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Effects of infrasound on the perception of a low-frequency sound

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Abstract – The study investigated the effects of an 8 Hz infrasound sinusoid, presented at a sensation level (SL) of 9 decibels (dB), on the detection of i) a 64 Hz pure tone and ii) an 8 Hz sinusoidal amplitude modulation imposed on a 64 Hz sinusoidal carrier, presented at an SL of 25 dB. Two phase relations between infrasound and amplitude modulation were used: 0° (in phase) and 180° (in antiphase). Detection thresholds of the 64 Hz pure tone were, on average across 19 normal-hearing listeners, 4.6 dB higher in the presence than in the absence of the infrasound. Modulation detection thresholds also increased in the presence of the infrasound, on average by about 3 dB. Large individual differences in modulation detection thresholds were observed with respect to the two phase relations. On average across all listeners, however, the difference in modulation detection thresholds between in-phase and antiphase infrasound was not significant. The study shows that supra-threshold infrasound masks frequency components in the low audio-frequency range and affects the perception of amplitude modulations imposed on them.

Keywords: Infrasound, Low-frequency sound, Amplitude modulation, Absolute threshold, Phase effects

1 Introduction

Several studies showed that the human auditory system can perceive infrasound, i.e., sound with frequencies below 20 Hz, provided that the sound pressure level (SPL) of the corresponding signal is high enough (e.g., [1–7]). The exact mechanisms of auditory infrasound perception are still not fully understood. One hypothesis is that the infrasound interacts with other sound components in the audio-frequency range, i.e., the range from 20 Hz to 20 kHz, which is typically considered to be most relevant for human auditory perception [8]. In typical acoustical environments, emissions of infrasound are usually accompanied by concurrent emissions of sound components in the audio-frequency range. But additional components in the audio-frequency range may also originate from internal sources, such as blood flow or the motion of muscles. The overall aim of this study was, therefore, to examine the interaction between infrasound and low-frequency audio sound with respect to masking and the perception of amplitude modulations.

Masking is understood as the increase of the detection threshold of one stimulus by the presence of another stimulus, here referred to as the *masker*. In the audio-frequency range, it is well-known that the detection thresholds of a narrowband target stimulus (e.g., a sinusoid) is increased when a masker in an adjacent frequency region is presented simultaneously [8]. Using infrasound sinusoids, Burke et al. [7] found that the presence of a 100 Hz pure tone at a sensation level (SL) of 50 decibels (dB) caused a significant increase in the detection threshold at 12 Hz by 10 dB. At 5 Hz, the increase was 3 dB, but it did not reach significance. They also tested the effect of infrasound sinusoids on the detection of audio-frequency stimuli. Using a 12 Hz masker at an SL of 10 dB, they measured a small amount of masking at a target frequency of 100 Hz, but, again, it was not significant. One objective of the present study was to test whether a significant masking effect is observed when a slightly lower target frequency of 64 Hz is used. An 8 Hz infrasound sinusoid was used as a potential masker. This frequency lies between those of the infrasound sinusoids used by Burke and colleagues (i.e., 5 Hz and 12 Hz).

Another type of possible interaction might occur at the level of amplitude-modulation perception. Marquardt and Jurado [9] reported that human listeners had difficulties to distinguish a 63 Hz carrier modulated at 8 Hz from a 63 Hz pure tone in the presence of a supra-threshold 8 Hz infrasound sinusoid. These studies support the hypothesis that infrasound may be perceived as amplitude modulation. Thus, infrasound and simultaneously presented audio-frequency sounds may interact in a more complex way than merely in terms of energetic masking, i.e., by affecting the perception of amplitude modulations. A second objective of the present study was, therefore, to investigate how the

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presence of an 8 Hz infrasound sinusoid would affect the detection of an amplitude modulation of 8 Hz imposed on a pure tone with a low frequency of 64 Hz. In the following, this interaction is referred to as *modulation masking.*

If infrasound is indeed perceived as an amplitude modulation, as the data in [9] indicate, and if both the infrasound and the amplitude-modulated stimulus are presented simultaneously, then the phase relation between infrasound and modulator should play a role. A third objective of the present study was, therefore, to test how the detection of the 8 Hz amplitude modulation changes when the 8 Hz infrasound sinusoid is simultaneously presented in phase (0°) or in antiphase (180°) to the modulator.

2 Methods

2.1 Listeners

Nineteen listeners (12 female, 7 male; ages between 20 and 39 years, median age 25 years) participated in the experiments. Fourteen listeners were paid volunteers and five were members of the Department of Experimental Audiology of the Otto von Guericke University Magdeburg. Listeners were otologically normal as confirmed by a questionnaire for hearing testing (Annex A of ISO 389-9; [10]). Audiometric hearing levels of those ears that were used for the infrasound experiment were lower than or equal to 15 dB for all audiometric frequencies between 125 Hz and 2 kHz. Listeners were instructed about the goal of the study and about the pseudonymized use of their data according to the General Data Protection Regulation (GDPR) of the European Union. The Declaration of Helsinki was adhered to in all measurements. Ethics approval was obtained from the ethics committee of the Medical Faculty of the Otto von Guericke University Magdeburg (ethics approval 79/17).

2.2 Experiments and stimuli

The present study comprised experiments on detection thresholds of sinusoidal signals (detection experiments) and experiments on thresholds for detection of a sinusoidal amplitude modulation imposed on a sinusoidal carrier (modulation detection experiments).

Detection thresholds were measured for sinusoids with a frequency of 8 Hz (infrasound) and 64 Hz (low-frequency sound). This is referred to as *experiment 1* in the following. In addition, the threshold of the 64 Hz sinusoid was measured in the presence of a supra-threshold 8 Hz sinusoid. In this *experiment 2*, the level of the 8 Hz sinusoid was set to 9 dB above the listeners' individual threshold for this frequency (which was obtained in experiment 1), i.e., to an SL of 9 dB. The frequencies were about the same as in [9], and the level of the infrasound sinusoid was in the range of that used in [7]. Experiment 2 quantifies the amount of masking of the low-frequency sound by the supra-threshold infrasound. In experiments 1 and 2, all sinusoids had a starting phase of 0°.

In the modulation detection experiments, a sinusoidal amplitude modulation at a frequency of $f_\mathrm{M} = 8$ Hz was imposed on a sinusoidal carrier with a frequency of $f_\mathrm{C} = 64$ Hz using the following equation:

$$s(t) = A \cdot \sin(2\pi \cdot f_\mathrm{C} \cdot t) \cdot (1 + m \cdot \sin(2\pi \cdot f_\mathrm{M} \cdot t)), \quad (1)$$

where A is the amplitude of the carrier and m the modulation index. Modulation detection thresholds were determined in terms of modulation depths, expressed as $20 \cdot \log_{10}(m)$ dB (see the following section for details of the procedure). The carrier level (determining A in Eq. (1)) was set to 25 dB above the listeners' individual threshold for that frequency (which was measured in experiment 1), i.e., to an SL of 25 dB. In *experiment 3*, the modulation detection threshold was determined in the absence of any other sound, serving as a reference (Ref) threshold. In *experiment 4*, modulation detection thresholds were determined in the presence of the same supra-threshold infrasound that was used in experiment 2 (see above), i.e., of an 8 Hz sinusoid, presented at an SL of 9 dB. Two phase relations between the infrasound and the modulator were considered: in phase (0°) and in antiphase (180°) to the modulator. The phase relation was changed by altering the starting phase of the infrasound.

The numbering of the experiments also determined the order in which each listener completed them. Prior to the experiments, the listeners were familiarized with infrasound stimuli. In this familiarization phase, listeners could replay an 8 Hz sound as often as they wanted by pressing a button; they could also freely adjust the level of the sound by means of a slider. The maximum loudness level for this familiarization phase and the experiments was 60 phon (derived from [2]).

All signals used in the experiments had a duration of 1500 ms, including van-Hann ramps at the beginning and the end of the stimulus. Each ramp was 250 ms long, which corresponds to two cycles of 8 Hz.

2.3 Measurement setup and procedure

All stimuli were generated digitally in MATLAB (MathWorks, Natick, MA) with a sampling rate of 96 kHz and a resolution of 24 bit. The resulting signals were converted from digital to analog via an external sound card (RME Fireface, Haimhausen, Germany) and finally presented monaurally to the ear with a custom-made low-distortion sound reproduction system (LDREPS) [11]. A key part of the LDREPS is a RadioEar DD45 audiometric earphone transducer mounted in an air-sealed aluminum housing with a sound outlet in the front plate. A sound tube with a length of 25 cm connects the sound outlet to the ear insert of an Etymotic ER-10B+ low-noise microphone system. Two of these earphone transducers are part of the LDREPS. For the experiments of the present study, only one of the two was used.

The LDREPS used in the present study is an improved version of that used in [6]. The LDREPS used here incorporates, for safety reasons, a rapid frequency-dependent level-watching protective switch in the signal path between amplifier and transducer (instead of a passive low-pass filter as used before, which leads to the generation of unwanted distortion products). The switch interrupts the signal whenever the signal level exceeds a given frequency-dependent maximum value, i.e., the 80 phon equal-loudness level contour [12]. This was the highest level allowed by the ethics committee. In general, the ear insert of the LDREPS was fitted to the right ear of the listeners. Only for one listener, whose right ear was hearing impaired, the left ear was used.

Listeners were seated comfortably in a double-walled sound-insulated booth. To ensure a proper fit of the ear insert, the SPL of a 4 Hz signal, which had been calibrated in a B&K 4157 occluded-ear simulator (Brüel & Kjær, Nærum, Denmark), was always controlled in situ by means of the built-in low-noise microphone of the LDREPS prior to the next run of an experimental condition.

Detection thresholds and modulation detection thresholds were measured using an adaptive three-interval, three-alternative forced-choice procedure. The intervals of a trial were separated by 200 ms of silence. The interval duration was 1500 ms (i.e., the stimulus duration). The intervals of a trial were highlighted on a screen, which was positioned in front of the listener. A randomly chosen interval contained the target, i.e., the sinusoidal signal in the case of the detection experiments or the amplitude modulation in the case of the modulation detection experiment. The listener was requested to press a numbered button on a hand-held keyboard to indicate which of the intervals they thought had contained the target.

In the detection-threshold experiments (experiments 1 and 2), the level of the target sinusoid for the next trial was chosen based on the listener's response. A one-up two-down rule was applied, i.e., the level was increased after a false response and decreased after two consecutive correct responses. This procedure converges to a level for which the probability of a correct response is $p_{\mathrm{corr}} = 1/\sqrt{2} \approx 70.71\%$ [13, 14].

The target of the first trial was presented at a clearly supra-threshold SPL, which corresponds to a loudness level of about 20 phon (according to [2]). The initial step size was 4 dB; it was halved after each upper reversal until a final step size of 1 dB was reached. The run continued with the final step size for the next four reversals. The arithmetic mean of the SPLs at these four reversals was taken as the threshold estimate of the corresponding run. For each stimulus, thresholds were measured three times (one threshold per run). The arithmetic mean of the three threshold estimates was taken as the final threshold estimate of the corresponding stimulus. In experiment 1, the runs for the two frequencies were shuffled.

In the modulation detection experiments (experiments 3 and 4), essentially the same adaptive procedure was used as for the detection experiment, but now the modulation depth in dB was varied. The maximum allowed modulation depth was 0 dB (corresponding to $m = 1.00$). The run started at a supra-threshold modulation depth of -1 dB (corresponding to a modulation index of $m = 10^{-1\,\mathrm{dB}/20\,\mathrm{dB}} \approx 0.89$). The initial step size was 4 dB; it was halved after each upper reversal until a final step size of 1 dB was reached. The run continued with the final step size for four reversals. The arithmetic mean of the modulation depths at these four reversals was taken as the threshold estimate of the corresponding run. For each stimulus, modulation detection thresholds were measured three times (one threshold per run). The arithmetic mean of the three threshold estimates was taken as the final modulation detection threshold of the corresponding stimulus. In experiment 4, the runs for the two phase relations were shuffled.

2.4 Statistics

Throughout the present study, means and standard deviations are arithmetic means and arithmetic standard deviations, unless specified otherwise. Significance levels of statistical tests are $\alpha = 0.05$. Correlations are quantified using Pearson correlation coefficients, denoted by r. In the present study the effect sizes were classified by the authors as follows: no/none for $0 < |r| \leq 0.25$, small/weak for $0.25 < |r| \leq 0.5$, medium/moderate for $0.5 < |r| \leq 0.75$, and large/strong for $0.75 < |r| < 1$.

3 Results

3.1 Detection thresholds

Figure 1 shows the detection thresholds measured in experiments 1 and 2. The top panel shows thresholds in quiet for the 8 Hz target. The bottom panel shows thresholds for the 64 Hz target when presented in quiet (circles) or together with the supra-threshold infrasound (diamonds). Open symbols indicate individual mean data and the error bars indicate the mean ± one intra-individual standard deviation. Filled symbols (far right) indicate group mean thresholds and the corresponding error bars the mean ± one inter-individual standard deviation. Colored boxes connecting the two thresholds for the 64 Hz target in the bottom panel quantify the amount of masking. Green boxes indicate an increase in the SPL at threshold due to the infrasound (i.e., positive masking) and red boxes a decrease (i.e., a negative masking).

Single-listener detection thresholds for the 8 Hz target (open circles in the top panel) ranged from 91.0 dB to 113.0 dB. For most listeners, standard deviations were small. Only for listeners L14 and L17, large differences between the three individual threshold estimates were observed, resulting in a standard deviation of 11.1 dB for L14 and 9.7 dB for L17. The group mean threshold (filled circle in the top panel) was 104.5 dB (±5.0 dB).

For the 64 Hz target, thresholds in quiet (open circles in the bottom panel) also varied across listeners, ranging from 38.8 dB to 59.1 dB. The single-listener standard deviations ranged from 0.3 dB to 5.1 dB. Note that a low threshold at 8 Hz does not necessarily imply that threshold is also low at 64 Hz. For example, listener L18 had the lowest threshold in quiet for the 8 Hz target of all listeners but the highest threshold in quiet for the 64 Hz target. On average across all listeners, the threshold in quiet for the 64 Hz target (filled circle in the bottom panel) was 45.5 dB (±5.8 dB).

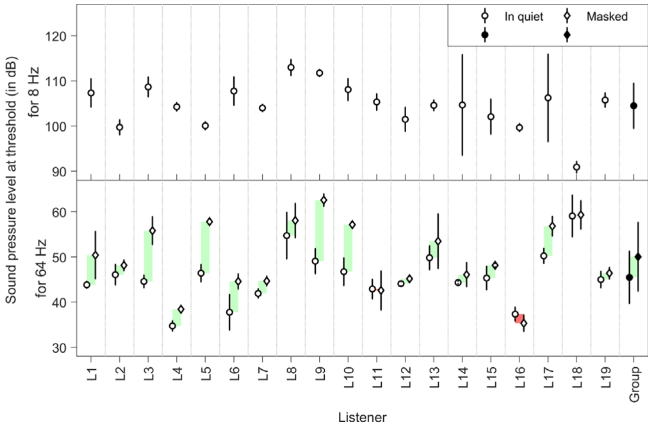

Figure 1. Mean (symbols) and standard deviation (error bars) of the sound pressure level at threshold for a sinusoidal target. Individual data are shown with open symbols and group mean data with filled symbols on the far right. The top panel shows thresholds for the 8 Hz target. The bottom panel shows thresholds for the 64 Hz target in quiet (circles) and in the presence of an 8 Hz sinusoid, presented at an SL of 9 dB (diamonds). Colored boxes in the bottom panel quantify the amount of masking. Green boxes indicate positive masking (i.e., an increase in the SPL) and red boxes negative masking (i.e., a decrease in the SPL).

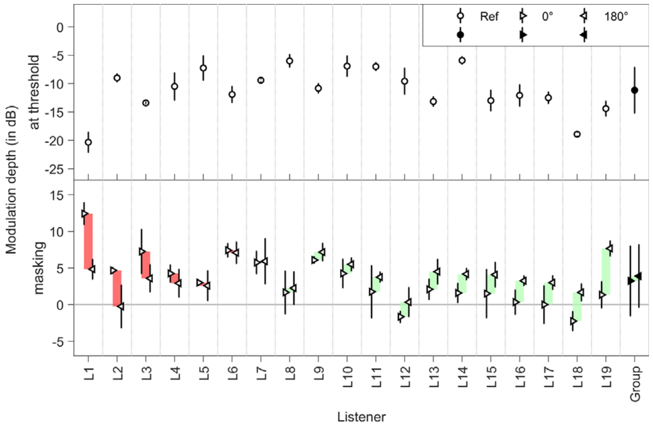

Figure 2. Mean (symbols) and standard deviation (error bars) of the modulation depth at threshold for an 8 Hz modulated 64 Hz carrier (circles, top panel) and the change in threshold (masking) when measured in the presence of an 8 Hz sinusoid presented at an SL of 9 dB (triangles, bottom panel). Right-pointing and left-pointing triangles indicate the masking when infrasound and modulation are presented in phase and in antiphase, respectively. As in Figure 1, open symbols indicate single-subject data, filled symbols on the far right average data of all listeners. Error bars indicate the mean ± one standard deviation. Colored boxes in the bottom panel quantify the strength of the phase effect. Red boxes indicate a stronger masking for 0° and green boxes for 180°. The listeners were sorted and numbered based on this phase effect.

Overall, the average thresholds in quiet of all listeners for the two target frequencies agree with those reported in the literature [2, 3, 5, 6].

Except for listeners L11 and L16 (red boxes), single-listener thresholds of the 64 Hz target in the presence of the infrasound sinusoid (diamonds in the bottom panel) were higher than the corresponding single-listener thresholds in quiet for this frequency (circles). Thus, in general, the infrasound masked the audio-frequency sound. For listener L11, the threshold difference was only 0.3 dB and considerably smaller than the standard deviation of this listener for these thresholds. For L16 the difference was 2.0 dB, which was comparable to the corresponding standard deviations for this listener (1.5 dB and 1.8 dB). Thus, for the two listeners showing negative masking, the effect was rather small, compared to the variations in the threshold estimates of the listener.

On average across all listeners, the difference between the two thresholds was 4.6 dB. The difference was significant (two-sided paired-sample *t*-test, $p < 0.001$). Thus, the 8 Hz infrasound had a significant masking effect on the 64 Hz target.

3.2 Modulation detection thresholds

The top panel of Figure 2 shows the modulation detection thresholds for an 8 Hz modulated 64 Hz carrier measured in experiment 3, i.e., in the absence of a simultaneously presented 8 Hz infrasound. The bottom panel shows the difference between the thresholds obtained in experiment 4 and the corresponding threshold in experiment 3, i.e., the masking due to the presence of the infrasound. Right-pointing and left-pointing triangles indicate the masking when modulation and infrasound are in phase (0°) and in antiphase (180°), respectively. In both panels, error bars indicate the mean ± one standard deviation. Open symbols indicate single-listener data, filled symbols group mean data. Colored boxes in the bottom panel quantify the strength of the phase effect. Red boxes indicate a stronger masking for the in-phase condition and green boxes for the antiphase condition.

Modulation detection thresholds of experiment 3 (open circles in the top panel) varied largely between listeners, ranging between −20.3 dB and −5.9 dB. These inter-individual differences were considerably larger than the listeners' individual standard deviations ($\leq$2.4 dB). On average across all listeners, the modulation depth at threshold (filled circle in the top panel) was −11.2 dB (±4.0 dB). The individual modulation detection thresholds were in the range of those reported in the literature for low carrier levels [15–19].

The masking due to the presence of the infrasound (open triangles in the bottom panel) varied across listeners between −2.3 dB and 12.4 dB. A negative masking indicates that the infrasound facilitates the detection of the amplitude modulation. This was the case for three listeners (L2, L12, L18) for one of the two phases, but it was not the same phase for the three listeners. For all other listeners, the presence of the infrasound led to an increase in modulation detection threshold. The effect of the phase largely differed across listeners (colored boxes in the bottom panel). Note that the listeners were sorted and numbered based on this phase effect, i.e., listener L1 had the strongest phase effect

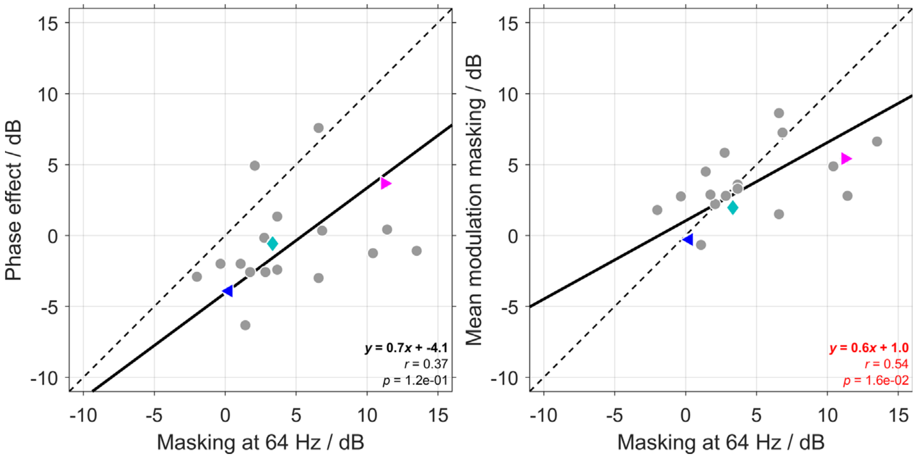

Figure 3. Scatter plots of the single-listener modulation masking data against amounts of masking at the carrier frequency of 64 Hz. The ordinate of the left panel refers to the phase effect, which is the difference in modulation depth at threshold between the two phase relations. The ordinate of the right panel refers to the amount of modulation masking averaged across the two phase relations. The example data of three listeners are highlighted with different symbols and colors: purple right-pointing triangle for L3, cyan diamond for L8, and blue left-pointing triangle for L18. The other data points are shown with gray dots. Superimposed on the scatter plot is a Deming regression line (black solid line; MATLAB implementation by [20]). The dashed line indicates the diagonal.

with a higher masking for the in-phase infrasound and L19 had the strongest phase effect in the opposite direction. The effect sizes for the different listeners vary continuously. Only for six listeners (L1 to L6), the masking was larger for the in-phase infrasound than for the antiphase infrasound (red boxes). For the other listeners, the opposite phase effect was observed (green boxes). A statistical analysis of individual effect sizes was not feasible.

On average across all listeners, the masking of the modulation (filled triangles on the bottom panel) was 3.2 dB (±4.7 dB) for 0° and 3.9 dB (±4.3 dB) for 180°. Both amounts of modulation masking were significant (two-sided paired-sample *t*-tests; for 0° versus Ref: $p < 0.001$; for 180° versus Ref: $p < 0.001$). Thus, the infrasound significantly impaired the detection of amplitude modulation imposed on a low audio-frequency carrier, irrespective of the phase relation.

The average phase effect, quantified as the difference in average modulation depth at threshold between 0° and 180°, was only 0.7 dB and did not reach significance (two-sided paired-sample *t*-test, $p \approx 0.389$). The correlation between the modulation detection thresholds in the reference condition and the magnitude of the phase effect, i.e., the difference between the in-phase masking and anti-phasic masking, did also not reach significance ($r = -0.14$ and $p \approx 0.581$).

3.3 Relation between detection and modulation

One could surmise that the individual effects of the infrasound sinusoid on the modulation detection (colored boxes in the bottom panel of Fig. 2) were related to the effect of masking on the detection of the carrier (colored boxes in the bottom panel of Fig. 1). For example, listener L3, for whom an in-phase infrasound induced a larger amount of modulation masking than anti-phase infrasound, had a comparably large amount of masking at 64 Hz; listener L8, for whom the two phase relations induced similar amounts of modulation masking, had a smaller amount of masking at 64 Hz; and listener L18, for whom an anti-phase infrasound induced a larger amount of modulation masking than an in-phase infrasound, had an even smaller amount of masking at 64 Hz.

To examine the relations more closely, the modulation masking data were compared to the masking of the 64 Hz pure tone. The results are summarized in Figure 3 as scatter plots. The data points of the three listeners discussed in detail in the previous paragraph are highlighted using colored triangles and diamonds. The other data points are shown with gray dots. In addition to the data points, Deming regression lines are shown as black solid lines. The Deming regression differs from the simple linear regression in that it accounts for errors in observations on both the abscissa and the ordinate (MATLAB implementation by [20]).

The ordinate of the left panel, which is labelled "Phase effect/dB", refers to the difference in modulation depth at threshold between 0° and 180°. The phase effect weakly correlated with the masking at 64 Hz, but the correlation did not reach significance ($r = 0.37$ and $p \approx 0.123$). The ordinate of the right panel, which is labelled "Mean modulation masking/dB", refers to the modulation masking averaged across the two phase relations. The mean modulation masking correlated moderately and significantly with the masking at 64 Hz ($r = 0.54$ and $p < 0.016$).

The analysis shows that the amount of modulation masking was generally related to the amount of masking at the carrier frequency; but the data do not allow 1) to infer from the amount of masking at 64 Hz the amount of modulation masking and vice versa and 2) to predict from a listener's amount of masking at 64 Hz the phase effect of this listener.

4. Discussion

4.1 Detection thresholds

The first objective of the present study was to test whether the presence of an infrasound sinusoid would mask the detection of a low-frequency pure tone. The group data show that the 64 Hz pure tone was masked by 4.6 dB when an 8 Hz sinusoid at an SL of 9 dB was presented simultaneously.

Masking of low-frequency audio sounds by infrasound was already reported by Jurado et al. [21], who measured psychoacoustic tuning curves for low-frequency sinusoidal targets. They showed that an 18.9 Hz sinusoid masks a 31.5 Hz target presented at an SL of 15 dB, when the masker SPL is high enough. For their four listeners, this masker SPL ranged from about 98–105 dB.

Using a notched-noise method, Jurado and Moore [22] estimated the filter characteristics of low-frequency targets, including 63 Hz, which is close to the 64 Hz used in the present study. Their Figure 6 shows the derived auditory filter shapes (dashed lines) and the combination of auditory filter and middle-ear filter (solid lines). For a target frequency of 63 Hz, they obtained an auditory filter that attenuates frequencies below 20 Hz by about 25 dB (bottom panel of Fig. 6 in [22]). Combined with the middle-ear filter, the attenuation continues to increase towards lower frequencies. Extrapolating their derived combined filter to a frequency as low as 8 Hz, an attenuation due to the auditory filter of slightly more than 50 dB is predicted for this masker frequency. Note that this is even less than the difference in thresholds in quiet between the 8 Hz target and the 64 Hz target, which was 60 dB in the present study. Based on these considerations, an 8 Hz sinusoid, which is presented at an SL of 9 dB, should mask the 64 Hz target.

For the following considerations, it is assumed that the 8 Hz sinusoid would be processed in the auditory filter with the lowest center frequency. For simplicity, it is further assumed that the lowest auditory filter is centered at 64 Hz, i.e., also the 64 Hz pure tone is processed in this filter. Under this assumption, the SL of the 8 Hz sinusoid, which was chosen to be 9 dB in experiment 2, is equivalent to the excitation level in this filter. The SL of the 64 Hz target at threshold was measured to be 4.6 dB. Since the intensities of the 8 Hz and the 64 Hz signals add, the total level in this lowest auditory filter at threshold is 10.3 dB, i.e., 1.3 dB higher than the level without the 64 Hz target. This is in good agreement with the level-discrimination threshold shown by Jesteadt et al. [23] for sinusoids with frequencies in the range from 200 Hz to 8 kHz at this low baseline level of 9 dB. This similarity to the level-discrimination threshold supports the hypothesis that the infrasound and the audio-frequency sound of the present study are processed in the same auditory filter and that the threshold is determined by the minimum level increase in the filter that is required for detection.

The results of the present study differ from the findings by Burke et al. [7]. In their study, the presence of a suprathreshold infrasound did not cause any significant change in detection threshold for sounds in the audio-frequency range. The discrepancy between their findings and the findings of the present study may be due to the design of the stimuli, at least for the 5 Hz masker. All stimuli in the present study were equally long (1500 ms, including two ramps of 250 ms each). The stimuli used by Burke and colleagues did not only have different ramp durations (200 ms for 100 Hz, 250 ms for 12 Hz, and 600 ms for 5 Hz), but for detection of 5 Hz in quiet, the total duration of the sinusoid was twice as long (2000 ms) as the total duration of all other sinusoids (1000 ms). Due to the different durations, the SL of the 5 Hz sinusoid that was used to mask a pure tone in the audio-frequency range was presumably lower than the intended SL. Using the model of temporal integration of infrasound presented by Friedrich et al. [24, 25], the level difference between the 2000 ms and the 1000 ms long 5 Hz sinusoid is estimated to be around 3.7 dB. Thus, it is possible that the maximum SL of the 5 Hz masker was not 5 dB, as intended by the authors, but only 1.4 dB. It is possible that the 5 Hz sinusoid would have masked the audio-frequency sound if a higher level of the infrasound had been used. However, this argument based on duration cannot explain why also the 12 Hz infrasound presented at an SL of 10 dB did not mask the 100 Hz pure tone. The main reason for not obtaining a masking in [7] is presumably the higher target frequency, which is likely to be processed with a center frequency equal to or at least close to the signal frequency of 100 Hz, i.e., not in the lowest auditory filter. For simplicity, it is again assumed that a 12 Hz target is detected in the auditory filter centered at 64 Hz, i.e., the excitation level of a 12 Hz sinusoid presented at an SL of 10 dB is 10 dB in this auditory filter. The attenuation at 12 Hz by the auditory filter centered at 100 Hz can, according to Jurado and Moore [22] (see their Fig. 6), be assumed to be about 10 dB higher than that of the 64 Hz auditory filter. Thus, the auditory filter centered at 100 Hz is excited by the 12 Hz sinusoid at 10 dB SL with a level of about 0 dB, i.e., should hardly affect the detection of the 100 Hz target in this auditory filter.

Noticeably, Burke et al. [7] found a significant masking in the opposite direction: A 100 Hz pure tone with an SL of 50 dB caused a significant increase in detection threshold of the infrasound target with a frequency of 12 Hz (by 10 dB). In the present study, the masking of an 8 Hz sinusoid by a 64 Hz pure tone was not determined because the focus of the present study was to examine the impact of infrasound on the perception of low-frequency audio sound. Still, assuming that infrasound and low-frequency audio sound are processed in the same filter and that detection is based on changes in level in this filter, the 25 dB 64 Hz pure tone should have masked the 8 Hz target.

4.2 Modulation detection thresholds

The second objective of the present study was to investigate how the presence of an infrasound sinusoid affects the detection of an amplitude modulation by a modulator with the same frequency as the infrasound that was imposed on a

Table 1. Thresholds (Thr.) and modulation (Mod.) depth at threshold of a second measurement day (experiments 1, 4, and 3 in this order) at a different day, taken from Friedrich et al. [30]. Four listeners participated: L2, L3, L10, and L18 (labeled L4, L1, L2, and L3 in the original publication). Measurement values in decibel are given as mean ± one standard deviation and differences from the results of the first measurement day are indicated in brackets.

	L2	L3	L10	L18
Repeated after (in days)	45	51	45	3
Thr. for 8 Hz in quiet (in dB)	104.8 ± 0.8 (+3.0)	104.2 ± 0.3 (+1.6)	102.1 ± 0.7 (+5.2)	103.5 ± 0.7 (+0.5)
Thr. for 64 Hz in quiet (in dB)	34.1 ± 1.7 (+3.7)	43.6 ± 0.7 (+1.4)	39.6 ± 1.3 (+4.2)	42.6 ± 1.7 (−0.7)
Mod. depth for Ref. (in dB)	−12.5 ± 1.0 (+0.6)	−13.9 ± 1.4 (−0.5)	−13.1 ± 1.0 (−7.2)	−7.9 ± 0.5 (−1.5)
Mod. depth for 0° (in dB)	−2.3 ± 0.7 (−2.2)	−13.9 ± 0.9 (+0.8)	−7.5 ± 0.9 (−0.4)	−4.1 ± 1.4 (+0.4)
Mod. depth for 180° (in dB)	−3.1 ± 2.4 (−1.7)	−7.5 ± 1.7 (+0.7)	−12.8 ± 1.4 (−2.7)	−4.6 ± 2.1 (+1.1)

low-frequency pure tone. The group data of the present study show that the presence of an 8 Hz sinusoid at an SL of 9 dB led to an increase by more than 3.2 dB in modulation depth at threshold of an 8 Hz modulation imposed on a 64 Hz sinusoidal carrier, presented at an SL of 25 dB. Thus, infrasound interferes with the processing of amplitude modulation in the low audio-frequency range. This supports the hypothesis that infrasound may indeed be perceived as amplitude modulation, as suggested by the data of Scholz et al. [26], Bian and Scherrer [27], and Marquardt and Jurado [9].

Following this line of argument, the phase relation between amplitude modulation and infrasound should play a role in modulation detection. On the basis of this hypothesis, a 180° out-of-phase addition should decrease the modulation depth, making the modulation less audible, i.e., increasing the modulation depth at threshold. In contrast, an in-phase addition should decrease the modulation depth at threshold. A similar effect was, e.g., found by Verhey et al. [28] for the interaction of a higher-order envelope (i.e., the venelope [29]) and the (first-order) modulation. The present study tested the phase relations of 0° and 180°. Large individual differences with respect to the phase effect were observed. On average across all listeners, however, the masking was the same for the two phases.

For a companion investigation with four listeners of the present study, experiments 1, 4, and 3 were repeated (in this order and with the same stimuli) up to 51 days after the original experiment. The results of the repeated measurements, reproduced from Friedrich et al. [30], are summarized in Table 1. The results indicate that 1) the listeners' three individual thresholds per condition are consistent within a measurement day, 2) single-listener thresholds can generally be reproduced on another measurement day, and 3) individual phase effects are reproducible in magnitude and direction. This suggests that the individual phase effects, observed in the companion investigation as well as in the present study, are unlikely to have arisen by chance.

Phase effects for a comparable stimulus in the audio-frequency range were reported by Schlittenlacher et al. [31]. They showed that a 50 Hz sinusoid increased the amplitude modulation detection thresholds of a modulated 3 kHz carrier for modulation frequencies in the range from 20 Hz to 100 Hz. For the modulation frequency of 50 Hz, also different phase relations between the low-frequency sinusoid and the modulator were tested. On average across all of their twenty normal-hearing listeners, the low-frequency pure tone increased the modulation detection threshold. A maximum was found for 270° and a minimum for 90°. The average difference was 10 dB. The difference between the phase relations of 0° and 180° was only about 2 dB. Since their inter-individual standard error was about 1 dB, this difference is presumably not significant. This would agree with the present study for the interaction between infrasound and amplitude-modulation detection in the low audio-frequency range. Unfortunately, Schlittenlacher et al. [31] did not show individual data. It is therefore not possible to decide if the phase relation that induced the maximal effect varies between listeners.

The study of Schlittenlacher et al. [31] can be considered as a follow-up study of Wakefield and Viemeister [32], who examined the interaction between a low-frequency tonal component and a high-frequency band-limited noise, modulated at the frequency of the tone. For 400 Hz presented at an SPL of 90 dB, they showed individual phase effects for their five listeners (their Fig. 3) for three carrier levels. For a carrier level comparable to the SL of 25 dB used in the present study, two listeners had the highest threshold for a phase relation of 270° and one at 180°. The other two listeners were not able to detect the modulation for all of the phases that were tested. For one listener, this was the case for 270° and 315°, for another listener this was the case for 45° and 90°. Their study show that the phase effect largely varies across listeners. This agrees with the data of the present study. Based on this comparison, it is likely that stronger individual phase effects would have been observed if more phase relations had been used, because the chosen phase relations may not have led to the maximum effect.

Individual differences in the effect of the phase relation were observed in experiments on modulation detection interference (MDI, Yost et al. [33]). For example, Yost and Sheft [34] measured, among others, the phase effect between target and interferer on MDI. For two of their three listeners, a slightly positive difference in MDI for an 8 Hz modulation between an in-phase and an antiphase interferer was found, whereas for the third listener a negative difference was measured, i.e., the opposite phase effect. The direction of the phase effect also depended on the modulation frequency, thus even for the same listener different phase effects were observed. They concluded that their data showed “a lack of a phase effect” on MDI. Moore and Shailer [35] found for their four listeners that the stimulus duration influences the phase effect. For a duration of 200 ms, no difference in MDI was found between the in-phase and the antiphase condition. For 1000 ms, the MDI was higher for the antiphase condition than for the in-phase condition. The authors noted that this finding contrasted to results of Moore et al. [36], who reported no phase effect. Note that, in these studies, usually only a very limited number of listeners participated in the experiments, which may explain the variability in the results. In general, irrespective of the phase relation, the modulated interferer leads to an increase in modulation threshold. This aspect of the MDI data is comparable to the group data of our experiment, where a similar masking was obtained in the modulation experiment due to the presence of the infrasound.

Overall, the comparison to the data where a low-frequency tone masks modulation of a high-frequency carrier and to the MDI data both seem to be largely consistent with what is found in the present study of an infrasound masking the modulation of a low-frequency carrier. It is likely that the two effects that are reported in the literature for the audio-frequency range are based on different mechanisms: One is based on across-frequency modulation processing (MDI), whereas the other is based on the interaction of audio-frequencies with modulations. It remains to be seen which of the two mechanisms, if any, is responsible for the interaction of infrasound with amplitude modulation in the audio-frequency range.

Further evidence of an interaction between infrasound and amplitude modulation in the audio-frequency range was recently provided by Zajamsek et al. [37]. They used sound samples from a wind farm that contained a 46 Hz tone amplitude modulated at 0.8 Hz with modulation depths between −4.5 dB and −18.8 dB (when expressed as $20 \cdot \log_{10}(m)$ dB). They found a small but significant effect of infrasound at 0.8 Hz on the probability to detect the amplitude modulation at this frequency. This is in qualitative agreement with the present study, in which a different modulation frequency and rather artificial sounds were used – sounds which are however easier to control and manipulate with respect to amplitude modulations.

5 Summary and conclusion

Detection thresholds of a low-frequency stimulus (64 Hz) were masked by an infrasound sinusoid (8 Hz; SL: 9 dB). The increase in threshold was, on average across 19 listeners, 4.6 dB.

Modulation detection thresholds of a low-frequency stimulus (64 Hz; SL: 25 dB) were masked by an infrasound sinusoid (8 Hz; SL: 9 dB) that was presented either in phase (0°) or in antiphase (180°) with respect to the modulator. The increases in threshold were, on average across 19 listeners, 3.2 dB for 0° and 3.9 dB for 180°.

The difference in average modulation detection threshold between 0° and 180° did not reach significance. Hence, the group data did not exhibit an effect of the phase relation on the modulation detection.

In contrast to the group data, the single-listener data revealed individual effects of the phase relation, with some listeners having a stronger effect for the in-phase infrasound than for the antiphase infrasound, others showed the opposite effect and yet others about the same masking for both phase relations.

The data indicate that supra-threshold infrasound may affect the perception in the low audio-frequency range.

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Data availability statement

The research data are available on request from the authors.

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