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Investigation of the unpleasantness of infrasound combined with audio sound using psychoacoustic scaling methods

Elisa Burke[1,2], Euginia Putri Stederi[1], Stefan Uppenkamp[2], Christian Koch[1]

[1]Physikalisch-Technische Bundesanstalt, Germany, elisa.burke@ptb.de
[2]Medizinische Physik, Carl von Ossietzky Universität Oldenburg, Germany

Abstract
At many immission sites, human exposure to infrasound (f < 20 Hz) is usually accompanied by sound in the audio-frequency range (audio sound, 20 Hz $\leq f <$ 20 kHz). This gives rise to the question of whether the interaction between infrasound and audio sound affects the quality of auditory perception. Psychoacoustic experiments were performed within the framework of the EARS 2 project of the European Metrology Programme for Innovation and Research (EMPIR). Recent results in this project had already shown that detection thresholds for infrasound were increased when simultaneous audio sound is present. The current study deals with the hypothesis that the unpleasantness related to infrasound is changed when infrasound is presented along with audio sound. A rating task on a numerical scale and a pairwise comparison task were conducted to quantify and to compare the unpleasantness of (1) isolated infrasound (sinusoid), (2) isolated audio sound (sinusoid and broadband), and (3) the combination of both, at different sound pressure levels. Normal hearing listeners aged from 18 to 30 years participated in the hearing tests. The results should be of use to improve the understanding of the impact of combined noise on humans and their well-being in the vicinity of potential noise sources.
Keywords: Infrasound, Unpleasantness, Psychoacoustic scaling methods

1 INTRODUCTION

The effect of infrasound (frequencies $f < 20\,\text{Hz}$) on humans is a matter of current research and debate. In the recent years, the human exposure to infrasound increased and there are more and more individuals feeling annoyed by noise with infrasound components, like road and rail traffic noise and wind turbine noise (e. g. [1, 2]).

Since human exposure to infrasound is usually accompanied by sound in the common audio frequency range (audio sound, $20\,\text{Hz} \leq f < 20\,\text{kHz}$), the question arises whether the interaction of infrasound and audio sound is a contributing factor for the large annoyance of environmental noise with infrasound components. Only few studies so far have investigated the effect of combined infrasound and audio sound stimuli on human perception. For instance, Møller investigated the annoyance of infrasound (sinusoid at 16 Hz) combined with audio sound (narrowband noise centred at 1000 Hz) by exposure in a whole-body pressure-field chamber. He observed that “Combinations of audio and infrasonic noise were in general given a rating close to, or slightly above, the rating of the most annoying individual noise conditions” [3].

Within the research project EARS 2 (project of the European Metrology Programme for Innovation and Research EMPIR) our aim was to realize a profound investigation of the human perception of combined infrasound and audio sound stimuli. We focussed on the perception of sound by means of the human auditory system and excluded other ways of sensation, like somatosensory mechanisms. Therefore, we applied a specially developed sound source system delivering infrasound and audio sound stimuli directly to the participant’s ear canal by means of a foam eartip.

Recent results in this project revealed that detection thresholds for audio sound were hardly affected by the presence of infrasound. On the contrary, thresholds for infrasound can significantly increase when simultaneous audio sound is present (results of a pilot study [4], manuscript of the complete data set is submitted).

The present study takes the previous findings a step further by investigating the perceived unpleasantness, a precursor of annoyance, for combined infrasound and audio sound stimuli. We wanted to investigate whether the combination of infrasound and audio sound is rated as more unpleasant than isolated infrasound and isolated audio sound stimuli. We were especially interested in whether this also applies for the combination of audio sound with infrasound below threshold level, since levels of infrasound in environmental noise are often below threshold level (e.g. [1]). In addition, the masking effect of audio sound on infrasound may affect the perceived unpleasantness for infrasound combined with audio sound, especially, when infrasound is presented at a near threshold level.

We performed two different rating tasks, a numerical scale rating task and a paired comparison task, in order to examine whether both methods provide similar results. The results discussed in this paper are an outcome of a pilot study with six participants.

2 Materials and methods

2.1 Setup

The infrasound and audio sound stimuli were each generated by separated sound sources, both were realized as electrodynamic loudspeakers mounted in damped wooden boxes. Tubes coupled the sound sources to the same audiometric ear tip (E-A-RTone/ E-A-RLink, Standard Insert Foam Eartips), which was used for monaural presentation of the acoustic stimuli. The infrasound and audio sound signals were digitally generated at 96 kHz sample rate in MATLAB and they were fed into separate channels of an external soundcard (RME Fireface UC). The outputs were connected to amplifiers (type Beak BAA 120 for infrasound signals, type Tira BAA 120 for audio signals).

During the hearing tests, the sound source system and the participant were located in an anechoic room providing a sufficient low-background sound level even in the infrasonic frequency range. The audiometric eartip was inserted into the participant's right ear and the contralateral ear was occluded with an earplug. A mouse and a computer screen were placed in front of the participant.

The sound pressure level of the audio sound stimuli were calibrated with an IEC 60318-4 [5] occluded ear-simulator (Brüel & Kjær 4157, with ear canal extension DB 2012), whereas the sound pressure level of the infrasound stimulus was calibrated with a $\frac{1}{2}''$ low-frequency pressure-field microphone (Brüel & Kjær 4193, with UC0211) coupled to a cavity with a volume of $1.3\,\mathrm{cm}^3$, which is approximately equivalent to the volume of the human ear canal.

2.2 Stimuli

In the unpleasantness rating task, 26 different stimuli (Table 1), including isolated infrasound, isolated audio sound, and combined infrasound and audio sound stimuli, were used. A sinusoid at 12 Hz was applied as infrasound stimulus, and a sinusoid at 1000 Hz and a bandlimited pink-noise stimulus (broadband) with the frequency range between 250 Hz and 4000 Hz were used as audio sound stimuli.

The stimuli were presented at different sound pressure levels. The sinusoid at 12 Hz was presented at 95 dB SPL and 110 dB SPL (Table 1, No. 1 - 2, No. 15 - 26), which represents sound pressure levels around and clearly above the average threshold level reported in [6, 7] that is values between 90 dB SPL and 93 dB SPL for a sinusoid at 12.5 Hz. Since the sound pressure levels of environmental infrasound noise are often below threshold level we were especially interested in whether audio sound combined with infrasound at a level below threshold is more unpleasant than isolated audio sound. Therefore, the infrasound stimulus was also presented at 80 dB SPL when it was simultaneously presented with audio sound (No. 9 - No. 14). The sinusoid at 1000 Hz was presented at 20, 50, and 70 dB SPL. The broadband stimulus was also presented at three sound pressure levels (21, 36, and 53 dB SPL) having the same loudness as the sinusoidal stimulus at 1000 Hz according to [8]. The duration of each stimulus was set to 2 seconds to keep the total duration of the pairwise comparison task cycle with 650 pairs of stimuli within an acceptable range for the test person. The same duration of the stimuli was applied to the numerical scale ratings so that the results of both procedures remain comparable.

Cosine-squared windows with a ramp duration of 0.25 seconds were applied to stimulus onsets and offsets. The broadband stimulus was digitally pre-shaped to equalise the frequency response of the audio sound source.

Table 1. Stimuli for the unpleasantness rating tasks

No.	Infrasound: Stimulus	Level [dB SPL]	Audio sound: Stimulus	Level [dB SPL]
1	12 Hz	95	-	-
2	12 Hz	110	-	-
3	-	-	1000 Hz	20
4	-	-	1000 Hz	50
5	-	-	1000 Hz	70
6	-	-	Broadband	21
7	-	-	Broadband	36
8	-	-	Broadband	53
9	12 Hz	80	1000 Hz	20
10	12 Hz	80	1000 Hz	50
11	12 Hz	80	1000 Hz	70
12	12 Hz	80	Broadband	21
13	12 Hz	80	Broadband	36
14	12 Hz	80	Broadband	53
15	12 Hz	95	1000 Hz	20
16	12 Hz	95	1000 Hz	50
17	12 Hz	95	1000 Hz	70
18	12 Hz	95	Broadband	21
19	12 Hz	95	Broadband	36
20	12 Hz	95	Broadband	53
21	12 Hz	110	1000 Hz	20
22	12 Hz	110	1000 Hz	50
23	12 Hz	110	1000 Hz	70
24	12 Hz	110	Broadband	21
25	12 Hz	110	Broadband	36
26	12 Hz	110	Broadband	53

2.3 Psychoacoustic methods

Two different psychoacoustic scaling methods were applied to investigate the unpleasantness for combined infrasound and audio sound stimuli (stimuli, see Table 1). For each participant, a pairwise comparison task was performed as the first experiment, and, after that, a 11-point-numerical rating task was conducted. The experiments were implemented in MATLAB.

2.3.1 Pairwise comparison unpleasantness task

In the pairwise comparison task, the participants were asked to compare the unpleasantness of all combinations of the 26 stimuli listed in Table 1, excluding the comparison of two identical stimuli. Each measurement trial consisted of the presentation of one pair of stimuli and, simultaneously, two panels labelled "1" and "2" were successively highlighted in red colour on the computer screen in front of the participant. Then, the participant was asked to indicate which stimulus was more unpleasant for him/her by clicking on the respective panel. Each comparison of one pair of stimuli was repeated once, but in reverse presentation order. So in total 650 comparisons (26*25) were conducted. The order of the comparisons was pseudo-randomized.

2.3.2 11-point numerical unpleasantness rating task

In the 11-point numerical unpleasantness rating task, the participant successively rated the unpleasantness caused by each stimuli (listed in Table 1) by means of a 11-point numerical scale according to the ICBEN recommendations [9]. The scale displayed on the computer screen ranged from "0" labelled "not at all unpleasant" (translated into German: "überhaupt nicht unangenehm") to "10" labelled "extremely unpleasant" (translated into German: "extrem unangenehm"). The unpleasantness rating was repeated once for each stimulus, so that in total 52 unpleasantness ratings were performed. The presentation order of the stimuli was pseudo-randomized

2.4 Participants

Six listeners aged between 18 and 30 years participated in the hearing tests. None of them had experience with psychoacoustic experiments with infrasound prior to this study. All of the participants were otologically normal as tested by an otoscopic examination and by standard audiometry. They had hearing thresholds better than 15 dB HL for the right ear for pure tones between 125 Hz and 8000 Hz.

3 RESULTS AND DISCUSSION

The numerical scale ratings of unpleasantness were averaged across the two repeated ratings for each stimuli. The boxplot of the averaged numerical ratings of the participants to each stimulus are illustrated in Figure 1. The left panel shows the results for isolated infrasound, for the isolated broadband stimulus, and for infrasound combined with the broadband stimulus. The right panel shows the results for isolated infrasound, for the isolated sinusoid at 1000 Hz, and for infrasound combined with the sinusoid at 1000 Hz. The colour of the boxplot indicates the audio sound level of the stimuli and the position of the boxplot on the x-axis indicates the infrasound level of the stimuli.

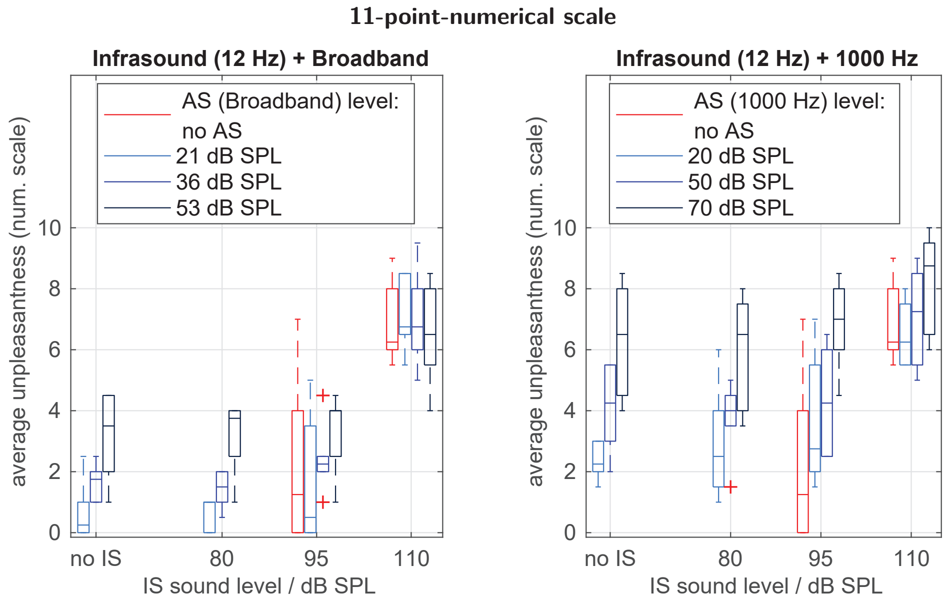

Figure 1. Boxplots of average unpleasantness ratings of six participants using a 11-point numerical scale for different stimuli combinations for infrasound (IS) and audio sound (AS) (list of all stimuli, see table 1).

To analyse the results of the pairwise comparison task, it was calculated for each stimulus how often on average the participants rated the particular stimulus as more unpleasant than the other 25 stimuli. Thus, the results lie in the range between "0" (minimal unpleasantness) and "25" (maximal unpleasantness). Figure 2 shows the results of the pairwise comparison task illustrated as boxplots for each stimuli arranged in the same way as the results in Figure 1.

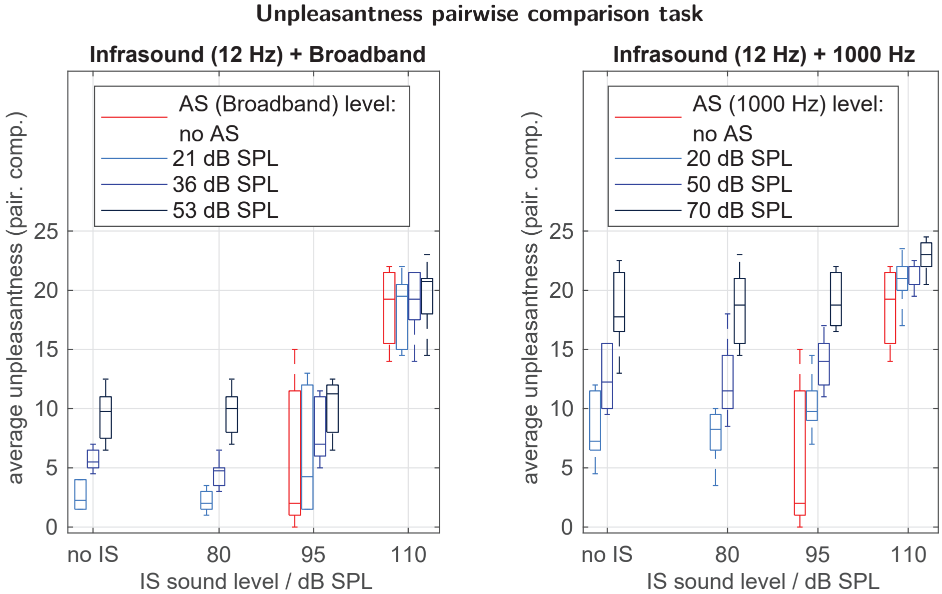

Figure 2. Boxplots of average unpleasantness ratings of six participants based on a pairwise comparison task for different stimulus combinations of infrasound (IS) and audio sound (AS) (list of all stimuli, see table 1) .

Comparing the distributions of the boxplots in Figures 1 and 2, it can be seen that the results of the pairwise comparison task and of the numerical scale ratings are consistent. There was a significant positive correlation between both procedures (Pearson's correlation coefficient $\rho = 0.86$, Spearman's rank correlation coefficient $r_s = 0.87$). When specific stimulus conditions with many data points at the lower limit on the numerical rating scale (stimuli No. 1, 6, 12, 18) were excluded from the analysis, then, the correlation coefficients changed to $\rho = 0.82$ and $r_s = 0.83$. Taking into account the good agreement between both measurement procedures the results of both procedures are discussed together in the following.

It was found that, in general, the unpleasantness of the isolated stimuli increased with increasing sound pressure level as expected, and this applies to both, infrasound and audio sound stimuli. Comparing the unpleasantness of the audio sound stimuli, the sinusoid at 1000 Hz was rated more unpleasant than the broadband stimulus at the same loudness. That was also to be expected since tonal sounds are usually perceived as more unpleasant than non-tonal sounds. The stimuli being rated as most unpleasant were the infrasound stimulus at 110 dB SPL and the sinusoid at 1000 Hz presented at 70 dB SPL alone or combined with audio sound and infrasound, respectively.

Another important finding of our study is that the stimulation with isolated audio sound and with audio sound combined with infrasound at a level below threshold (12 Hz at 80 dB SPL) resulted in the same unpleasantness rating. This finding might indicate that environmental noise with inaudible infrasound components, is not significantly more unpleasant than noise with no infrasound components.

When infrasound was presented at 95 dB SPL, which is slightly above the average threshold level according to [6, 7], it seems that the simultaneous stimulation with audio sound presented at a low and medium level (broadband: 21 and 36 dB SPL, sinusoid: 20 and 50 dB SPL) slightly increases the perceived unpleasantness compared to the unpleasantness of respective isolated infrasound and isolated audio sound stimuli. On the contrary, when infrasound at 95 dB SPL was combined with the audio sound stimulus at the high level (broadband: 53 dB SPL, sinusoid: 70 dB SPL) the perceived unpleasantness corresponds more closely to the unpleasantness of the isolated audio sound stimuli. A possible reason might be the masking effect of audio sound on infrasound. Recent results of this project had shown that infrasound threshold were masked by audio sound when presented at a sufficient level (results of a pilot study [4]). Due to the masking effect the infrasound stimulus presented at a near threshold level might be inaudible or hardly audible and, therefore, the unpleasantness of the combined stimuli corresponds to the unpleasantness of the isolated audio sound stimulus.

When infrasound was presented at a clearly audible level of 110 dB SPL simultaneously with audio sound, the unpleasantness of these stimuli were dominated by the unpleasantness of the infrasound, since the unpleasantness of the combination seems to be equal to the unpleasantness of isolated infrasound stimulus. Moreover, the unpleasantness of the stimulus combination of the sinusoid at 1000 Hz with the infrasound stimulus at 110 dB SPL might even increase with increasing audio sound level compared to the unpleasantness of the isolated infrasound stimulus. However, this effect could not be observed for the broadband stimulus combined with high-level infrasound.

Comparing the results of our study with the results of Møller's study [3], we have to point out that we used other measurement procedures and we used monaural presentation by an insert-earphone sound source system instead of a whole-body pressure-field chamber like Møller. Nevertheless, the results are in good agreement since both studies showed that the combination of infrasound and audio sound are rated as equal, or slightly more, annoying than the most annoying isolated stimuli.

4 CONCLUSION

Within this pilot study, first trends were reported for the unpleasantness of infrasound combined with audio sound. The results of the two different unpleasantness rating tasks are consistent. Furthermore, the results of this study suggest that the interaction of infrasound presented at a level above threshold combined with audio sound affects unpleasantness ratings. On the contrary, our data indicate that if there is any effect of below-threshold infrasound on the unpleasantness ratings for combined infrasound and audio sound stimuli, this effect must be very small. However, the experiments are to be carried out with a considerably larger number of participants to validate these findings.

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