Hearing threshold measurements of infrasound combined with audio frequency sound

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ABSTRACT

Within the framework of the European project *EMPIR 15HLT03 "Ears II"* this study aims at a better understanding of the human response to infrasound. The purpose of this study is to examine which role the combination of infrasound (< 20 Hz) and sound in the audio frequency range (between 20 Hz and 20 kHz) plays for the perception of infrasound. One hypothesis to be validated is that the interaction between infrasound and audio-frequency sound may explain the perceptibility of infrasound. Another aim is to investigate whether the presence of infrasound influences the hearing threshold of audio frequency sound.

In order to test these hypotheses detection threshold measurements were performed separately for infrasound and audio-frequency sound stimuli. Then thresholds were measured for infrasound stimuli in the presence of audio-frequency sound and for audio-frequency sound stimuli in the presence of infrasound.

The measurement setup consisted of an infrasound source and an audio-frequency sound source, each coupled by a sound tube to the same eartip that was used for monaural presentation of the acoustic stimuli.

1. INTRODUCTION

An increasing number of individuals are being exposed to infrasound. It is well known that certain individuals may be particularly sensitive and that their quality of life is considerably degraded by a range of symptoms (insomnia, concentration disorders, restlessness, migraine), e.g. [1]. Unfortunately, even technology indispensable for a sustainable development in the European Union (like renewable energy technology and road traffic) also produces infrasound noise. It is, therefore, an important overall need with respect to many aspects of quality of life to gather more basic knowledge about infrasound perception and impact mechanisms.

Infrasound detection thresholds, loudness estimates and other psychoacoustical characteristics are reported from a number of studies, e.g. [1, 2, 3].

It is, however, still not clear, how human beings process infrasound. Our study aims at contributing to knowledge about the perception mechanisms for infrasound and low-frequency sound by investigating the interaction between infrasound and audio-frequency sound with respect to the detection thresholds. Moreover, we think it is worth investigating whether the presence of infrasound influences the hearing threshold of audio-frequency sound.

This study confines the perception of infrasound to "hearing by means of the human auditory system". All other ways of sensation, e.g. somatosensory mechanisms, are intentionally ruled out for our investigation. Therefore we used insert earphone sound sources, both for the infrasound and the audio-frequency stimuli.

The results presented in this conference paper are outcome of a pilot study for further research within the framework of the project.

2. MATERIALS AND METHODS

2.1. Measurement setup

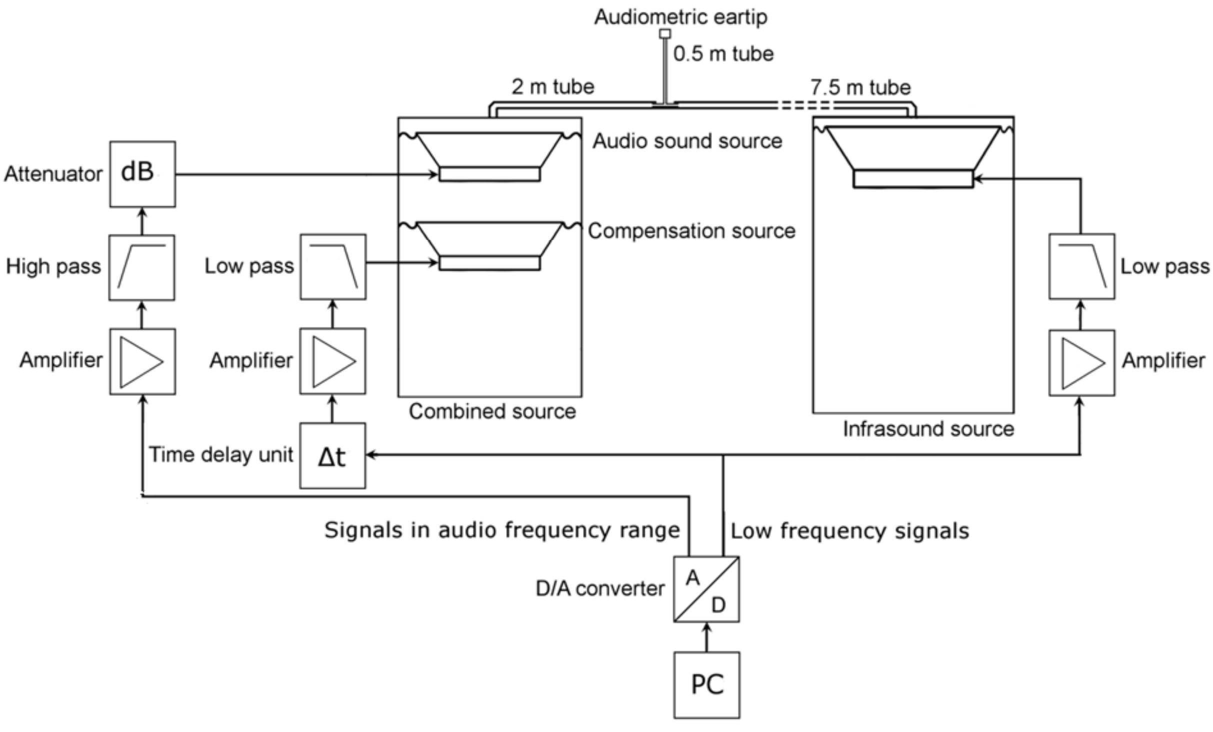

Figure 1: Schematic view of setup for the detection threshold measurement of infrasound and audio frequency sound stimuli using the insert earphone sound source system.

In order to obtain a controlled auditory stimulation with infrasound combined with audio frequency sound we used a specially developed insert earphone sound source system (see Figure 1). The sound source system consisted of an infrasound source and an audio-frequency sound source, both realized as damped wooden boxes into which loudspeakers were mounted hermetically. Their sound was transferred to the audiometric eartip (E-A-RTone/ E-A-RLink, Standard Insert Foam Eartips) by means of connecting tubes. The eartip was inserted into the test subject's right ear for monaural presentation of the acoustic stimuli. The contralateral ear was occluded with an ear plug.

The test subject as well as the sound sources and the sound tubes were located in an anechoic room with sufficiently low background noise levels. A computer display and a keyboard, which were necessary for the experimental procedure (see section 2. 5., *Psychoacoustic measurement procedure*), were placed in front of the subject. The computer controlling the experiments was located outside the anechoic room. The infrasound and the audio-frequency waveforms were calculated with *MATLAB* at 96 kHz sample rate. An external sound card (RME Fireface UC; infrasound and audio-frequency components in separate channels) generated analogue output signals that were fed to three separate amplifiers (type Beak BAA 120 for the compensation and the infrasound source, type Tira BAA 120 for the audio sound source).

The infrasound source contained a 13" electrodynamic loudspeaker (Beyma 15P80/Nd) generating the infrasonic pure-tone stimuli with sufficiently high sound pressure levels at low harmonic distortion [4]. The upper 8" electrodynamic loudspeaker (Beyma 8P300Fe/N) inside the combined source (hereafter referred to as *audio sound source)* generated the stimuli in the audio frequency range up to 4 kHz.

A major difficulty associated with the combination of infrasound and audio-frequency sound is that infrasound which is transferred by the sound tube to the audio sound source may cause a technical modulation by displacing the audio sound source loudspeaker's membrane. In order to compensate this modulation, down to a sufficiently (i.e., imperceptible) low level, an additional 8" loudspeaker (Beyma 8P300Fe/N) (hereafter referred to as *compensation source*) was mounted in the box, below the audio sound source. The compensation source emitted infrasound with the same frequency as the infrasound source but with a frequency-dependent time shift adjusted with a time delay unit (part of Behringer Ultradrive Pro DCX 2496).

Second-order low-pass filters (f_c = 25 Hz) were inserted between the amplifiers and the loudspeakers for the infrasound source and the compensation source, and a second-order high-pass filter (f_c = 460 Hz) as well as a 30 dB attenuator were inserted into the signal path of the audio sound source for suppressing the amplifiers' 50 Hz hum and its harmonics sufficiently to be well below the normal hearing threshold level.

2.2. Stimuli

In the low-frequency range we used pure-tone stimuli at 12 Hz and 20 Hz.

Band limited pink-noise stimuli were applied in the audio-frequency range: a one-third octave pink noise and a four octave wide pink noise, both centred at 1 kHz. The pink-noise signals were digitally pre-shaped by multiplying them with the inverted frequency response of the audio sound source in order to get a flat acoustical spectrum of the stimuli.

All stimuli were windowed with a $\cos^2$ function of a well-defined duration. Three oscillations for each $\cos^2$ ramp were chosen for the 12 Hz stimuli, resulting in 0.25 s duration of each $\cos^2$ ramp. The duration of the $\cos^2$ ramps applied to the 20 Hz pure tone and to the pink-noise stimuli was 0.2 s.

The sound pressure levels of the low-frequency stimuli were calibrated with a ½" low-frequency pressure-field microphone (Brüel & Kjær, type 4193 + UC0211) that was placed in a cavity having an equivalent ear canal volume of 1.3 cm^3, whereas the audio-frequency pink-noise stimuli were calibrated with an occluded-ear simulator (Brüel & Kjær, type 4157 + ear canal extension DB 2012). The sound tubes from the sound sources were coupled to the cavity and the ear canal extension, respectively, by means of the eartip.

2.3. Experimental design

The test subject received written and oral instructions prior to the beginning of the first experiment.

The threshold measurements performed in this study were separated in three experiments (see Table 1). Each experiment was divided in several experimental runs. One experimental run comprised one threshold measurement of the target stimulus in silence or in presence of a background stimulus at a specific sound pressure level.

Table 1: Overview of the experimental design of the detection threshold measurements.

	Target stimulus	Background stimulus	Sound pressure level of background stimulus / dB SL
Experiment 1	Pink noise 250 - 4000 Hz	-	-
	Pink noise 890 - 1121 Hz	-	-
	20 Hz*	-	-
	12 Hz	-	-
Experiment 2	12 Hz	Pink noise 250 - 4000 Hz	0, +35, +65
	12 Hz	Pink noise 890 - 1121 Hz	0, +35, +65
Experiment 3	Pink noise 250 - 4000 Hz	12 Hz	-10, 0, +10
	Pink noise 890 - 1121 Hz	12 Hz	-10, 0, +10

*The experimental run at 20 Hz was only intended to allow the subjects to familiarize themselves with the unusual perception of low-frequency sound.

First (see Table 1, Experiment 1) detection threshold measurements were performed for infrasound and audio-frequency stimuli in silence. The experiment began with detection threshold measurements of the two bandlimited pink-noise audio-frequency signals, followed by a shortened detection threshold measurement for 20 Hz, which was only intended to allow the subjects to familiarize themselves with the unusual perception of low-frequency sound. Therefore it was not included in the measurement evaluation. Finally, the detection threshold of the 12 Hz infrasonic stimulus was measured.

The two following experiments comprised detection threshold measurements of infrasound stimuli in the presence of audio-frequency sound (Experiment 2) and detection threshold measurements of audio-frequency stimuli in the presence of infrasound (Experiment 3).

Both experiments were separated into six experimental runs with different combinations of target stimulus, background stimulus and sound pressure level of the respective background stimulus (see Table 1). The sound pressure levels of the background stimuli were adjusted with reference to the individual threshold level (i.e. in dB Sensation Level, dB SL) determined in Experiment 1. The experiments were performed in random order, but the experimental runs of Experiments 2 and 3 were not mixed. The presentation order of the six experimental runs within each experiment was randomized.

After each experiment the subjects were asked in a free interview to describe their perception of the stimuli and to report if they had perceived any abnormalities or discomfort during the experiment.

The three experiments were separated by at least a 15-minutes break and performed for each subject within one day. The experimental procedure was repeated two times for each subject on separate days.

2.4. Subjects

Three test subjects (3 males, 28, 29 and 30 years old) participated in a pilot study of the hearing threshold measurements of infrasound combined with audio-frequency sound. All subjects were otologically normal according to ISO 389-9 [5] and had hearing thresholds better than 15 dB HL between 125 and 8000 Hz for either ear. The Declaration of Helsinki was adhered to in all our measurements.

2.5. Psychoacoustic measurement procedure

The detection threshold measurements were carried out with the MATLAB-based software framework AFC [6]. We set up a 3-alternative forced choice (3-AFC) experiment combined with an adaptive 1-up-2-down rule.

According to the 3-AFC method each measurement trial consisted of three time intervals labelled ‘1‘, ‘2‘, and ‘3‘ that were successively presented to the subject and separated by a pause of 0.2 s. The current interval was highlighted in red colour on the display in front of the subject. The target stimulus was allocated randomly to one of the three intervals in every trial.

The duration of each interval and, consequently, the duration of the target signal in all three experiments was 1 s, as usual for conventional hearing threshold measurements. After the presentation of the three intervals the test subjects were forced to indicate in which interval they had heard the stimulus by pressing the respective keyboard button ‘1‘, ‘2‘, or ‘3‘. If they had not heard the stimulus in any interval, they had to make a guess. After responding, the test subjects received feedback on the display, whether their response had been correct or wrong, and another measurement trial began.

In Experiment 1 the threshold of the target stimulus was measured in silence. However, in Experiments 2 and 3 a background stimulus was added. The background stimulus was not presented continuously. It started 0.2 s prior to the presentation of interval 1 and ended 0.2 s after the presentation of interval 3. Hence, between each measurement trial, while the test subjects took their decision, there was silence.

Depending on the response of the test subject, the sound pressure level of the target stimulus was varied according to the adaptive 1-up-2-down rule that converges to the 71% correct-answer probability on the psychometric function [7]. The sound pressure level limit that caused an immediate termination of the experiment was set to 128 dB SPL for 12 Hz, 105 dB SPL for 20 Hz, and 80 dB SPL for the pink-noise stimuli, but none of these levels have actually been reached during this study.

At the beginning of each experimental run the level of the target stimulus was set to an easily audible level (30 dB SPL for the pink-noise stimuli, 90 dB SPL for the 20 Hz stimulus and 105 dB SPL for the 12 Hz stimulus). The initial step size was 4 dB, and after each upper reversal (a response leading to an upward step followed by a response leading to a downward step) the step size was reduced by 1 dB until a final step size of 2 dB was reached. Then the measurement phase began. It ended upon the completion of 8 following reversals. The detection threshold measurement of 20 Hz was shortened to 4 reversals in the measurement phase, because this experimental run was only intended to allow the subjects to familiarize themselves with the unusual perception of low-frequency sound. Finally, the hearing threshold level was calculated as the median value of all amplitudes of the reversals during the measurement phase.

After a completed experimental run the subject started the next experimental run by pressing an arbitrary button.

3. RESULTS

All test subjects were able to perceive the stimuli applied in this study and did not report any discomfort or abnormalities. Some of the test subjects described the perception of the infrasound stimuli at 12 Hz as a ”rumbling” sound.

On average 42 presentations were performed during a single experimental run for one threshold measurement with a duration of around 4 minutes.

3.1. Thresholds of a pure-tone infrasound stimulus at 12 Hz combined with audio-frequency stimuli

The results of this part of the investigations are shown in Figure 2.

The mean values (over the three measurements) of the individual detection threshold levels for the 12 Hz stimulus (see Figure 2 (a)) range from 88.5 to 94 dB SPL with a maximal individual difference between test and retest of 6 dB.

Panels (b) – (g) show the change of the detection threshold levels of 12 Hz stimuli caused by the presence of the background stimulus. Comparing the threshold levels of the 12 Hz stimuli in silence and in the presence of a background stimulus above threshold at +35 and + 65 dB SL, we observed a significant increase of the detection threshold level, amounting up to 20 dB in the case of the pink-noise background stimulus at 250 – 4000 Hz with 65 dB SL (see Figure 2 (f)). The differences between the 12 Hz thresholds with 0 dB SL background vs. silence were below ± 5dB with a slight tendency to an increase of the threshold levels (see Figure 2 (b) and (c)).

Comparing the results between the three subjects, we observed differences between the individual thresholds at 12 Hz in silence and the threshold shift caused by the presence of the background stimuli. For example, subject B, having the highest threshold level of the three subjects with a mean threshold level of 93 dB at 12 Hz in silence, also showed the highest threshold shift at the different background stimuli configurations. On the contrary, subject A, with lowest threshold level at 12 Hz (mean value: 89 dB SPL), showed the lowest threshold shift in most cases.

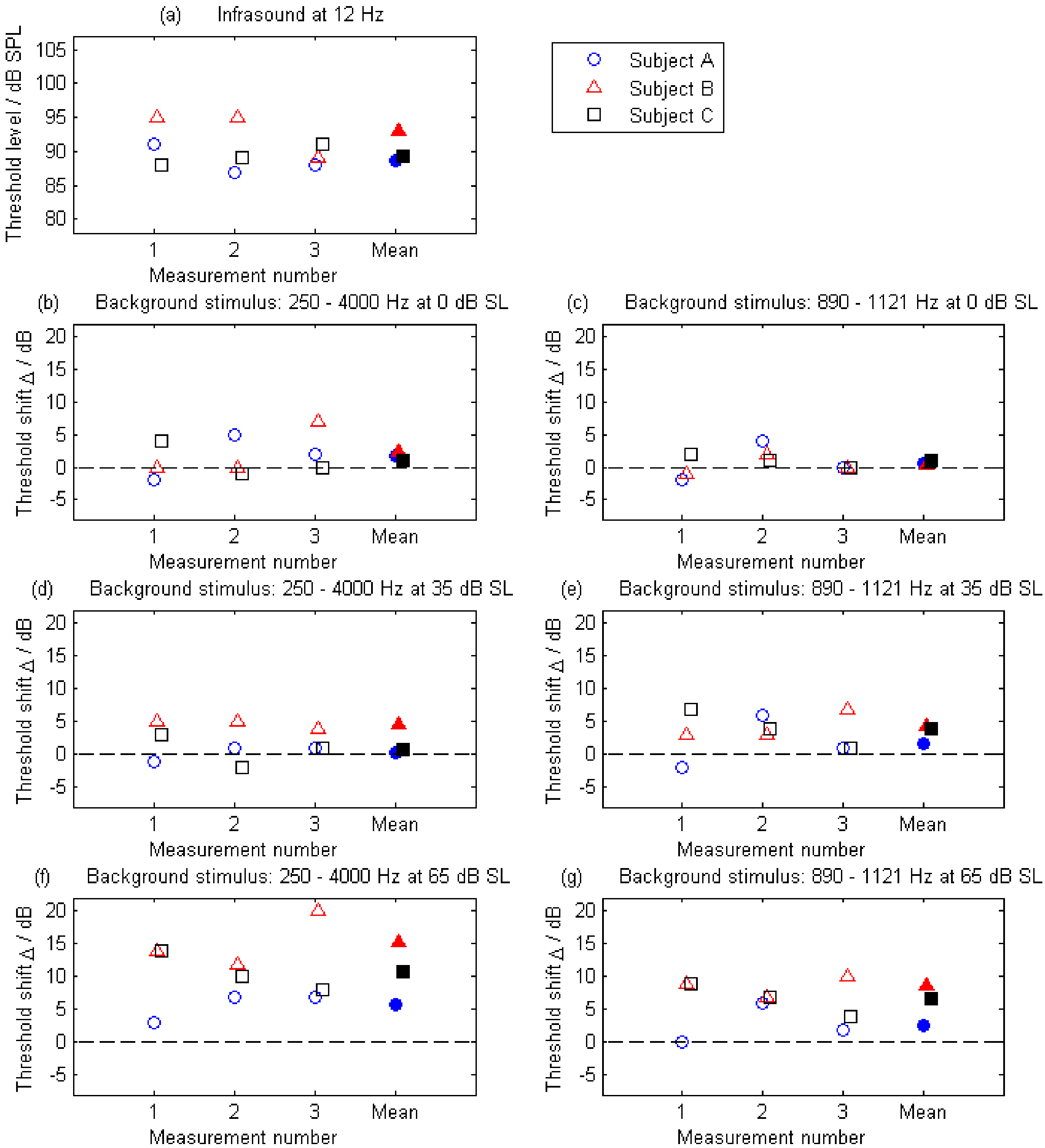

Figure 2: Individual detection threshold levels for the infrasonic 12 Hz stimulus, determined three times on separate days with the insert earphone sound system.
Mean values of the 3 measurements for each test subject are also shown (filled symbols).
(a): Experiment 1: Detection threshold levels of three test subjects for the infrasound stimulus at 12 Hz in silence.

(b) - (g): Comparison of Experiment 2 and 1: Shift of the detection threshold level of 12 Hz stimuli caused by the presence of background stimulus. Each shift Δ was calculated by subtracting the detection threshold level of the 12 Hz stimulus measured in silence (Experiment 1) from the detection threshold levels of the 12 Hz stimulus in the presence of the two pink-noise stimuli at the respective sound pressure level (Experiment 2).

3.2. Thresholds of pink-noise stimuli in the audio frequency range combined with infrasonic 12 Hz stimulus

The mean values of the individual threshold levels for the pink-noise stimuli at 250 - 4000 Hz and 890 – 1121 Hz were between 1 and 5 dB SPL and between 10.5 and 12 dB SPL, respectively. They are shown in Figure 3, panels (a) and (b). We observed a maximal individual difference between test and retest of 4 dB for the four-octave and 8 dB for the third-octave pink-noise stimulus, respectively.

Considering the comparison of the detection threshold level of the pink-noise stimulus at 250 - 4000 Hz in silence and in presence of the 12 Hz pure-tone stimuli, we observed no significant change, with a maximal difference of ± 4 dB (Figure 3, (c), (e), and (g)). However, in the case of the pink-noise stimulus at 890 - 1121 Hz we observed, in the majority of cases, a slight increase of the threshold level caused by the presence of the background stimulus, amounting up to 7 dB (Figure 3, (d), (f), and (h)).

We observed no significant difference between the individual threshold levels of the stimuli in silence and their threshold shifts in the presence of the 12 Hz background stimuli.

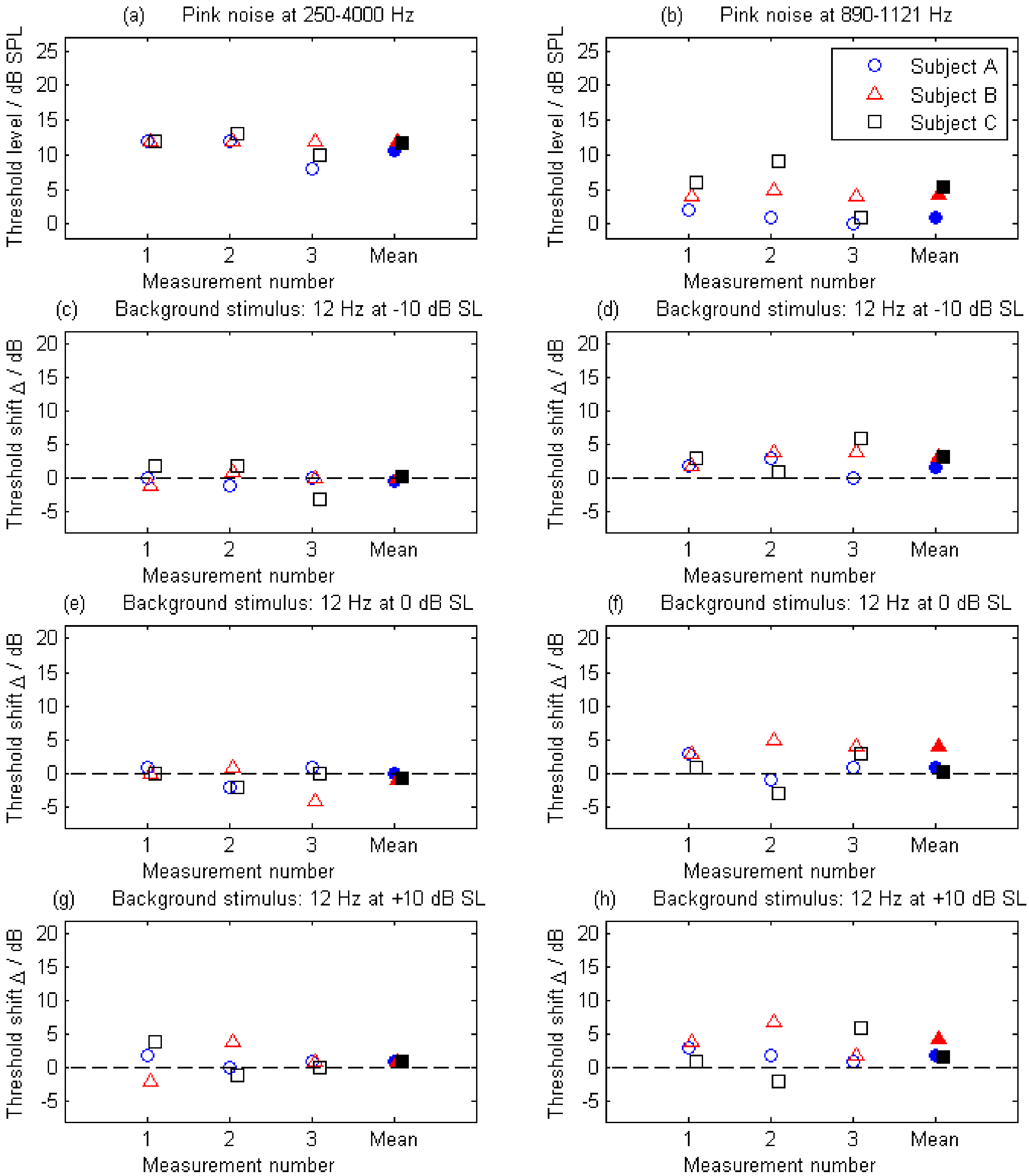

Figure 3: Individual detection threshold levels for the pink-noise stimuli, determined three times on separate days with the insert earphone sound system.
Mean values of the 3 measurements for each test subject are also shown (filled symbols).
(a): Results of Experiment 1: Detection threshold levels from three subjects for the pink-noise stimuli at 890 - 1121 Hz and at 250 - 4000 Hz in silence
(b) - (g): Comparison of Experiment 3 and 1: Shift of the detection threshold level of the pink-noise stimuli in the range of 890 - 1121 Hz and at 250 - 4000 Hz caused by the presence of the background stimulus. Each threshold shift Δ was calculated by subtracting the detection threshold level of the pink-noise stimuli measured in silence (Experiment 1) from the detection threshold levels of the pink-noise stimuli in the presence of the 12 Hz stimulus at the respective sound pressure level in dB SL (Experiment 3).

4. DISCUSSION

Due to the small sample size, the results only indicate possible trends concerning the detection thresholds of infrasound and audio-frequency stimuli. These trends are discussed below.

The threshold levels for the 12 Hz stimulus (Figure 2 (a)) were in good agreement with the results reported in [4] who measured an average threshold level of around 90 dB SPL at 12.5 Hz with an insert earphone infrasound source.

Comparing the *thresholds levels of the pink-noise stimuli in the audio frequency range* with each other, we observed that the detection threshold level of the broadband pink-noise stimulus was obviously higher (poorer) than that of the narrow-band pink-noise stimulus (Figure 3 (a) and (b)). This is assumed to be due to the energy of the former being spread over a high number of critical bands (15 critical bands between 250 Hz and 4 kHz) according to [8], while the third-octave band around 1 kHz comprises only approximately 1.5 critical bands.

Threshold levels for both the 12 Hz stimulus (Figure 2(a)) and the narrow-band pink-noise stimulus (Figure 3 (b)) showed a wider spread of measurement values than the threshold levels for the broadband pink-noise stimulus (Figure 3 (a)), indicating that it might be more difficult to detect both, infrasound stimuli and narrow-band pink-noise stimuli, than broadband pink-noise stimuli. This may be linked to greater temporal fluctuations of the narrow-band noise than the broadband noise, as well as the perceived ”rumbling” of the 12-Hz pure-tone as reported by the subjects in the interviews.

We observed an *increase of the threshold level of infrasound in presence of audio-frequency stimuli*. Complainants report that interfering low-frequency sound or infrasound is perceived the more acute or annoying, the quieter the residential or working area in question is, i.e., the less audio-frequency sound is present [9, 10, 11]. For conventional masking, it would be very unusual that a masker more than four octaves above the test tone (12 Hz to 250 Hz for the broadband noise) could have any effect on the test tone, because for audio frequencies, noticeable downward masking requires frequency spacing of less than two octaves [8]. Furthermore, there is no characteristic place for 12 Hz on the basilar membrane, and the cochlea is not supposed to have any amplification means, i.e., outer hair cells tuned to that frequency. Consequently, masking is very unlikely to happen in the conventional way, and we ought to find a different mechanism.

On the other hand, the tendency towards threshold *shift of the narrow-band noise* caused *by the 12 Hz* tone (Figure 3 (d), (f), and (h)) might be the effect of a conventional upward masking by the high-level infrasound. However, it still needs to be explained why the narrow-band noise is more affected by the masking than the broadband noise.

All in all, the trends discussed above need to be further investigated by listening tests with a greater number of test subjects. Finally, we are going to add more stimuli (e.g. infrasonic stimulus at 4 Hz).

5. CONCLUSION

With a specially developed insert earphone sound source system, which allows calibrated auditory stimulation with combined low-distortion infrasound and audio-frequency signals, detection thresholds were measured for infrasound stimuli in the presence of audio-frequency sound and vice versa.

The sound source system, in conjunction with the 3-AFC measurement procedure, worked reasonably well. In this pilot study, the feasibility of instrumentation and procedure were shown, and first trends concerning the thresholds and the interaction of infrasound and audio-frequency stimuli were described.

Further investigations with a considerably larger number of test subjects are to be carried out for gathering statistically reliable experimental data in order to validate the hypotheses that the interaction between infrasound and audio-frequency sound may explain the perceptibility of infrasound and that the presence of infrasound influences the hearing threshold of audio frequency sound.

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