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JASA LETTER TO THE EDITOR

Infrasound tones at sensation threshold level elicit measurable Frequency-Following responses (L)

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ABSTRACT:
Even barely detectable levels of infrasound are often reported to cause annoyance and complaints. We carefully measured the individual sensation threshold of a pure tone and recorded immediately after the brain's frequency-following response (FFR) at this intensity using the same stimulator. In contrast to 87-Hz tones, 8-Hz tones elicit an FFR already at sensation threshold. Control stimuli with trains of 1-kHz tone pips having the repetition rate of the infrasound tone frequency and sensation threshold intensities evoked no significant FFR. Thus, slow periodicity, causing synchronous activation of auditory nuclei, is not explaining the FFR to low-level infrasound alone.
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I. INTRODUCTION

Environmental noise containing spectral components in the infrasound range (i.e., below 20 Hz) are reported as being intrusive and continued exposure leads frequently to complains (Araújo Alves *et al.*, 2020; Leventhall, 2004). Surprisingly, when measurements are taken, their sound pressure levels are often barely above sensation, which requires relatively large sound pressure levels [e.g., Kuehler *et al.* (2015)]. Although infrasound does not give a tonal sensation (Jurado *et al.*, 2021), it has been established that infrasound is perceived by the auditory system [reviewed by Leventhall (2007)] and consequently activates the auditory cortex (Behler and Uppenkamp, 2020). Knowledge about the excitation of the peripheral auditory system by infrasound is summarized in Jurado *et al.* (2022).

In a previous study (Jurado and Marquardt, 2020), we noticed that steady 11-Hz tones presented at a sound pressure level close to hearing threshold often elicited a statistically significant frequency-following response (FFR).[1] If exclusively infrasound has the potency to evoke a brain response already near sensation threshold, this might hold an explanation why especially noise sources containing relatively low levels of infrasound can lead to adverse reactions.

In our previous study, we did not measure individual sensation thresholds, so we cannot say whether an FFR was indeed evoked at the individual's threshold. In our current study, we therefore carefully measured individual sensation threshold levels just before the FFR measurement, to evaluate whether at threshold levels infrasound tones do indeed evoke an FFR while audio frequency tones (here, 87 Hz) do not.

II. METHODS

Ten subjects (23–44 years, 3 females) participated in these experiments. They had normal hearing (<20 dB HL, 500–4000 Hz) and tympanometry (middle ear pressure within ±50 daPa). For each subject, measurements with stimulus frequencies of 8 Hz and 87 Hz were made, both on the same day (in random order). The 87-Hz stimulation was chosen because its FFR coincides with a peak in FFR fine structure (Tichko and Skoe, 2017) and is clearly in the human audio frequency range. Experiments were run inside an electromagnetically shielded and sound-isolated cabin (double-walled) at the Acoustics Laboratory of Universidad de Las Américas.

Prior to the FFR recording, the subject's sensation threshold for the stimulus used was measured using the same acoustic setup. A two-interval 2AFC 3-down 1-up adaptive procedure was applied [see Jurado *et al.* (2020) for details]. The duration of the 8-Hz stimuli was 3 s, including two raised-cosine ramps of three cycles. The 87-Hz stimuli had a duration of 1 s, including ramps of four cycles.

During the subsequent FFR recordings, stimuli were presented at threshold and at 40-phon.[2] The latter was to confirm the presence of an FFR at a clearly audible level. The recordings to 20-s presentations at threshold and 10-s presentations at 40-phon were interleaved. Each presentation was repeated 90 times, giving a total recording duration of 30 min and 15 min, respectively.

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For five of the ten participants, these measurements were repeated on a later day with trains of tone-pips that had repetition rates equal to the pure-tone frequencies, a carrier frequency of 1 kHz, and, for the threshold measurements, a duration of 1 s. Each tone burst was 3 cycles long, including two raised-cosine ramps of one cycle. These additional measurements were made to investigate whether any long periodicity would be sufficient to evoke an FFR at sensation threshold.

In a further series of measurements, two of these five subjects participated in additional recordings in response to infrasound pure tones and pip-trains at multiple sound pressure levels near threshold. The tones were presented at –5 dB SL and 0 dB SL, and the pip-trains were presented at 0 dB SL, +5 dB SL and +10 dB SL. Again, threshold (defining 0-dB SL) of the respective stimulus was determined just before the FFR recording with the levels of the 20-s presentations interleaved (90 repetitions each).

The 8- and 87-Hz pure tones were produced by a custom-made infrasound source with low-harmonics, similar to that used by Kuehler *et al.* (2015). It consisted of an 18-in. Kevlar-membrane subwoofer speaker (Sundown Audio, Newton, NC, USA), built into a wooden enclosure with its front tightly covered by a 2-cm thick acrylic plate. The source was placed outside the cabin to avoid electromagnetic inference. (This was verified by recordings with the acoustic pathway being plugged.) The stimulus was delivered to the inside of the cabin via an 11-m long tube (20 mm in diameter) that was connected to sections of thinner tubes, the last to be pierced through the ER10C-14A earplug of an ER10C probe (Etymotic Research, IL, USA). The probe contained a microphone used for *in situ* sound calibration and two loudspeakers, one of which produced the 1-kHz pip-trains. *In situ* calibrations were performed after each placement of the ER10C probe. The electrical signal was adjusted so that the intended sound pressure waveform in the subject's ear canal was produced. For further detail, see Jurado *et al.* (2022).

Audio stimuli were converted at 48 kHz by a Fireface-802 audio device (RME, Audio AG, Haimhausen, Germany). Its electrical output for the 1-kHz pip-trains drove the ER-10 °C speakers directly, but the pure-tone signals were amplified by a BEAK power amplifier (type BAA 120, Frankenblick, Germany). To protect the participants from overexposure, a combination of an attenuator and a passive low-pass filter ($f_c = 32$ Hz, 12 dB/octave) limited the maximum loudness level of tones at any frequency to be lower than 105 phon.

FFRs were recorded with an ActiChamp amplifier and its EP-preamp module (Brain Products, Germany) at 25-kHz

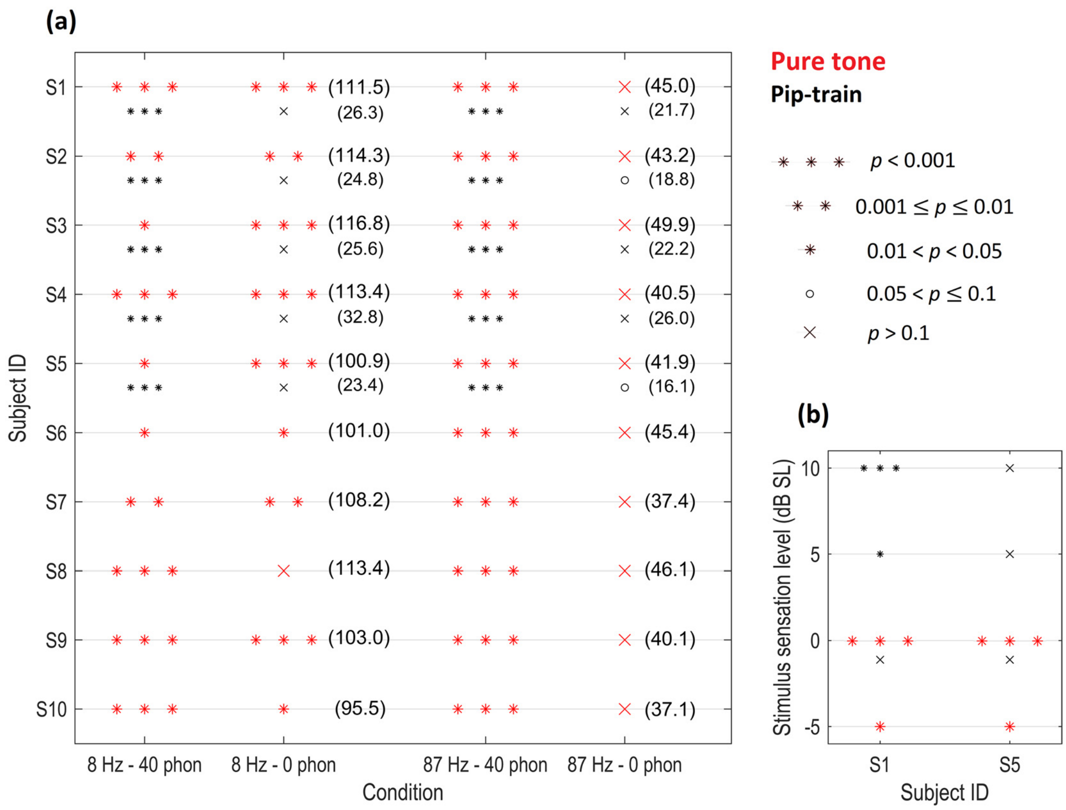

FIG. 1. (Color online) (A) Significance levels for FFRs obtained with 8- and 87-Hz pure tones (N = 10; larger red symbols on top) and pip-trains (N = 5, S1–5; smaller symbols underneath). Stimuli were presented at 40 phon and 0 dB SL. Individual sensation threshold levels are given in parenthesis in dB SPL. For S4, this significance level is based on the second harmonic, undoubtedly reflecting a response to the 40-phon pip-train ($p = 2.7 \times 10^{-16}$; the 8-Hz fundamental was not significant). (B) Significance levels for two subjects, who participated in an additional experiment in which the infrasound tone and the pip-train with infrasound repetition rate had multiple sound pressure levels near sensation threshold. Note that for S5, infrasound frequency and pip-train rate were 11 Hz (see footnote 3).

sampling rate. The subject watched a silent movie. A standard ABR configuration was used, with the vertex electrode referenced to the mastoid of the stimulated left ear and the ground electrode attached to the sternum. Together with the audio stimulus, synchronized trigger signals were generated by the Fireface-802 every second to extract and sort segments of one second duration from the filtered continuous EEG recording (0.5–200 Hz bandpass plus 60-Hz notch filter) using the Fieldtrip MATLAB toolbox (Oostenveld *et al.*, 2011). After being downsampled to 4096 Hz, individual's EEG spectra were computed from a weighted average (Hoke *et al.*, 1984), whereby segments containing the stimulus onsets were excluded. The significance of the relevant FFR spectral components was calculated by assessing their phase coherence across the individual spectra of the un-weighted segments [Rayleigh test, see Mardia and Jupp (2000)].

III. RESULTS

FFRs to all 40 phon stimuli were significant [$p < 0.05$; see Fig. 1(A)]. To our surprise, nine out of the ten subjects also had a significant FFR, evoked by an 8-Hz tone[3] at the individual's sensation threshold level. In contrast, a significant FFR was neither observed with the 87-Hz tone, nor with the 1-kHz pip-trains of 8-Hz or 87-Hz repetition rate at their threshold levels. The individual sensation threshold levels are listed in Fig. 1(A).

The two subjects that participated in additional low-SL measurements both had significant FFRs to infrasound tones even when presented at a sound pressure level 5 dB below their individual sensation threshold[4] [Fig. 1(B)]. One subject also had significant FFRs to pip-trains at +5 dB SL and +10 dB SL. Despite having shown a robust FFR to the 40-phon pip-train, the other subject had no response at these levels.

EEG spectra, averaged across all subjects, are shown in Fig. 2. At the loudness level of 40 phon, the average FFR magnitude for the 8-Hz tone was significantly larger than for 87 Hz (means: 50.1 dB and 39.7 dB re 1 nV, respectively; paired *t*-test: $T_8 = 5.10$, $p = 9.25 \times 10^{-4}$). In contrast to the pip-train response at 0 dB SL, the FFR component following

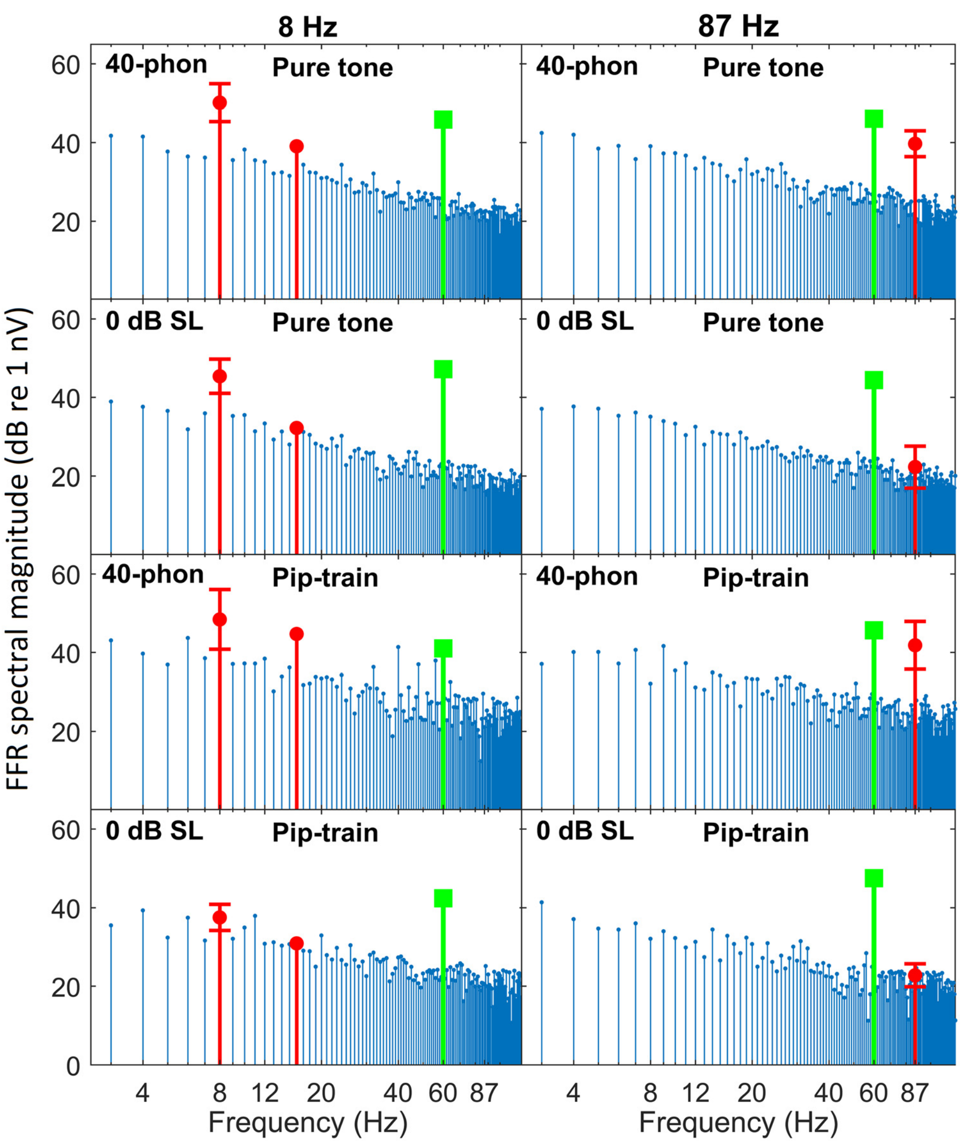

FIG. 2. (Color online) Mean FFR spectra obtained for 8- and 87-Hz tones (N = 9) and pip-trains (N = 4) for the 40-phon and 0-dB SL conditions across all subjects. Error bars show ± 1 SD. Data from S5 were excluded from these averages, as this subject was tested with 11-Hz instead of 8 Hz. Fundamental and 2nd-harmonic (the latter only for 8 Hz) frequencies are shown in red with filled circle marker. The 60-Hz mains component is shown in green and filled square marker.

the 8-Hz tone at 0 dB SL is visibly above the noise floor. No such response can be discerned to the 87-Hz tone at 0 dB SL, despite a noise floor that was 17 dB lower.

IV. DISCUSSION

According to literature, FFR thresholds are on the order of ∼30–40 dB SL [at least for $f \geq 125$ Hz; e.g., Batra *et al.* (1986), Bidelman and Powers (2018), and Picton (2010)]. Also, auditory-steady state responses (ASSRs) to amplitude-modulated tones start to appear only 10–15 dB above sensation threshold (Lee *et al.*, 2016; Picton *et al.*, 2005). Thus, the ability of infrasound to elicit measurable FFRs down to and even below sensation threshold (despite a higher noise floor) appears rather specific to this kind of stimulation. Already in our previous study, we had observed that many subjects had a significant FFR in response to 11-Hz tones at a normative level[1] of 0 dB HL (Jurado and Marquardt, 2020).

Large FFR responses could be a result of superposition of synchronized activity across numerous neural generator sites (Tichko and Skoe, 2017). In contrast to the 87-Hz tone, the long stimulus periodicity of infrasound tones exceeds the latency differences of the nuclei along the auditory pathway up to the primary auditory cortex, hence providing such synchrony. Note that this should also be the case for our 8-Hz pip-train stimuli, which had the same periodicity, however, for which we did not observe significant FFRs at threshold levels.

Thus, the question remains, what is unique about infrasound stimulation to elicit an FFR already at sensation threshold level? Infrasound tones have no characteristic place on the basilar membrane. The lowest frequency on the human cochlear tonotopic map is approximately 45 Hz (Jurado *et al.*, 2011). Consequently, there is not a spatially narrow excitation peak like in response to the tone-pips, which had a 1-kHz carrier. Note also that in response to infrasound, the cochlear partition moves in-phase along its entire length. The result is a spatially wide mechanical excitation pattern that might cause synchronized modulation of spontaneous neural activity across a vast number of auditory nerve fibers when infrasound tones are presented at barely detectable levels. We speculate that this, together with the synchrony of the neural generators along the auditory pathway, gives rise to a measurable FFR already at sensation threshold. We further suggest that this synchronized, whole brain response is possibly a cause of the adverse reactions to infrasound.

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The authors have no conflicts to disclose. The study was approved by the Universidad de Las Américas (approval code CJO-201105-001).

[1]A sound pressure of 95.3 dB SPL was used by Jurado and Marquardt (2020) as the normative infrasound hearing threshold (0 dB HL) for an 11-Hz tone [proposed by Møller and Pedersen (2004)].

[2]These were 13 dB above the individual threshold for 8-Hz tones and 40 dB above for 87-Hz tones and pip-trains. See Møller and Pedersen (2004) and ISO (2003).

[3]One subject was measured with 11 Hz instead of 8 Hz because he participated in a screening for another experiment, and a significant FFR was only obtained at 11 Hz (not at 8 Hz). Also, the pip-train had a repetition rate of 11 Hz for this subject.

[4]According to psychometric functions (PF, cumulative Gaussian) fitted to each of their two staircases data (maximum-likelihood fit), the percent correct values for detecting the infrasound tones at 5 dB below threshold (i.e., 106.5 and 95.9 dB SPL for S1 and S5, respectively) were on average 56.7%, suggesting that these stimuli were not consciously detectable. Both subjects reported informally after the FFR recording to not have been aware of the −5 dB SL infrasound stimulation.

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