DOI: 10.61782/fa.2025.0582

MODELLING THE INTERACTION OF INFRASOUND AND LOW-FREQUENCY SOUNDS

Jesko L. Verhey[1*] **Björn Friedrich**[1]
[1] Department of Experimental Audiology, Otto von Guericke University Magdeburg, Leipziger Str. 44, 39120 Magdeburg, Germany

ABSTRACT

Recently, we showed that a sinusoidal infrasound affects the perception of low-frequency sounds in the audio-frequency range (cf. [1]). Masking of a 64 Hz pure tone due to the presence of a supra-threshold 8 Hz infrasound was observed as well as masking of temporal amplitude modulation (AM) of a 64 Hz carrier with a modulation frequency of 8 Hz. This study investigates to what extend these masking effects can be explained on the basis of the filter characteristics of the peripheral auditory system. A special focus will be on the effect of the relative phase between the amplitude modulation and the infrasound on the strength of masking. It will also be investigated, if individual differences can be explained by variations of the filter characteristics.

Keywords: *infrasound, low-frequency sound, amplitude modulation, masking modelling.*

1. INTRODUCTION

Infrasounds are commonly defined as sounds with a frequency spectrum within the range of 1 Hz to 20 Hz (ISO 7196:1995, [2]; ANSI/ASA S1.1:2013, [3]). The audio-frequency range is commonly defined as the frequency range between 20 Hz and 20 kHz [2]. Interestingly, according to [3], "audio frequencies roughly range from 15 Hz to 20 kHz", i.e., the infrasound-frequency range and audio-frequency range overlap in this standard. Several studies showed that even lower frequencies down to 1.5 Hz are perceived by the hearing system, if the infrasound level is high enough (e.g., [4]). Fundamental aspects of auditory processing in the audio-frequency range seem to be observed in infrasound perception through the ear as well, such as spectral [5] and temporal integration [6].

Although there is evidence that infrasound is processed by the auditory system, it is still not fully understood how infrasound is perceived. One hypothesis is that the non-linear processing within the ear generates distortion products that contribute to the perception of infrasound [7]. Joost et al. (2021, [8]) tested this hypothesis by measuring distortions in the ear canal with a low-distortion sound reproduction system. Although distortion products were detected in all listeners for at least one of the tested signal frequencies, their levels were considerably lower (> 10 dB) than the reference threshold levels for the distortion-product frequencies. In addition, the presence of distortions seems to be unrelated to the thresholds for the listener. Thus, their data argues against an infrasound perception through harmonic distortions.

An alternative hypothesis of auditory infrasound processing is that infrasound is perceived as amplitude modulation in the audio-frequency range. Zwicker [9] showed in a masking-pattern experiment that a sound with a very low frequency of 20 Hz modulates the perception of short higher-frequency tones and that this interaction depends on the phase of the low-frequency sounds. They interpreted their data in the light of basilar-membrane displacement due to the low-frequency sound. Although his study did only used a frequency equal to the maximum of the infrasound frequency range, it is likely that lower frequencies would yield similar results. Marquardt and Jurado [10] provided a direct support of the modulation hypothesis. They showed that listeners had difficulties to distinguish a 63 Hz carrier modulated

*Corresponding author: jesko.verhey@med.ovgu.de

at 8 Hz from a 63 Hz pure tone in the presence of a supra-threshold 8 Hz infrasound sinusoid.

Motivated by [10], Friedrich et al. [1] measured, among others, modulation depths at thresholds for a 64 Hz carrier in the presence of a supra-threshold sinusoidal infrasound masker. The infrasound frequency was equal to the modulation frequency (8 Hz). The infrasound was either in phase (0°) or out of phase (i.e., in antiphase, 180°) to the modulator. The sensation level of the infrasound was 9 dB and that of the carrier 24 dB. Nineteen listeners participated in the experiment. For the majority of listeners, the phase relation between infrasound and modulation affected the modulation depth at threshold. The effect could be as large as 8 dB. Some listeners had lower modulation depth at threshold in the in-phase condition, others in the antiphase condition. On average across all nineteen listeners, the effect was smaller than one decibel and not significant. Friedrich et al. [11] showed in four listeners, that the phase effect is quite robust, i.e., essentially the same effect was obtained when re-measured ten months later. In a following-up study, Friedrich et al. [12] measured in two listeners the effect of the relative phase between infrasound and modulation for phases 0°, 45°, 90°, 135°, 180°, 225°, 270°, and 315. The study showed individual data of the two listeners. They had opposite phase effects when only the phases 0° and 180° were measured. The data indicate that the extreme values for the modulation depth at threshold for those two listeners were not at 0° and 180°. On average across the two listeners, the minimum threshold for modulation was obtained at 90° and the maximum at 270°.

The aim of the present study is to model the interaction between infrasound and low-frequency audible sound by considering basic mechanisms of auditory processing. A special focus will be on the above mentioned phase effect in the interaction between infrasound and amplitude modulation of a low-frequency carrier in the audio-frequency range.

2. MODEL APPROACH

A common approach to model the frequency–place transformation at the level of the basilar membrane is to analyse the incoming sound with a band of overlapping auditory (band-pass) filters [13]. The approach in the present study is that the masking infrasound and the low-frequency signal in the audio-frequency range interact in the auditory filter with the largest excitation due to the (masked) audio sound. This is a common assumption of the power-spectrum model [14].

Jurado et al. [15] showed that there is a lower limit with respect to the centre frequency of the auditory filters. They measured psychoacoustical tuning curves for signal frequencies 31.5 Hz, 40 Hz, 50 Hz, 63 Hz, and 80 Hz. Their data indicate that the minimum centre frequency for the auditory filter is around 50 Hz to 63 Hz.

Using a notched noise paradigm, Jurado and Moore [16] measured an auditory-filter width of around 30 Hz for a centre frequency of 63 Hz. This is close to the *ERB* predicted by the following Eqn. 1:

$$ERB(f_C)=24.7+0.108 \cdot f_C \qquad (1)$$

with f_C as the centre frequency of the auditory filter in Hertz.

Overall, the data of [16] and Jurado et al. (2011) indicate that an auditory filter centred at the carrier frequency of Friedrich et al. [1] exists and that this filter has a bandwidth of roughly one *ERB*. For the simulations of the present study, a gammatone filter is used with the following Eqn. 2 as an impulse response:

$$g(t)=a \cdot t^{n-1} \cdot exp(-2\pi b\ ERB(f_C)) \cdot cos(2\pi f_C\ t+\varphi) \qquad (2)$$

with a and b as scaling parameters, φ as the starting phase, and n as the order of the filter (e.g., [13]). Note that this auditory filter is symmetric on a linear frequency scale, whereas the data in Jurado and Moore (2010) indicate a slight asymmetry, which is, for simplicity, not considered in the present study.

The auditory-filter width is not exactly the same for all listeners (e.g., [17]). This is especially the case for hearing impaired listeners but is also found, to a lesser extent, for normal hearing listeners. For example, Bharadway et al. [18] derived an auditory-filter width from their notched noise data in a forward-masking paradigm They reported psychoacoustic frequency tuning of their 26 listeners with an average auditory-filter width of 249 Hz and a standard error of 24 Hz for a signal frequency of 4 kHz.

The present study accounts for the above-mentioned inter-individual variability by simulating auditory processing with several values of b in Eqn. 1. In addition, it is investigated, if the shape but not the auditory filter width is changed by using a different filter order (3 instead of 4). An order of 3 was, e.g., used in Breebaart et al. [19].

Prior to the auditory filtering at level of the cochlea, the incoming signal is filtered by the outer- and middle-ear. For simplicity, it is assumed that this filter can be realised as a filter with a decrease of 24 dB per decade towards lower

frequencies in the whole range of frequencies considered here, i.e. below 100 Hz. This attenuation per decade is extrapolated from a figure of Zwislocki, redrawn on https://entokey.com/anatomy-and-physiology-of-hearing/.
In the present study, the effect of outer and middle-ear filter is only realised as a frequency specific attenuation, i.e., it does not alter the phase of the signals. In addition, for simplicity, the attenuation at 64 Hz is set to 0 dB.

3. RESULTS AND DISCUSSION

Fig. 1 shows three examples of transfer functions of the simplified outer- and middle-ear filter (doted grey line), the auditory filter (thin dashed line) and the combined filter (thick solid line). The value for b was 0.8, 1, and 1.25 for the bottom, middle, and top panel, respectively. Note that the combined filter has a steeper slope on the low-frequency side than on the high frequency side. This agrees qualitatively with the derived filters shown in [16]. Due to the outer- and middle-ear filter, the 8 Hz signal is attenuated by 21.7 dB. The total attenuation depends on b. It is 57.1 dB, 49.9 dB, and 40.8 dB for b equal to 0.8, 1, and 1.25, respectively.

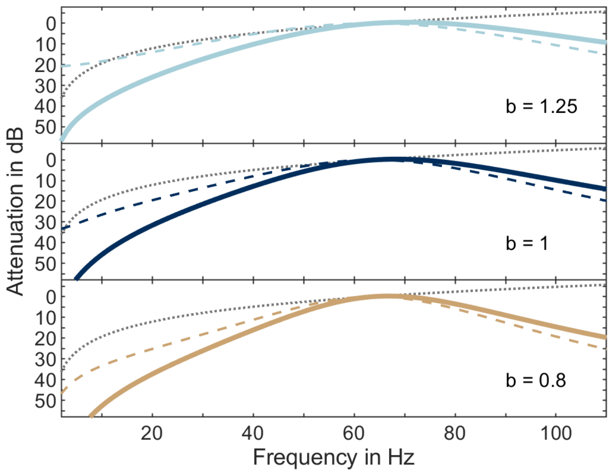

Figure 1. Transfer functions of outer- and middle-ear filter (doted grey line), the auditory filter (thin dashed line) and the combined filter (thick solid line). Each panel shows a different version of the auditory filter (see running text for details).

Fig. 2 shows the filtered version of 8 Hz infrasound (solid grey line) and of the amplitude-modulated tone with a carrier frequency of 64 Hz. In addition, the envelope of the latter signal is shown with a thin dotted line. In each panel, a different auditory filter is used (for the transfer functions of the corresponding filters, see Fig. 1).

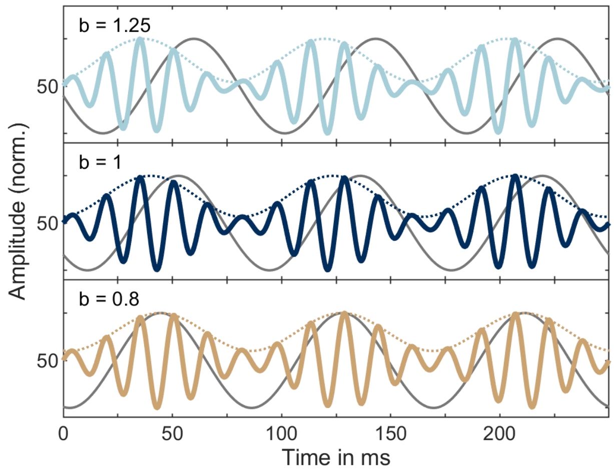

Figure 2. Time signals after filtering with the combined filters shown in Fig. 1 with solid lines. The solid grey line is the filtered 8 Hz signal with an initial phase difference of 0°, the thick solid line the filtered amplitude modulated 64 Hz tone and the dotted line the Hilbert envelope of the latter signal. All signal are normalised to an amplitude of one.

The filtering changes the phase relation between the in-phase 8 Hz signal and amplitude modulation. For $b = 8$, modulation and infrasound are still in phase (difference less than 1°). For the standard one *ERB* wide filter (b = 1), the two signals are 37° out of phase, and for the b = 1.25, the phase difference is 67°. If for the largest b also the filter order n is changed to 3, then the phase difference between the filterer signals amounts to 97 degrees (not shown).
On average across the listeners, the 8 Hz signal [1] had a sound pressure level of about 114 dB. When attenuated with the intermediate filter shown in Fig. 1, it has a level of 65 dB. This level is not much lower than the average level of the low-frequency carrier which was about 71 dB. It is likely that the modulation and the infrasound interact changing the task of modulation detection to one of modulation discrimination. This explains the increase in modulation depth at threshold in the presence of the infrasound in most listeners, irrespective of the phase relation between infrasound and amplitude modulation.
Two listeners in [1] showed a decrease in threshold for one phase relation. Such an unmasking can also be explained by assuming that the modulation due to the infrasound is

subthreshold and enhances the low-frequency carrier in such a way that it is audible at a lower modulation depth.

4. ACKNOWLEDGMENTS

This study was supported by the Deutsche Forschungsgemeinschaft (Projects "Infrasound and its relevance for audible sound" [FE 1192/3-2|VE 373/4-2] and "Binaural infrasound perception" [project number 513548136]).

5. REFERENCES

[1] B. Friedrich, H. Joost, T. Fedtke, J. L. Verhey: "Effects of infrasound on the perception of a low-frequency sound," *Acta Acustica*, vol. 7, no. 60, pp. 1–8, 2023.

[2] ISO 7196:1995 "Acoustics — Frequency-weighting characteristic for infrasound measurements," International Organization for Standardization, Geneva, 1995.

[3] ANSI/ASA S1.1-2013 "Acoustic terminology," Standard Secretariat, Acoustical Society of America, 35 Pinelawn road, Suite 114E, Melville, NY 11747-3177, 2013.

[4] G. Leventhall: "What is infrasound?," *Progess in Biophysics & Molecular Biology*, vol. 93, pp. 130–137, 2007.

[5] B. Friedrich, H. Joost, T. Fedtke, J. L. Verhey: "Spectral integration of infrasound at threshold," *The Journal of the Acoustical Society of America*, vol. 147, pp. EL259–EL263, 2020.

[6] B. Friedrich, H. Joost, T. Fedtke, J. L. Verhey: "Temporal integration of infrasound at threshold," *PLoS One*, vol. 18, no. 7, pp. e0289216, 2023.

[7] G. Békésy: "Über die Hörschwelle und Fühlgrenze langsamer sinusförmiger Luftdruckschwankungen,“ *Annalen der Physik*, vol. 26, pp. 554–566. 1936.

[8] H. Joost, B. Friedrich, J. L. Verhey, T. Fedtke: "Is infrasound perceived by the auditory system through distortions?" *Acta Acustica*, vol. 5, no. 4, pp. 1–10, 2021.

[9] E. Zwicker: "Masking-period patterns produced by very-low-frequency maskers and their possible relation to basilar-membrane displacement," *The Journal of the Acoustical Society of America*, vol. 61, pp. 1031–1040, 1977.

[10] T. Marquardt, C. Jurado: "Amplitude modulation may be confused with infrasound," *Acta Acustica united with Acustica*, vol. 104, pp. 825–829, 2018.

[11] B. Friedrich, H. Joost, T. Fedtke, J. L. Verhey: "Einfluss des Infraschalls auf die Wahrnehmung von Amplitudenmodulationen im Hörfrequenzbereich," in *Proc. of the DAGA 2023*, (Hamburg, Germany) pp. 1171–1172, 2023.

[12] B. Friedrich, H. Joost, T. Fedtke, J. L. Verhey: "Einfluss der relative Anfangsphase auf die Verdeckung eines amplitudenmodulierten tieffrequenten Tons durch einen tonalen Infraschall," in *Proc. of the DAGA 2024*, (Hannover, Germany), pp. 1263–1265, 2024.

[13] T. Irino and R. D. Patterson, "A time-domain, level-dependent auditory filter: the gammachirp," *The Journal of the Acoustical. Society of America*, vol. 101, no. 1, pp. 412–419, 1997.

[14] H. Fletcher: "Auditory patterns,'' *Review of Modern Physics* 12, pp. 47–65, 1940.

[15] C. Jurado, C. S. Pedersen, B. C. J. Moore: "Psychophysical tuning curves for frequencies below 100 Hz," *The Journal of the Acoustical Society of America*, vol. 129, pp. 3166–3180, 2011.

[16] C. Jurado, B. C. J. Moore: "Frequency selectivity for frequencies below 100 Hz: Comparisons with mid-frequencies," *The Journal of the Acoustical Society of America*, vol. 128, pp. 3585–3596, 2010.

[17] M. Nitschmann, J. L. Verhey, B. Kollmeier: "Monaural and binaural frequency selectivity in hearing-impaired subjects", *International Journal of Audiology* 49, pp. 357–367, 2010.

[18] H. M. Bharadwaj, S. Masud, G. Mehraei, S. Verhulst, B. G. Shinn-Cunningham: Individual Differences Reveal Correlates of Hidden Hearing Deficits," *The Journal of Neuroscience*, vol. 35, pp. 2161–2172, 2015.

[19] J. Breebaart, S. van de Par, S., A. Kohlrausch: "Binaural processing model based on contralateral inhibition. I. Model structure," *The Journal of the Acoustical Society of America*, vol. 110, no. 2, pp. 1074–1088, 2001.