

# Wind turbine infrasound: Phenomenology and effect on people

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## 1. Introduction

Global efforts to improve sustainability have led to the rapid growth in the use of renewable energy sources such as wind energy (Deshmukh et al., 2019). This, in turn, has led to increasing numbers of wind turbines near residences and increasing exposure of the occupants to wind turbine infrasound. There are strongly partisan and contradictory findings on whether this poses a health risk. There are those who believe that since infrasound cannot be heard, it cannot do any damage. However, there is growing international evidence that it annoys some people and that this may lead to long-term health problems. This work provides an interpretive review of the multi-disciplinary research in the fields of acoustic theory, wind turbine noise, structural coupling with infrasound and the role of the central nervous system (CNS) in the human experience (Fig. 1). It provides a new perspective on the way in which wind turbine infrasound interacts with dwellings based on the fundamental properties of the sound waves. It also provides an explanation for why a small proportion of residents have a strong adverse reaction to the persistent, episodic infrasound and proposes a simple mitigation strategy. In doing so, it advances the understanding of wind as an important source of renewable energy.

Airborne sound is a sinusoidal variation in pressure that travels as a longitudinal wave through the air with a particular frequency, wavelength and amplitude. Amplitude is an objective measure of the sound pressure level (SPL) and 'loudness' is the subjective perception of the sound by the ear. The amplitude is extremely small; the average sound from a television has a pressure variation of 0.02 Pa or 20 millionths of the ambient pressure of 101.3 kPa (Le Pichon, Blanc and Hauchecorne,

2010). Perfect hearing is defined as the ability to hear airborne sounds with frequencies ranging from 20 Hz to 20,000 Hz, which corresponds to wavelengths of approximately 17 m to 17 mm respectively. The ear is particularly sensitive to sounds above 100 Hz, so early sound research focused on sounds at the higher end of the frequency spectrum and their associated effect on hearing loss. Sound below 100 to 250 Hz is called low frequency noise (LFN) and sound below about 20 Hz is called infrasound (Baliatsas et al. 2016; Mühlhans, 2017). The latter is the focus of this research. There are both natural and anthropogenic sources of infrasound. Natural sources include the eruption of volcanoes, sound produced by large animals (such as whales, elephants and rhinoceroses), thunder, avalanches and ocean waves. Anthropogenic sources include explosions, trains, submarines, machinery (such as compressors, motors and wind turbines) and the vibration of large structures such as bridges.

Infrasound has several unique properties that can be broadly categorised as, firstly, phenomenological properties and, secondly, properties relating to its effect on people.

Audible sound becomes uniformly softer with distance, losing energy to the atmosphere and obstacles and dispersing its energy as it expands to larger volumes. This is not quite the case with infrasound, which can get louder over certain distances. Because it is a plane wave, rather than a spherical wave, centred on the source, it does not suffer the geometrical effects of being spread over a volume that increases as the square of the distance. Consequently, the rubric of sound pressure level decreasing with inverse of the square of the distance is approximately true for audible sound but is not true for infrasound. Infrasound has very long wavelengths that do not interact with small objects, and it suffers very little diminution over distance. For example, 1 Hz sound is

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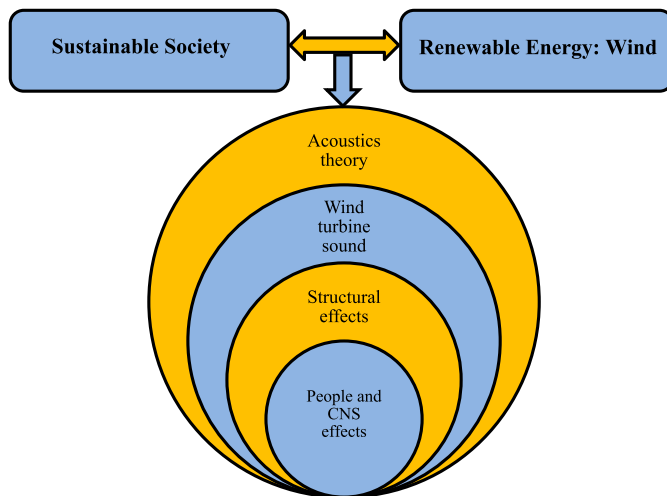


Fig. 1. Research framework: an interpretive inter-disciplinary review on wind energy as an important aspect of a sustainable society.

experimentally measured to be absorbed at 0.003 dB/100 km compared with 100 Hz sound which is absorbed at 30 dB/100 km (McComas et al., 2018). The eruption of Mount Etna in 2016 is a commonly cited example of the persistence of infrasound over long distances; it was detected 1, 200 km away with a sound pressure level that was 20% of its value at 5 km away (Bedard and Georges, 2000; Marchetti et al., 2019).

Lightweight structures are capable of responding to infrasound because the natural frequency of vibration of their elements can approach an infrasound frequency (Granzotto, Di Bella, and Piana, 2020). Its energy can therefore be transduced into sound at harmonics of the dominant infrasound frequencies and can also produce parasitic vibrations in coupled structures. Vardaxis, Bard and Persson Waye (2018) note that laboratory tests on sound transmission through building elements are not as good as field tests because they do not capture the interaction of the whole building structure in sound propagation. There is an added difficulty in studying the behaviour of infrasound, namely that most standard microphones are not capable of detecting sound frequencies below about 20 Hz, so micro-barometers must be used (CCA, 2015). The transmission of infrasound over large distances is well known and there is a global monitoring system (IMS) which consists of a network of 60 stations using micro-barometer arrays to detect explosions as part of the Comprehensive Nuclear-Test Ban Treaty (CTBT) (Bedard and Georges, 2000; Sutherland and Bass 2004; Le Pichon, Blanc and Hauchecorne, 2010). Another problem is that sound monitoring equipment commonly uses an 'A-rating' process that emphasizes the frequencies to which the human ear is most sensitive. This results in over-weighting 1,000 to 7,000 Hz sound, under-weighting 20 to 1,000 Hz sound and completely filtering out anything below 20 Hz. Despite this, A-rating is still commonly used to measure environmental sound and is the basis for dismissing claims of the presence of infrasound (Boretti, Ordys and Al Zubaidy, 2018).

Reports on the effects of infrasound on people are contradictory, and, in the case of wind turbines, have produced strong partisans. This disagreement is only possible because there is no clear and consistent explanation of the data. This is the second focus in this research. The ear is less sensitive to infrasound than it is to higher frequencies and many researchers believe that 'if the sound cannot be heard, it cannot be harmful' [Zagubi n and Wolniewicz, 2020]. If this logic were correct, then by analogy infrared light would not be harmful to humans because it is not visible. In fact, infrasound is audible providing it is sufficiently loud (at a high enough sound pressure level) and it can also be sensed by the vestibular system and by cells in the skin as a vibration (CCA, 2015; M ller and Pedersen, 2004; Baliatsas et al., 2016; M hlhans, 2017). Magnetic resonance imaging (MRI) shows activity in the auditory cortex

of people exposed to 8 Hz infrasound at a loudness of 20 phn (Baeza Moyano and Gonzalez Lezcano, 2022; Boretti, Ordys and Al Zubaidy, 2018). There are many reports of infrasound causing physiological and psychological harm to people. M hlhans (2017) provides a very comprehensive review that debunks many common myths about infrasound. The rapid expansion of wind turbine installations has raised concern about the potential health risks to nearby residents (Deshmukh et al., 2019) and the Council of Canadian Academies undertook a comprehensive review of this area (CCA, 2015). The findings of this report are:

- The sound signature from wind turbines is complex; it covers a wide range of frequencies (including infrasound), the outdoor SPLs vary depending on distance, wind speed and wind direction and amplitude modulation can result in low frequency 'swishing' or 'thumping' noises.
- There is evidence that exposure to wind turbine noise causes annoyance. This may be influenced by other factors such as attitude towards wind turbines, economic aspects and visual impacts. Evidence suggests that the infrasound and LFN components of the sound are the most likely cause of long-term annoyance.
- There is limited evidence that exposure to wind turbine noise causes sleep disturbance.
- Exposure to wind turbine noise does not appear to cause hearing loss, stress or other health effects such as tinnitus, vertigo, nausea, cardiovascular diseases, diabetes, etc. It is unclear whether these could be caused by pure annoyance.
- Epidemiological studies have limitations such as inadequate measurements, bias, poor controls and too short an exposure to the sound.

More recent work has confirmed many of these findings. The sound signature from wind turbines is discussed in Section 3.

van Kamp and van den Berg (2018, 2021) provide a detailed review of the literature on the effect of LFN and infrasound from wind turbines on the health of nearby residents, including annoyance, sleep disturbance, cardiovascular disease, metabolic effects, and mental and cognitive impacts. They also consider non-acoustic factors such as the visual impact of wind turbines, people's perceptions and attitudes about wind turbines and their involvement in planning wind turbine farms. They show that annoyance is the most common effect and that the louder the noise, the greater the annoyance. The annoyance may also be increased by visual impacts and by rhythmic pulses on the dwellings. The annoyance itself may be the root of sleep disturbance and other long term health effects. Vardaxis, Bard and Persson Waye (2018) and Baliatsas et al. (2016) have shown that people are more annoyed by LFN and infrasound, than by higher frequency sounds, and that it may interfere with sleep and concentration. There are also studies showing that some individuals are more sensitive to infrasound than others (Burke, Uppenkamp and Koch, 2020; Jurado and Marquardt, 2020). However, the tests were conducted at much greater loudness levels than are typically present in buildings near wind turbine farms (Zagubi n and Wolniewicz, 2020; Baeza Moyano and Gonzalez Lezcano, 2022).

Baliatsas et al. (2016) report that much of the published epidemiological research suffers from poor methodology such as short time exposure to LFN, poor or no control testing and a reliance on subjective data rather than objective medical data. Zagubi n and Wolniewicz (2020) discuss the 'nocebo' effect where adverse health symptoms are produced psychosomatically by negative expectations. To eliminate these problems, this research focusses on studies using rats and on studies where responses to infrasound are measured objectively, for example using blood pressure and heart rate readings. The mechanism of the response of the autonomic nervous system (ANS) to infrasound is discussed in Section 4.

One of the most rigorous studies into the effects of wind turbine infrasound on people is reported in Majjala et al. (2021). They studied

two groups of people living near a wind turbine farm. The first group of people, called the 'symptomatic group', reported symptoms of stress that were thought to be caused by wind turbine infrasound. The second group of people, called the 'control group', experienced no discomfort from living near a wind turbine farm. The researchers measured the blood pressure and the heart rate of both groups in a series of tests where recorded and acoustically accurate wind turbine infrasound was randomly interspersed with other sounds and they compared the response with each individual's response to a 3-minute standard cold pressor test. They found no difference in the measured response of the two groups when they were unaware of their exposure to infrasound. However, when the two groups were told that they would be exposed to infrasound, the symptomatic group had a strong stress reaction while the control group had no reaction. The reason for this difference is discussed in the context of the ANS in Section 4.

In summary, this work elucidates the phenomenological behaviour of infrasound in order to provide an explanation for its interaction with the built environment. It then examines the effect of infrasound on the central nervous system in an effort to understand why it causes chronic noise stress in a small number of people. The impact of this work is, firstly, to resolve the controversies that rage around the subject and secondly, to provide a reasonable hope of mitigating a problem that causes severe distress to many people.

## 2. Materials and methods

A systematic literature review was conducted using the three-stage PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analysis) method (Page et al., 2021). The first stage, planning and identification of the initial pool of literature involved the following steps:

- Selecting the initial eligibility criteria, namely, peer-reviewed academic articles, reports and books written in English with a focus on those published since 2012.
- Using Google Scholar and EBSCO Discovery search engines with search terms including a combination of the words infrasound, aperture, attenuation, transmission, buildings, health effect, exposure, central nervous system, autonomic nervous system, noise, wind turbine and soundscape.

In the second stage, the resulting literature was screened to check for relevance to the research themes: phenomenology of infrasound and its interaction with the built environment and the effect of infrasound on the central nervous system. Exclusion criteria were:

- Small studies concerning subjective, anecdotal evidence from small sample sets, and
- Studies on the health effects of exposure to loud noise, and
- Studies on sound above 250 Hz in frequency.

Citations of the remaining literature were used to identify more recent published studies. A total of 58 articles were used (Fig. 2). The final stage was synthesising the literature into the research themes. These are discussed in Sections 3 and 4.

## 3. The phenomenology of infrasound

Infrasound behaves very differently from audible sound; it travels long distances with far less attenuation and has different interactions with buildings. Infrasound from wind turbines is different from other infrasound sources because it is present over long periods of time, is episodic in nature and is becoming more prevalent as the number of wind turbines increases. Therefore, it is important to understand the effect of wind turbine infrasound on people. These aspects are discussed below. Table 1 summarizes the themes and citations for this section.

### 3.1. The behaviour of infrasound waves

At 20°C, the speed of sound,  $c$ , in air is approximately 343 m/s and the wavelength,  $\lambda$ , and the frequency,  $f$ , are related by Eq. (1):

$$c = f\lambda \quad (1)$$

This means that 1 Hz infrasound has a wavelength of about 343 m while 10,000 Hz which is audible sound has a wavelength of about 34.3 mm. With such disparate wavelengths, it is not surprising that infrasound and audible sound behave differently and need to be treated differently. The spherical wave front of audible sound is curved, while infrasound is found to be planar. In order to capture infrasound, McComas et al. (2018) describe 5-element infrasound arrays placed on a 38 m aperture

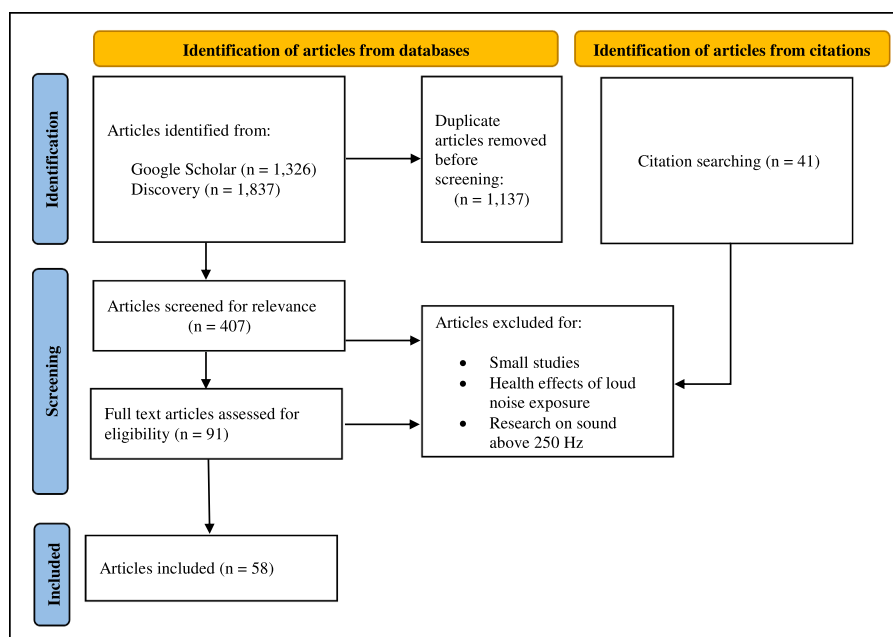


Fig. 2. PRISMA flow diagram of the method. (Source: Page et al., 2021).

**Table 1**  
Review of infrasound phenomenology.

Theme	Citations
Acoustics theory: wave behaviour, propagation, attenuation	Baliatsas et al. 2016; Bedard and Georges, 2000; Evans, Bass and Sutherland, 1972; Javeloyes, Pendás-Recondo and Sánchez, 2021; Keith, Daigle and Stinson, 2018; Le Pichon, Blanc and Hauchecorne, 2010; Le Pichon, Ceranna and Vergoz, 2012; Marchetti et al., 2019; Marcillo et al., 2015; McComas et al., 2018; Mühlhans, 2017; Nuryantini, Zakwandi and Ariayuda, 2021; Sutherland and Bass 2004
Infrasound in the environment: structural interaction, measurement	Baliatsas et al., 2016; Bedard and Georges, 2000; Boczar et al., 2022; Boretti, Ordys and Al Zubaidy, 2018; CCA, 2015; Granzotto, Di Bella and Piana, 2020; Jakobsen, 2005; Keith, Daigle and Stinson, 2018; Krahe et al., 2019; Le Pichon, Blanc and Hauchecorne, 2010; McComas et al., 2018; Sutherland and Bass 2004; Tonin, 2018; van Kamp and van den Berg, 2018; Vardaxis, Bard and Persson Waye, 2018
Wind turbine: sound signature, factors affecting transmission, amelioration in dwellings	Bertagnolio and Fischer, 2021; Boczar et al., 2022; Blumendeller et al., 2022; Boretti, Ordys and Al Zubaidy, 2018; CCA, 2015; D'Amico, Van Renterghem and Botteldooren, 2022; Deshmukh et al., 2019; Jakobsen, 2005; Keith, Daigle and Stinson, 2018; Marcillo et al., 2015; Öhlund and Larsson, 2015; Okada, Yoshihisa and Hyodo, 2019; Tonin, 2012; Tonin, 2018; Weckendorf et al., 2016

and on a 120 m aperture and provide detail on the signal processing. The sensors are placed, in the horizontal plane, at the centre and on the periphery of a large circle. The diameter of this circle is termed the aperture. Measuring a passing infrasound wave has considerably improved precision if the simultaneous output of several microphones is used, each at a different location. This can also permit the azimuth of the sound source to be determined. Inside buildings, just one microphone is adequate.

When there is a point source of audible sound with power,  $P$ , and no obstructions, the sound spreads out radially from the source and the sound intensity,  $I$ , varies with distance,  $r$ , from the source according to the inverse square law:

$$I = \frac{P}{4\pi r^2} \quad (2)$$

The intensity decrease with distance is called distance attenuation or distance damping and is a conservation of energy effect; energy intensity decreases as the sound waves spread out. It is demonstrated in Nuryantini, Zakwandi and Ariayuda (2021) that Eq. (2) is approximately true over short distances and it assumes that there is no absorption of the sound wave energy (termed dissipation) by the air. This assumption is generally not quite correct; there is also 'classical' attenuation of sound wave energy through atmospheric absorption which is primarily Stokes-Kirchoff energy loss due to viscosity and heat conduction (Evans, Bass and Sutherland, 1972). The latter can be explained in terms of the perfect gas law; sound waves are a succession of pressure fluctuations, which may also be viewed as a succession of temperature fluctuations. High pressure regions have higher air particle collisions and are therefore regions of higher temperature. For a 10,000 Hz sound wave the temperature extremes occurs over about 17 millimetres so that thermal conduction is more rapid and the wave energy dissipates more quickly than for lower frequencies. For a 1 Hz wave, the temperature extremes occur over about 172 metres so heat conduction in the air is relatively

small, as attenuation. This means that infrasound suffers much less energy loss through thermal effects compared with audible sound (Mühlhans, 2017). There is additional sound energy absorption through molecular relaxation.

From Stokes' law, classical sound attenuation is approximately proportional to the square of the sound wave's frequency. Therefore, the attenuation of a 10,000 Hz sound is  $10^8$  times greater than the attenuation of a 1 Hz sound.

The Huygens-Fresnel principle states that every point on a wavefront may be regarded as a point source of secondary wavelets and Javeloyes, Pendás-Recondo and Sánchez (2021) provide an analysis of the theoretical propagation path of a wave viewed as an anisotropic (direction-dependent), rheonomic (time-dependent) cone structure. But the notion of a point source in infrasound is problematic; a very small sphere oscillating in volume with a period of one second would not be detected a hundred kilometres away. Infrasound that is produced from a conical surface, such as a loudspeaker, can only be detected a short distance away, so infrasound can be played to subjects using special headphones. Long-range infrasound propagation is more complex; it depends on the source, on atmospheric conditions and on the location of the source, both in terms of its height above ground and the nature of the surrounding terrain. It is a rule of thumb that wave trains are not affected by obstacles of smaller dimension than the wavelength. Because there are geometrically more small objects than large objects, higher frequencies are affected disproportionately. Infrasound from wind turbines has been measured at distances up to 90 km from the source and infrasound from explosive sources has been measured up to 2,000 km away (Keith, Daigle and Stinson, 2018). A semi-infinite hemisphere of air is not plausible in a troposphere less than 16 km thick so numerical modelling of infrasound attenuation is complex; it assumes that the infrasound behaves as a linear elastic wave that is affected by the characteristics of the atmospheric boundary layer (ABL) such as highly stratified winds and the creation of waveguides extending up some hundreds of metres (Marcillo et al., 2015). Le Pichon, Ceranna and Vergoz (2012) provide a detailed discussion of propagation models based on numerical solutions to the wave equation. These are used in the IMS infrasound detection network. The assumption that infrasound is a linear elastic wave leads to close agreement with empirical data. The attenuation coefficient,  $A_p$ , of the pressure wave at a distance  $R$  (in km) from the source is given by Eq. (3) (Le Pichon, Ceranna and Vergoz, 2012):

$$A_p(f, V_{eff-ratio}) = \frac{1}{R} 10^{\frac{\alpha(f)R}{20}} + \frac{R^\beta(f, V_{eff-ratio})}{1 + 10^{\frac{\delta-R}{\sigma(f)}}} \quad (3)$$

The parameters  $\alpha$ ,  $\beta$ ,  $\delta$ , and  $\sigma$  are determined by regression on measured data. The first term in Eq. (3) is the near-field attenuation and represents the decrease in SPL due to geometric spreading and exponential decay. The second term is the far-field attenuation due to the different layers of the atmosphere (troposphere, stratosphere, mesosphere and thermosphere) which act as a series of ducts on the sound waves. The phenomenon is analogous to the reflections of sound waves by ocean thermoclines in sonar systems. The attenuation coefficient,  $A_p$ , is a function of the wave frequency,  $f$ , and the variable,  $V_{eff-ratio}$  which is the ratio of the effective sound speed at 50 km altitude and the sound speed at ground level. Le Pichon, Blanc and Hauchecorne (2010) provide a comprehensive discussion. Fig. 3 is a plot of Eq. (3) for varying  $V_{eff-ratio}$  (the gray lines) and for  $V_{eff-ratio} = 1$  (the red line) for infrasound with a frequency of 1.6 Hz. The plot shows the surprising variation of sound pressure level with distance. In particular, the envelope of gray lines shows that at 5 km from the source the attenuation is about -15 dB, at 20 km the attenuation is about -35 dB, at 100 km the attenuation is about -80 dB, and at 150 km the attenuation varies from -30 to -80 dB. Therefore, depending on the conditions, it is possible for the infrasound to be louder at 150 km from the source than it is at distances of 20 to 100 km from the source. This is very different from audible sound, which

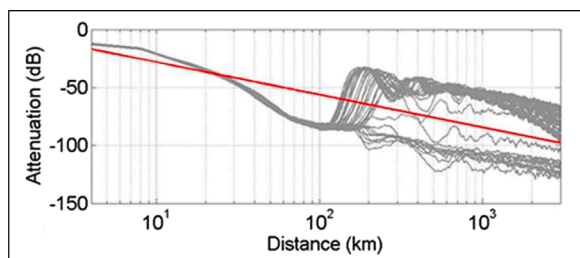


Fig. 3. Attenuation of 1.6 Hz sound with distance. (Source: Le Pichon, Ceranna and Vergoz, 2012).

gets attenuated proportionately with the square of the distance from the source as expressed in Eq. (2).

### 3.2. Infrasound in the built environment

In the built environment, large structures such as bridges, dams and buildings vibrate at a natural frequency that is in the infrasound frequency spectrum. McComas et al. (2018) describe measurements of 10 Hz infrasound from a bridge and show that features such as highways can act as wave guides, providing enhanced transmission of the sound, while tall buildings can create acoustic shadows. van Kamp and van den Berg (2018) review studies on vibration in dwellings near wind turbines. They discuss the phenomenon of periodic pressure pulses coinciding with the natural frequency of vibration of the structure to create higher than expected SPLs in the dwelling as well as higher frequency, audible vibrations.

We propose that the profound attribute of infrasound in coupling with the lightweight structures of a building can be explained as follows. Structural members generally have some freedom of deflection; a floor can move up and down in the manner of a diaphragm and a wall or window will flex in and out in the same way. Such deflections require relatively small force compared with that required to move them laterally by an equal amount. The large dimensions of infrasound pressure regions will readily apply considerable forces to large surfaces, causing deflection. If the frequency of infrasound and structure agree, there will be large resonant deflections. Specifically, vibration of the floor will set up vibration of a bed on the floor and this vibration may be felt by a sleeping person, even if it is not audible. This vibration can, in turn, produce harmonics which may extend into the audible range. Further, parasitic oscillations of coupled objects may also transduce the subaudible frequency; for example, the shower door may vibrate with an audible rattle. Most lightweight structures in a built environment have low natural frequencies of vibration and are susceptible, in this way, only to infrasound. High frequency sound cannot couple with these elements (Vardaxis, Bard and Persson Waye, 2018).

Infrasound has a peculiar ability to permeate a house, through the walls, doors and windowpanes or through open apertures. Consider the passage of sound through a diaphragm such as a floor, wall or windowpane. In particular, consider a large window, fixed and sealed at its edges. Sound pressure waves hitting the exterior glass cause the pane to vibrate which, in turn, produces pressure waves in the inside air. There is no other possible mechanism; if the distal surface of the diaphragm does not vibrate, the air in the room cannot vibrate from the sound. The window is relatively stiff and although it will deform in a simple mode (the whole diaphragm moves, with maximum deflection at the centre), it will not readily deform in higher modes because it is stiff. In order to deform appreciably, it requires approximately constant pressure over its whole surface. If it is pushed here and pulled there, its reluctance to bend will result in very little deformation at points of high or low pressure. High frequency sound, from a source orthogonal to the window, will necessarily be quite close (because it does not travel far) and will produce concentric circles of high and low pressure. If it strikes the window obliquely, the pressure pattern will be more jumbled and

the glass will move very little, being restrained by its stiffness. By comparison, low frequency sound has such large wavelength (17 m for 20 Hz sound) that the full window will fall within a similar pressure regime, whether the source is orthogonal or oblique. If a component frequency of the sound coincides with the natural frequency of vibration of the pane, the effect will be stronger. The same argument also applies to walls, roofs and floors. The bottom line is that infrasound can invade buildings much more readily than audible sound. The transmission of low frequency pressure waves is reduced when rigid materials such as brick and concrete are used in buildings (Granzotto, Di Bella and Piana, 2020).

If there are several open apertures in the walls, each will receive a succession of pressure waves and, by Huygens-Fresnel's principle, each aperture will seem to the auditor in the room to be the source of the sound. For audible sounds, the air in each aperture will not vibrate synchronously because the differing distances from the source to the aperture are significant compared with the short wavelengths. For infrasound, all the apertures will tend to be synchronous, so the vibration of the air in the room will be larger.

In summary, the behaviour of infrasound in the built environment is very different from the behaviour of audible sound. It can travel huge distances, invade structures, couple with the components of structures and transduce its energy into the audible range.

### 3.3. Wind turbine infrasound and its effect on nearby residences

Many sources of infrasound are intermittent, irregular and of short duration. The exception is infrasound from windmills which is episodic and persists over many hours. This section looks at the characteristics of wind turbine sound signatures and the typical SPL of infrasound from wind turbines.

There are several studies on the mechanism of sound production from wind turbines showing that it is generated primarily from aerodynamic effects and, to a lesser extent, by movement of the mechanical components (Bertagnolio and Fischer, 2021). The aerodynamics involves air flow around the blades in the form of trailing edge noise, tip noise, blunt trailing edge noise and stalled flow noise. These span a wide range of frequencies from infrasound (due to tip noise) up to about 16,000 Hz. High frequency sound does not travel far from the source so it will not affect people living a few kilometres away (Boczar et al., 2022; Deshmukh et al., 2019). Tonin (2012) and D'Amico, Van Renterghem and Botteldooren (2022) describe impulsive sound from wind turbines at a frequency of about 1 Hz which is the blade passing frequency (BPF) and Boczar et al. (2022) present 2-dimensional power spectral densities (PSDs) from a single wind turbine showing both infrasound and LFN.

Boczar et al. (2022) discuss the difficulty in measuring wind turbine infrasound, both in terms of isolating the source from other infrasound sources, such as the wind, and in terms of the equipment used to measure the acoustic signal. The standard IEC 61400-11 is used for measuring acoustic signals emitted by operating wind turbines in the audible range and the PN-EN 61400-11 standard, Annex A.2 is used to extend the measurements to the IF sound.

Jakobsen (2005) provides an early review of all published measurements of infrasound from wind turbines and notes that there is difficulty comparing measurements because of all the variables (types of wind turbine, wind speed, proximity to other wind turbines, distance of the sensor from the wind turbine, etc.), some of which are not stated in the literature. He cites G-weighted infrasound levels 100 m from the source of about 70 dB from an upwind turbine and 80 to 100 dB from a downwind turbine with a distance attenuation of 3 to 6 dB per distance doubling. In more recent studies, Okada, Yoshihisa and Hyodo (2019) confirm that the highest SPLs of infrasound occur downwind from the turbine and D'Amico, Van Renterghem and Botteldooren (2022) present PSDs showing the effect of wind speed. Öhlund and Larsson (2015) show that, in addition to wind speed and direction, wind turbine sound transmission is strongly affected by local climatic conditions such as

temperature, relative humidity and air pressure and the variation in these parameters with distance from the ground. [Boczar et al. \(2022\)](#) report power spectral density plots (PSDs) showing that wind turbines produce infrasound below 9 Hz, around 16 Hz and LFN at about 25 Hz and that increasing wind speed shifts the frequencies slightly higher. [Blumendeller et al. \(2022\)](#) present power spectral density plots (PSDs) measured simultaneously at a wind turbine farm, and outside and inside houses located just over 1 km away. They show that infrasound arises from the blade rotation at the blade passing frequency (BPF) and its multiples and that these are also present inside the houses. When the wind turbine stops, the infrasound tones disappear in the houses. In general, the infrasound SPL is lower inside the houses than it is at the wind turbine, however, just as [van Kamp and van den Berg \(2018\)](#) postulated, the indoor SPL is **higher** for certain infrasound frequencies due to resonance of the structures and different houses have different resonant frequencies. [Blumendeller et al. \(2022\)](#) note the need for more sound monitoring in the audible range to determine whether the effect of infrasound coupling with the structure can produce higher frequency resonances at significant SPLs. There is some evidence to suggest that infrasound in structures causes pictures on walls and objects on shelves to vibrate and rattle which may annoy occupants ([Tonin, 2018](#); [Krahé et al., 2019](#); [Jakobsen, 2005](#)) and lead to a lack of ‘acoustic comfort’ ([Vardaxis, Bard and Persson Waye, 2018](#)).

In summary, the sound signature from wind turbines is very variable and complex. However, there is ample evidence that wind turbines produce infrasound and that it couples with nearby buildings, in some cases amplifying resonant infrasound frequencies. It may also produce higher frequency sound and this is an area where more research is needed. [Table 1](#) summarizes the themes and citations that are reviewed in this section.

#### 4. The effect of infrasound on people

##### 4.1. A review of the effect on infrasound on people and animals

Clearly no infrasound problem could exist without a biological response to it. The explanation for the biological response has not received much consideration in the literature, other than dismissing it as a ‘nocebo’ effect or a by-product of assorted socio-economic factors. As mentioned in the introduction, people are more annoyed by infrasound from wind turbines than from other sources and there are many reports of its adverse effect on health ([Baeza Moyano and Gonzalez Lezcano, 2022](#); [Michaud et al., 2016](#)). [van Kamp and van den Berg \(2018, 2021\)](#) and [Tonin \(2018\)](#) review this field and discuss whether two pathologies, namely Vibroacoustic Disease (VAD) and Wind Turbine Syndrome (WTS) occur in people living near wind turbines and having long-term exposure to infrasound. VAD is associated with thickening of cardiovascular structures together with depression, irritability and decreased cognitive skills. WTS symptoms include sleep disturbance, headache, tinnitus, ear pressure, dizziness, vertigo, nausea, visual blurring, tachycardia, irritability, problems with concentration and memory and panic episodes. [Tonin \(2018\)](#) cites a 2015 Australian Senate Select Committee on Wind Turbines that concluded there was credible evidence from people living near wind turbines complaining of adverse health symptoms. Annoyance and sleep disturbance seem to be the most common symptoms and subjective data from surveys suggests that these get worse as the house gets closer to the wind turbine source ([Turunen et al., 2021a](#); [van Kamp and van den Berg, 2018, 2021](#)). The Council of Canadian Academies study confirms the finding that wind turbine infrasound can cause annoyance and sleep disturbance ([CCA, 2015](#)). [Michaud et al. \(2016\)](#) note that annoyance increases with increase in SPL and with increasing duration of noise, suggesting that some people become sensitized to the irritation while others become habituated.

Conversely, there are many studies that have investigated the effect of infrasound on people and failed to find measurable health effects. [Szychowska et al. \(2018\)](#) played different sounds to people in an

anechoic chamber and asked them to rate their annoyance. When the testers could see wind turbine images simultaneously with the sound, they were more annoyed than when they were just exposed to the sound. Similarly, as mentioned in the introduction, [Maijala et al. \(2021\)](#) present a very careful study, playing infrasound to a group of people with WTS symptoms and an asymptomatic control group and measuring their autonomous nervous system (ANS) response using blood pressure and heart rate. The control group were unaffected by the infrasound and the WTS group only exhibited symptoms when they were told that they were being exposed to wind turbine infrasound (whether it was actually present or not). The infrasound exposure was at 89 dB for several minutes.

[Baeza Moyano and Gonzalez Lezcano \(2022\)](#) review several cases of people living near wind turbine farms who suffered from annoyance and interrupted sleep and discusses the evolutionary value of responding to noise as a source of danger. However, they also note that the percentage of people displaying symptoms is small compared with all people living near wind turbines. This is confirmed in a study by [Turunen et al., 2021b](#) who found that only about 5% of residents reported adverse symptoms. Both studies conclude that infrasound may cause a wide range of symptoms in some people, but, aside from annoyance, there is no clear evidence that it does cause the symptoms. The study by [Turunen et al., 2021b](#) included a few children who appeared to suffer from wind turbine infrasound related symptoms but the findings were not statistically significant. [Zagubiéń and Wolniewicz, \(2020\)](#) found that children in school were not affected by wind turbine infrasound and opined that this might be because they were less likely to expect that turbine noise might be problematic. In adults, personal factors and social variables are just as likely to produce symptoms such as annoyance. [Peri, Becker and Tal \(2020\)](#) notes that there may be cultural differences in the perception of wind turbines, probably due to differing familiarity; people who have had little experience of wind turbines are more likely to fear that their noise will be problematic.

[Baeza Moyano and Gonzalez Lezcano \(2022\)](#) point out that laboratory studies have mixed results but that some people appear to be hypersensitive to infrasound, in agreement with [Michaud et al. \(2016\)](#). The studies themselves need to avoid common errors such as exposing people to infrasound for short periods of time ([Krahé et al., 2019](#)), using SPLs that are much greater than those near wind turbines and producing symptoms psychosomatically by negative expectations (the ‘nocebo’ effect). Objective measures such as EEG, ECG, blood pressure, heart rate and nystagmus (eye movement) provide more reliable data than subjective questionnaires asking how the testers feel. Laboratory tests where a narrow sample of infrasound frequencies is used, may fail to capture the entire sound signature in a house near a wind turbine.

##### 4.2. An explanation of chronic noise stress symptoms

Prolonged exposure to loud noise is known to cause neurological disorders such as cognitive decline and hearing loss in both people and rats ([Samad et al., 2022](#); [Haider et al., 2020](#)). Like other stressors, noise stress causes activation of the Sympathetic-Adreno-Medullar (SAM) axis leading to the production of stress hormones and a cascade of unpleasant consequences. This syndrome is detailed by [Kryter \(1972\)](#). If the noise persists, most people adapt to it with a mediation response based on homeostasis with activation of the Hypothalamus-Pituitary-Adrenal (HPA) axis. For a detailed description see [Goodoy et al. \(2018\)](#) and [Russell and Lightman \(2019\)](#). For those who cannot adapt, the stress becomes progressively more serious. The factors that allow only some people to develop protective adaptation are very complex ([Ellis and Del Giudice, 2019](#)). In extreme tests with rats, sustained levels of stress hormones and neurotransmitters damaged the immune system, organs and tissues, parts of the brain atrophied and there was increased chronic low-grade inflammation and psychological deterioration which manifested as symptoms such as cardiovascular problems, diabetes, cancer, autoimmune malfunction, depression and anxiety ([Mariotti, 2015](#)).

Haider et al. (2020) and Seidman and Standring (2010) review the physiological and psychological effects. There is evidence of similar brain damage in rats exposed to infrasound and LFN (Huet-Bello et al., 2017).

It is important to know that the human nervous system has a sub-system called the reticular activation system whose function is to assess subconscious inputs. In particular, the importance of any sound cannot be assessed until the sound has been processed. Obviously, survival down the ages required that our forebears could be alerted to danger when they were asleep and whether or not they were concentrating on the sounds around them. The point is that humans hear everything around them at all times. Consequently, sleep will not insulate them from a persistent noise if they find it disturbing. Rabellino et al., (2019) describe this as the Innate Alarm System (IAS).

The SPL of wind turbine infrasound is not usually above 70dB, which would not normally be classified as "loud" (because the ear is less sensitive to infrasound than it is to audible sound), but it is persistent and there is evidence that some people are sensitized to it. Latremolier and Woolf (2009) describe the sensitization of the central nervous system (CNS) when it is repeatedly exposed to stressors; the properties of the neurons change so that the person reacts even when the source of stress is removed.

The process that occurs is that the sufferers are probably able to perceive some rhythmical input that they associate with windmills. Possibly, but not probably, some of the sufferers might be able to hear infrasound. What is more likely is that the sufferers perceive some interaction between structures in the house and the infrasound. Mostly, windmills are not placed in high occupancy areas, so the environmental sound level is usually very low, perhaps 10-15 dB. The probable sequence of events is that, in very quiet surroundings, some vibration in the house is transferred directly through the coupled floor and bed to the sleeping person or some vibration is transduced by the structure into the audible range. This disturbs the person, who becomes increasingly irritated, and this leads to loss of sleep. Over a period of time, this experience is repeated until the prospect of another disturbed night causes distress. After many such nights, the sufferer learns that the advent of the soft sounds will condemn him to considerable distress. He then enters the syndrome of classic phobias. This is well discussed by Frumeno et al. (2021) and Samra and Abdijadid (2018). A similar phenomenon is observed after severe earthquakes such as those in Japan in 2011 and in New Zealand in 2010 (Honma et al., 2012; Kemp et al., 2011). The stress caused some people to become hypersensitive to small vibrations and to report significant mental health problems such as anxiety, paranoia, sleep problems, depression and dizziness (Beaglehole et al., 2019).

The arachnophobe does not fear that the picture of a spider will leap from the page and do harm to him. The claustrophobe does not fear that the walls will actually close about him and crush him to death. What they fear is the unpleasant sensations that are caused by contemplating spiders or confined spaces. This fear is entirely real, even if the spider on the page is not, and the fear can be measured by biometric responses such as elevated heart rate.

This explains the behaviour described in Majjala et al. (2021), which on the face of it is inexplicable. In this authoritative experiment, excellently reproduced samples of windmill infrasound acoustic signatures were played to two cohorts of test subjects; one cohort claimed to be sensitised to windmill noise and the other did not. Here, test subjects could not hear the actual infrasound profile of windmills as experienced in the house of the subject. This was because the experiment lacked structures to transduce the infrasound into the audible range. Clearly the experiment, excellent though it was, did not adequately represent the experience of infrasound over an extended period in a quiet house that happened to have structures that transduced the sound. The people with the established phobia were just as frightened by the suggestion that there was infrasound in the room as arachnophobes would have been if they were told that there were spiders in the room or claustrophobes told

that the walls could slide together until the subject could not move. One of the authors is an arachnophobe and the other is a claustrophobe, so we have real experience of this phenomenon. Not surprisingly, the subject people with WTS reacted strongly when falsely told that wind turbine infrasound was present. The reaction was clearly shown to be genuine by biometric responses.

It seems therefore that sensitivity to wind turbines follows the same pattern as other phobias. Initially, the person becomes aware of the audible sound from the wind turbines in the quiet rural environment. Thereafter, they sense infrasound vibration transmitted through floors and beds while sleeping and/or hear higher frequency noise from harmonics or parasitic coupling in the structure. Over time, the person becomes irritated and suffers a cascade of stress symptoms such as disturbed sleep. The sufferer then learns to fear the experience and becomes hypersensitive and the adverse response can be triggered merely by seeing a moving wind turbine or by being told that a wind turbine is present.

Table 2 summarizes the themes and citations that are reviewed in this section.

## 5. Discussion and conclusions

The key to understanding the phenomenology of infrasound lies in its extremely large wavelengths and its extremely low attenuation over very long distances. A significant portion of the infrasound from wind turbines can be measured in nearby residences, with dominant infrasound episodes at the BPF. While the level of infrasound is below the threshold of hearing, some residents become sensitized either to the infrasound vibration through floors and beds or to higher frequency, audible sound in the structure, caused by resonance. When this happens, they suffer the symptoms of chronic stress. The autonomous nervous system is involved in much the same way as it is for other phobias.

There is no suggestion that the solution to infrasound sensitivity is to remove all sources of infrasound from the built environment - this is as ludicrous as suggesting the elimination of all spiders to solve arachnophobia, or all small spaces to solve claustrophobia. Wind turbines

**Table 2**  
Review of the effect of infrasound.

Topic	Citations
Biological response to infrasound (in people and animals)	Baeza Moyano and Gonzalez Lezcano, 2022; Baliatsas et al., 2016; CCA, 2015; Boretti, Ordys and Al Zubaidy, 2018; Burke, Uppenkamp and Koch, 2020; Deshmukh et al., 2019; Huet-Bello et al., 2017; Jurado and Marquardt, 2020; Krahé et al., 2019; Latremolier and Woolf, 2009; Möller and Pedersen, 2004; Mühlhans, 2017; Rabellino et al., 2019; Szychowska et al. 2018; Seidman and Standring, 2010; Zagubién and Wolniewicz, 2020
Wind turbine infrasound physiological and psychological effect on people	Baeza Moyano and Gonzalez Lezcano, 2022; Baliatsas et al., 2016; Deshmukh et al., 2019; CCA, 2015; Jakobsen, 2005; Krahé et al., 2019; Majjala et al., 2021; Michaud et al., 2016; Mühlhans, 2017; Peri, Becker, and Tal, 2020; Szychowska et al. 2018; Tonin, 2018; Turunen et al., 2021(a and b); van Kamp and van den Berg, 2018; van Kamp and van den Berg, 2021; Vardaxis, Bard and Persson Waye, 2018; Zagubién and Wolniewicz, 2020
Chronic noise stress, the ANS and phobia	Beaglehole et al., 2019; Ellis and Del Giudice, 2019; Frumeno et al. 2021; Goodoy et al., 2018; Haider et al., 2020; Honma et al., 2012; Huet-Bello et al., 2017; Kemp et al., 2011; Kryter, 1972; Mariotti, 2015; Russell and Lightman, 2019; Samad et al., 2022; Samra and Abdijadid, 2018; Seidman and Standring, 2010

provide a valuable source of renewable energy and are likely to become more prevalent in the future.

This work has explained infrasound behaviour and its effect on people. Future research is needed to determine which frequencies of wind turbine sound signatures are most annoying to nearby residents and whether these can be eliminated through better design of the blades. Solid house construction using concrete and brick, is likely to have less active coupling with infrasound and will therefore generate fewer resonant frequencies, but this is hardly a solution for those who are currently suffering a very real problem.

Boretti, Ordys and Al Zubaidy (2018) suggest that active infrasound cancellation (anti-sound by playing the same sound waves out of phase to cancel them) might be an effective remediation. However, this seems impractical as it is very difficult to create infrasound within an entire structure. A sensible and inexpensive solution would be to monitor problematic houses with sound equipment and accelerometers to measure audible noise and inaudible vibration. This would detect low frequency tympanic vibration of floors. Remediation would involve installing bracing to eliminate the annoying vibrations. Weckendorf et al. (2016) review the bracing design approaches used for damping vibrations in timber floors. Ground floors are easier to brace than upper floors. If an upper floor problem is identified, the bed could be moved to an area where the floor vibrates less. This remediation might be done by the owners of wind turbine farms and would probably be an inexpensive but rewarding public relations exercise.

In order to become more sustainable, there is a global effort to increase the use of renewable energy sources, such as wind. Therefore, wind turbine installations will increase in the future and more residents will be exposed to this source of persistent infrasound. The debate on whether or not the infrasound poses significant health risks to residents has reached an impasse. By addressing the needs of nearby residents, future research can move in a more constructive direction, which will improve the perceptions of wind turbines and ultimately benefit their uptake.

## Declaration of Competing Interest

The authors declare that they have no known conflicting financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data Availability

No data was used for the research described in the article.

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