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A Review of the Possible Perceptual and Physiological Effects of Wind Turbine Noise

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Abstract

This review considers the nature of the sound generated by wind turbines focusing on the low-frequency sound (LF) and infrasound (IS) to understand the usefulness of the sound measures where people work and sleep. A second focus concerns the evidence for mechanisms of physiological transduction of LF/IS or the evidence for somatic effects of LF/IS. While the current evidence does not conclusively demonstrate transduction, it does present a strong prima facia case. There are substantial outstanding questions relating to the measurement and propagation of LF and IS and its encoding by the central nervous system relevant to possible perceptual and physiological effects. A range of possible research areas are identified.

Keywords

auditory transduction, infrasound, low-frequency sound, wind turbine noise

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Introduction

In recent years, there has been growing debate about the effects of wind turbine noise (WTN) on human health. A number of reviews have recently been published (e.g., Knopper et al., 2014; McCunney et al., 2014; Schmidt & Klokker, 2014; Van Kamp & Van Den Berg, 2017), some under the auspice of different government bodies in Australia (National Health and Medical Research Council, 2015), Canada (Council of Canadian Academies, 2015), and France (Lepoutre et al., 2017), with some appearing in the indexed scientific literature (most recently the Health Canada study; D. Michaud, 2015; D. S. Michaud et al., 2016a, 2016b; D. S. Michaud, Keith, et al., 2016). Many of these studies have adopted an epidemiological approach including various meta-analyses of the existing research reports concerning the health effects of WTN. By contrast, the popular press portrays a largely polarized picture where the discourse often appears less informed and more opinionated than scientifically based.

There are clearly complex factors surrounding complaints about WTs that, apart from the health and safety concerns, include financial and other material factors and potential interactions with individuals' perceptions of devices themselves, including their appearance and the sounds they make. These factors are all potential contributors to the annoyance produced by WTs. Many of these concerns—sometimes referred to as nocebo effects—have been recently reviewed in the literature (Chapman & Crichton, 2017; C. H. Hansen, Doolan, & Hansen, 2017). There seems, however, to have been little discussion (or systematic review) of potential perceptual and physiological effects of WTN at the level of the individual. This provides the principal motivation for this review. This review does not consider the important question of whether WTN affects human health, given the reviews and debates referred to earlier, but focuses on two important foundational issues. The first section reviews recent research examining the nature of the sound generated by WTs with a particular focus on the low-frequency sound (LF) and infrasound

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(IS), together with the mechanisms of its generation, propagation, and measures of human exposure. The objective of this first part is to understand the accuracy and usefulness of measures of this sound pressure at locations where people work and sleep. The second issue for focus concerns whether there are plausible mechanisms of transduction of LF/IS or evidence for somatic effects of LF/IS. This is an important question as a key link in any argument attempting to relate WTN exposure to ill health is the extent to which that sound can have a somatic influence. In closing, some of the existing peer-reviewed research examining the perceptual effects of exposure to LF and IS in the laboratory setting is reviewed.

This review has been confined largely to the scientific literature represented by the relevant peer-reviewed articles in indexed journals.

WTN, LF, and IS

There are a range of potential sound generators produced by WTs which include mechanical generators (gearboxes, electrical generators, cooling systems, etc., in the WT nacelle) as well as interactions between the moving blades and the air, particularly where there are variations in flow, angle of incidence, and pressure.

Sound produced by rotating blades on modern upwind WTs (where the rotor is on the front of the nacelle when viewed from the direction that the wind is coming) results in part from an interaction between the airflow disturbed by the rotating blade interacting with the supporting tower (e.g., Jung, Cheung, Cheong, & Shin, 2008; Sugimoto, Koyama, Kurihara, & Watanabe, 2008; reviewed in detail Van den Berg, 2006; Zajamšek, Hansen, Doolan, & Hansen, 2016). The sound generated by this mechanism is tonal in nature with a fundamental frequency at the blade passing frequency (BPF) and a series of six or so harmonics (Figure 1; for further details, see Schomer, Erdreich, Pamidighantam, & Boyle, 2015, their Figures 2 and 3). The fundamental frequency is dependent on the rate of rotation and number of blades and for a modern WT, the sound energy produced by this mechanism is generally well below 20 Hz.

Other sources of sound include the aerodynamic noise generated by air flow across and leaving the trailing edge of the blades (trailing edge noise) and mechanical noise from the nacelle equipment. By contrast with BPF noise, the aerodynamic noise from the blades is broadband with a low-pass roll-off (~5 dB per octave > 1 kHz; Figure 2; Oerlemans, Sijtsma, & López, 2007, their Figures 5, 9, and 11). The center frequency (500–750 Hz, A-weighted) is related to the size and power generation capacity of the turbine with a downward shift of around 1/3 octave comparing 2.3 to 3.6 MW turbines to <2 MW turbines accompanied by a relative increase in the proportion of energy at low frequencies for larger turbines (Moller & Pedersen, 2011).

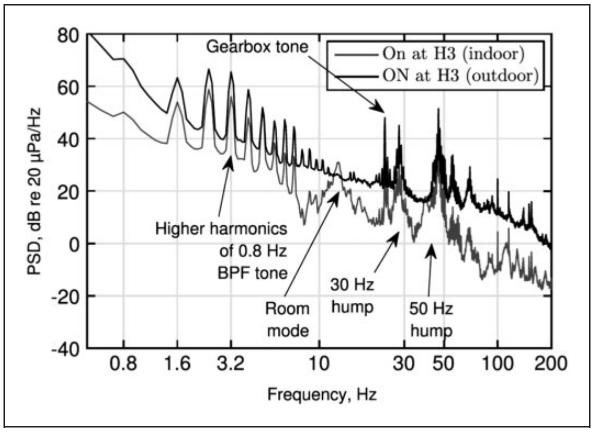

Figure 1. Comparison of indoor and outdoor spectral density recorded at an unoccupied dwelling approximately 3 km from a wind turbine. BPF = blade passing frequency; PSD = power spectral density.
Source: Reproduced with permission from Zajamsek et al. (2016), Figure 4.

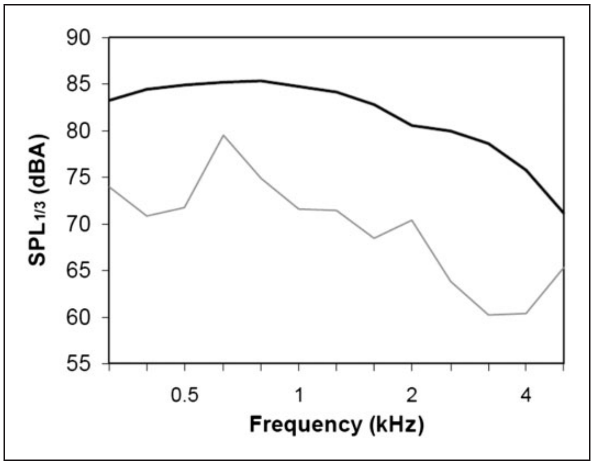

Figure 2. A-weighted average spectra of hub noise (thin line) and blade noise (thick line) recorded from a three-bladed pitch–controlled GAMESA G58 wind turbine (rotor diameter 58 m) using an acoustic array of 148 Panasonic WM-61 microphones 58 m upwind from the turbine.
Source: Reproduced with permission from Oerlemans et al. (2007).

In summary, from both a theoretical and an empirical standpoint, there is ample evidence demonstrating that a component of the sound energy produced by a WT is in the low and infrasonic frequency range. There are three other characteristics of LF that are relevant to understanding the measurements of sounds produced by WTs.

First, both modeling and measurement data have shown that the atmospheric boundary layer which extends from ground level to between 100 to thousands

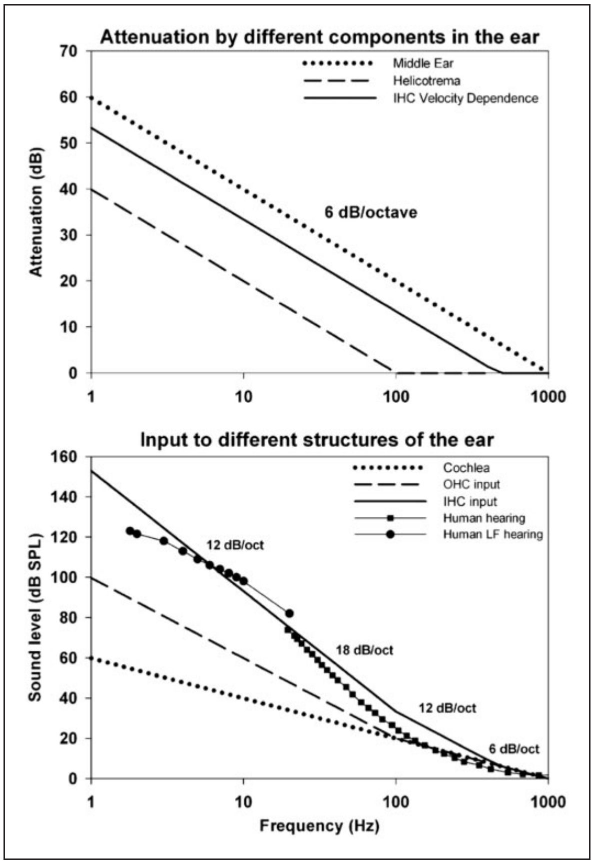

Figure 3. Upper panel: Estimated properties of high-pass filters associated with cochlear signal processing (based on Cheatham & Dallos, 2001). The curves show the low-frequency attenuation provided by the middle ear (6 dB/octave below 1000 Hz), the helicotrema (6 dB/octave below 100 Hz), and by the fluid coupling of the IHC resulting in the IHC dependence on stimulus velocity (6 dB/octave below 470 Hz). Lower panel: Combination of the three processes in the upper panel into threshold curves demonstrating: input to the cochlea (dotted) as a result of middle ear attenuation, input to the IHC as a result of additional filtering by the helicotrema, and input to the IHC as a result of their velocity dependence. Shown for comparison is the sensitivity of human hearing in the audible range (ISO226, 2003) and the sensitivity of humans to infrasound (Moller & Pedersen, 2004). The summed filter functions account for the steep (18 dB/octave) decrease in sensitivity below 100 Hz. OHC = outer hair cells; IHC = inner hair cells; LF = low-frequency sound.
Source: Reproduced with permission from Salt and Hullar (2010), Figure 3.

of meters can act as a low-frequency wave guide under a variety of common meteorological conditions (for review, see Marcillo, Arrowsmith, Blom, & Jones, 2015). With a stable boundary layer, which is common at night, LF radiation occurs as cylindrical waves and follows a two-dimensional decay model (−3 dB per doubling of distance) when measured downwind of a source (Zorumski & Willshire, 1989) in contrast to a three-dimensional decay model for higher frequency audible sound. Under such conditions, therefore, LF and IS levels decay more slowly with distance when compared with higher frequencies. Consistent with this, propagation of sound at the BPF from a 60-turbine wind farm has been recently measured using particularly sensitive equipment as far as 90 km from the source (Marcillo et al., 2015).

Second, IS and LF have wavelengths comparable with the dimensions of building structures such as homes which also allows for resonant interactions with those structures. Recent high-resolution data recorded inside and outside dwellings demonstrate such building cavity resonance in the 10 - to 20-Hz range (Pedersen, Møller, & Waye, 2007; Schomer et al., 2015; Zajamšek et al., 2016) along with other building resonances over a 2- to 80-Hz range. Third, sound attenuation provided by building walls is much less at low frequencies compared with higher frequency sounds (K. L. Hansen, Hansen, & Zajamšek, 2015; Thorsson et al., 2018) and very irregular because of the building resonances. These two observations indicate that exterior measures of LF and IS pressure are not necessarily good predictors of interior sound pressures as these are dependent on the particular characteristics of the structure.

Accurate measures of the sound pressure levels of LF and IS around WTs is complicated because of the very long wavelengths of sound at such low frequencies, and the high susceptibility of measurement microphones to atmospheric turbulence (i.e., wind noise). Special strategies such as very high performance wind-shields (Dauchez, Hayot, & Denis, 2016; K. Hansen, Zajamsek, & Hansen, 2014; Turnbull, Turner, & Walsh, 2012; Zajamšek et al., 2016) and the use of microphone arrays with sophisticated signal processing (Walker, 2013) are needed. There is a complex relationship between the wind speed and angle of incidence, atmospheric conditions, terrain, distance to the source and the number and distribution of sources, and the measurement of LF and IS (for an excellent review, see Van den Berg, 2006). External measures are complicated by wind noise and other interactions with the measuring instrument. The greater majority of measurements are external (rather than internal where the greatest disability is reported) and use A weighting which effectively filters out LF and IS frequencies. Even lower pass weightings (e.g., C weighting) exclude crucial low frequencies particularly at the BPF and first few harmonics. Measures made external to dwellings are not necessarily good predictors of dwelling interior pressures where people spend the majority of their time (particularly sleeping). In turn, internal measurements are also complicated, and often avoided by acousticians because of the influence of the room modes and occupational sources of noise, such as refrigerators and other household equipment. That there is a wide range of reported levels of LF and IS in and around wind farms should not be surprising, given the diversity of relevant factors (e.g., cf. Jung et al., 2008; Schomer et al., 2015; Sugimoto et al., 2008; Van den Berg, 2006). Given some of the physiological work reviewed later (particularly that relating to hydrops and basilar membrane biasing), use of a dosimetry approach to LF and IS exposure may prove a more appropriate measure for determining human exposure although this would require the development of new equipment and measurement techniques.

Sound Pressure Weighting Scales and WTN

The abovementioned considerations indicate that a complete understanding of sound energy emitted by WTs requires careful measurement and modeling approaches that are sensitive to the full range of possible sound frequencies. While the current practice of measuring and analyzing WTN using an A-weighted correction offers convenience and practicality, it will necessarily filter out much of the LF energy actually emitted by a WT. This approach appears to be motivated by practical measurement considerations and the assumption that, from the point of view of human perception, the auditory system sensitivity to sound level (loudness perception) is nonlinear and rolls off very sharply for frequencies below 1 kHz reaching −50 dB by 20 Hz (Keith et al., 2016; Yokoyama, Sakamoto, & Tachibana, 2014). These authors also argued that the A-weighted sound level of a wind farm is highly correlated with the sound levels of the LF and IS, and so A-weighted measures could act as a proxy for LF and IS levels. This supposition is, however, based on 1/3 octave C-weighted measures extending only to 16 Hz which is well above the BPF and it is not consistent with some recent data (e.g., Hansen, Walker, Zajamsek, & Hansen, 2015; Schomer et al., 2015). As reviewed earlier, there are also complicating factors relating to the potential difference in the propagation of IS and LF compared with the middle to high frequencies to which humans are sensitive. This suggests that, even if A-weighted measures are correlated with the total WT energy at a particular point in space, this may not provide an adequate indication of the relative sound levels at other distances from the source (see also Moller & Pedersen, 2011).

There is clearly a need for more research and development of methods to accurately measure and assess the level of exposure of individuals to LF and IS particularly in the built environment where individuals live and sleep. To be clear, in the first instance, this work needs to focus on the collection of high-quality scientific data to provide insights into the mechanisms and processes in play. While this may subsequently have implications for methods of making acoustic measurements in the field, the emphasis first needs to be on collecting high-quality scientific data to address the questions of sound propagation and human exposure.

Perceptual Sensitivity

Perceptual sensitivity to LF and IS has been studied for more than 80 years (reviewed in Moller & Pedersen, 2004), and although there is no international standard, the experimental data are in good agreement. Threshold rises sharply from 80 dB (SPL) at 20 Hz to around 124 dB SPL at 2 Hz and the perceptual effects also include vibration and the sensation of pressure at the ear drums. Consistent with these data, Yokoyama et al. (2014) showed that listeners were insensitive to resynthesized WTN in the laboratory at levels up to 56 dBA.

For a variety of biomechanical and other physiological reasons, the cochlea is known to be a highly nonlinear transducer. Given the relatively high sound levels required to achieve perceptual response to IS, the question arises as to whether this represents neural transduction at the fundamental frequency or sensitivity to nonlinear distortion products produced on the basilar membrane. While mechanisms of transduction are considered in more detail later, recent functional magnetic resonance imaging (fMRI) data (Dommes et al., 2009; Weichenberger et al., 2015) show auditory cortical activation to a 12-Hz tone at thresholds that are broadly consistent with those reviewed by Moller and Pederson (2004). This indicates that, regardless of whether IS is transduced as a fundamental or as a consequence of nonlinear distortion products, it does lead to activation of the auditory cortex providing a primary neural representation of these acoustic stimuli.

A more recent fMRI study (Weichenberger et al., 2017) took a different analytical approach using a regional homogeneity resting mode analysis and a relatively prolonged (200 s) 12-Hz stimulus. They report that subliminal sound levels (2 dB below measured threshold) also activated brain regions known to be involved in autonomic and emotional processing: In particular, the anterior cingulate cortex and amygdala—the latter is believed to be involved with stress and anxiety-related psychiatric disorders. The amygdala is also part of the nonleminiscal auditory pathway that mediates subcortical processing and has input to the reticular activating system, a key component regulating arousal and sleep (for discussion, see Weichenberger et al., 2017). This latter observation provides some explanation as to how subliminal IS stimulation could lead to arousal and potentially mediate sleep disturbances reported by some individuals.

Related to the question of individual differences, Moller and Pedersen (2004) make the observation that the dynamic range of the auditory system decreases significantly at low frequencies, demonstrated in the extreme compression of the equal loudness contours at 2 Hz (20–80 phon from 130 to 140 dB). This indicates that even small changes in pressure can result in very large changes in loudness perception. Likewise, small variations in threshold between individuals could produce significant differences in perceived loudness for the same pressure level stimulus. This would also result in differences in suprathreshold levels which, when taken in the context of the recent report of Weichenberger et al., could in turn explain some of the individual differences in reported physiological effects of WTN. A simple test of this prediction would be to measure the IS thresholds of individuals reporting physiological effects of exposure to WTN compared with those who report no effects under the same exposure conditions. If this proved to be discriminatory, then simple IS threshold measures would provide an indicator of likely susceptibility to WTN. Such measurements could involve perceptual impressions (Kuehler, Fedtke, & Hensel, 2015) or objective assessments such as fMRI (Weichenberger et al., 2017) or magnetoencephalogy (Bauer et al., 2013).

Physiological Transduction of LF and IS

Before considering the evidence for potential sensory or other transduction of LF and IS, it is useful to contextualize this discussion. As indicated in the Introduction section, a critical component in any argument attempting to link the sound level output from WTs (or any mechanical device) to ill health is the extent to which sound energy is able to influence the human body perceptually or somatically. If there is no influence, then it would be difficult to argue that reported health effects could be induced by sound or vibration. For instance, people in urban environments are exposed daily to significant qualities of low-level microwave radiation in the form of communications transmissions (radio, TV, cellular network, etc.) without any known effects of ill health (Valberg, Van Deventer, & Repacholi, 2007). This would likely be a consequence of the fact that, at these levels of exposure, microwave radiation is not an effective stimulus perceptually or somatically for the human body. By contrast, there is much debate and opinion as to whether the human nervous system is sensitive to the infrasonic and LF that is emitted by WTs. There are, unfortunately, very few peer-reviewed publications that consider the potential physiological mechanisms that might underlie sensory transduction of LF and IS. There is a much wider range of opinion pieces on the topic presented in a variety of formats (popular science magazines, newspaper articles, and self-published monographs and newsletters). Subsequently, we will consider principally reports or reviews in peer-reviewed scientific publications.

In a review in *Hearing Research*, Salt and Hullar (2010) outline a number of possible mechanisms by which the LF and IS could influence the function of the inner ear and lead to neural stimulation that may or may not be perceived as sound. These authors describe how, under normal physiological circumstances, the inner ear is remarkably insensitive to LF and IS. This results from the need to mechanically tune the sensory apparatus to sounds of greatest biological interest (in this case, from 100 Hz to a few kilohertz which is the range of human communication and of the inadvertent sounds of movement of predator or prey). Consequently, the anatomical structures of the cochlea would suffer significant damage in response to large mechanical displacements that would result from stimulation by even relatively low pressure LFs (for sounds of constant pressure, particle displacement is inversely proportional to frequency at +6 dB per octave).

There are three principal mechanisms providing this protective attenuation (see Figure 3; Salt & Hullar, 2010; for a very detailed review, see Dallos, 2012). First, the band-pass characteristics of the middle ear are roughly centered on 1 kHz and attenuate frequencies below that at 6 dB/octave. For a constant pressure, this inversely matches the increase in particle displacement so that for frequencies below 1 kHz, movement of the stapes and the amplitude of displacement input to the cochlea is constant. Second, low-frequency stimulation of the cochlea is reduced by the shunting of perilymph fluid between the chambers of the scala tympani and scala vestibuli through the helicotrema resulting in 6 dB/octave attenuation for frequencies less than 100 Hz. Third, the auditory transduction receptors, the inner hair cells (IHC) are sensitive to fluid velocity in the cochlea which results in a further attenuation of 6 dB octave below about 470 Hz. These three mechanisms add linearly to reduce stimulation of the IHC by 18 dB/octave between 100 Hz and 20 Hz.

Salt and Hullar (2010) make the important observation that as the outer hair cells (OHC) are sensitive to displacement (i.e., they are mechanically coupled and not fluid coupled to the tectorial membrane) which is constant for low frequencies, so even under physiologically normal conditions, at these low frequencies they should be stimulated at lower sound levels than the IHC. This prediction is borne out by the thresholds of endolymphatic potentials in the guinea pig cochlea to 5-Hz stimuli which represent strial current gated by OHC activity (Salt, Lichtenhan, Gill, & Hartsock, 2013). In contrast to the original estimates of OHC threshold (~40 dB lower than IHC at 5 Hz; Salt & Hullar, 2010), gain calculations in the later work suggest that the human apical cochlea could be similarly activated at around 55 dB to 65 dB SPL (corresponding to −38 to −28 dBA). This surprisingly high level of sensitivity of

OHCs to LF (when compared with IHC activation and perceptual threshold) is strongly supported by recent work examining the spontaneous otoacoustic emissions in humans (Drexl, Krause, Gürkov, & Wiegrebe, 2016; see also Drexl, Otto, et al., 2016; Jeanson, Wiegrebe, Gürkov, Krause, & Drexl, 2017; Kugler et al., 2014). It has been known for quite some time using human distortion product otoacoustic emissions (e.g., Hensel, Scholz, Hurttig, Mrowinski, & Janssen, 2007) as well as in vivo animal data (Patuzzi, Sellick, & Johnstone, 1984) that LF and IS do affect cochlear processing and that the cochlea aqueduct does pass IS frequencies into the inner ear (Traboulsi & Avan, 2007). The perceptual and other downstream consequences, however, are still not well studied. The more recent focus on the modulation of OHC activity is likely to provide important insights as to the physiological effects of IS and LF on cochlear processing. While the sensory role of OHCs are currently not well understood, they do carry sensory information via Type-II afferent fibers into the brain and probably play a role in signaling the off-set bias (and therefore operating point) of the basilar membrane and therefore also affect IHC transduction.

Before considering the effects of possible dysfunction of this system, it is worth summarizing the implications mentioned earlier. The healthy human ear significantly attenuates low-frequency input to the IHCs below around 100 Hz (~18 dB/octave). It is likely that at very low frequencies (<20 Hz), the OHCs are responding to stimuli at levels well below those producing activation of the IHCs. It is acoustic stimulation of the IHC which is the effective perceptual stimulus for hearing. Nonetheless, OHCs also have a sensory (afferent) input to the brain, although their stimulation is unlikely to lead to auditory perception per se. What is critical to emphasize at this juncture is that although the mechanisms outlined by Salt and Hullar (2010) are plausible and based on a large body of well-founded research, they do not by themselves constitute a demonstration of direct transduction of LF and IS by the inner ear. The effects of LF on OHC activity, however, could modulate transduction by the IHC, and such affects would likely be perceptible.

These data do provide, however, a strong prima facia case for neural transduction of LF and IS that needs to be properly examined at a functional and perceptual level in both animal and human models. Some critics of Salt and Hullar (2010) have argued that the level of LF and IS required to stimulate the OHCs is much greater than that recorded near wind farms. Given, however, the range of technical issues in making such acoustic measurements and the diversity of reported levels reviewed earlier, this claim is similarly limited by the available acoustic data. Furthermore, the recent work examining the guinea pig endocochlear potential (Salt et al., 2013) and human otoacoustic emissions (e.g., Drexl, Otto, et al., 2016; Kugler et al., 2014) indicate even greater levels of sensitivity of OHCs to LF when compared with the perceptual threshold mediated by IHC activity than first predicted. This suggests the need for a review of such conclusions.

Salt and Hullar (2010) also review the consequences of some pathologic conditions of the inner ear in terms of the potential to increase sensitivity to LF and IS. For instance, blockage or increased resistance of the helicotrema by a condition such as endolymphatic hydrops will reduce fluid shunting and reduce the attenuation for frequencies <100 Hz by up to 6 dB. Acute endolymphatic hydrops can be induced by exposure to low frequencies, although the relationship is complex and suggests that a dosimetry approach to exposure could be most informative. Hydrops would also lead to changes in the operating point of the basilar membrane resulting in a variety of changes in IHC sensory transduction including increased distortion. A further mechanism considered by Salt and Hullar is the increased fluid coupling of vestibular cells to sound input produced by changes in the input impedance of the vestibular system in conditions such as superior canal dehiscence (SCD), which can result in sound induced dizziness or vertigo, nausea, and nystagmus (Tullio phenomena).

Schomer et al. (2015) also examine potential physiological mechanisms that could mediate effects of LF and IS. They draw a link between the nauseogenic effects of low-frequency vestibular stimulation in seasickness and the potential vestibular stimulation by IS under normal listening conditions (as opposed to pathologic conditions of SCD). Using data collected by the U.S. Navy on nauseogenic effectiveness of low-frequency vestibular stimulation produced by whole body motion, they found significant overlap between the most effective nauseogenic frequencies and BPF of modern and larger WTs. Using a first-order model, they also demonstrate a better than order of magnitude equivalence between the force applied to the otoconia in the vestibular apparatus produced by whole body motion of 0.7 Hz at 5 m/s^2 peak and by IS of 0.7 Hz at 54 dB (SPL). Building on previous anatomical work (Uzun-Coruhlu, Curthoys, & Jones, 2007), Schomer et al. argue that pressure normal to the surface of the macular in the inner ear will provide an effective stimulus to the vestibular hair cells in the same way as the sheer motion between the otoconial membrane produced during linear acceleration of the head. While a plausible explanation, it is important to recognize that this suggestion is highly speculative and no data have yet been provided to support this latter assertion. Leventhall (2015) has also questioned this model although not in a peer-reviewed forum. Of note, however, the comparison with seasickness does add to the argument that a dosimetric approach to exposure may be more appropriate than measures of peak or root-mean-square sound pressure.

Perceptual Effects of Laboratory Exposure to LF and IS

A number of laboratory studies have directly exposed human listeners to IS and LF (e.g., Crichton, Dodd, Schmid, Gamble, & Petrie, 2014; Tonin, Brett, & Colagiuri, 2016) either directly recorded from WT (e.g., Yokoyama et al., 2014) or synthesized to reproduce key elements of these recordings (e.g., Tonin et al., 2016). A range of exposure symptoms have been reported but no systematic or significant effects of IS and LF have been demonstrated.

In general, sample sizes have been relatively small (e.g., $n=2$, Hansen, Walker, et al., 2015; $n=72$, Tonin et al., 2016) with studies likely to be statistically under powered (see Supplementary Material). Exposure times have been in the order of minutes to a few 10 s of minutes with a diversity of presentation levels above and below the IS/LF levels reported in the field.

Some free field stimulus playback systems have failed to deliver sound at the BPF and low-order harmonics frequencies (Yokoyama et al., 2014) while others have used headphone playback (Tonin et al., 2016). Many studies have not been blinded or double blinded, while others have been specifically designed to examine the effects of demand characteristics by manipulating expectancy (e.g., Crichton et al., 2014; Tonin et al., 2016). The latter studies have demonstrated, unsurprisingly, that manipulation of expectancy regarding the physiological effects of WT IS and LF has a moderate effect on the number and strength of symptoms reported by subjects regardless of the noise exposure conditions. Interestingly, Tonin et al. (2016) also report in their double-blind study that the presence of IS increased concern about health effects of WTN-expressed postexposure although subjects reported not hearing the IS stimulus.

In summary, there appears a prima facia case for the existence of sensory transduction of LF and IS and its representation in the nervous system. While a number of plausible mechanisms have been proposed, the actual mechanism of transduction has yet to be demonstrated. There are some laboratory-based studies examining the exposure to either recorded or simulated WTN, but the current data regarding potential perceptual or physiological are inconclusive.

General Summary and Conclusions

Although not an exhaustive survey of this literature, this review indicates that there are questions relating to the measurement and propagation of LF and IS and its encoding by the central nervous system (e.g., Dommes et al., 2009; Weichenberger et al., 2017) that are relevant to the possible perceptual and physiological effects of WTN but for which we do not have a good scientific understanding. There is much contention and opinion in these areas that, from a scientific perspective, are not well founded in the data, simply because there are little data available that effectively address these issues. This justifies a clear call to action for resources and support to promote high-quality scientific research in these areas.

Some of the research questions that arise from this review include the need for the following:

1. A more complete characterization and modeling of the sound generated by individual WTs and the large aggregations that comprise the modern windfarm. Such research needs to consider the spectrum from the BPF to its higher harmonics and incorporate the different propagation models that apply to different frequency ranges along with the effects of terrain, atmospheric conditions, and other potential modifiers of the sound.
2. The development of a more complete understanding of the interactions between WTN and the built structures in which people live and sleep. Such research needs to consider the different modes of excitation including substrate vibration, cavity resonances (including Helmholtz resonance and the interconnection of rooms), and differential building material sound insulation. New methods need to be developed for accurately and effectively measuring acute and chronic exposure (dosimetry) and for managing wind and other interference in the measurements.
3. Structural and aeronautic engineering research to discover ways to minimize the BPF generation and other potentially annoying sound sources.
4. Research to directly examine the effects of IS on the cochlea and vestibular apparatus. Although different theories have been advanced as to how IS and LF might be transduced and excite the central nervous system, there are little direct data demonstrating whether and how this occurs.
5. Research to better understand the neural connectivity of the putative transducers in the inner ear and an understanding of the consequences of their possible activation by IS and LF, notwithstanding the recent brain imaging data demonstrating differential activation of different brain structures (including the auditory cortex) by IS.
6. Research to better characterize the physiology of individuals who report susceptibility to WTN with a focus on whether these individuals represent a statistical tail of a normally distributed population or display other dysfunction or pathology that mediates susceptibility (e.g., SCD or lymphatic hydrops). In particular, an examination is required of the

hypothesis that small individual differences in threshold sensitivity to IS could underlie the differential activation of the anterior cingulate cortex and amygdala at subliminal sound levels.

This is not intended to be an exhaustive list of possible research areas. A research initiative to encourage and develop a very wide diversity of proposals is warranted as it is from the depth, capacity, and ingenuity of the researchers that work in these areas that the insights and the most effective research questions will come.

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References

Bauer, M., Baker, C., Barham, R., Hensel, J., Kling, C., Trahms, L., . . . Sander, T. (2013). Magnetoencephalography of deep lying auditory sources using acoustical devices for infra-and ultrasound stimulation. *Biomedical Engineering/ Biomedizinische Technik*. doi:10.1515/bmt-2013-4135

Chapman, S., & Crichton, F. (2017). *Wind turbine syndrome: A communicated disease*. Sydney, Australia: Sydney University Press.

Cheatham, M., & Dallos, P. (2001). Inner hair cell response patterns: Implications for low-frequency hearing. *The Journal of the Acoustical Society of America*, *110*(4), 2034–2044. doi:10.1121/1.1397357

Council of Canadian Academies. (2015). *Understanding the evidence: Wind turbine noise*. Ottawa, ON: The Expert Panel on Wind Turbine Noise and Human Health, Council of Canadian Academies.

Crichton, F., Dodd, G., Schmid, G., Gamble, G., & Petrie, K. (2014). Can expectations produce symptoms from infrasound associated with wind turbines. *Health Psychology*, *33*(4), 360–364. doi:10.1037/a0031760

Dallos, P. (2012). *The auditory periphery biophysics and physiology*. New York, NY: Elsevier.

Dauchez, N., Hayot, M., & Denis, S. (2016). Effectiveness of nonporous windscreens for infrasonic measurements. *The Journal of the Acoustical Society of America*, *139*(6), 3177–3181. doi:10.1121/1.4954260

Dommes, E., Bauknecht, H., Scholz, G., Rothemund, Y., Hensel, J., & Klingebiel, R. (2009). Auditory cortex stimulation by low-frequency tones—An fMRI study. *Brain Research*, *1304*, 129–137.

Drexl, M., Krause, E., Gürkov, R., & Wiegrebe, L. (2016). Responses of the human inner ear to low-frequency sound. In P. van Dijk, D. Başkent, E. Gaudrain, E. de Kleine, A. Wagner, & C. Lanting (Eds), *Physiology, psychoacoustics, and cognition in normal and impaired hearing* (pp. 275–284). Cham, Switzerland: Springer International Publishing. doi:10.1007/978-3-319-25474-6_29

Drexl, M., Otto, L., Wiegrebe, L., Marquardt, T., Gürkov, R., & Krause, E. (2016). Low-frequency sound exposure causes reversible long-term changes of cochlear transfer characteristics. *Hearing Research*, *332*, 87–94. doi:10.1016/j.heares.2015.12.010

Hansen, C. H., Doolan, C. J., & Hansen, K. L. (2017). Effects of wind farm noise and vibration on people. In C. H. Hansen, C. J. Doolan, & K. L. Hansen (Eds), *Wind farm noise: Measurement, assessment* (pp. 436–475). Chichester, England: John Wiley. doi:10.1002/978 1118826140

Hansen, K., Walker, B., Zajamsek, B., & Hansen, C. (2015, April). *Perception and annoyance of low frequency noise versus infrasound in the context of wind turbine noise*. Paper presented at the Sixth International Meeting on Wind Turbine Noise, Glasgow, Scotland.

Hansen, K., Zajamsek, B., & Hansen, C. (2014). Identification of low frequency wind turbine noise using secondary windscreens of various geometries. *Noise Control Engineering Journal*, *62*(2), 69–82. doi:10.3397/1/376207

Hansen, K. L., Hansen, C. H., & Zajamšek, B. (2015). Outdoor to indoor reduction of wind farm noise for rural residences. *Building and Environment*, *94*, 764–772. doi:10.1016/j.buildenv.2015.06.017

Hensel, J., Scholz, G., Hurttig, U., Mrowinski, D., & Janssen, T. (2007). Impact of infrasound on the human cochlea. *Hearing Research*, *233*(1), 67–76. doi:10.1016/j.heares.2007.07.004

ISO, B. (2003). 226: 2003: Acoustics–Normal equal-loudness-level contours. *International Organization for Standardization*, 63.

Jeanson, L., Wiegrebe, L., Gürkov, R., Krause, E., & Drexl, M. (2017). Aftereffects of intense low-frequency sound on spontaneous otoacoustic emissions: Effect of frequency and level. *Journal of the Association for Research in Otolaryngology*, *18*(1), 111–119. doi:10.1007/s10162-016-0590-8

Jung, S. S., Cheung, W.-S., Cheong, C., & Shin, S.-H. (2008). Experimental identification of acoustic emission characteristics of large wind turbines with emphasis on infrasound and low-frequency noise. *Journal of the Korean Physical Society*, *53*(4), 1897–1905.

Keith, S. E., Feder, K., Voicescu, S. A., Soukhovtsev, V., Denning, A., Tsang, J., . . . van den Berg, F. (2016). Wind turbine sound power measurements. *Journal of the*

Acoustical Society of America, *139*(3), 1431–1435. doi:10.1121/1.4942405

Knopper, L. D., Ollson, C. A., McCallum, L. C., Whitfield Aslund, M. L., Berger, R. G., Souweine, K., & McDaniel, M. (2014). Wind turbines and human health. *Frontiers in Public Health*, *2*, 63. doi:10.3389/fpubh.2014.00063

Kuehler, R., Fedtke, T., & Hensel, J. (2015). Infrasonic and low-frequency insert earphone hearing threshold. *The Journal of the Acoustical Society of America*, *137*(4), EL347–EL353. doi:10.1121/1.4916795

Kugler, K., Wiegrebe, L., Grothe, B., Kössl, M., Gürkov, R., Krause, E., & Drexl, M. (2014). Low-frequency sound affects active micromechanics in the human inner ear. *Royal Society Open Science*, *1*(2). doi:10.1098/rsos.140166

Lepoutre, P., Avan, P., De Cheveigne, A., Ecotiere, D., Evrard, A. S., Moati, F., ... Toppila, E. (2017). *Evaluation des effets sanitaires des basses fréquences sonores et infrasons dus aux parcs éoliens* [Evaluation of the health effects of low sound and infrasonic frequencies due to wind farms]. Maisons-Alfort, France: IFSTTAR-Institut Français des Sciences et Technologies des Transports, de l'Aménagement et des Réseaux.

Leventhall, G. (2015, May). Application of regulatory governance and economic impact of wind turbines. *Submission to the Select Committee on Wind Turbines*. Retrieved from https://www.aph.gov.au/Parliamentary_Business/Committees/Senate/Wind_Turbines/Wind_Turbines/Submissions?main_0_content_1_RadGrid1ChangePage=13_20

Marcillo, O., Arrowsmith, S., Blom, P., & Jones, K. (2015). On infrasound generated by wind farms and its propagation in low-altitude tropospheric waveguides. *Journal of Geophysical Research: Atmospheres*, *120*(19), 9855–9868. doi:10.1002/2014JD022821

McCunney, R. J., Mundt, K. A., Colby, W. D., Dobie, R., Kaliski, K., & Blais, M. (2014). Wind turbines and health: A critical review of the scientific literature. *Journal of Occupational and Environmental Medicine*, *56*(11), e108–e130. doi:10.1097/JOM.0000000000000313

Michaud, D. (2015). Health and well-being related to wind turbine noise exposure: Summary of results. *The Journal of the Acoustical Society of America*, *137*(4), 2368–2368. doi:10.1121/1.4920604

Michaud, D. S., Feder, K., Keith, S. E., Voicescu, S. A., Marro, L., Than, J., ... van den Berg, F. (2016a). Exposure to wind turbine noise: Perceptual responses and reported health effects. *The Journal of the Acoustical Society of America*, *139*(3), 1443–1454. doi:10.1121/1.4942391

Michaud, D. S., Feder, K., Keith, S. E., Voicescu, S. A., Marro, L., Than, J., ... van den Berg, F. (2016b). Self-reported and measured stress related responses associated with exposure to wind turbine noise. *The Journal of the Acoustical Society of America*, *139*(3), 1467–1479. doi:10.1121/1.4942402

Michaud, D. S., Keith, S. E., Feder, K., Voicescu, S. A., Marro, L., Than, J., ... Lavigne, E. (2016). Personal and situational variables associated with wind turbine noise annoyance. *The Journal of the Acoustical Society of America*, *139*(3), 1455–1466. doi:10.1121/1.4942390

Moller, H., & Pedersen, C. S. (2004). Hearing at low and infrasonic frequencies. *Noise and Health*, *6*(23), 37.

Moller, H., & Pedersen, C. S. (2011). Low-frequency noise from large wind turbines. *The Journal of the Acoustical Society of America*, *129*(6), 3727–3744. doi:10.1121/1.3543957

National Health and Medical Research Council. (2015). *NHMRC statement and information paper: Evidence on wind farms and human health*. Canberra: Author (Australia). Retrieved from http://bit.ly/1gC2yRy

Oerlemans, S., Sijtsma, P., & López, B. M. (2007). Location and quantification of noise sources on a wind turbine. *Journal of Sound and Vibration*, *299*(4), 869–883. doi:10.1016/j.jsv.2006.07.032

Patuzzi, R., Sellick, P., & Johnstone, B. (1984). The modulation of the sensitivity of the mammalian cochlea by low frequency tones. III. Basilar membrane motion. *Hearing Research*, *13*(1), 19–27. doi:10.1016/0378-5955(84)90091-1

Pedersen, S., Møller, H., & Waye, K. P. (2007). Indoor measurements of noise at low frequencies—Problems and solutions. *Journal of Low Frequency Noise, Vibration and Active Control*, *26*(4), 249–270. doi:10.1260/026309207783571389

Salt, A. N., & Hullar, T. E. (2010). Responses of the ear to low frequency sounds, infrasound and wind turbines. *Hearing Research*, *268*(1–2), 12–21. doi:10.1016/j.heares.2010.06.007

Salt, A. N., Lichtenhan, J. T., Gill, R. M., & Hartsock, J. J. (2013). Large endolymphatic potentials from low-frequency and infrasonic tones in the guinea pig. *The Journal of the Acoustical Society of America*, *133*(3), 1561–1571. doi:10.1121/1.4789005

Schmidt, J. H., & Klokker, M. (2014). Health effects related to wind turbine noise exposure: A systematic review. *PLoS One*, *9*(12), e114183doi:10.1371/journal.pone.0114183

Schomer, P. D., Erdreich, J., Pamidighantam, P. K., & Boyle, J. H. (2015). A theory to explain some physiological effects of the infrasonic emissions at some wind farm sites. *The Journal of the Acoustical Society of America*, *137*(3), 1356–1365. doi:10.1121/1.4913775

Sugimoto, T., Koyama, K., Kurihara, Y., & Watanabe, K. (2008, August 20–22). *Measurement of infrasound generated by wind turbine generator*. Paper presented at the SICE Annual Conference, The University of Electrocommunications, Japan.

Thorsson, P., Persson Waye, K., Smith, M., Ögren, M., Pedersen, E., & Forssén, J. (2018). Low-frequency outdoor–indoor noise level difference for wind turbine assessment. *The Journal of the Acoustical Society of America*, *143*(3), EL206–EL211. doi:10.1121/1.5027018

Tonin, R., Brett, J., & Colagiuri, B. (2016). The effect of infrasound and negative expectations to adverse pathological symptoms from wind farms. *Journal of Low Frequency Noise, Vibration and Active Control*, *35*(1), 77–90. doi:10.1177/0263092316628257

Traboulsi, R., & Avan, P. (2007). Transmission of infrasonic pressure waves from cerebrospinal to intralabyrinthine fluids through the human cochlear aqueduct: Non-invasive measurements with otoacoustic emissions. *Hearing Research*, *233*(1), 30–39.

Turnbull, C., Turner, J., & Walsh, D. (2012). Measurement and level of infrasound from wind farms and other sources. *Acoustics Australia*, *40*(1), 45–50.

Uzun-Coruhlu, H., Curthoys, I. S., & Jones, A. S. (2007). Attachment of the utricular and saccular maculae to the temporal bone. *Hearing Research*, *233*(1), 77–85. doi:10.1016/j.heares.2007.07.008

Valberg, P. A., Van Deventer, T. E., & Repacholi, M. H. (2007). Workgroup report: Base stations and wireless networks—Radiofrequency (RF) exposures and health consequences. *Environmental Health Perspectives*, *115*(3), 416doi:10.1289/ehp.9633

Van den Berg, G. P. (2006). *The sound of high winds. The effect of atmospheric stability on wind turbine sound and microphone noise*. (Unpublished doctoral dissertation). University of Gronigen, the Netherlands.

van Kamp, I., & van den Berg, F. (2018). Health effects related to wind turbine sound, including low-frequency sound and infrasound. *Acoustics Australia*, *46*(1), 31–57. doi:10.1007/s40857-017-0115-6

Walker, B. (2013, August 28–30). *Infrasound measurement, interpretation and misinterpretation*. Paper presented at the Proceedings of the Fifth International Meeting on Wind Turbine Noise, Denver, CO.

Weichenberger, M., Bauer, M., Kühler, R., Hensel, J., Forlim, C. G., Ihlenfeld, A., . . . Kühn, S. (2017). Altered cortical and subcortical connectivity due to infrasound administered near the hearing threshold–Evidence from fMRI. *PLoS One*, *12*(4), e0174420. doi:10.1371/journal.pone.0174420

Weichenberger, M., Kühler, R., Bauer, M., Hensel, J., Brühl, R., Ihlenfeld, A., . . . Kühn, S. (2015). Brief bursts of infrasound may improve cognitive function—An fMRI study. *Hearing Research*, *328*, 87–93. doi:10.1016/j.heares.2015.08.001

Yokoyama, S., Sakamoto, S., & Tachibana, H. (2014). Perception of low frequency components in wind turbine noise. *Noise Control Engineering Journal*, *62*(5), 295–305.

Zajamšek, B., Hansen, K. L., Doolan, C. J., & Hansen, C. H. (2016). Characterisation of wind farm infrasound and low-frequency noise. *Journal of Sound and Vibration*, *370*, 176–190. doi:10.1016/j.jsv.2016.02.001

Zorumski, W., & Willshire, W. Jr (1989). Low frequency acoustic propagation in an atmospheric boundary layer. *AIAA Journal*, *27*, 6–12.