ACTA ACUSTICA UNITED WITH ACUSTICA
Vol. 104 (2018) 825 – 829

DOI 10.3813/AAA.919232

Amplitude Modulation May Be Confused with Infrasound

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Summary
Environmental infrasound is usually accompanied by low-frequency (LF) sounds. Considering that inner hair cell transduction equals half-wave rectification, activity of low-frequency auditory nerve fibres may be indistinguishable whether elicited by LF sound that is amplitude-modulated at an infrasonic rate, or LF sound that is superimposed onto infrasound that "biases" the basilar membrane position. We tested whether listeners are able to distinguish a 63-Hz carrier tone, amplitude modulated at 8 Hz, from a 63-Hz pure tone that was perceptually loudness-modulated by an 8-Hz biasing tone. Using a maximum-likelihood procedure, 12 participants first adjusted the intensity of the 8-Hz tone so that the perceived modulation of the pure tone matched a reference amplitude-modulated tone. Both stimuli types were then presented in random order, and participants had to identify presentations which contained the infrasound tone. About half the participants performed close to chance. The best had 81% correct. Experiments with a 125-Hz carrier tone gave similar results. Although performance may improve in a 2-interval discrimination task, this would not be representative of real listening conditions. Results suggest that slowly amplitude-modulated LF sounds may underlie complaints about environmental infrasound, where measured infrasound levels are well below sensation threshold.

PACS no. 43.66.-x

1. Introduction

Noise spectra assessed in response to complaints about environmental infrasound most often reveal that the sound pressures of spectral components in the infrasound range (< 20 Hz) are well below sensation threshold and therefore should be inaudible to human listeners (e.g. [1]). Commonly, such finding closes the complaint case. The measured spectra, however, often cross the auditory sensation threshold somewhere between 20 Hz and 100 Hz. These supra-threshold low-frequency noise components might have pronounced envelope fluctuations with spectral content well below 20 Hz, which might be easily mistaken as containing supra-threshold infrasound.

Using simple sinusoidal stimuli, we tested under laboratory conditions whether listeners can actually distinguish between stimuli mixes that contain true infrasound and stimuli that are amplitude-modulated (AM) at an infrasonic rate, i.e. do not actually contain frequency components below 20 Hz. This might well not be the case if one considers the similarity in auditory nerve (AN) output that these two stimuli produce. Figure 1 illustrates the two stimulus types under consideration. Because the inner hair cell releases neuro transmitter only during basilar membrane (BM) movement towards scala vestibuli, signals become effectively half-wave rectified. In order to illustrate this operation, the lower parts of the signals that are not coded by the AN are greyed out in the figure. Comparison of the remaining upper parts shows schematically that the spiking probabilities of the AN fibres in response to those two stimuli are almost identical.

Of course, this scenario is given only if the stimulus components are not spectrally resolved by the cochlea. This might easily be the case at its very apical end because the lowest auditory filters have relatively wide spectral tuning and more importantly, the lowest stimulus frequency that has a characteristic place on the human BM is assumed to be as high as 50 Hz (see reviewing remarks in [2, pages 51–52]), if not even 80 Hz [3]. In other words, all frequency components lower than this share the very apical end of the BM as their characteristic place (the place of maximum vibration amplitude). The condition illustrated in Figure 1 is therefore not unlikely, and our test results show that listeners have indeed great difficulty in distinguishing these two types of stimuli with carrier tones of 63 Hz and even 125 Hz.

Received 9 March 2018,
accepted 9 September 2018.

2. Methods

2.1. Instrumentation

The infrasound source used in this study is identical to that used by Kuehler *et al.* [4]: From a hermetically enclosed electrodynamic loudspeaker, an 8-Hz biasing tone was transmitted via an 8-m long polyethylene tube to the listener's ear. (It was originally developed to be used in MEG and fMRI experiments.) For the last 40 cm, the 14 mm inner diameter of this tube was reduced via a coupling into a more flexible tube with 2.5 mm inner diameter that took at its end an audiometric ear tip (ER3-14A, Etymotic Research) that was hermetically fitted in the listener's ear canal. Before, in-between and after all psychometric measurements, the fitting was tested by measuring the SPL in situ with a miniature microphone (Knowles FG-23453) that was coupled to the ear canal via a small plastic tube (20 mm length, 1 mm inner diameter) that penetrated the foam of the ear tip. It was calibrated in a 1.3-cm3 cavity using a Brüel & Kjær 4153 microphone. A second such plastic tube penetrated the ear tip foam to deliver the other sounds into the ear canal. These were produced by a small insert earphone (ER4B, Etymotic Research) that was directly driven by the line output of the audio device (RME Fireface UC). Using separate sound sources ensured that AM due to hardware non-linearities were < 1%. In contrast, the line output of the 8-Hz biasing tone was low-pass filtered (6 dB/octave, passive, fc = 10 Hz) before power amplification (BEAK Type BAA 120).

This filter, together with the acoustic low-pass filtering effect of the 8-m polyethylene tube and appropriate electric attenuation, made sure that at maximum electric output of the audio device, the sound pressure in the ear canal could not exceed 105 phon [5, 6].

2.2. Subjects

Ten female and four male normal-hearing subjects (18 to 49 years), without self-reported hearing abnormality, were recruited. Their auditory threshold for 8 Hz, 63 Hz and 125 Hz was tested using the standard audiometric procedure (but with 3-dB instead of 5-dB steps). None of the subjects had thresholds above 10 dB HL [5, 6]. However, one male and one female subject were unable to perform the psychometric procedure so that only 12 subjects completed the study.

2.3. Stimulus conditions

A total of eight reference AM stimuli were used, four with a carrier frequency of 63 Hz and four with 125 Hz. We predicted that the infrasound detection might be easier at larger sound pressure, and modified therefore two further parameters of the AM tone for which we expected the required biasing tone level (L_{RBT}) to vary to produce a matching perceived loudness modulation of the biased pure tone: the modulation depth of the AM tone (25% and 37.5%) and its sound pressure. All modulations were clearly audible. Since we expected a suppression in loudness due to biasing [7], the AM tones and pure tones to be biased were set to equal peak level. Levels corresponded to either 40 phon, or 50 phon of the pure tone (ISO 226). The phase of the amplitude modulation and that of the 8-Hz biasing tone was independent and random in each trial. The duration of all stimuli was 1200 ms, including 250 ms cosine ramps at onset and offset.

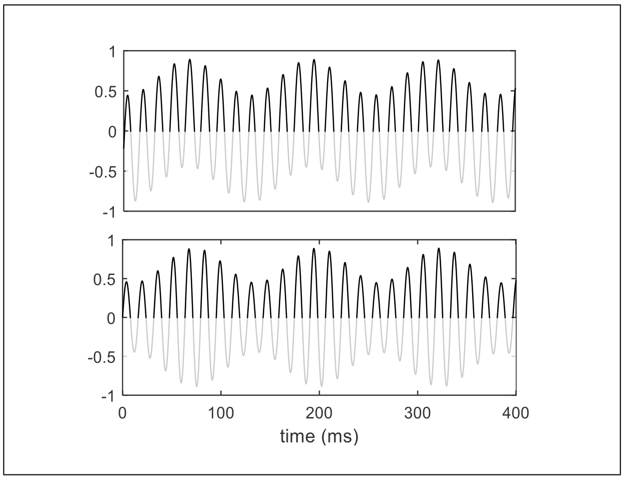


Figure 1. The two stimulus types considered in this study: a biased tone (upper panel) and an AM tone (lower panel). The half-wave rectified versions of the signals (only the upper parts) are almost indistinguishable.

2.4. Procedures

The measurement of each subject, including breaks, took up to three hours. It was done in the ear of their preference. Before the discrimination task could commence, L_{RBT} had to be determined for the eight AM reference stimuli. Initially, subjects made themselves familiar with the infrasound biasing tone and its effect on the pure tone in a simple L_{RBT} adjustment procedure (buttons "up" and "down"), starting from low levels. For all eight conditions, they were asked to set the biasing tone level so that the pure tone in the second interval was perceived with equal modulation as the leading reference AM tone. These served as individual starting levels for the subsequent, more accurate maximum-likelihood-tracking (MLT) procedure. Here, both kind of stimuli were presented in random order in two intervals. In a 2AFC task, the subjects were asked: "Which of the two intervals was stronger modulated?" The tracks of the eight conditions, each ending after sixteen trials, were interleaved in random order. For each condition, the average L_{RBT} of three repeats defined the individual's L_{RBT}, unless a value deviated by more than 4 dB from any other, in which case it was excluded from the average.

The L_{RBT} were then individually set for the final discrimination task, which was a 1-interval, yes-no procedure with the question: "Did this stimulus contain infrasound?" For each of the eight conditions, a total of 50 trials were presented, where half consisted of the AM tone and half of the corresponding biased tone (containing the infrasound at L_{RBT}). This gave a total of 400 trials, which were presented in random order. The variation in loudness and modulation depth across the eight stimulus conditions made the task less monotonous for the subjects. Before the actual test, the subjects had a training session with feedback, using a shorter series of 48 trials. No feedback was given during the formal test.

3. Results and discussion

Before looking at how well listeners were able to distinguish the AM stimuli from the stimuli that truly contained infrasound, let us first consider the infrasound levels that the listeners adjusted during the MLT procedure so that the perceived modulation of the biased tones matched that of the corresponding AM reference stimulus.

The mean data across subjects for all 8 stimuli conditions are shown in Figure 2.

According to the infrasound equal-loudness contours proposed by Møller and Pedersen [5], L_{RBT}s fell roughly in the range of 20–40 phon, and were therefore well above the 8-Hz perception threshold of most human listeners (approx. 100 dB SPL [4]). Although the levels across the eight conditions stayed for each individual typically within a range of 10 dB and resembled roughly the pattern of the mean data, the individual curves were quite offset from each other (For individual L_{RBT}, see the table below.)

As to expect, an increase in L_{RBT} is required to achieve an increased perceptual modulation that matches the increase of modulation depth from 25% to 37.5% in the reference AM stimuli. Apart from this offset, the two curves look rather similar across the remaining parameter variations. Similarly expected, the louder 50-phon probe tones require generally more intense infrasound tones than the softer 40-phon probe tones.

It has to be pointed out, however, that a simple linear superposition model, as illustrated in Figure 1, does not quantitatively account for these results: A 25% modulation depth in the half-wave rectified output signal would require a BM-biasing amplitude that is 25% of the probe tone BM response amplitude. Similarly, a 37.5% modulation depth would require a BM-biasing amplitude of 37.5% of the probe tone BM response amplitude. This theoretical 3.5-dB increase in L_{RBT} is not observed for the 40-phon data. The required increase in BM biasing amplitude would also just linearly scale up with probe tone amplitude if the perceived modulation could be simply explained by linear superposition of the two tones. In other words, the roughly 7-dB increase in probe tone level (from 40 to 50 phon) should then also require a roughly 7-dB increase in L_{RBT} in order to maintain the same amplitude modulation of the half-wave rectified output signal. However, this is only the case for the 63-Hz condition with 37.5% modulation depth, but was clearly lower in the other conditions. This brings us to the last, rather puzzling observation: We expected that the 125-Hz carrier tone requires a slightly higher biasing tone level than the lower 63-Hz carrier tone, because its excitation centroid being located at a more basal and stiffer BM location. However, this is only the case with 40-phon carrier tones.

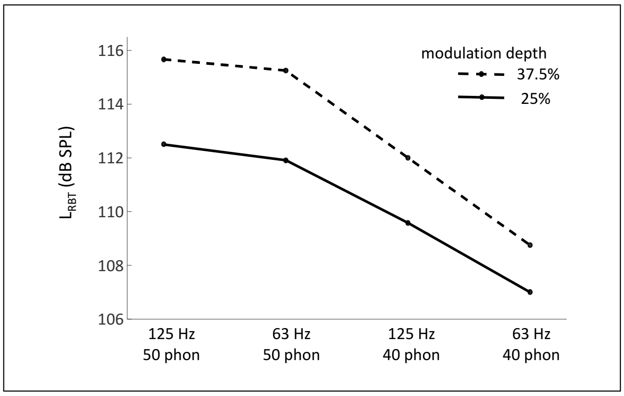


Figure 2. Average L_{RBT} across subjects.

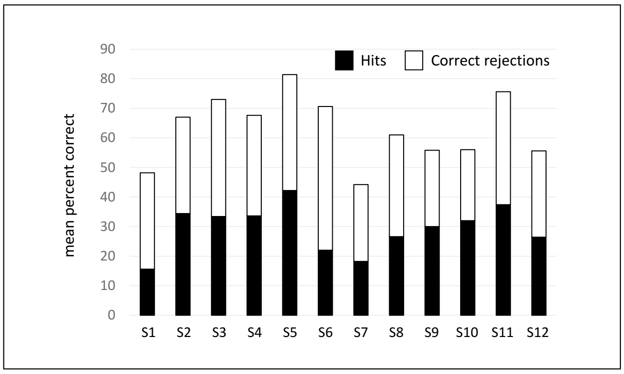
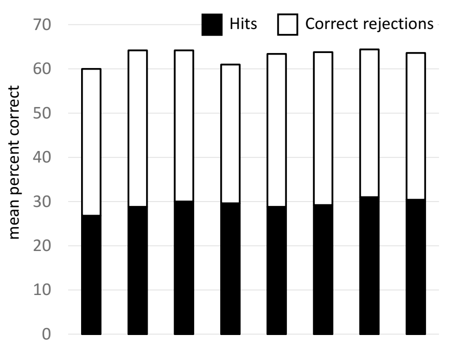


Figure 3. Average discrimination performance across all eight conditions for each of the 12 subjects. The length of each percent-correct bar is divided according to the contributions of hits and correct rejections to the total of the correct responses.

We therefore conclude that perceptual modulation of an LF tone during infrasound exposure cannot be simply explained by linear superposition of the two. We believe that large cochlear microphonic potentials, experimentally observed by Salt *et al.* [8] in guinea pigs, might cause an "electrical" biasing of the inner hair cell neurotransmitter release, leading to a modulation of the AN output. The involved electrical phenomena are likely very non-linear, and only a detailed model of these rather complex processes might have the potential to quantitatively explain the present results, as well as previously published data on modulation of the AN activity by low-frequency biasing tones (e.g. [9, 10, 11]).

Although the adjustment of biasing tone levels was a prerequisite to address the main question of this study, the data so far have not yet answered whether listeners can pick out the stimuli that contain the infrasound tone. Discrimination results per condition showed that the number of subjects scoring above 64% was always about half. Note that only scores above 64% have a chance of correctly guessing below 5% ($n = 50$). In other words, in each condition about half of subjects performed no better than chance. Taken the performance across all eight conditions (Figure 3), however, most subjects performed well above



Mod. depth (%)		37.5	37.5	37.5	37.5	25	25	25	25	
Level (phon)		50	50	40	40	50	50	40	40	
Frequency (Hz)		125	63	125	63	125	63	125	63	Avg.
S1	L_{RBT}	112	114	109	110	108	111	105	107	110
	N_{Hits}	8	4	12	5	7	8	11	7	8
	N_{CR}	15	18	15	18	15	14	18	18	16
S2	L_{RBT}	111	107	107	106	111	106	105	103	107
	N_{Hits}	13	18	17	19	18	16	17	20	17
	N_{CR}	17	17	19	15	12	20	14	17	16
S3	L_{RBT}	114	115	110	109	108	108	105	102	109
	N_{Hits}	13	16	16	16	17	15	19	21	17
	N_{CR}	20	18	20	20	23	19	20	18	20
S4	L_{RBT}	115	114	107	108	109	109	105	102	109
	N_{Hits}	18	13	14	18	17	17	22	15	17
	N_{CR}	18	18	15	14	18	21	18	14	17
S5	L_{RBT}	116	118	112	113	113	115	110	110	113
	N_{Hits}	19	23	20	22	19	22	21	23	21
	N_{CR}	21	19	18	17	20	21	21	19	20
S6	L_{RBT}	117	116	114	112	113	114	112	109	113
	N_{Hits}	14	9	14	9	9	12	12	9	11
	N_{CR}	24	25	25	24	25	25	24	23	24
S7	L_{RBT}	119	116	116	111	115	111	114	111	114
	N_{Hits}	6	9	9	13	12	9	8	7	9
	N_{CR}	13	16	17	8	11	14	10	15	13
S8	L_{RBT}	109	108	105	99	108	102	103	103	105
	N_{Hits}	12	16	13	12	10	12	17	15	13
	N_{CR}	13	19	18	20	21	15	15	17	17
S9	L_{RBT}	118	121	117	110	115	120	114	108	115
	N_{Hits}	14	17	15	13	14	17	14	16	15
	N_{CR}	14	15	12	8	15	12	17	10	13
S10	L_{RBT}	115	113	110	96	112	112	109	102	109
	N_{Hits}	14	16	18	16	15	17	15	17	16
	N_{CR}	10	13	12	9	15	13	9	15	12
S11	L_{RBT}	122	122	120	117	121	119	117	114	119
	N_{Hits}	18	20	17	19	18	18	19	20	19
	N_{CR}	17	18	20	22	17	20	20	19	19
S12	L_{RBT}	120	119	117	114	117	116	116	113	117
	N_{Hits}	12	12	15	15	17	12	11	12	13
	N_{CR}	17	16	14	13	15	13	14	14	15

Figure 4. The table header also labels the percent correct bars, which show the across-subject average score in each of the eight conditions. The length of each bar is divided proportional to the number of hits (N_{Hits}) and correct rejections (N_{CR}).

chance, since they scored in the average better than 55 % ($p < 0.05$ for $n = 400$). The best performance was that of listener 5, with an average of 81% correct responses across the eight conditions. He is one of the authors, and performed at this level similarly across all 8 conditions. In his best condition, he achieved 86% correct responses. But note that this does not necessarily mean that he detected the infrasound in 86% of the trials, as the percentage also includes correct guesses with a 50% chance. On the other end, subject 1 was amongst the worst performers, responding with 48% correct responses purely at chance. He is the other author and had also long experience in listening experiments with infrasound. In summary, it is fair to say that none of the listeners picked the stimuli containing the infrasound tone with great confidence.

Comparing the eight stimulus conditions, none of them appeared to be particularly hard or easy: As Figure 4 shows, the across-subject mean scores ranged between 60% and 64.3%. However, the pattern across the conditions was inconsistent amongst the listeners. In a 3-way ANOVA, neither modulation depth, carrier frequency, nor carrier level turned out to be a significant factor ($p = 0.58$, 0.97, 0.87 and $F = 0.31$, 0.0, 0.03, respectively). This was also the case when only considering the six best performing subjects. In other words, the easiest condition for one subject was one of the hardest conditions for another. Also surprising, there was no correlation of infrasound detectability with infrasound SPL when pooling all data ($R^2 = 0.00082$, $p > 0.05$). Individually, however, there were cases of significant positive as well as negative correlations, possibly reflecting different listening strategies.

4. Conclusion

It has been shown under laboratory conditions that a low-frequency tone that is 8-Hz amplitude-modulated is perceptually similar to a stimulus that contains a low-frequency tone and an 8-Hz infrasound tone. We speculate that other slowly amplitude-modulated low-frequency stimuli, which actually do not contain spectral content below 20 Hz, might also sound as they would contain infrasound. This finding may help to explain cases of annoyance attributed to infrasound, where measurements show audible low-frequency content, but with infrasound content well below sensation threshold. Nevertheless, given their perceptual similarity, LF sound that is slowly amplitude-modulated can still cause annoyance, similar to that attributed to true infrasound.

Acknowledgements

This study was supported by the European Metrology Programme for Innovation and Research (EMPIR, Grant No. 15HLT03 Ears II). EMPIR is jointly funded by the EMPIR participating countries within EURAMET and the European Union. We thank Jasdeep Benning for helping with the data collection.

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