rockwood 8" subwoofer, Sintron GmbH, Iffezheim, Germany) placed outside the sound-attenuated chamber. An acrylic glass plate with a 3-cm opening in the centre covered the loudspeaker. The latter was acoustically connected to the ear of the participant (who sat inside the sound attenuated chamber) via an 8.8-m long tube, sealed at one end into the loudspeaker's opening and going through an opening in the chamber's wall. The tube diameter gradually decreased and at its other end went through a pierced foam earplug (E-A-R Classic II PD01200, 3M, Nadarzyn, Poland), thereby delivering the LFS stimuli into the ear canal. The earplug had an additional perforation where another tube was inserted to connect a microphone (ER-10C, Etymotic Research Inc., Elk Grove Village, IL), used for in-situ calibrations in the participants' ear canal. To ensure accurate sound levels, the sound system was also calibrated beforehand using an ear simulator (Type 4157, Brüel & Kjær, Nærum, Denmark) and a calibrated measuring amplifier (Type 2636, Brüel & Kjær, Nærum, Denmark).

Psychoacoustic procedure

The LFHT measurement paradigm consisted of a one-up one-down staircase procedure used in combination with an adaptive two-alternative forced-choice paradigm (modified from [35]). Participants used a touchscreen, connected to a laptop situated outside the soundproof chamber, as a feedback device. On the touchscreen, two buttons were sequentially highlighted and represented two intervals. One of these intervals was randomly accompanied by the test stimulus, whereas the other was accompanied by silence. Participants were tasked with the identification of the interval in which the LFS was present, by pressing the corresponding button. The frequency-dependent stimulus start levels were adopted from [35], and for stimulus frequencies not described there, data interpolation was used. Based on the participants' response, the sound pressure level was adjusted accordingly: when the participants responded correctly or wrongly, the stimulus level was lowered or increased, accordingly. This process created reversal points, indicating transitions from wrong to correct responses, and vice versa. The measurements were concluded after completing 12 reversal points, and the LFHT was estimated by averaging the sound pressure levels corresponding to the last eight reversal points. To ensure precise adjustments, stimulus level increments and decrements were gradually reduced. At the beginning of the measurement, level increments were set to 12 dB, and level decrements to 4 dB. Level steps decreased progressively with increasing number of reversal points until a step size of 3 dB for increments, and 1 dB for decrements was reached. Before reaching the first

reversal point, the participants could indicate that the initial LFS presentation level was below their LFHT, if needed, prompting an increase in start level by 4 dB. This option was no longer accessible once the first reversal point was reached. If the maximum amplitude difference between the last eight reversal points exceeded 15 dB, indicating inconsistency in the participant's responses, the data was not included for analysis and the measurement was repeated. This was necessary for at least one measurement in 23 of the 28 LFSHs, with a total of 33 repeated measurements (out of 234 measurements in total).

3. SOAE testing

The experimental setup used for recording spontaneous otoacoustic emissions (SOAEs) in this study was identical to that used in a previous study (Kugler et al., 2014). However, in the present study, two ER-10C DPOAE probe systems (Etymotic Research Inc., Elk Grove Village, IL, USA) were simultaneously inserted into both ear canals. This approach reduced the required recording time and allowed us to remove SOAE candidates with similar frequencies, recorded in both ears, which were then considered to be artefacts. SOAE candidates recorded in both ears were excluded from the analysis if they were similar within a 10 Hz range, as it is improbable (although possible, see [37]) that SOAE would occur at very similar, or identical, frequencies in both ears of a participant. Signal generation -used here only for assessing the probe fit in the ear canal- and data acquisition were controlled with the same software and hardware as described in section 2. The microphone signals from the ER-10C probes were amplified by 30 dB using the microphone preamplifier of the external sound card. To maximise the detection of SOAEs, each measurement began with a 30-second trial to ensure favourable measurement conditions, excluded from the subsequent analysis. This was followed by a 2-minute measurement, which was included in the analysis. In cases where a high level of background noise occurred (mostly due to participants movement during the recording), the measurements were repeated, as an automatic evaluation of the signal-to-noise ratio (SNR) would reject SOAEs candidates in the subsequent analysis (see details below). Automatic identification of SOAEs followed the approach explained in detail in previous publications from this laboratory, e.g. [38], and the most essential steps are summarised here:

The magnitude spectrum of each recording was calculated using MatLab's pwelch function, implemented with a 0.5 s Hann window, 12.5% overlap, and a zero-padded FFT with a size of 1 s, resulting in a frequency bin width of 1 Hz. Candidate SOAEs were automatically detected in the magnitude spectrum by finding local maxima (minimum level: -15 dB SPL; minimum spectral distance between two maxima: 10 Hz) within a frequency range between 30 Hz and 5 kHz. SOAEs were considered valid if the power of the dominant SOAE spectral line differed significantly from the power

of the noise floor (F-test, critical value: 5.39; see Dobie and Wilson (1996)). The noise floor power was calculated as the averaged power in two 8-Hz wide frequency bands, situated 20 Hz above and 20 Hz below the peak frequency of the candidate SOAE. This produced a list of SOAEs from both ears for each participant.

As the noise floor is generally inversely proportional to frequency, it is expected that low-frequency SOAEs will be challenging to measure without attempts to improve the SNR. To achieve this, an additional measurement and analysis technique was used in all participants. A dual-microphone OAE probe (Path medical GmbH, Germering, Germany) was used, and signal acquisition followed the same procedure as described above. To improve the SNR, the cross power spectral density [39] of the two recorded signals from the same ear was calculated using MatLab's cpsd function, and SOAE candidates were identified in the resulting signal using the same procedures as described above. Newly detected SOAEs were only added to the list of SOAEs if their frequency differed by more than 10 Hz from already identified SOAEs (previously obtained using the two ER10C probes). Measurements with the dual-microphone probe were carried out unilaterally in the corresponding ear of individuals who reported unilateral LFSPs, while both ears were tested on those not lateralising their LFSP, and in all tested CG2 participants.

4. Statistical analysis

The statistics and machine learning toolbox was used in MATLAB 2024b (The MathWorks, Inc., Natick, Massachusetts, USA) for statistical analysis. The research questions are based on a between-subjects design (differences between the LFSH group, and the control groups). The threshold microstructure depths (dependent variable) obtained with different test tone frequencies (independent variable) was compared between the LFSH group and a control group by using a two-sided Wilcoxon rank sum test, employing the "ranksum" function. Furthermore, the distribution of microstructure minima and maxima (dependent variables), obtained as a function of test tone frequency relative to the SPF (independent variable) was compared between the LFSH group and the control group with a two-sample Kolmogorov-Smirnov test, using the "kstest2" function. The threshold for significance was $\alpha=0.025$ (adjusted for multiple comparisons according to the Bonferroni correction).

Results

1. Audiometric results, participant-operated frequency matching of the low-frequency sound percept, and questionnaire results

Audiometric results

11 LFSHs (39.3%) had conventional audiometry hearing thresholds of 20 dB HL or worse at one or more test frequencies between 125 Hz and 8000 Hz in at least one ear, which is an expected finding given the age range of the group tested. All control group participants had hearing thresholds better than 20 dB HL at all tested frequencies.

Participant-operated frequency matching

Across all the individuals where it could be matched (N=23), the median SPF was 50 Hz (see Fig. 1 for the distribution of self-reported LFSP frequencies). Five participants were unable to match their SPF, stating that its frequency composition was too complex to be matched with a pure tone. This number includes one participant who reported an LFSP frequency of 10 Hz, which was deemed unrealistic (see methods). Approximately 45% of the participants reported that they had attempted to measure a potential physical source of the LFSP, either themselves or with professional assistance. Approximately 20% of the participants were able to confirm such a physical source.

----------Fig. 1 around here----------

Fig. 1: Distribution of the self-reported SPFs from 23 participants (bin width 20 Hz). The median SPF was 50 Hz.

Questionnaire results

68% of the LFSHs reported that they cannot lateralize the LFSP. The remaining participants were almost evenly divided into two groups, with four individuals reporting lateralized LFSPs to the left ear and five individuals indicating LFSPs in the right ear. 86% of the LFSHs classified the LFSP as stressful. Additionally, 68% of the participants responded that family or household members were unable to hear the LFSP. 39% of the participants reported hearing additional sounds of unknown origin, described by them mostly as high-frequency tinnitus. One participant had previously experienced high-frequency tinnitus in conjunction with an episode of sudden hearing loss. Most participants rated their typical acoustic environment as rather quiet (71% chose a value lower than 5 on a linear scale from 1 (very quiet) to 10 (very noisy)), with a mean score of 4.2. 68% of the participants reported that the

LFSP was only audible in specific locations, and for 85% of the participants, it was not dependent on the time of day. Two participants (7%) reported that the percept was dependent on both time and place. For the four participants who described that the LFSP depended on the time of the day, the phenomenon was predominantly perceivable during the mornings and evenings. Most of the participants (ca. 93%) did not experience pitch changes of their LFSP, whereas ca. 60% described the perceived loudness of their LFSP as constant since their first encounter. The LFSP was not a constant phenomenon for ca. 45% of the LFSHs in this study, and 36% of the LFSHs indicated that the number of LFSP episodes was increasing over time. Participants were also asked to respond to a series of factors in relation to their ability to enhance or attenuate the LFSP (several answers could be given, see Fig. 2).

----------Fig. 2 around here----------

Fig. 2: Distribution of self-reported factors enhancing (A), or attenuating (B) the LFSPs. Participants could choose several factors.

Approximately 32% of the participants reported being unaware of any factors that enhance LFSPs. Others, with a similar percentage, respectively, mentioned that low-frequency sounds, stress, or external sound sources could enhance LFSPs. Additionally, participants were given the opportunity to define their own influencing factors, which were then summarized as 'other factors'. Here, weather conditions as enhancing factors and various activities such as travelling, outdoor activities, alcohol consumption, leisure activities or sports, and loud music as attenuating factors were mentioned. The most frequently selected options (ca. 60% of the participants) for attenuating factors were individual 'other factors', but around 30% of the participants also named pre-defined mitigating factors such as 'making music', 'head movements', 'external sound sources' and 'air travel'.

2. Low-frequency hearing thresholds

Considering the anticipated variability in low-frequency hearing thresholds resulting from the methodological approaches employed, data from a control group (CG1) was incorporated to establish a normal reference range (RR, see Fig. 3). The data from the control group was collected using the same configuration and methodologies as with the LFSH group. The thresholds obtained with six default test tone frequencies (see methods) were fitted with a third-order polynomial and taken as the normal hearing threshold (NHT). The LFHTs of the LFSHs were then compared to this NHT and RR (Fig. 3A). 48% of all LFHTs were lower than the interpolated NHT, and consequently 52% above the NHT,

398 indicating no significant clustering above or below the NHT. 5% of LFHTs were lower than the RR, and
399 6% of LFHTs were higher than the RR, or, in other words, 89% of the LFHTs were within the RR. Some
400 threshold values merit particular attention. Participants BT02 and BT025 presented thresholds
401 approximately 20 dB and 30 dB below the 2.5th percentile, respectively (at 28 Hz and 62 Hz,
402 respectively; see Fig 3A). This finding suggests that these individuals are unusually sensitive. In
403 contrast, participant BT04 presented an outlier threshold (at 79 Hz) ca. 25 dB above the RR, being an
404 example of unusual insensitivity at that frequency.

405 Seven participants from another control group (CG2) were also tested for comparison with randomly
406 chosen sets of test tone frequencies from the LFSH group (since a LFSP does not apply to them; see
407 Fig. 3B). Most of these thresholds (89%) fall within the established reference range.

408

409 ----------Fig. 3 around here----------

410

411 Fig. 3: Low-frequency hearing thresholds of 28 LFSHs (A) and 7 participants from CG2 for comparison
412 (B). Note that participants from CG2 contributed 20 hearing thresholds in total, as they were measured
413 several times. Different marker styles or colours represent thresholds from individual participants.
414 Thresholds from the LFSHs (A) were measured at the self-reported SPF and at additional 8 frequencies
415 around it (for 23 LFSHs, where one LFSH completed only measurements with 6 frequencies), or, if the
416 SPF was not available, at the 6 standard test tone frequencies (5 LFSHs, see methods). For comparison,
417 thresholds from seven CG2 participants (B) were measured at randomly chosen, individual sets of
418 frequencies from the LFSH group. The red line represents a polynomial fit to the low-frequency hearing
419 thresholds obtained from a larger set of subjects belonging to another control group (CG1, N=31) that
420 also did not report LFSPs. These reference thresholds were obtained with a standard set of frequencies.
421 The lower and upper black lines represent the boundaries of the RR, giving the 2.5th and 97.5th
422 percentile of the difference between the individual threshold values of CG1 and the polynomial fit,
423 respectively.

424

425 On closer examination of the high-resolution LFHTs, threshold microstructures could be observed
426 within both LFSHs and CG2, occurring between closely spaced test tone frequencies near the SPF (see
427 Fig. 4 for an example from a participant belonging to the LFSH group). The microstructure depth,
428 quantified as the difference between threshold minima and maxima, showed a tendency, albeit non-

429 significant, to be larger in LFSHs than in CG2 (medians: 16.3 dB (LFSH) and 12.6 dB (CG1), respectively,
430 p=0.06, z-value: 1.8871, rank sum: 584).

431

432 ----------Fig. 4 around here----------

433 Fig. 4: Representative example of hearing threshold microstructure from one participant in the LFSH
434 group (BT 01), who matched the SPF to 73 Hz. The difference between the maximum and the
435 minimum is the microstructure depth (in dB).

436

437

438

439 The distributions of individual threshold maxima and minima around the tested frequencies, expressed
440 relative to the SPFs showed no significant difference (two-sample Kolmogorov-Smirnov test; D=0.151,
441 p=0.68) between the participants from the LFSH group (see Fig. 5A), and those in CG2 (Fig. 5B),
442 indicating no specific difference in clustering of threshold minima and maxima.

443

444 ----------Fig. 5 around here----------

445

446 Figure 5: Microstructure of the hearing thresholds, expressed as a threshold maximum (black circles)
447 and threshold minima (red squares) as a function of test tone frequency. Test tone frequencies are
448 expressed relative to the individual SPF. The histograms represent the combined number of maxima
449 and minima in relation to the test tone frequency. Results are shown for the LFSP group (A) and control
450 group (CG2, B). For comparative purposes, randomly selected series of test tone frequencies from the
451 LFSH group were selected and tested with participants belonging to CG2 (B).

452

453

454 3. Spontaneous otoacoustic emissions

455 SOAEs were measured with two different OAE probes with the intention to maximize the number of
456 SOAE candidates and to reduce the noise floor, especially in the low-frequency region, thereby
457 facilitating the detection of low-frequency SOAEs. The employment of a dual-microphone probe and

the subsequent calculation of the cross-spectral density based on the two microphone signals clearly improved the noise floor (and thus the SNR) in comparison with conventional OAE probes (Fig. 6).

----------Fig. 6 around here----------

Fig. 6: Representative examples of SOAE spectra measured in both ears of one participant. Here, SOAEs in the right ear were successively measured with two different OAE measurement systems (spectra shown in A and B, respectively). The measurements presented in A and C, measured simultaneously in the right and left ear, respectively, were obtained using two ER-10C systems, while the measurement depicted in B was conducted employing a dual-microphone probe and a spectral cross-correlation procedure, resulting in an improvement of the SNR. Note that spectral lines with identical frequencies (within a margin of 10 Hz) in the right and left ear (A, C) were considered artefacts and omitted from the final analysis.

SOAE frequencies measured in the CG1 and LFSH groups ranged from 861 Hz to 4637 Hz (Fig. 7), indicating that SOAEs with frequencies lower than about 900 Hz are generally seldom to be found or at least rarely exceed sufficient SNR using available systems. As both ears were measured in 12 tested participants of CG1, and all LFSH participants who perceived the LFSP binaurally (in some cases several times to obtain adequate measurement results with the lowest possible background noise level), all measurable SOAEs were pooled from the respective test subjects. It was found that the SOAEs of both the LFSHs and CG1 were slightly undulating in frequency, which might be caused by factors external to the ear, such as body temperature [40] or changes in body position [41], which can be regarded as physiological. SOAEs deviating by a few Hz in repeated measurements were counted as one SOAE. In the participants from CG1, SOAEs were detected in 8 out of 12 participants (67%), while in the LFSH group, this was the case for 8 out of 28 participants (29%). A total of 20 SOAEs were measured in CG1 and 17 in the LFSH group.

----------Fig. 7 around here----------

Fig. 7: Number and frequency of valid SOAEs from the LFSH group (white columns) and CG1 (grey columns), bin size= 200 cents). Note the absence of SOAEs with frequencies below ca. 900 Hz. SOAE candidates above 5 kHz were not included in the analysis.

Discussion

The present study was conducted with the objective of testing two hypotheses concerning the perception of low-frequency sounds that appear to be perceivable only by a limited number of individuals and are commonly referred to as the "Hum phenomenon". At first glance, the observation that some complainants hear a physical sound source while others in their vicinity do not, suggests an unusually low LFHT in the relevant range. The hearing thresholds in the normal frequency range of the participants in this study agreed with their age, showing the usual signature of age-related hearing loss [42]. But normal audiometry with its frequency increments in octaves does neither consider very low test-tone frequencies nor the microstructure of hearing thresholds, a term summarising non-monotonic, quasi-periodic hearing threshold changes over a narrow range of test tone frequencies [43]. These highly individual peaks and troughs in the hearing thresholds might at least represent good candidates for unusually low hearing thresholds, and microstructures of LFHTs have been demonstrated before [16]. In other words, there is a good chance that regions with unusually low thresholds in the low-frequency range of hearing are being overlooked by conventional audiometry.

Measuring threshold microstructure is time-consuming and strenuous for the participants and therefore were test tone frequencies in this study limited to a very narrow frequency range, with very small frequency increments and decrements around the self-tested SPF. To limit the number of frequency steps required, frequency steps were increased with increasing distance from the SPF. The observed increased fine structure around the SPF could hence be the result of tighter "sampling", corroborated by the fact that the control groups show a comparable microstructure. Most of the measured thresholds fall within the central 95% of the NHTs (i.e. the range from the 2.5th to the 97.5th percentile) that we measured in a young, normal-hearing, non-LFSP-hearing cohort. Assuming that the LFSHs are indeed characterised by unusually low thresholds in the low-frequency range of hearing, it would be expected that a significant proportion of the measured thresholds are below the 2.5th percentile, the lower limit of the reference range, or at least in the lower half of the threshold

distribution. This was, with the notable exception of two thresholds from two participants, not the case. It is nonetheless not unlikely that in those cases of LFSPs where a physical sound source can be assumed to be underlying, it is simply a problem of normality, as threshold differences of up to about 20 dB can be expected between the most sensitive and least sensitive in a *normal* population [13]. In future studies, those in the familial units of LFSHs not hearing a LFSP should be included in the testing. The thresholds measured here concur with those reported in [17], were also individuals experiencing LFSPs were tested, and where no abnormally sensitive thresholds were found. As the authors of that study did not attempt to measure threshold microstructure, the possibility was raised that local threshold minima might not have been detected. Here, we showed that this is indeed the case, but threshold microstructure does not seem to be sufficient to explain LFSPs, as the control group in our study also showed comparable threshold microstructure, without reporting LFSPs. Still, present results suggest that within the small percentage of LFSP complainants in relation the overall population, there is an even smaller percentage of individuals that do present abnormally high sensitivity. The latter has been observed before (discussed in [10]), and might stem from anatomical variations in the inner ear. For example, intracochlear pressure produced by LFS been found to largely influenced by the helicotrema, which is an opening in the cochlear apex of the inner ear that shunts pressure differences across the cochlear fluid-filled scalae and thus decreases the inner ear's sensitivity for LFS. It has been found that dips and peaks in the intracochlear pressure are an expected effect of the helicotrema impedance, and that these are reflected in both hearing threshold and loudness perception for sounds below 100 Hz [16, 44]. Thus, anatomical variations in this structure might render a very small percentage of individuals more sensitive than normal.

Although not directly tested in this study, low-frequency tinnitus is a plausible explanation for LFSPs in those with normal hearing thresholds, and where no ESS can be identified. However, complainants might consider this unlikely, maybe because they externalise the LFSP they hear, which further complicates the consideration of the possibility that what they hear is a tinnitus-like phenomenon, when no external sound sources can be verified. The internalisation of a sound can be thought of as the consequence of the absence and/ or violation of binaural and other cues expected from a real sound source, compared to the cues available from a tinnitus source (or conventional headphones, for that matter). This includes spectral cues [45], reverberation [46], and changing binaural cues with head movements [45, 47, 48]. Externalisation, on the other hand, occurs if those cues are available and realistic [48, 49]. While some cues are available to humans when it comes to the localisation of low-frequency sound sources, minimum audible angles are much larger compared to sound sources in the normal frequency range, even more so in a room small enough to have dominant room modes [50]. Since available natural cues for localising low-frequency sound sources in a room are quite rudimental, even an internal generator of a tinnitus-like LFSP might satisfy the conditions needed to externalise

553 the percept. Reports about subjective tinnitus (albeit non low-frequency) with perceived spatial
554 localisations outside of the head exist [51]. For those suffering from a tinnitus-like percept, retraining
555 strategies involving alternating listening to artificial sound sources presented in the sound field and
556 within the ear canal might facilitate the process of internalisation, normally occurring in those
557 experiencing subjective tinnitus [51].

558 Some LFSHs with normal hearing thresholds might also have developed an aversion to sound emissions
559 from ESS. Such 'LFS misophonia' may have resulted from repeated, continuous exposure to these
560 sounds and a learned recognition of them (for a review on misophonia, see [52]). In this context it is
561 worth noting that a large proportion of LFSHs in this study matched the frequency of their LFSP to a
562 pure tone of around 50 Hz. 50 Hz is the frequency of the power grid in Germany (the study site), and
563 thus it is not unlikely that repeated exposure to sound with similar spectral content existed from home
564 appliances or audio equipment.

565 Participants in this study included both complainants who reported that a LFS source could be
566 identified, and those who could not. About 2/3 of LFSHs in this study reported that it was only them
567 who heard the LFS. Thus, the LFSHs in this study may have involved both cases of unusually low LFHT,
568 and cases with normal LFHTs where possibly an aversion to these sounds was developed. The LFHTs
569 measured in this study suggest that both case types were present, albeit the majority of LFSHs
570 presented normal LFHTs and only a few could be classified as especially sensitive.

571 The second hypothesis explored in this study suggests that the perception of LFSPs is due to hearing
572 one's own spontaneous otoacoustic emissions in the low-frequency range. However, SOAEs are
573 typically not audible to their owners, despite sound levels which may exceed the hearing thresholds
574 for that frequency [18]. Additionally, low-frequency SOAEs can be difficult to measure, and in the
575 present study these were not detected at frequencies below about 900 Hz in either the LFSH group or
576 the control group. This finding is consistent with previous research on SOAE frequencies in the normal
577 population. It is, however, unclear if unsuccessful attempts have been previously made to measure
578 SOAEs in the low-frequency range, or whether the lack of reported SOAE frequencies in this range has
579 been due to arbitrarily restricting the search for candidate SOAEs to frequencies higher than ca. 500
580 Hz [18]. Since the absence of SOAEs with frequencies below about 900 Hz could simply indicate that
581 the SNR was not sufficiently large at low frequencies, we attempted to improve it by using dedicated
582 equipment and signal processing. Despite these efforts, no SOAEs with frequencies below
583 approximately 900 Hz could be found. It seems that, based on our results, two rare events need to
584 coincide for SOAEs to serve as an explanation for a LFSP: the occurrence of supra-threshold, low-
585 frequency SOAE, and their audibility. This renders hearing SOAEs an unlikely explanation for LFSPs.

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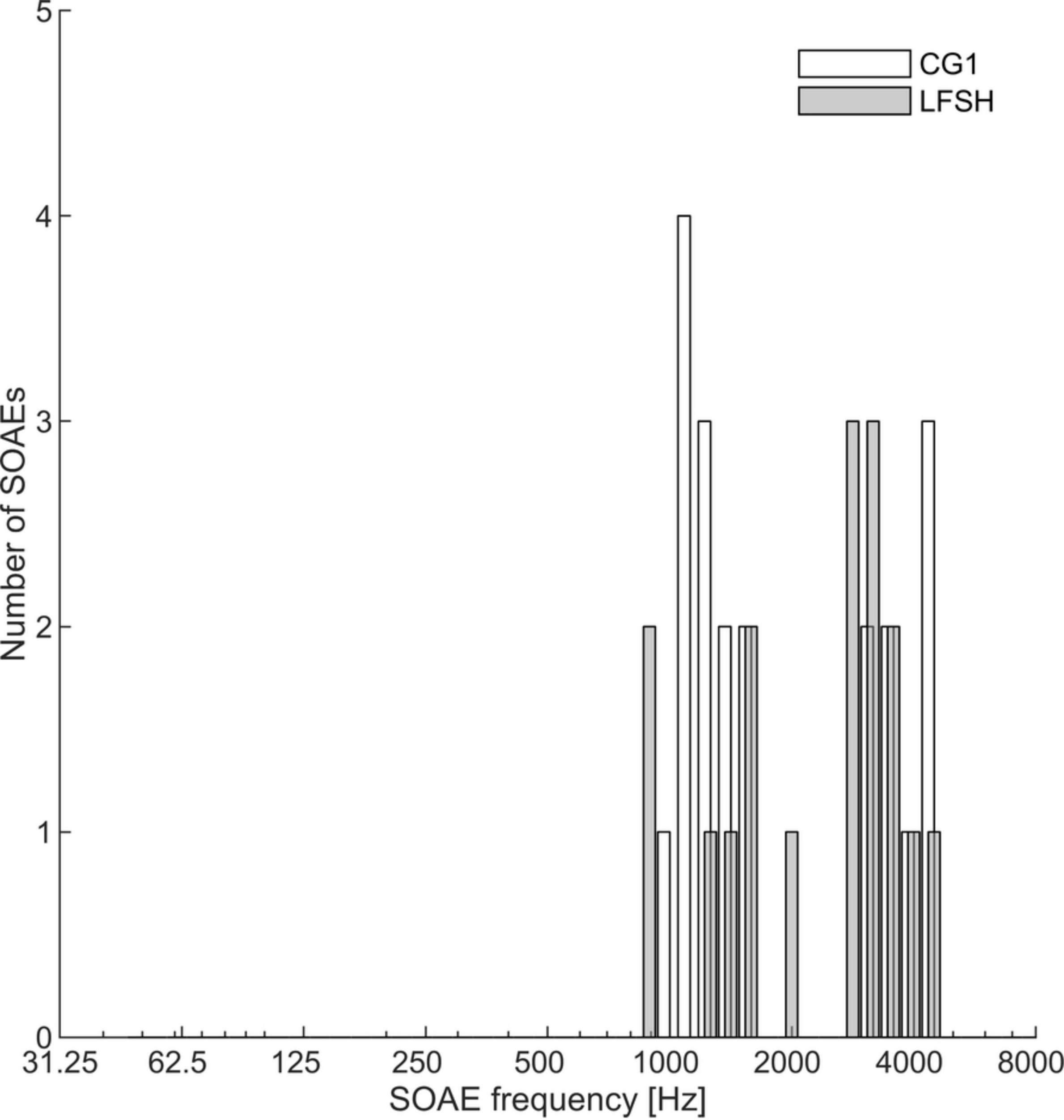
CG1
LFSH
Number of SOAEs
0
1
2
3
4
5
31.25
62.5
125
250
500
1000
2000
4000
8000
SOAE frequency [Hz]

Figure 7

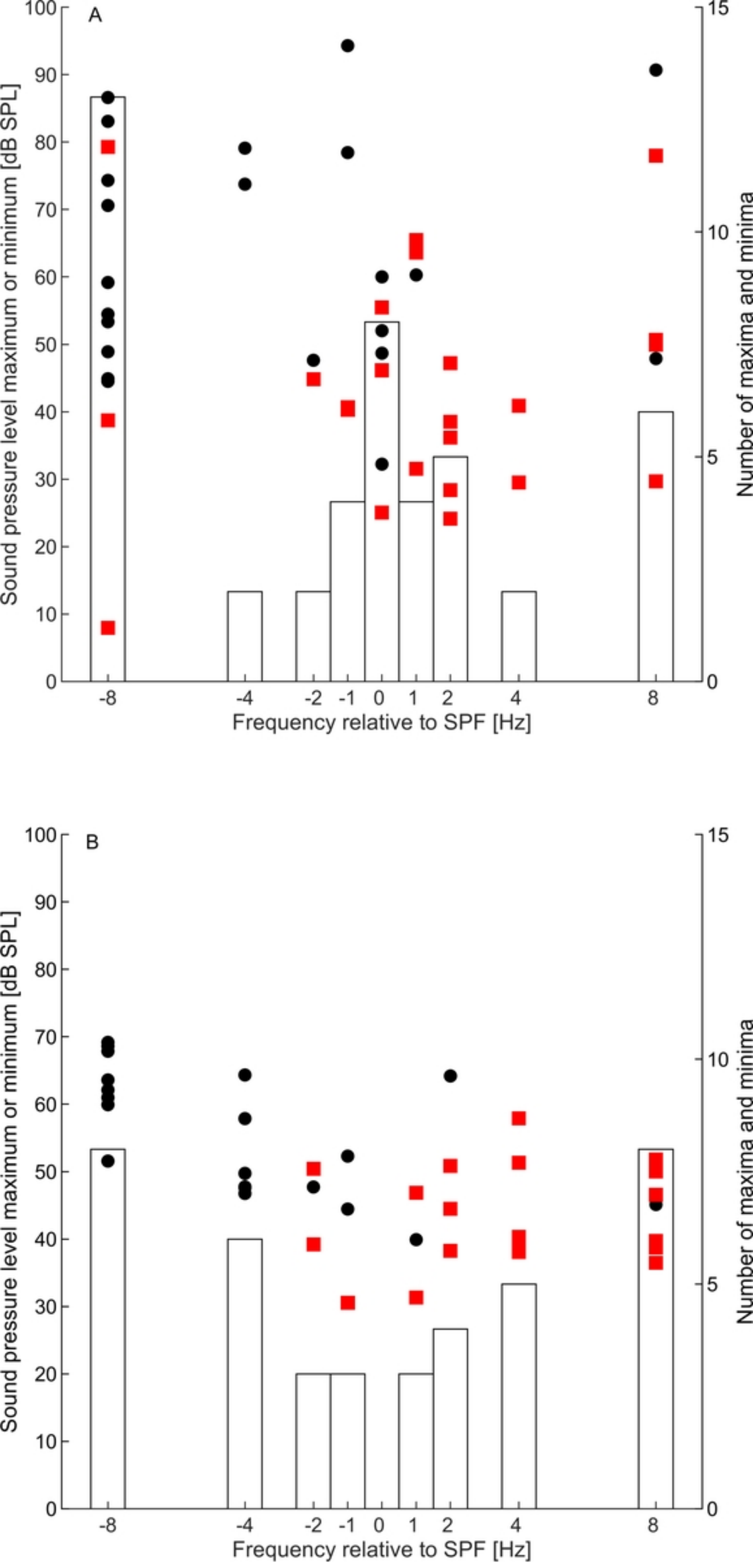
A
B
Sound pressure level maximum or minimum [dB SPL]
Number of maxima and minima
Frequency relative to SPF [Hz]
-8
-4
-2
-1
0
1
2
4
8
0
10
20
30
40
50
60
70
80
90
100
5
15

Figure 5

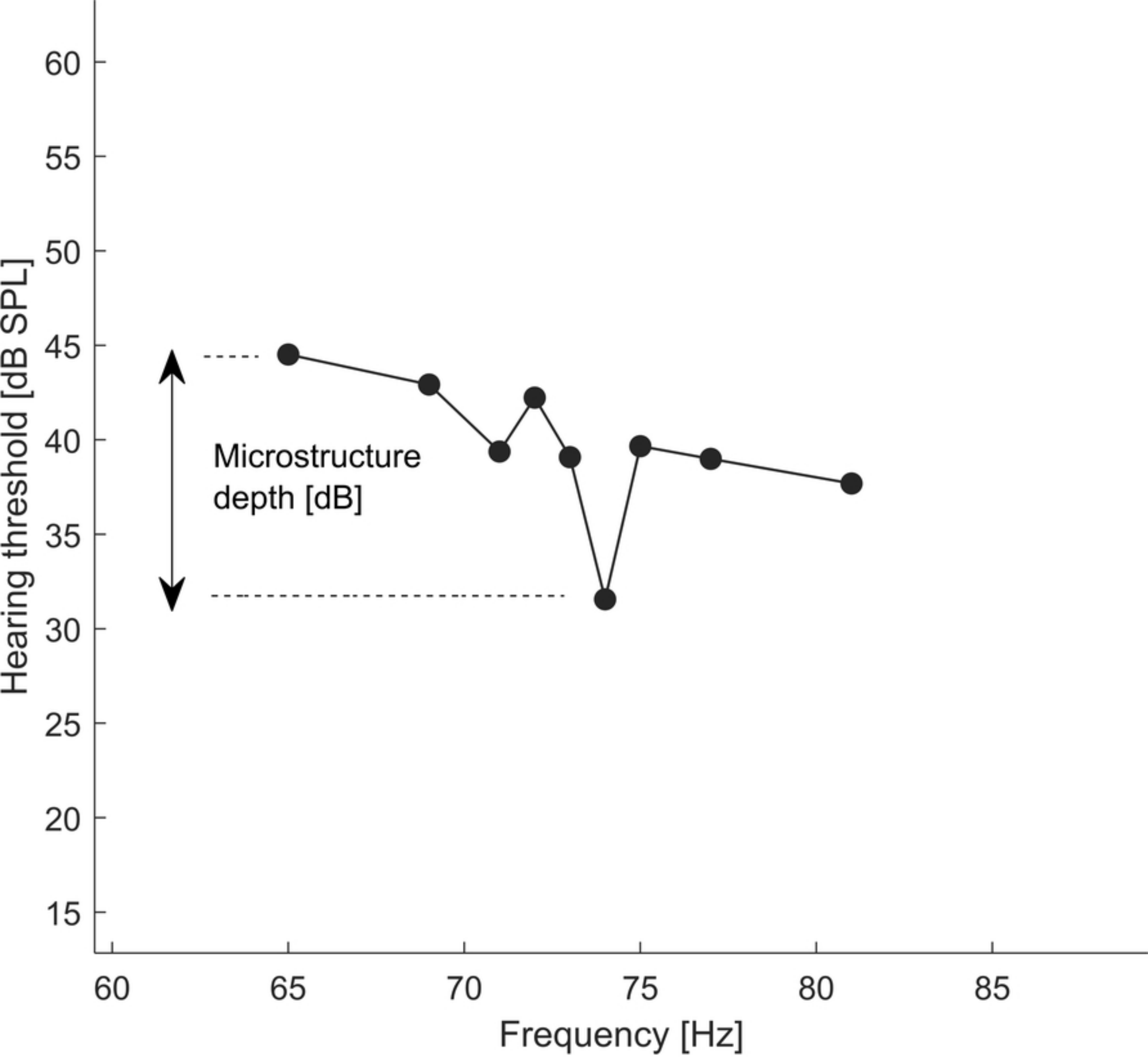
Hearing threshold [dB SPL]
60
55
50
45
40
35
30
25
20
15
Microstructure
depth [dB]
60
65
70
75
80
85
Frequency [Hz]

Figure 4

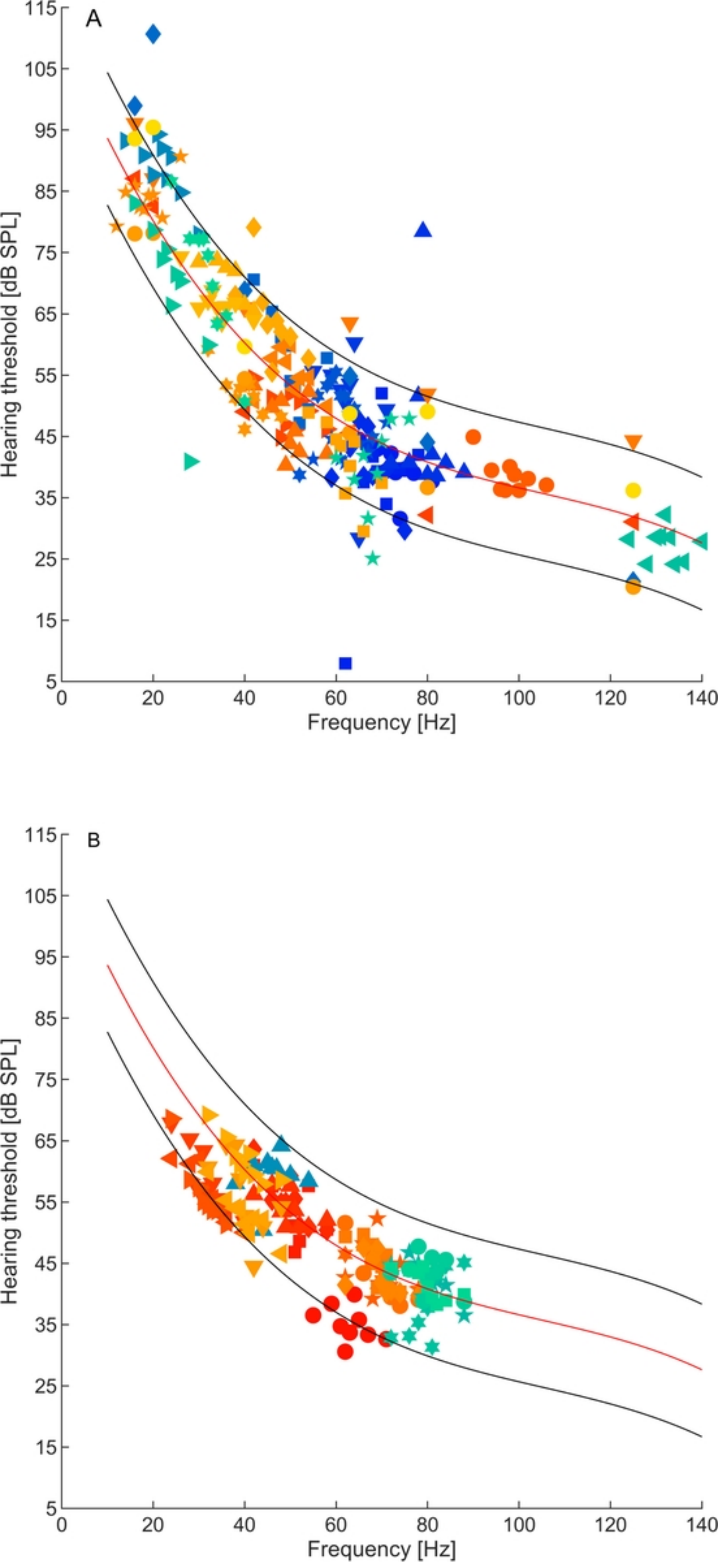
A
B
Hearing threshold [dB SPL]
Frequency [Hz]
115
105
95
85
75
65
55
45
35
25
15
5
0
20
40
60
80
100
120
140

Figure 3

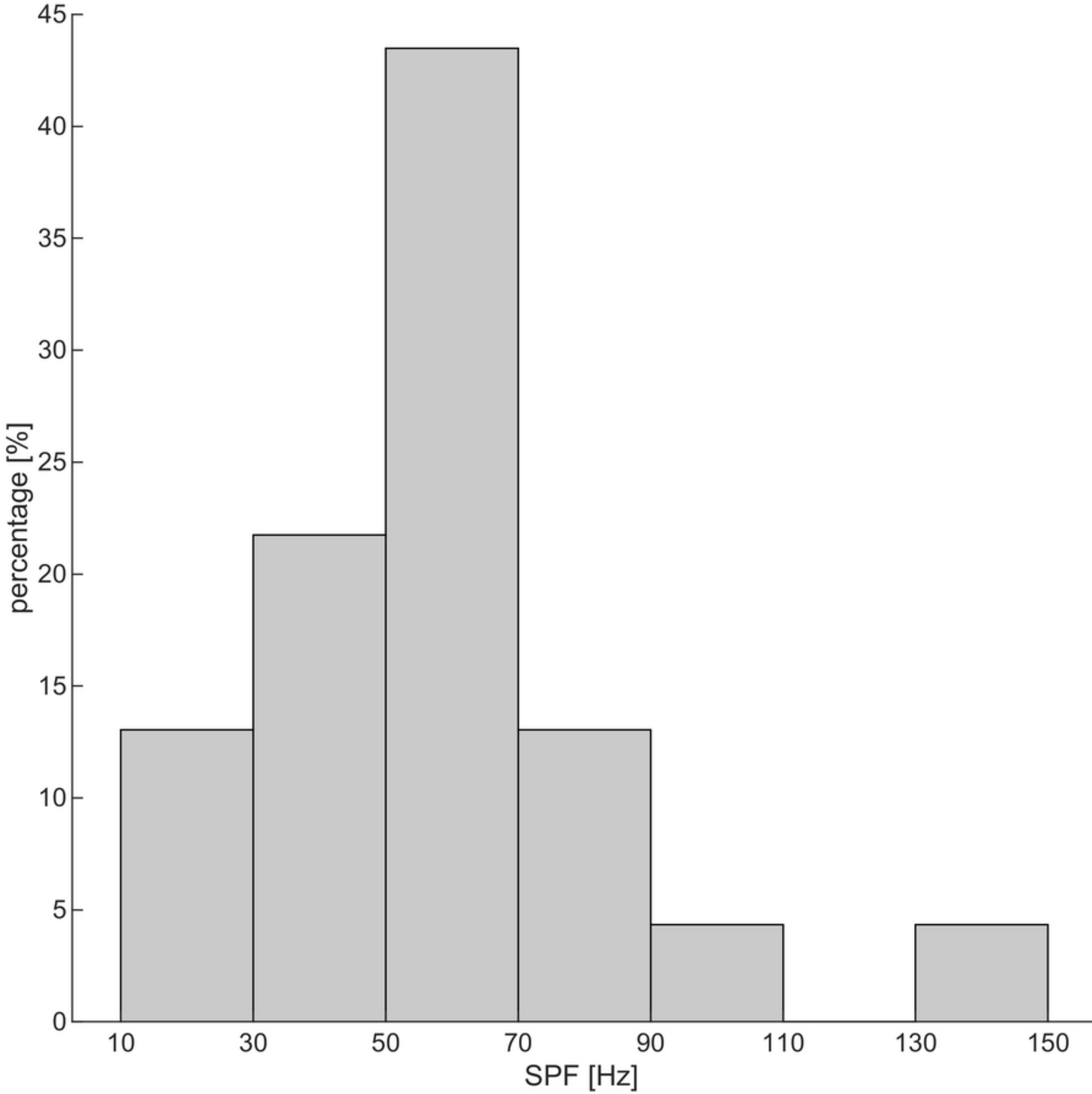
45
40
35
30
25
20
15
10
5
0
percentage [%]
10
30
50
70
90
110
130
150
SPF [Hz]

Figure 1

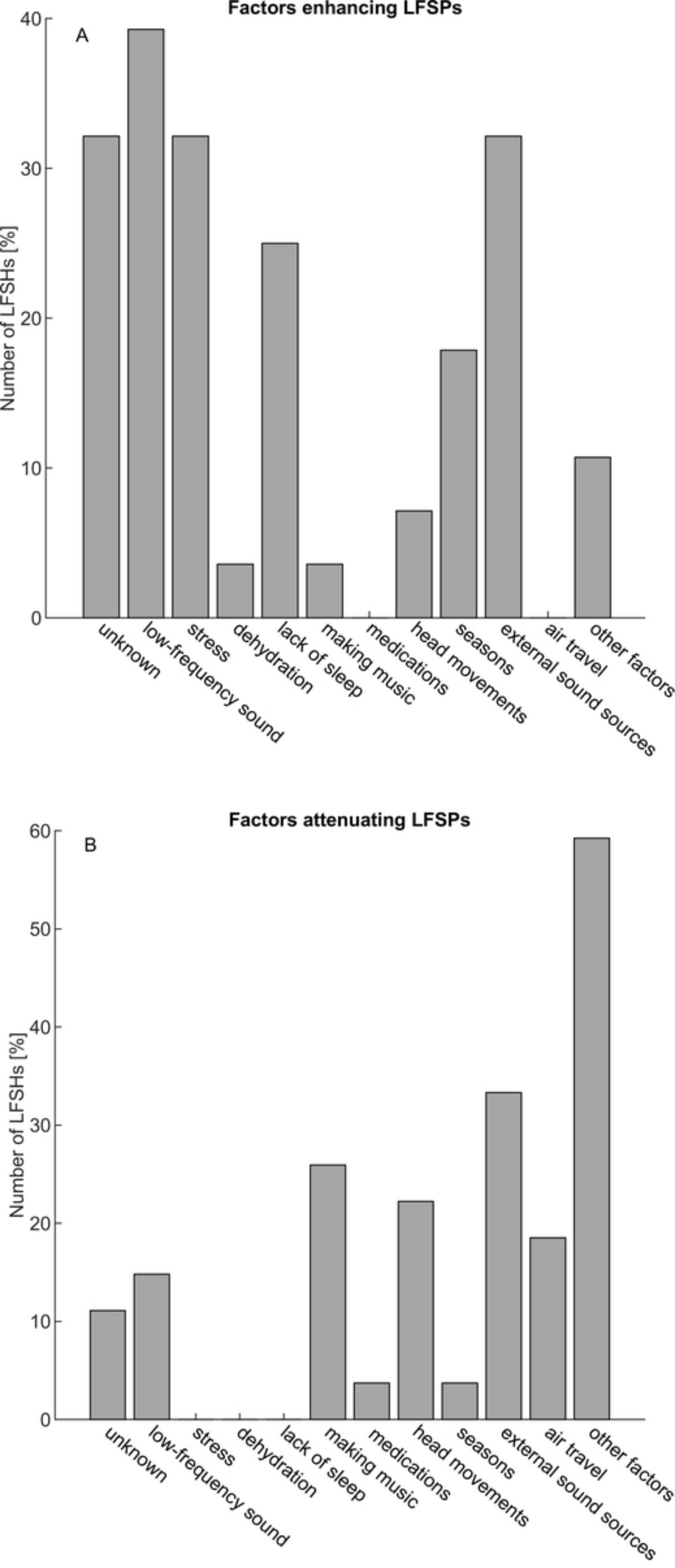
Factors enhancing LFSPs
A
Number of LFSHs [%]
0
10
20
30
40
unknown
low-frequency sound
stress
dehydration
lack of sleep
making music
medications
head movements
seasons
external sound sources
air travel
other factors
Factors attenuating LFSPs
B
Number of LFSHs [%]
0
10
20
30
40
50
60
unknown
low-frequency sound
stress
dehydration
lack of sleep
making music
medications
head movements
seasons
external sound sources
air travel
other factors

Figure 2

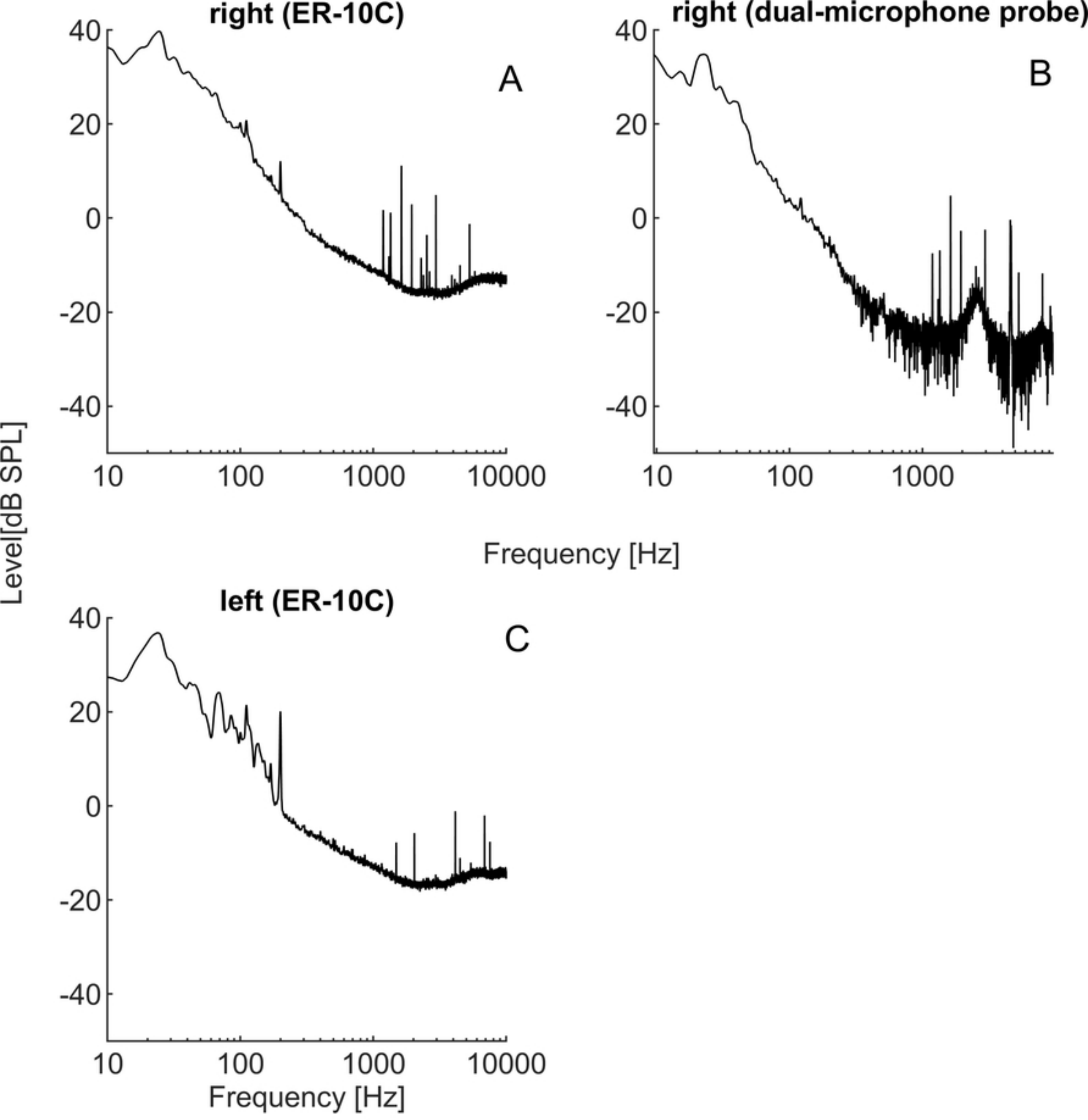
right (ER-10C)
A
right (dual-microphone probe)
B
left (ER-10C)
C
40
20
0
-20
-40
10
100
1000
10000
Frequency [Hz]
evel[dB SPL]

Figure 6