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Detection Thresholds for Combined Infrasound and Audio-Frequency Stimuli

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Summary
This study investigated whether the presence of audio sound (20 Hz < frequency f < 20 kHz) influences the detection threshold for infrasound (f < 20 Hz), and, vice versa, whether the presence of infrasound influences the detection threshold for audio sound. Monaural detection thresholds of thirteen otologically normal listeners were repeatedly determined for infrasound stimuli (sinusoids at 5 Hz and at 12 Hz) and for audio sound stimuli (sinusoids and bandlimited pink noise), separately and in presence of the respective other sound type. The measurements were performed with an adaptive 1-up-2-down 3-alternative forced-choice (3-AFC) procedure. Threshold levels for infrasound stimuli were not affected by audio sound at +5 dB sensation level (SL), but they were significantly increased by the presence of some of the audio sound stimuli presented at +50 dB SL. For example, thresholds for the detection of infrasound increased on average by around 5 dB when simultaneously presented with a pink-noise stimulus (frequency range: 250 Hz– 4000 Hz). On the other hand, the presence of infrasound with levels up to +10 dB SL did not cause any significant change in the detection thresholds for audio sound. This could be an indication that infrasound might even be more annoying in a quiet environment.

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1. Introduction

It is now well established that humans are able to perceive infrasound (*abbr.* IS, frequency f < 20 Hz) at least down to 2 Hz (see, e.g. the review paper by Møller and Pedersen [1]). However, the sensation of IS differs from that of sound in the common audio-frequency range (audio sound, *abbr.* AS, 20 Hz < f < 20 kHz) in a way that the sensation has a rather discontinuous character accompanied by a feeling of pressure instead of a tonal sensation [1]. Moreover, there is a steep increase of human detection thresholds for frequencies below 100 Hz so that high sound pressure levels are needed for humans to detect IS [1, 2]. In addition, the distances between equal-loudness-curves [1, 3, 4] and equal-annoyance curves [5, 6] are smaller for IS than for AS stimuli. Therefore, a small increase in SPL (sound pressure level) for IS can result in a significant increase in perceived loudness and annoyance. Furthermore, there are no auditory filters tuned to infrasonic frequencies, since the lowest centre frequency of an auditory filter lies between 40 Hz or 50 Hz as estimated by psychoacoustic tuning curves [7].

The decrease in sensitivity towards infrasonic frequencies is caused by different processes acting as a high-pass filter for the sound transferred inside the human ear. This includes the middle-ear attenuation (decrease in SPL by 6 dB/octave for frequencies below about 1000 Hz [8]) and the shunt mechanism of the helicotrema (decrease in SPL by 6 dB/octave for frequencies below 40 Hz [9]). In addition, the sensitivity of the inner hair cells decreases by 6 dB/octave, since they are mechanically excited dependant on the velocity of the basilar membrane [10]. This decreased sensitivity of the inner hair cells is assumed to be to some extent compensated by the outer hair cells, since the outer hair cells, which contact the tectorial membrane, are sensitive to the large basilar membrane displacements caused by IS [11].

At many immission sites, humans are exposed to noise with frequency components both in the AS and in the IS frequency range. Therefore, the question arises whether interactions between IS and AS may influence the quality of the auditory perception.

An important potential interaction of IS and AS is the effective amplitude modulation of AS caused by IS, since the hearing system of humans is especially sensitive to amplitude modulation (AM) at frequencies between 2 Hz and 5 Hz [12, 13]. When IS and AS are simultaneously present, effective amplitude modulation may be generated on a physiological level: Experiments with guinea pigs had demonstrated that IS can modulate AS by cyclically changing the cochlear amplifier gain [14]. This is in line

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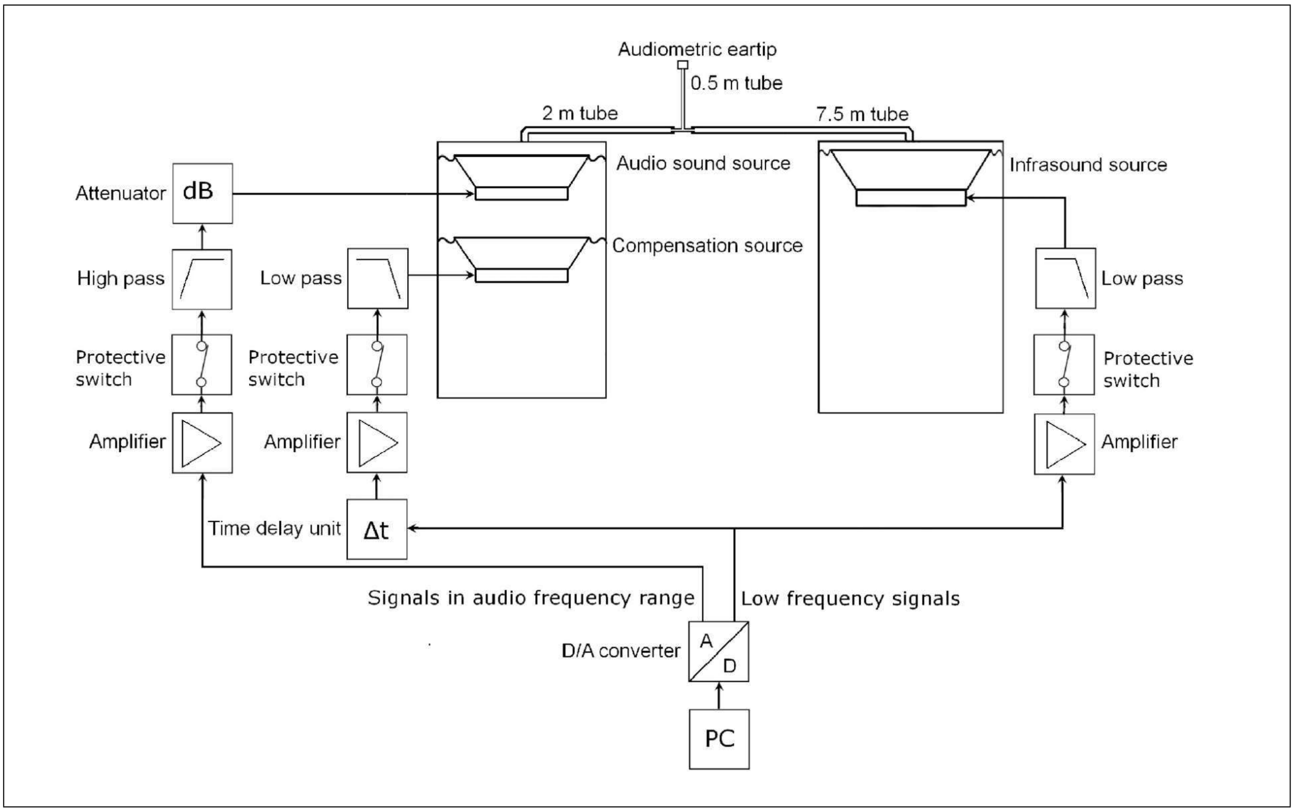

Figure 1. Schematic view of the setup for the detection threshold measurements for IS and AS stimuli using the insert earphone sound source system [19].

with the results of psychoacoustic experiments showing that human listeners can hardly distinguish between AS combined with IS and AS that is amplitude modulated at infrasonic frequencies [15].

Another potential interaction of IS and AS may be masking effects, meaning that threshold levels for IS or for AS stimuli are increased when simultaneously presented with the other sound type as masker stimulus. It is well known for stimuli in the audio-frequency range that threshold levels increase when a masking stimulus is presented in an adjacent frequency region, and that there is a spread of masking towards higher frequency regions with increasing masker level [12]. These effects are easily modelled in terms of critical bands in the audio-frequency range (see, e.g. [16]). However, it is reasonable to assume that perception mechanisms for IS differ from those for AS. Therefore, potential masking effects for IS stimuli as masker or target stimuli may also not be the same as those for AS stimuli, and they are unlikely to be modelled in a similar way as known from the audio-frequency range. The study of Finck [17] revealed a broad masking effect of high-level IS (10 Hz at 130 dB SPL) on thresholds for AS tones up to 4800 Hz. A pilot study conducted prior to the actual study presented in this paper indicated small or no effects of IS presented up to +10 dB SL (sensation level) on the threshold levels for AS stimuli, but a considerable increase of the individual threshold level for the IS stimuli caused by the presence of AS background stimuli [18].

The purpose of this study was to deliver a more profound investigation of masking effects for IS combined with AS. In particular, it was investigated whether the presence of IS changes detection thresholds for AS and, vice versa, whether the presence of AS changes detection thresholds for IS. One hypothesis was, that the modulation effect caused by IS can reduce the threshold level for AS. On the other hand, the presence of IS may cause an increase of the detection thresholds, similar to masking effects. Downward masking effects caused by AS on thresholds in the infrasonic frequency range were, however, assumed to be unlikely, unless the AS stimuli are presented within the low frequency range.

2. Materials and methods

2.1. Measurement setup

Monaural detection threshold measurements were performed with a specially developed insert earphone sound source system (see Figure 1) which is described and characterized in more detail in [19]. The IS and AS stimuli were generated by separate electrodynamic loudspeakers, called the IS source and the AS source, mounted inside two different housings. Sound tubes (two polyethylene tubes: 1.5 m and 7.5 m length, 14 mm inner diameter; one silicone tube: 0.5 m length and 3 mm inner diameter) and a t-piece coupled the sound sources to an audiometric eartip (E-A-RTone/E-A-RLink Standard Insert Foam Eartip) as illustrated in Figure 1. The audiometric eartip was inserted into the participant's right ear canal for monaural presentation of the acoustic stimuli. The contralateral ear of the participant was occluded with an ear plug. An additional loudspeaker, known as the compensation source, was mounted below the AS source. It delivers IS to the back of the AS loudspeaker membrane to compensate the displacements of the membrane caused by the IS down to an imperceptible level [19].

The waveforms of the IS and AS signals were generated with a MATLAB-based software framework AFC [20] at 96 kHz sample rate. An external sound card (RME Fireface UC) generated analogue output signals (IS and AS components in separate channels) that were fed to three separate amplifiers (BAA 120 BEAK for AS signals, BAA 120 TIRA for IS signals). Protective switches were inserted in each signal path to avoid that excessively loud signals could be presented in case of equipment malfunction. The sound sources, the sound tubes, and the participant were located in an anechoic room providing a sufficiently low background noise level even in the infrasonic range (see Figure 2 for background noise levels) during the listening tests. A computer display and a keyboard, which were required for the experimental procedure (see Section 2.5 *Psychoacoustical measurement procedure*), were placed in front of the participants. The computer controlling the experiments was located outside the anechoic room.

The calibration of the AS stimuli was performed in an IEC 60318-4 [22] occluded-ear simulator (Brüel & Kjær 4157, with ear canal extension DB 2012). The IS stimuli were calibrated with a $\frac{1}{2}''$ low-frequency pressure-field microphone (Brüel & Kjær 4193, with UC0211) that was placed in a cavity having a volume of $1.3\,\mathrm{cm}^3$, equivalent to that of the average human ear canal. During calibration, the sound tube from the sound source system was connected to either the cavity or to the ear canal extension, respectively, by means of the eartip.

2.2. Participants

The detection threshold measurements were performed with fifteen participants (seven females, eight males, between 18 and 30 years old). Two participants were not able to participate in all measurement sessions of this study so that the threshold levels were evaluated for the remaining thirteen participants. None of them had experience in psychoacoustic measurements with IS prior to this study. All participants were otologically normal as confirmed by a questionnaire for hearing testing (Annex A in ISO 389-9 [23]) and by otoscopic examination. Hearing thresholds were better than 15 dB HL between 125 Hz and 8000 Hz in the right ear as tested by standard pure tone audiometry according to ISO 8253-1 [24], with a step size of 1 dB.

The Declaration of Helsinki was adhered to in all our measurements and a positive vote of the local ethics committee (PTB ethics application 3/16) was given.

2.3. Stimuli

Detection threshold levels were repeatedly determined for IS stimuli and for AS stimuli, both separately and during the presence of the respective other sound type. IS stimuli were sinusoids at 5 Hz and at 12 Hz. The aim was to investigate whether the effects on the detection threshold measurements are similar for IS stimuli at different frequencies, which are well below the lower frequency limit for AS (between 16 Hz and 20 Hz), and which have a distance of more than one octave to each other, taking into account that the sound source system is applicable for stimulation with IS down to 4 Hz [19]. Three different AS stimuli were applied in the detection threshold measurements: a sinusoid in the low-frequency range at 100 Hz, an additional sinusoid at a higher frequency of 1000 Hz, and a broadband pink-noise stimulus with the frequency range between 250 Hz and 4000 Hz. These stimuli were selected to investigate whether the bandwidth (broadband pink-noise centred at 1000 Hz vs. sinusoid at 1000 Hz) or the distance between AS and IS stimulus frequencies (sinusoid at 100 Hz vs. sinusoid at 1000 Hz) may lead to different results in the detection threshold measurements.

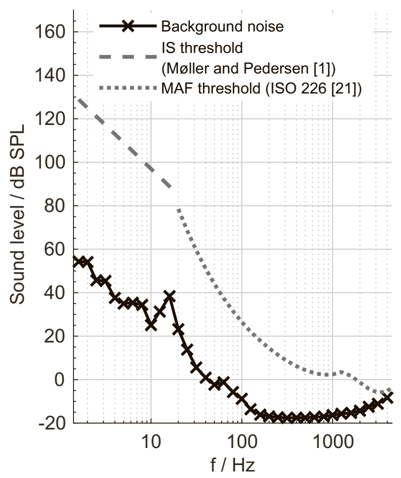

Figure 2. Background noise levels in the anechoic room and average threshold levels in the infrasonic and audio frequency range.

Stimulus onsets and offsets were time-windowed using a $\cos^2$ function providing ramp durations of 200 ms for AS stimuli, 250 ms for sinusoids at 12 Hz, and 600 ms for sinusoids at 5 Hz (Table I). Because the frequency response of the AS sound source was not sufficiently flat in the frequency region covered by the pink-noise stimuli, the latter were digitally pre-shaped in order to equalise the frequency response of the AS source. The acoustical spectrum of the pink-noise stimuli was monitored with a signal analyser (Norsonic Real Time Analyser 840) and turned out to be flat within 3 dB. A new sample of pink-noise was generated prior to each stimulus presentation, in order to minimise a potential effect of random signal peaks on the detection threshold measurements (i.e., "running noise").

In the following, the term target stimulus (TS) defines the stimulus for which the threshold level was measured. The term background stimulus refers to the stimulus which was presented in addition to the target stimulus in some measurements. The duration of the target stimuli and, thus,

Table I. Stimuli parameters applied in the detection threshold measurements.

Stimulus	Duration of target stimulus	Duration of cos^2 ramp	Start level	Limit level
Sinusoid at 5 Hz	2000 ms	600 ms	115 dB SPL	130 dB SPL
Sinusoid at 12 Hz	1000 ms	250 ms	105 dB SPL	128 dB SPL
Sinusoid at 100 Hz	1000 ms	200 ms	50 dB SPL	93 dB SPL
Sinusoid at 1000 Hz	1000 ms	200 ms	20 dB SPL	80 dB SPL
Broadband (250 Hz–4000 Hz)	1000 ms	200 ms	30 dB SPL	85 dB SPL

the duration of the intervals within the 3-AFC measurement procedure (see Section 2.5 *Psychoacoustical measurement procedure*) was set to 1000 ms, except for the sinusoid at 5 Hz, the duration of which was set to 2000 ms (see Table I). In order to present the background stimulus at its full amplitude during the presentation of the three intervals in each measurement trial, the background stimulus started 200 ms– 600 ms (corresponding to the ramp duration, Table I) prior to the presentation of the first interval and ended 200 ms– 600 ms after the presentation of the third interval.

2.4. Experimental paradigm

The measurement sessions were divided into three experiments. Each experiment was divided in several runs performed in random order with different combinations of target stimulus TS and background stimulus BS (see Table II). Within one measurement session only one IS stimulus, either a sinusoid at 5 Hz or at 12 Hz, was applied. All sessions started with Experiment 1 (see Table II). In this experiment detection thresholds were measured for isolated target stimuli (without background stimulus). The threshold measurement for the IS target stimulus was always performed twice within one session. The intention of the first measurement was to train the participants to correctly identify the IS target stimulus.

The two following experiments, Experiment 2 and Experiment 3, were performed in random order. These experiments comprised threshold level measurements for the same target stimuli as in Experiment 1. In addition to the target stimulus, a background stimulus was presented at a specific sound pressure level (see Table II, column 3). The sound pressure levels of the background stimuli were adjusted with reference to the individual threshold level for this stimulus (i.e. sensation level, dB SL) determined in Experiment 1.

In Experiment 2, threshold levels were determined for IS in the presence of AS (see Table II). The sound pressure levels of the AS background stimulus were set to +5 dB SL and +50 dB SL, in order to compare the effect of the stimuli presented at one sound pressure that was just audible and at one sound pressure level that was clearly perceptible, although not too loud.

In Experiment 3, threshold measurements were performed for AS in the presence of IS (see Table II). The IS background stimulus was presented at two different levels, one below (−10 dB SL) and one above the individual threshold level. As reference for the individual threshold level for the IS background stimulus, the second measurement determined for the isolated IS stimulus within Experiment 1 was selected. Average detection thresholds for sinusoids have previously been reported as 110 dB SPL at 5 Hz and 90 - 93 dB SPL at 12.5 Hz [1, 2]. Since the dynamic range of the human auditory system between threshold and uncomfortably loud is steeply decreasing with decreasing infrasonic frequency [1, 3], the level above the individual threshold level was set to +10 dB SL for the background stimulus at 12 Hz and it was set to +5 dB SL for the background stimulus at 5 Hz. The intention of this was to apply above-threshold sounds that were sufficiently far away from being perceived as discomfortable. In addition, it was of particular interest to investigate the influence of IS presented at a level below the individual threshold on the perception of AS, because levels of IS measured in

Table II. Experimental runs performed within one threshold measurement session with different combinations of target stimulus *TS* and background stimulus *BS*. One experimental run comprised the threshold measurement for the target stimulus *TS* in the presence of the background stimulus *BS* or without background stimulus.

	Target stimulus *TS*	Background stimulus *BS*
Experiment 1	Broadband	-
	1000 Hz	-
	100 Hz	-
	12 Hz or 5 Hz	-
	12 Hz or 5 Hz	-
Experiment 2	12 Hz or 5 Hz	Broadband at +5 dB SL
	12 Hz or 5 Hz	Broadband at +50 dB SL
	12 Hz or 5 Hz	1000 Hz at +5 dB SL
	12 Hz or 5 Hz	1000 Hz at +50 dB SL
	12 Hz or 5 Hz	100 Hz at +5 dB SL
	12 Hz or 5 Hz	100 Hz at +50 dB SL
Experiment 3	Broadband	12 Hz at −10 dB SL or 5 Hz at −10 dB SL
	Broadband	12 Hz at +10 dB SL or 5 Hz at +5 dB SL
	1000 Hz	12 Hz at −10 dB SL or 5 Hz at −10 dB SL
	1000 Hz	12 Hz at +10 dB SL or 5 Hz at +5 dB SL
	100 Hz	12 Hz at −10 dB SL or 5 Hz at −10 dB SL
	100 Hz	12 Hz at +10 dB SL or 5 Hz at +5 dB SL

environmental noise usually are also well below the perception threshold, e.g. [25].

Prior to the beginning of the first threshold measurement the participants received written and oral instructions. After each experiment, the participants were asked in a free interview to describe subjective details of their perception of the stimuli and to report if any abnormalities or discomfort occurred during the experiment. For each participant, any threshold measurement session covering the set of the three experiments was performed within one day. In total, one session had a duration of around 1.5 to 2 hours, including breaks. The threshold measurement sessions were repeated twice for each participant and for each IS stimulus on separate days to estimate the reliability of the measurements and therefore gather robust detection threshold data.

2.5. Psychoacoustical measurement procedure

The detection thresholds were determined using a 3-alternative forced-choice (3-AFC) procedure. The sound pressure level of the target stimulus was varied in accordance with the adaptive 1-up-2-down rule that converges at the 71%-point of the psychometric function [26]. The participants received feedback on the display, whether their response had been correct or wrong to help them identifying the IS stimuli correctly.

For ensuring participants' safety, a maximum sound pressure level was implemented digitally in the experimental procedure for all stimuli (limit values, see Table I). These limits have been approved by the positive vote of the local ethics committee. The experiment would have been terminated if the stimulus had reached its predefined limit more than four times during one run. However, this has never occurred during this study.

At the beginning of each run the levels of the target stimuli were set to a value that is expected to be easily audible on average (start levels, see Table I). The initial step size of 6 dB was used for AS stimuli and a step size of 4 dB was used for the IS stimulus. The reason for this difference in step size is the much smaller dynamic range of the human auditory system for IS compared to AS [1, 3]. The step sizes were reduced to 3 dB after the first upper reversal and to 2 dB after the second upper reversal. Then, the measurement phase began, and it ended upon the completion of the eight following reversals. The detection threshold level was then calculated as the median value of all levels at the reversals during the measurement phase.

2.6. Statistical analysis

Individual threshold levels $L_{indiv}(TS, BS)$ were measured at least three times for each participant and for each target stimulus TS with background stimulus BS or with no background stimulus ($BS = 0$) in separate sessions. Individual threshold shifts $\Delta_{indiv}(TS, BS)$ were calculated for each participant by subtracting the individual threshold level for the isolated target stimulus TS, i.e. $L_{indiv}(TS, BS = 0)$, from the individual threshold for the same target stimulus TS in the presence of a specific background stimulus BS, i.e. $L_{indiv}(TS, BS \neq 0)$ both measured within the same session. Thus, a positive threshold shift for a target stimulus TS, $\Delta_{indiv}(TS, BS) > 0$, indicates that the threshold level for this target stimulus TS was increased when the background stimulus BS was present. Average threshold shifts $\bar{\Delta}_{indiv}$ were calculated as the arithmetic mean of the threshold shifts across the three repeated measurement sessions for each participant and each stimulus condition.

Three factorial analysis of variance (ANOVA) for repeated measures were performed, for IS and for AS threshold levels separately. The factors were (1) *session* (three repeated measurements for each combination of target stimulus and background stimulus), (2) *target stimulus* (ANOVA for IS: sinusoid at 5 Hz and at 12 Hz; ANOVA for AS: broadband stimulus, sinusoid at 100 Hz and sinusoid at 1000 Hz) and (3) *background stimulus* (different background stimuli each presented at a specific level including the measurement without background stimulus, i.e. $BS = 0$). The intention of the ANOVA was to investigate the statistical significance (significance level $\alpha_{ANOVA} = 0.05$) of the effect of all factors on the threshold levels, and the interaction between the factors. Post-hoc *t*-tests were performed for all factors.

3. Results

3.1. Three factorial analysis of variance for IS and AS thresholds

In general, all participants were able to perceive the stimuli applied in this study and did not report any discomfort or abnormalities in the context of this study.

The ANOVA for AS threshold levels revealed a significant effect of *target stimulus* ($p < 0.001$), *background stimulus* ($p < 0.001$) and *session* ($p = 0.034$), but no significant interaction between factors. The repeated measures ANOVA for IS showed that there were significant effects of the *target stimulus* ($p < 0.001$), *background stimulus* ($p < 0.001$) and *session* ($p = 0.038$) on the threshold levels for IS. In addition, a significant interaction between *target stimulus* and *background stimulus* ($p < 0.001$) was found for the IS threshold levels.

Post-hoc *t*-tests for the factor *session* using the Bonferroni correction ($\alpha_{session} = 0.016$) did not reveal a significant difference for AS thresholds. On the other hand, for IS thresholds, there is a significant difference ($p = 0.015$) between session 1 and session 2 with an average decrease of 1.0 ± 0.3 dB. However, this difference is even smaller than the minimum step size of 2 dB within the 3-AFC procedure. It can therefore be concluded that the factor *session* has, if at all, a negligible effect on the threshold levels. Therefore, average threshold levels were evaluated as arithmetic means across the repeated measurements.

The influence of the factors *target stimulus* and *background stimulus* on the threshold levels were examined further in selected post-hoc *t*-tests (see Section 3.3).

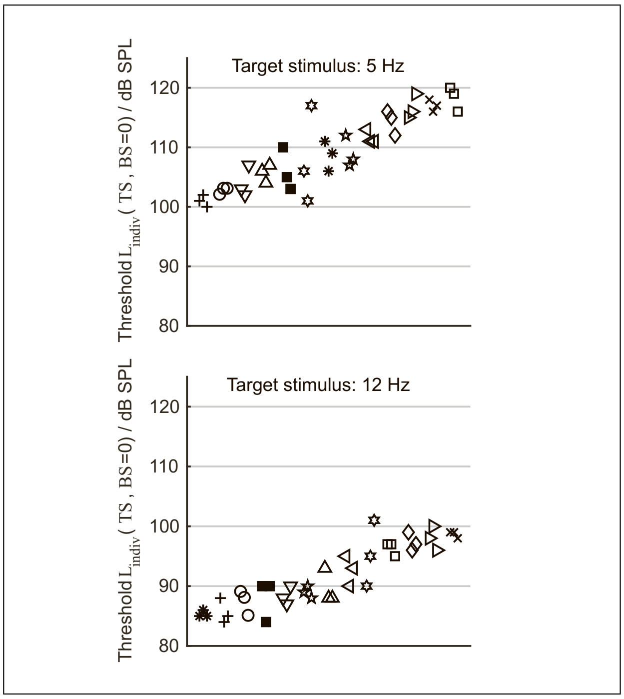

Figure 3. Individual detection threshold levels $L_{indiv}(TS, BS = 0)$ of 13 otologically normal participants for the isolated sinusoid at 5 Hz and at 12 Hz generated by the insert earphone sound system. The threshold levels were determined three times for each subject on separate days. Each marker indicates the threshold levels for one participant. The three threshold levels of each participant were arranged on the horizontal axis in ascending order of their arithmetic mean.

3.2. Detection threshold levels for isolated IS and AS stimuli

In Figure 3 the results of the threshold levels of each of the thirteen participants determined for an isolated sinusoid at 5 Hz and at 12 Hz are shown. Each marker indicates the threshold levels for one participant. The thresholds were determined three times for each participant on separate days. Average thresholds across all participants and associated standard deviations of the single value were 109 dB SPL± 6 dB for the sinusoid at 5 Hz and 92 dB SPL ± 5 dB for the sinusoid at 12 Hz. The standard deviations of the individual threshold levels were on average 2.4 dB for the threshold levels at 5 Hz and 2.1 dB for the threshold levels at 12 Hz.

Mean threshold levels for AS stimuli, in total measured six times for each participant, were 29 dB SPL± 3 dB for the sinusoid at 100 Hz, 5 dB SPL ± 5 dB for the sinusoid at 1000 Hz and 13 dB SPL ± 3 dB for the broadband stimulus. The standard deviations of the individual thresholds were on average 1.9 dB for 1000 Hz, 3.6 dB for 100 Hz, and 2.0 dB for the broadband stimulus.

A significant correlation was found between the individual thresholds for the IS stimulus at 5 Hz and the respective thresholds at 12 Hz (Spearman correlation coefficient $r_{5Hz,12Hz} = 0.79$, $p_{5Hz,12Hz} = 0.001$). Comparing the threshold levels for the isolated AS stimuli, a correlation was observed between the threshold levels of the broadband stimulus and the 100 Hz stimulus ($r_{Broadband,100Hz} = 0.78$, $p_{Broadband,100Hz} = 0.002$). However, no correlation was found between the threshold levels for the isolated IS and the isolated AS stimuli.

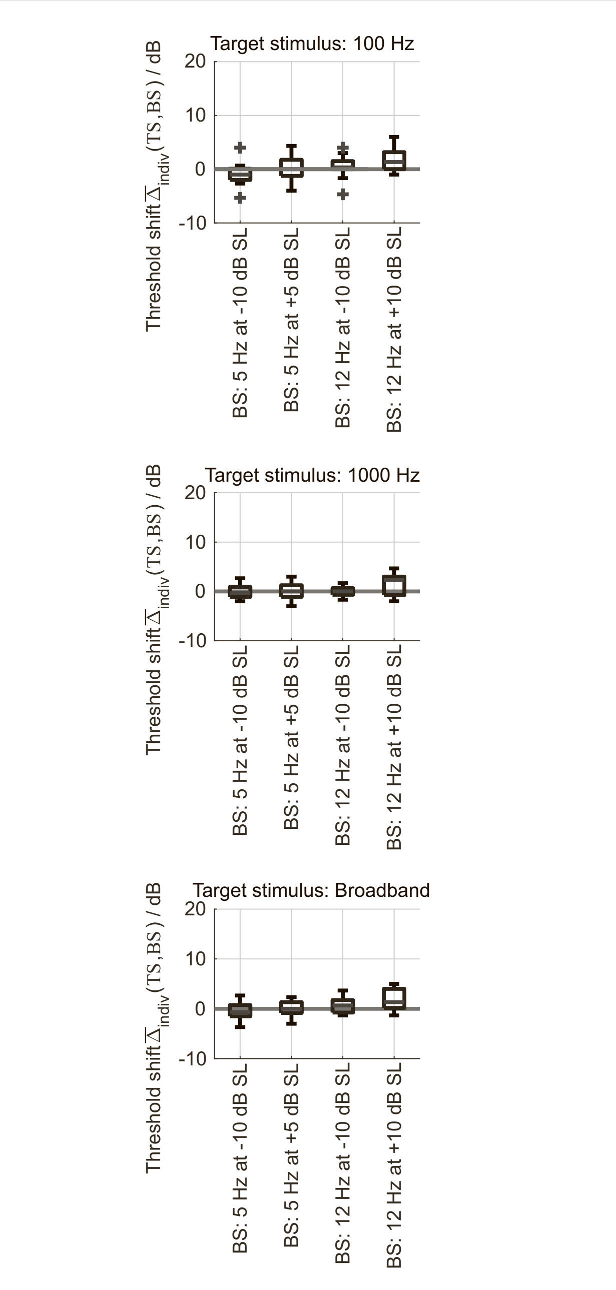

Figure 4. Boxplot of the individual threshold shifts (averaged across repeated measurements) $\bar{\Delta}_{indiv}(TS, BS)$ of 13 participants for AS stimuli (sinusoid at 100 Hz and at 1000 Hz and a broadband pink-noise stimulus) combined with different infrasound background stimuli (BS) (sinusoid at 5 Hz and at 12 Hz) below and above the individual threshold level (in dB SL). None of the threshold shifts were significant.

3.3. Detection threshold shifts for IS and AS target stimuli

Figures 4 and 5 show the boxplots of the average threshold shifts $\bar{\Delta}_{indiv}$ of the thirteen participants for IS and AS

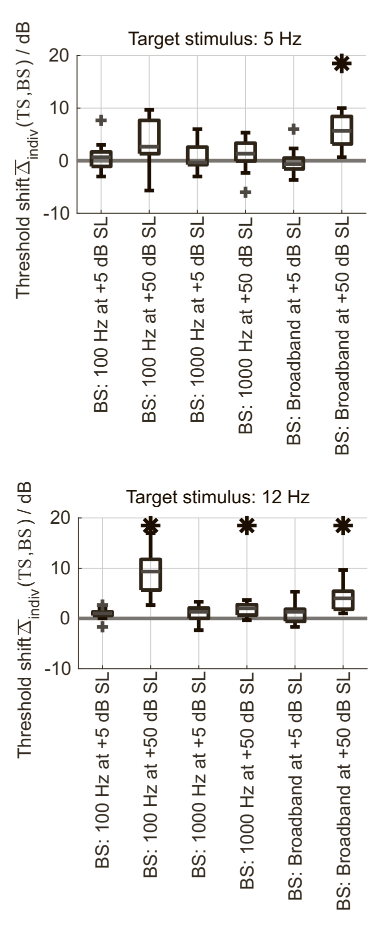

Figure 5. Boxplot of the individual threshold shifts (averaged across repeated measurements) $\bar{\Delta}_{indiv}(TS, BS)$ of 13 participants for sinusoids at 5 Hz and at 12 Hz combined with three different AS background stimuli (BS) (sinusoid at 100 Hz and at 1000 Hz and the broadband pink-noise stimulus) each presented at a specific sound pressure level (5 dB SL and 50 dB SL). Significant threshold shifts were indicated by an asterisk *.

target stimuli. The whiskers extend to the most extreme data points that are located inside 1.5 times the interquartile range above the upper quartile and below the lower quartile. Data points located outside these limits are indicated by a plus sign.

The significance of the threshold shifts was tested by means of paired *t*-tests for each stimulus combination (see Table III). This parametric test was chosen since the paired samples were normally distributed according to Shapiro-Wilk tests ($\alpha_{Shapiro-Wilk} = 0.05$), except one paired sample (No. 17, Table III, $p_{Shapiro-Wilk} = 0.003 < 0.050$). The null hypothesis ($H_0$) for each *t*-test was that there is no difference between the paired samples of threshold levels for the target stimulus TS in the presence of a specific background stimulus in comparison to the thresholds for the same stimulus TS with no background sound. Multiple testing was compensated for by Bonferroni correction ($\alpha_{t-test} = 0.0042$). Significant threshold shifts are indicated by asterisks in Figures 4 and 5 and in Table III.

3.3.1. Threshold shifts for AS target stimuli caused by IS background stimulus

Figure 4 illustrates that the average threshold shift for AS caused by the presence of IS ranges from −5 dB to +6 dB. The *t*-tests indicated that the threshold shifts for AS target stimuli were not significant for all conditions. However, a closer investigation of individual results reveals that two participants had threshold shifts around +5 dB for all three AS target stimuli in the presence of the background stimulus 12 Hz presented at +10 dB SL.

3.3.2. Threshold shifts for IS target stimuli caused by AS background stimulus

The threshold shift for the IS stimulus caused by the presence of AS at the lower intensity of +5 dB SL ranges from −3 to +8 dB (see Figure 5). The threshold shifts for IS stimuli caused by the presence of AS at +50 dB SL showed that some participants were hardly affected in their detection of IS by the presence of AS, whereas others showed large shifts for IS thresholds amounting up to +17 dB in the case of the threshold for 12 Hz caused by the presence of the background stimulus 100 Hz at +50 dB SL. On average, the biggest effects across the sample of more than +3.5 dB were observed for the combination of the sinusoid at 5 Hz and at 12 Hz with the AS background stimuli at 100 Hz and the broadband stimulus, both presented at +50 dB SL.

The results of the *t*-tests showed that the threshold shifts for IS target stimuli were not significant for AS background stimuli presented at the lower intensity of +5 dB SL. However, when the AS background stimuli were presented at the higher intensity of +50 dB SL, the threshold shift for the sinusoid at 12 Hz was statistically significant for all AS background stimuli and the threshold shift for the sinusoid at 5 Hz was statistically significant in the case of the broadband background stimulus.

It should be mentioned that one participant had a considerably smaller shift than all other participants for the threshold for 5 Hz IS in presence of 100 Hz AS presented at +50 dB SL, with $\bar{\Delta}_{indiv}$(5 Hz,100 Hz presented at +50 dB SL) = −6 dB. Treating this as one outlier and excluding the data for this participant from the group analysis, the remaining data for the threshold shift at 5 Hz in the presence of 100 Hz at +50 dB SL is reaching significance ($p = 0.001 < 0.004$). The average shift across the sample for this stimulus combination would then increase to +4.5 dB.

4. Discussion

4.1. Threshold shifts for infrasound and audio sound

This study found that detection thresholds for IS were significantly increased when some of the AS stimuli were presented at a sufficient level. On the other hand, this study did not reveal a significant effect of infrasound on the detection thresholds for audible sound, in contrast to the initial hypothesis.

Table III. Results of the t-tests comparing the threshold levels for the isolated stimuli TS and threshold level for these stimuli TS in the presence of a background stimulus BS. The average threshold shift across the sample $\bar{\Delta}_{sample}(TS, BS)$ and associated standard deviations σ (single value with 68% confidence interval), the p-value of the multiple paired t-tests are listed. Significant results of the multiple paired t-tests (i.e. $p < \alpha_{t-test} = 0.0042$) were each indicated by an asterisk*. $\bar{\Delta}_{sample}$ (TS, BS) $\pm\sigma$: Average threshold shift across the sample (dB).

	t-test No.	Target stimulus TS	Background stimulus BS	$\bar{\Delta}_{sample}$ (TS, BS) $\pm\sigma$	Two-sided p-value of the t-test
Threshold shift for infrasound	1	5 Hz	100 Hz at +5 dB SL	0.62 ± 2.67	0.4215
	2	5 Hz	100 Hz at +50 dB SL	3.69 ± 4.39	0.0104
	3	5 Hz	1000 Hz at +5 dB SL	0.74 ± 2.57	0.3171
	4	5 Hz	1000 Hz at +50 dB SL	1.21 ± 3.06	0.1806
	5	5 Hz	Broadband at +5 dB SL	−0.31 ± 2.46	0.6604
	6	5 Hz	Broadband at +50 dB SL	5.51 ± 2.96	< 0.0001*
	7	12 Hz	100 Hz at +5 dB SL	0.95 ± 1.04	0.0063
	8	12 Hz	100 Hz at +50 dB SL	9.13 ± 4.18	< 0.0001*
	9	12 Hz	1000 Hz at +5 dB SL	1.03 ± 1.57	0.0360
	10	12 Hz	1000 Hz at +50 dB SL	1.79 ± 1.28	0.0003*
	11	12 Hz	Broadband at +5 dB SL	0.97 ± 1.98	0.1019
	12	12 Hz	Broadband at +50 dB SL	4.05 ± 2.51	0.0001*
Threshold shift for audio sound	13	100 Hz	5 Hz at −10 dB SL	−0.90 ± 2.15	0.1580
	14	100 Hz	5 Hz at +5 dB SL	0.46 ± 2.11	0.4466
	15	100 Hz	12 Hz at −10 dB SL	0.10 ± 2.33	0.8764
	16	100 Hz	12 Hz at +10 dB SL	1.67 ± 2.22	0.0189
	17	1000 Hz	5 Hz at −10 dB SL	0.08 ± 1.42	0.8479
	18	1000 Hz	5 Hz at +5 dB SL	0.03 ± 1.02	0.9295
	19	1000 Hz	12 Hz at −10 dB SL	0.08 ± 1.89	0.8856
	20	1000 Hz	12 Hz at +10 dB SL	1.51 ± 2.31	0.0361
	21	Broadband	5 Hz at −10 dB SL	−0.64 ± 1.82	0.2277
	22	Broadband	5 Hz at +5 dB SL	0.69 ± 1.52	0.1274
	23	Broadband	12 Hz at −10 dB SL	−0.08 ± 1.63	0.8680
	24	Broadband	12 Hz at +10 dB SL	1.72 ± 2.11	0.0125

The reason for the observed effect of AS on the threshold levels for IS is not yet clear. For energetic masking, it would be very unusual that a masker more than four octaves above the test tone (5 Hz and 12 Hz to 250 Hz for the broadband noise, and 12 Hz to 1000 Hz) could have any effect on the test tone, because for audio frequencies, noticeable downward masking requires frequency spacing of less than two octaves [12]. Only in the case of the 100 Hz stimulus, an energetic masking effect would be a possible reason for the threshold increase. Furthermore, there is no characteristic place any more on the basilar membrane for 12 Hz and for 5 Hz tones [7]. Therefore, the observed masking is very unlikely to happen in a similar way as known from audible sounds in different frequency bands.

The study by Salt *et al.* [14] showed that infrasonic responses from guinea pigs recorded as endolymphatic potentials were suppressed by AS with increasing sound pressure level of AS. This indicates that there might be other physiological effects causing the threshold increase for IS.

On the other hand, the threshold increase for IS in the presence of AS might rather be attributed to an effect of attention, that is, to a more cognitive effect. When IS is presented simultaneously with AS the attention of the listeners may be shifted towards the perception of AS, which is indeed in accordance with statements from the interviews conducted after each experiment. Some participants reported that, in general, it was more difficult for them to detect IS than AS and that this effect was even more pronounced when IS had to be detected in the presence of AS. In addition, some participants showed especially large threshold shifts for IS up to +17 dB, indicating that this effect strongly varies across individuals.

It has to be noted, that some internal physiological noise was audible for some participants in the anechoic environment used for the experiments. Seven participants reported that the IS stimuli sounded like their own audible physiological noise, e.g. the heartbeat, or they reported that the interaction of IS and the physiological noise makes it even more difficult to detect IS. The presence of the physiological noise might affect the detection thresholds for isolated IS. This is another possible reason for the similarity of thresholds for isolated IS and for IS in the presence of AS at +5 dB SL, because in both conditions there was some AS present at a low level (either audible internal physiological noise or the presented AS background stimulus).

4.2. Accuracy of the measurements

Robust detection threshold data were gathered within this study, as the measurements for all combinations of target stimulus and background stimulus investigated in this study were performed three times for each participant, and there was no systematic effect of the repetitions. However, it should be noted that the variance for the detection thresholds and, therefore, the accuracy of the inferred threshold shifts is limited by the predefined minimum step size of 2 dB within the 3-AFC procedure employed here. Since there are no comparable data of threshold levels for combined IS and AS stimuli from other studies yet, the accuracy can only be estimated for the threshold levels for isolated IS, which serves as the basis for any further calculations, like the sensation level of IS background stimulus and the threshold shifts for IS. The thresholds for isolated IS reported here are consistent with the monaural insert-earphone threshold levels from 18 participants determined by Kühler *et al.* [2], as well as with the second order binaural infrasound-threshold estimation by Møller and Pedersen [1]. They reported average detection thresholds around 110 dB SPL for a sinusoid at 5 Hz and 90 - 93 dB SPL for a sinusoid at 12.5 Hz. In addition, the standard deviations reported in this study are similar to the frequency independent standard deviations around 5 dB for the frequency range between 2 Hz and 1000 Hz reported in [1] and the interquartile-range around 6 dB and 9 dB for threshold levels at 5 Hz and at 12 Hz reported in [2]. This underlines the validity of our results for the thresholds for isolated IS stimuli.

4.3. Comparison between thresholds for isolated infrasound and audio sound

It was investigated whether there is a link between individual threshold levels for IS and AS. The comparison of standard deviations of the thresholds for IS and AS showed that interindividual differences for IS threshold levels were on average bigger than those for AS, which is also consistent with the thresholds for sinusoids at frequencies up to 125 Hz obtained in [2]. Another important finding is that there was no significant correlation between the detection thresholds for IS and AS stimuli, but there was a significant correlation between the thresholds for the sinusoid at 5 Hz and at 12 Hz. These findings suggest that there are certain individuals being especially sensitive to IS, independent of their hearing status in the AS range. One reason for this might be that the perception of AS and IS are based on different mechanisms. Møller and Pedersen [1] suggested that people with a particularly narrow or blocked helicotrema might be especially sensitive to IS, because the high IS pressure inside the cochlea is counterbalanced for them more slowly.

4.4. Statements from the interviews

The statements within the interviews give an impression how isolated IS and the combination of IS and AS are being perceived. The perception of IS is described like a pressure or tactile sensation, which is in line with many prior studies, e.g. [1, 27]. Moreover, a few participants associated the perception of IS with a modulation effect and other participants suggested that they detected the IS stimuli through a change of the hearing sensation of the AS background stimulus. Both are in line with the results from the study of Marquardt and Jurado [15] who found that IS combined with AS cannot be distinguished from AS that is amplitude modulated at infrasonic frequencies.

4.5. Limitations and future research

At this stage, this study was limited to young listeners aged between 18 and 30 years with normal hearing. Therefore, it would be desirable to repeat this study with other groups of listeners, like older population, hearing-impaired listeners or individuals being particularly sensitive to IS, and to compare the results of these groups with the findings of this study.

Based on our results, it can be concluded that modulation effects caused by infrasound [14, 15] do not affect hearing thresholds for audible sound, since, contrary to the initial hypothesis, audio sound thresholds were not decreased by the presence of infrasound. If there is any masking effect of IS on the threshold level for AS, this effect must be very small. However, this does not imply that there is no influence at all of IS on the auditory perception of AS. It would therefore be desirable to investigate whether the interaction of IS and AS might possibly affect other psychoacoustic quantities like loudness and/or annoyance. Modulation effects might affect the quality of the auditory perception when both, infrasound and audio sound are presented at a level well above threshold. The statements within the interviews indicate that there is an audible modulation effect. Further studies should be intended to investigate whether this modulation effect might be a possible reason for the large annoyance related to noise with IS components.

Furthermore, this study found that threshold levels for infrasound were increased by the presence of audible sound presented at a sufficient level. This could be an indication that infrasound might even be more annoying in a quiet environment.

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