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**Noise**

**Session 3aNSa: Wind Turbine Noise I**

**3aNSa6. Amplitude modulation of audible sounds by non-audible sounds:  
Understanding the effects of wind turbine noise**

**Jeffery Lichtenhan\* and Alec Salt**

**\*Corresponding author's address: Washington University in St. Louis, St Louis, MO 63110, [LichtenhanJ@ent.wustl.edu](mailto:LichtenhanJ@ent.wustl.edu)**

Our research has suggested a number of mechanisms by which low-frequency noise could bother individuals living near wind turbines: causing endolymphatic hydrops, exciting subconscious pathways, and amplitude modulation of audible sounds. Here we focus on the latter mechanism, amplitude modulation. We measured single-auditory-nerve fiber responses to probe tones at their characteristic frequency in cats. A 50 Hz tone, which did not cause an increase in spontaneous firing rate (i.e., was not audible to the fiber when presented alone) was used to amplitude modulate responses to the probe tone. We found that as probe frequency decreased, a lower level of the low-frequency non-audible tone was needed to achieve criterion amplitude modulation. In other words, low-frequencies that are coded in the cochlear apex require less low-frequency sound pressure level to be amplitude modulated as compared to higher-frequencies that are coded in the cochlear base. This finding was validated, and extended to lower frequencies, by amplitude modulating gross measures of onset-synchronous (compound action potentials) and phase-synchronous (auditory nerve overlapped waveforms) in guinea pigs. Our results suggest that that infrasound generated by wind turbines may cause amplitude modulation of audible sounds, which is often the basis for complaints from those living near wind turbines.

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## INTRODUCTION

There are a number of scientifically plausible mechanisms how low-frequency noise generated by wind turbines may be the cause of various symptoms reported by some people living near wind turbines.

*i)* Exposure to low-frequency tones has been shown to produce symptoms associated with endolymphatic hydrops – the accumulation of the fluid that supplies the transducer current of cochlear hair cells (Salt 2004; Kirk & Patuzzi 1997; Kirk et al. 1997; Hirsch & Ward 1952). The hallmark symptoms associated with ears with post-mortem verified hydrops are unilateral fluctuating low-frequency hearing loss, vertigo, tinnitus, and a feeling of aural fullness (Nadol 2010). Similar to symptoms associated with hydrops, exposure to low-frequency sound, such as that from wind turbines, may cause dizziness or impaired balance (e.g., Tamura et al. 2012; Bowdler 2011; Punch et al. 2010).

*ii)* Type II auditory nerve fibers that spiral along the tonotopic axis of the cochlea and synapse on cochlear outer hair cells respond in a manner that is consistent with what would be expected from excitation by intense low-frequency acoustic stimulation (Weisz et al. 2012). Outer hair cells have a low probability of neurotransmitter release and, when one does release, it provides only a fraction of the excitation required for a type II fiber to fire. Therefore, several simultaneous inputs from many outer hair cells are required for type II-fiber firing, suggesting that the most effective stimulus would be that which maximally excites a broad cochlear length. Large outer-hair-cell potentials and broad cochlear displacement in response to infrasound and low-frequencies within the range of audibility (Salt et al. 2013) suggest that type II fibers would fire most efficiently by such stimuli. While type II firing may be subconscious if evoked by sound from wind turbines, type II fibers innervate a region of the central auditory nervous system that extends to innervate regions responsible for, among other things, regulating attention, arousal, and pain/stress (Salt & Kaltenbach 2011; Kaltenbach & Godfrey 2008; Benson & Brown 2004; Brown et al. 1988). Additionally, the presence of infrasound has been shown to enhance acoustic startle from audible sounds (Jones et al. 2010), which could be a result of type II firing. Conceivably, stimulation of this neural pathway could lead to the sleep disturbances that have clearly been quantified: Some people living near wind turbines had poorer quality of sleep and were sleepier during the day (e.g., Nissenbaum et al. 2012).

*iii)* Amplitude modulation of audible sounds by low-frequency and infrasonic bias tones is the action of suppressing and un-suppressing responses. Some people living near low-frequency industrial noise have reported being annoyed by, among other symptoms, feelings of throbbing and rumbling sensations (Pedersen et al. 2009; Pedersen & Waye 2004). Such reports may possibly be explained by amplitude modulation of audible sounds by low-frequency noise and infrasound. The noise generated by wind turbines need not be audible to annoy people, as infrasound can amplitude modulate sounds within the range of audibility.

In this report we address the third scientifically plausible mechanism, amplitude modulation. We quantify how infrasonic and low-frequency “bias tones” amplitude modulate auditory responses throughout the range of audible frequencies. Our results show that sounds with a small dynamic range – low frequencies that are audible – were amplitude modulated with quite low levels of infrasound, which suggests that very little low-frequency noise from wind turbines can lead to some of the symptoms reported by people living near wind turbines. Amplitude modulation of sounds with a large dynamic range – higher frequencies that are audible – would be less annoying (Broner 2008). Quantifying amplitude modulation as we have done here is important because the infrasound that is emitted by wind turbines (Jakobsen 2005) has been dismissed as a problem to human health since it is below the normal hearing threshold (e.g., Møller & Pedersen 2011). Using empirical studies to understand the manner by which infrasound and low-frequency noise can influence perceived sounds is therefore relevant to human health.

## METHODS

### Our Approach was Based Classical Human Paradigms

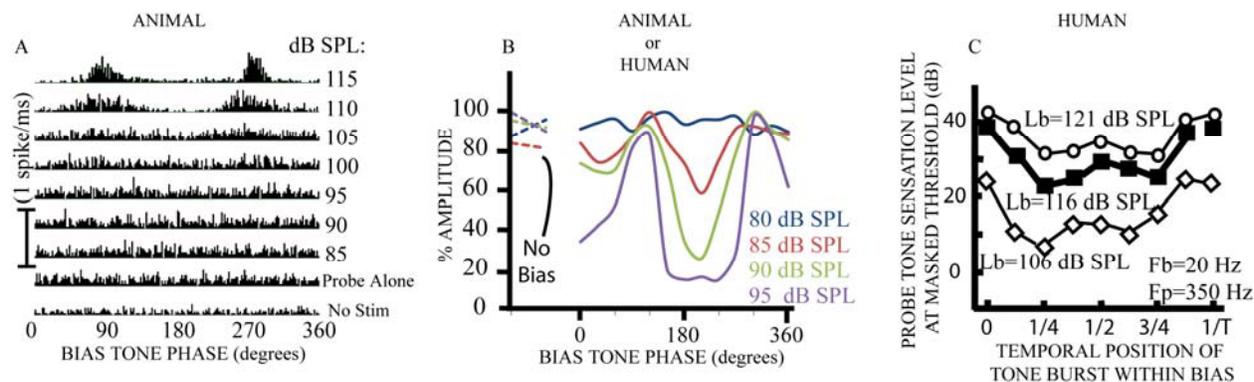
Low-frequency and infrasonic bias tones were used to represent wind-turbine generated low-frequency noise. Bias tones are low-frequency acoustic sinusoids presented to the ear in order to slowly displace the basilar membrane and organ of Corti everywhere throughout the cochlear length. The result is that a simultaneously presented probe tone will be amplitude modulated throughout the dynamic range of its associated *in vivo* transducer function and will be suppressed and unsuppressed through time when, respectively, the probe is positioned at saturating and non-saturating regions of the transducer curve. In other words, the bias tone amplitude modulates the response to the probe tone.

Bias tones can be used in both animal and human experimental paradigms. Fig 1 demonstrates the similarity among empirical measures from both animals and humans using bias tones. **Fig 1A** shows a single-auditory-nerve-fiber response histogram. This shows the firing rate over the course of one cycle of the bias tone at various levels of the bias tone levels. (The frequency and level of the probe was 17.60 kHz and 40 dB SPL, respectively. The frequency of the bias tone was 50 Hz and the levels of the bias tone are indicated to the right in Fig 1A.) As level of the bias tone was increased, the firing was suppressed at particular phases of the bias tone. For this example, 50% amplitude modulation of firing rate occurred with a bias level of approximately 100 dB SPL.

**Fig 1B** demonstrates amplitude modulation of the compound action potential during one cycle of a bias tone. The compound action potential is a measure that can be obtained from a non-invasive or minimally invasive electrode and reflects the gross firing of numerous single-auditory-nerve-fibers (Goldstein & Kiang 1958). Bias-tone-based amplitude modulation of compound action potentials can be performed in animals, as is demonstrated in Fig 1B, or in humans by measuring compound action potentials with an electrode placed on the tympanic membrane, as described by Lichtenhan and Chertoff (2008), and presenting low-frequency bias tones, as described by Bian and Scherrer (2007). Fig 1B shows that amplitude modulation of the compound action potential behaved in a similar way to that measured with highly invasive procedures used for Fig 1A: Amplitude modulation occurred in a sinusoidal fashion that was proportional to the oscillating pressure of the bias tone. (The probe frequency and level were fixed at 6.399 kHz and 40 dB SPL, respectively.) In this example, 50% amplitude modulation occurred with a bias tone level between 85-90 dB SPL.

**Fig 1C** demonstrates the classic paradigm used in human experiments that inspired the animal experiments described in in Figs 1A and 1B. Specifically, we made Fig 1C directly from parts of Fig 1 of Zwicker (1977). While the measures in Figs 1A and 1B use non-behavioral objective measures, Zwicker measured psychoacoustical behavioral responses in humans. Brief probe tones were presented at various phases of the bias tone cycle and the listener responded if they heard the probe tone. The level of the probe tone was varied until it was just noticeable. This process was carried out for each bias level to obtain the measures seen Fig 1C. (The probe frequency and level are indicated directly on Fig 1C, as is the bias tone frequency and level.) As we saw with the objective measures in Figs 1A and 1B, amplitude modulation measured from behavioral responses in Figs 1A depend on signal conditions (e.g., bias tone level) and where the probe tone is positioned within the bias tone cycle. In other words, the general feature of all experiments shown in all panels of Fig 1 is that amplitude modulation of probe tone responses occurs once during each bias tone cycle for low bias tone levels and twice each bias tone cycle for higher bias tone levels.

The primary message from these data is that the experimental paradigm used for to obtain the electrophysiologic responses reported here has been used in both animals and humans, and thus our results are certainly not unique to laboratory cats and rodents. Amplitude modulation by low frequency sounds, such as bias tones, is a common characteristic of animal and human ears. While this report focuses on our efforts to use the technique illustrated in Figs 1A and 1B, the paradigms were inspired by classic experiments in humans illustrated in Fig 1C.



**FIGURE 1.** Fig 1A: Single-auditory-nerve fiber firing rate histograms as a function the phase of a 50 Hz bias tone. The bottom line labeled “No Stim” shows this fiber’s spontaneous rate in quiet, the second line (“Probe Alone”) is the firing evoked by a 40 dB SPL probe tone presented at this fiber’s characteristic frequency. The remaining lines are firing evoked with the probe held constant and 50 Hz bias tone level varied. Fig 1B: Compound action potential amplitude as a function of the phase of a 50 Hz bias tone obtained from a cat. The amplitude measures labeled “No Bias” meander around 100%. Suppression during the bias cycle depended on the phase bias tone at which the probe tone was presented and the level of the bias tone. Fig 1C: A reconstruction of Fig 1 from Zwicker 1977. Brief tone bursts were presented at various times within the 20 Hz bias-tone (Fb) cycle, and the human listener was instructed to report if they heard the 350 Hz probe tone (Fp). For each bias tone level (Lb), the probe tone level was varied until the probe was just noticeable. The primary take-home messages of this figure are *i)* when the

bias tone was presented with the probe tone, the amount of amplitude modulation varied with bias level – greater bias levels yielded greater amplitude modulation – and *ii*) modulation of the response to a high-frequency sound by low-frequency sounds is not unique to laboratory animals.

## Electrophysiologic Recordings

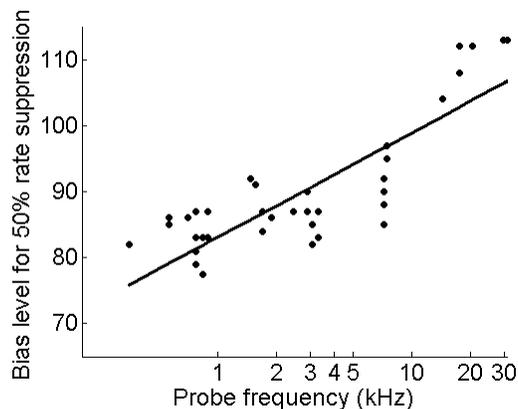
All measures used in this study were obtained from electrophysiologic recordings. Methods used for single-auditory-nerve-fiber recordings in cats followed that described by Kiang *et al.* (1965). Methods for compound action potential recordings in have been described by Lichtenhan (2012). Fifty Hz bias tones were presented to cat ears with a DT48 headphone coupled to the ear through a hollow ear bar. The general methods for recording low-frequency responses from the ear using the auditory nerve overlapped waveform (ANOW) were described by Lichtenhan *et al.* (2013). However, we implemented some changes for the purposes of these experiments reported here: *i*) the hardware and software for data acquisition was that described by Brown *et al.* (2009), *ii*) continuous tonal stimulation was used, *iii*) to alternate the phase of the tones, the tone amplitude was ramped down to zero, the phase was changed, and the amplitude was ramped back up with a 52 ms delay before data collection started. Bias tones for guinea pig experiments were 4.8 Hz presented through a Sennheiser HD 265. Probe tones for guinea pig experiments were presented through an Etymotic ER-10C. Cat experiments were approved by the Animal Care and Use Committee of the Massachusetts Eye and Ear Infirmary, and guinea pig experiments were approved by the Animal Studies Committee of Washington University in St. Louis.

## RESULTS

### Amplitude Modulation as a Function of Probe Frequency

#### *Amplitude Modulation of Single-Auditory-Nerve-Fiber Excitation*

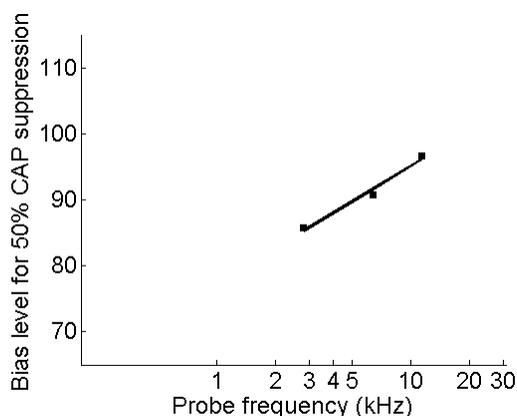
Amplitude modulation of single-auditory-nerve-fibers was quantified throughout the cochlear frequency range of one cat. Using firing-rate histograms like those in Fig 1A, we quantified the bias level needed to suppress firing rate by 50%. After a single-auditory-nerve-fiber was contacted with a glass electrode that was remotely positioned, a tuning curve was recorded to determine the characteristic frequency – the probe frequency for which as the lowest sound pressure is needed to achieve a criterion amount of firing. The spontaneous rate, the firing rate in the absence of an acoustic stimulus was also established. (“No Stim” in Fig 1A). A 40 dB SPL probe was presented alone at the characteristic frequency of the fiber (“Probe Alone”). The probe-tone level was held constant and the level of the 50 Hz bias level was increased. *Post hoc* analysis yielded a measure of the bias level needed to achieve 50% amplitude modulation. This process was carried out for 42 fibers that were encountered during one 24 hour period in this cat. The symbols of Fig 2 are the values of bias level needed to achieve 50% amplitude modulation. The trend line of Fig 2 quantifies that bias level varied at about 6 dB/octave, demonstrating that lower bias tone level were needed to achieve criterion amplitude modulation as probe frequency was lowered. This suggests that in humans, low-frequency sounds such as speech vowels are more sensitive to biasing tones and could be amplitude modulated by low-frequency sound generated by wind turbines.



**FIGURE 2.** Bias level needed for 50% amplitude modulation of firing rate, as a function of probe frequency, for single-auditory-nerve fibers. Each point is from a different single-auditory-nerve fiber. Probe tones were presented at 40 dB SPL at the single-auditory-nerve-fibers' characteristic, or "best", frequency and the 50 Hz bias level was varied. The trend line shows that as characteristic frequency increased, the amount of bias level needed to obtain criterion amplitude modulation also increased. Thus, audible sounds that are lowest in frequency (e.g., speech vowels) will be most easily amplitude modulated by low-frequency and infrasonic noises that are generated by wind turbines.

#### *Amplitude Modulation of Compound Action Potentials*

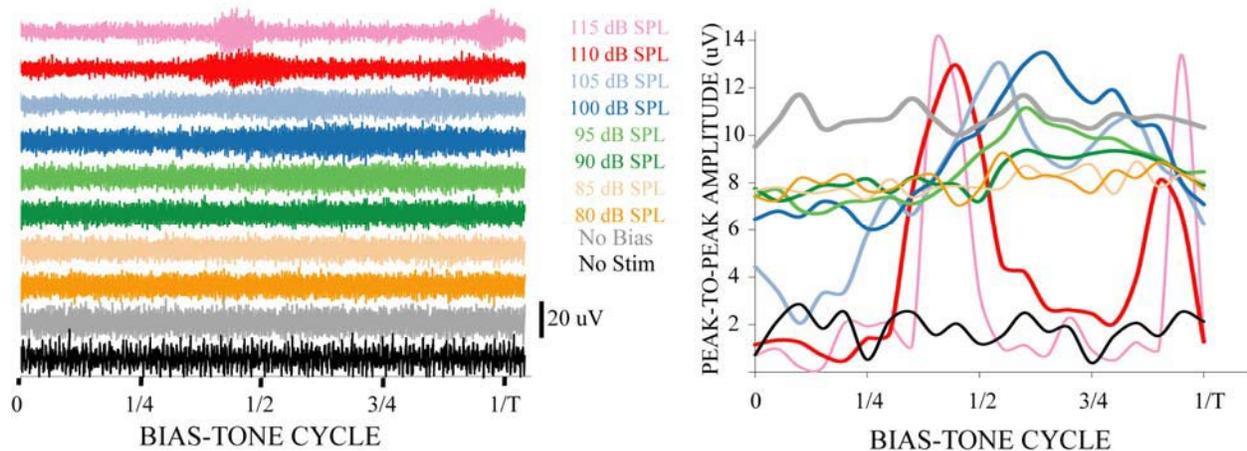
Compound action potentials were used as a measure to further investigate the finding in Fig 2 – decreases in probe-tone frequency require a lesser amount of bias pressure to cause amplitude modulation. The compound action potential is generated by the compound firing of numerous single-auditory-nerve action potentials. Data shown in Fig 3 were obtained from measures made from plots like those shown in Fig 1B. The trend in the compound action potential data of Fig 3 is similar to that found in single-auditory-nerve fiber data of Fig 2: As probe frequency increases, the amount of bias level needed to achieve criterion amplitude modulation must also increase. This demonstrates that the gradation of bias tone effects throughout the cochlea is not unique to measures made from single-auditory-nerve fibers.



**FIGURE 3.** Bias levels needed to achieve 50% amplitude modulation of compound action potentials evoked over a two-octave range in a cat. The probe levels were 40 dB SPL and frequency is indicated on the abscissa. The level of the 50 Hz bias level was varied to achieve 50% amplitude modulation. As the frequency of the probe tone decreased, the amount of bias tone level needed for criterion amplitude modulation decreased.

#### **Amplitude Modulation of the Auditory Nerve Overlapped Waveform (ANOW)**

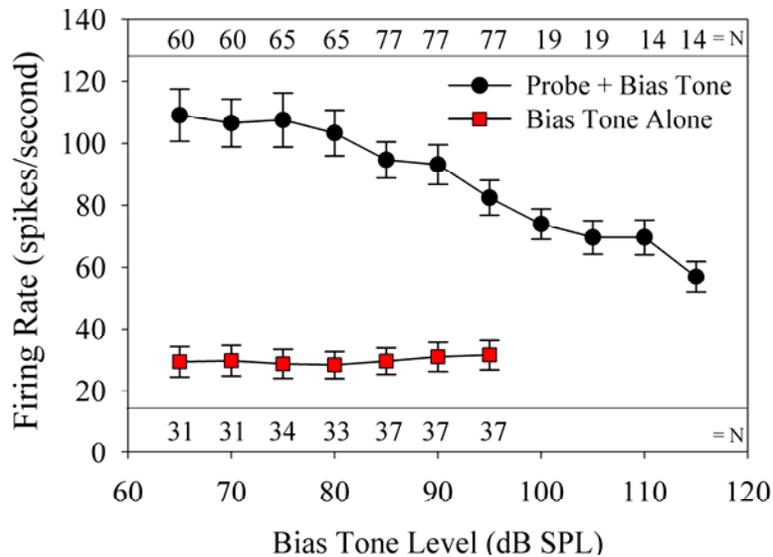
The Auditory Nerve Overlapped Waveform (ANOW) shows the phase-locked neural firing of primary afferent auditory-nerve fibers from the low-frequency cochlear apex (Lichtenhan et al 2013). The ANOW provides a minimally-invasive technique to investigate amplitude modulation of low-frequency probe tones. The results in Figs. 2 and 3 illustrate that much lower bias tone levels were needed to amplitude modulate neural responses from the cochlear apex as compared to other cochlear regions. The ANOW data of Fig. 4 clearly demonstrate that low-frequency neural responses to a 500 Hz tone were amplitude modulated by an infrasonic bias tone. One might expect that the trends in Figs. 2 and 3 from 50 Hz-biasing in cat ears would predict that the bias level needed to obtain 50% amplitude modulation of a 500 Hz probe in a guinea-pig ear should be in around 75 dB SPL – the ordinate value where a 500 Hz abscissa value would intersect. However, Fig. 4 shows that about 90-95 dB SPL was needed to achieve substantial amplitude modulation using a 4.8 Hz bias tone in guinea pig ears. This result does not indicate a species difference. It is consistent with the frequency-dependence of low-frequency biasing that Brown and Gibson (2011) reported from human ears: A greater bias level is needed to maintain criterion modulation as the *bias tone frequency* is decreased. Since the data in Figs 2 and 3 were obtained with a 50 Hz bias tone, they cannot be used to accurately predict the bias level needed for substantial amplitude modulation with the much lower frequency, 4.8 Hz bias tone.



**FIGURE 4.** Amplitude modulation of the auditory nerve overlapped waveform (ANOW) obtained with infrasonic biasing. In this example, the probe was a 55 dB SPL 500 Hz tone that alternated in polarity to cancel cochlear microphonic, and the bias tone was a 4.8 Hz tone that varied in level from 80 to 115 dB SPL in 5 dB steps. The left panel shows the raw ANOW during one cycle of the bias tone. The most visible amplitude modulation of the raw ANOW on this scale was from 110 and 115 dB SPL bias tones. The right panel shows the peak-to-peak ANOW amplitude obtained from sine-wave fits to segments of raw ANOW. The black lines in both panels quantify the noise floor, as no stimulus was present (“No Stim”) while the gray lines quantify ANOW amplitude without being amplitude modulated, i.e., with no bias tone was present (“No Bias”). As we saw in Fig 1, the degree of amplitude modulation depends on the level of the bias tone.

### Amplitude Modulation as a Function of Bias Tone Level

Fig. 5 shows auditory-nerve firing rate measured from a large number of single-auditory-nerve-fibers under various signal conditions. These data were obtained from histograms such as those in Fig 1A. Varying the bias tone level did not significantly change firing rate (red squares). These data show that the 50 Hz bias tones used in our studies is indeed infrasound to the cat ear, since it did not evoke excitation in these single-auditory-nerve fibers when presented at the levels shown. However, infrasound can clearly affect the response from probe tones presented within the range of audibility: Forty dB SPL probe tones presented at the characteristic frequency of the various fibers produced excitation, or an increase in firing rate above their spontaneous firing rate measured in silence. Simultaneously presenting a bias tone with the probe tone suppressed the firing rate in a level-dependent manner. In particular, as the bias level was increased, the response to the probe tone was decreased (suppressed). While 50 Hz presented alone did not cause excitation of auditory-nerve fibers, this bias tone frequency clearly affected responses to higher-frequency probe tones and caused amplitude modulation of the neural responses. This result is well explained by the effect of the bias tone on the stereocilia of outer hair cells (e.g., Salt & Lichtenhan 2011; Temchin et al. 1997; Cai & Geisler 1996).



**FIGURE 5.** Single-auditory-nerve firing was not altered by presenting the 50 Hz bias tone alone (red squares). In contrast, 40 dB SPL probe tones presented at each fiber's characteristic frequency evoked an increase in single-auditory-nerve firing. When a 50 Hz bias tone was presented simultaneously with the 40 dB SPL probe (black circles), the firing rate depended on the level of the bias tone. As bias level increased, the firing rate decreased. The number of fibers contributing to each datum is indicated above or below the datum. For example, measurements on 60 different single-auditory-nerve-fiber recordings yielded a mean firing rate of 110 spikes/second from a 40 dB SPL probe tone and a 65 dB SPL bias tone. The number of measurements contributing to each point was governed by the amount of time fibers could be held.

## CONCLUSIONS

### *Amplitude Modulation as a Basis for Complaints from those Living Near Wind Turbines*

We have quantified amplitude modulation throughout the cochlea with a paradigm that yields a result not unique to animals. Our invasive (single-auditory-nerve fiber) and minimally invasive (compound action potential) techniques were both based on Zwicker's (1977) classic human psychophysical paradigms. We found that lower bias tone levels were needed to amplitude modulate responses to low frequencies within the range of audibility as compared to higher audible frequencies, which is consistent with low-frequency sounds having a smaller dynamic range than higher frequency sounds. The range between the threshold of audibility and the threshold of pain – the dynamic range – is smaller for low-frequency sounds as compared to high-frequency sounds. The interpretation for these bias-tone-based paradigms is due to well-known aspects of the mechanics of the auditory periphery (e.g., Sirjani et al. 2004; Lichtenhan 2012). These peripheral effects are carried centrally as is shown by recent evidence from imaging studies that show that the human auditory cortex produces robust responses to infrasonic stimulation, such as 50 Hz repetition of audible sounds (Nourski et al. In Press) and 3 Hz amplitude modulation of audible sounds (Overath et al. 2011). These findings suggest that amplitude modulation of low-frequency audible sounds could be a basis for complaints of people living near wind turbines such as annoyance or, for example, feelings of throbbing and rumbling sensations (Pedersen et al. 2009; Pedersen & Waye 2004). Our studies have shown that the noise generated by wind turbines need not be audible to annoy people, since infrasound can amplitude modulate sounds that are within the range of audibility.

### *Amplitude Modulation and Cochlear Mechanics*

The bias tone level needed to achieve 50% amplitude modulation of probe-tone responses varied with the frequency of the probe, or distance along the cochlea (Figs 2 and 3). In particular, compared to higher probe tone frequencies, probes of lower frequencies within the range of audibility required lower bias tone levels to produce a criterion amplitude modulation. This is consistent with *i*) achieving criterion bias-tone-based amplitude modulation at any given cochlear location requires that the bias tone produce a criterion outer hair cell stereocilia displacement, *ii*) the criterion stereocilia displacement corresponds to a criterion basilar membrane displacement, *iii*) basilar

membrane displacement evoked from infrasonic and low-frequency bias tones depends on basilar membrane stiffness, and *iv*) basilar membrane stiffness increases from apex to base at approximately 6 dB/octave (Naidu and Mountain 1998; Bekesy 1960), which is approximately the gradation found in our data in Figs 2 and 3.

While we have quantified how low-frequency and infrasonic bias tones can amplitude modulate a variety of physiologic responses of the auditory system, we do not yet know to what extent real-world infrasound generated from wind turbines can cause amplitude modulation. For example, what level of wind-turbine-generated noise can cause amplitude modulation and at what distance from the wind turbine can amplitude modulation occur. Be that as it may, it is possible that amplitude modulation similar to what we show here could occur within the general region of wind turbines. In summary, amplitude modulation of audible sounds may be one part of the explanation of how wind-turbine-generated infrasound can be annoying and may also cause other symptoms that have been reported.

## ACKNOWLEDGMENTS

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