Wind farms, sound and health

health

Technical information

Sound and hearing are complex concepts. This fact sheet explains these concepts, particularly in relation to wind farms. It also outlines what we know, based on the existing evidence, about how noise may impact on human health.

For a less technical summary, see ***Wind farms, sound and health: Community information***.

State Government Victoria

Department of Health

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1. What do we mean by ‘wind farms’?

1.1. Wind turbines

Wind turbines are tall mechanical structures with rotating blades that look like windmills. Wind makes the blades rotate, and the energy generated is converted to electrical power.

The most common wind turbine in commercial use has a generator and three rotor blades mounted on top of a steel tower, which may be 80 m or more in height. They usually produce between 1.5 and 3.0 MW of electrical output.[1]

A wind turbine can be a single installation (for example, for domestic use) or part of a wind farm.

1.2. Wind farms

A wind farm is a group of two or more wind turbines in the same location, which are collectively used to generate electrical power.

2. What is sound?

Sound is produced by vibrations which cause pressure changes in an elastic medium, such as air. The resulting waves of pressure travel in all directions away from their source. When these sound waves fall on the human ear, the sensation of **hearing** is produced.[2]

Audibility refers to whether or not a sound can be heard; sounds which we can hear are **audible**; sounds which we can not hear are **inaudible**.

Noise is unwanted sound; "sound which is disagreeable, discordant or which interferes with…wanted sound".[3] This is subjective and depends on the listener; a noise for one person can be a sound for another.

Environmental noise (also known as noise pollution) can be caused by air and road transport, industry, and commercial and domestic activities.[4]

Sound has a number of **properties** which affect the way it is heard and interpreted. These are described in Sections 2.1–2.3.

2.1. Sound pressure level

The higher the pressure of a sound, the louder it seems to the listener (although 'loudness' also depends on other factors; Section 2.2).

'Sound pressure level' refers to the pressure of the sound when measured in the **decibel (dB)** scale (Section 3.3). It is also simply referred to as **'sound level'**.

Sound pressure level is dependent on:

- the *amount* of sound produced by the source of the sound
- the *distance* from the source at which the sound is heard or measured (the sound level decreases as the sound travels away from its source)
- the *effects of the surrounding environment* on the sound waves (sound travels better in some environments than others).

However, the sound pressure level does not change according to who is listening to the sound; it is therefore an *objective* property, which can be measured by an acoustician.

2.2. Loudness

Loudness refers to how intense a sound seems when heard by the human ear. Loudness is related to the sound pressure level, but also depends on other factors, such as the frequency, duration and character of the sound. Interpretation of loudness can vary between people; it is therefore a *subjective* property of the sound.

2.3. Frequency

Frequency (also referred to as **pitch**) is the rate of repetition of the pressure wave. Frequency is measured in **hertz (Hz)** or cycles per second.[3] Higher frequencies have a greater number of sound waves (or cycles) per second than lower frequencies; this is illustrated in Figure 1.

Bass instruments, such as the tuba or double bass, produce sounds of a lower frequency (or pitch) than smaller instruments such as the flute or violin.

For example:

- the lowest note of a double bass is 41 Hz
- the highest note on a piano is 4,186 Hz[6]
- most human speech is in the range 300–3,000 Hz.[7]

Sounds can be grouped into categories according to frequency, as shown in table 1.

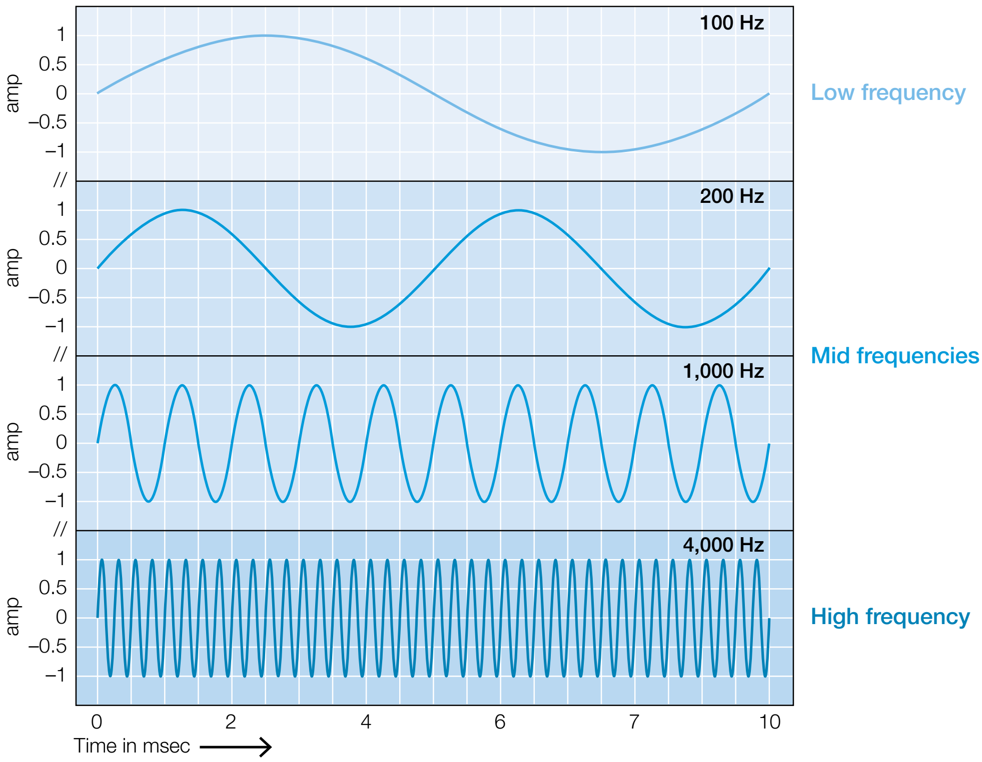
Table 1: Frequency categories of sound
(adapted from[3, 8])

Infrasound (very low frequency sound)	Below 20 Hz
Low frequency sound	Below 200 Hz
Mid frequency sound	200–2,000 Hz
High frequency sound	2,000–20,000 Hz
Ultrasound	Above 20,000 Hz

Most sounds contain a mix of many frequencies.

Sounds with mostly low frequencies often sound like a rumble, for example, thunder. Sounds with mostly high frequencies often sound like a buzz or whine, for example, mosquitoes.

Figure 1: Sound waves of different frequencies[5]



3. What sounds can people hear?

3.1. Perception of sound

The ear is the body's most sensitive detector of sound. Sound waves which are detected by the ears are converted into electrical impulses which are sent to the brain, producing the sensation of hearing.

There is no evidence that inaudible sounds can cause health effects, although there is much speculation, particularly in relation to infrasound.[9–11] This is explored further in Section 9.2.

3.2. Range of audible sound pressures

The human ear can detect a large range of sound pressures. The lowest sound pressure that humans can detect is called the **threshold of hearing** (or **audibility**). The most intense sound pressure that the ear can detect (without suffering any physical damage) is ten trillion (10^{12}) times more intense than the threshold of hearing.[12]

3.3. Decibels

The decibel (dB) scale provides a practical way of measuring the wide range of sound pressures that humans can detect. The **scale of human hearing** is typically 0 dB to 130 dB (threshold of pain).[12]

The human sensitivity to changes in sound level is provided in Table 2.

3.4. Frequency range of human hearing

A healthy young person can typically hear sounds from about 20 Hz to 20,000 Hz. However, frequencies outside of this range are also audible if the sound is loud enough. This is explored further in Section 5.4.

The sensitivity of the ear is different at different frequencies. The ear is most sensitive to sounds in the 300–10,000 Hz range, which is similar to the range of speech.[13]

3.5. Decrease in hearing sensitivity with age

As people get older, their hearing becomes less sensitive. This occurs more for high frequencies than low frequencies.[9] Therefore, people with age-related hearing impairment may be relatively more aware of low frequencies, compared to people with unimpaired hearing.[13]

Table 2: Subjective effect of changes in sound level

Increase in sound level (dB)	Change in loudness (subjective)	Example
1	Imperceptible	31 dB does not sound louder than 30 dB
3	Just perceptible	33 dB sounds just louder than 30 dB
5	Clearly noticeable	35 dB sounds clearly louder than 30 dB
10	Twice as loud	40 dB sounds twice as loud as 30 dB
20	Four times as loud	50 dB sounds four times louder 30 dB

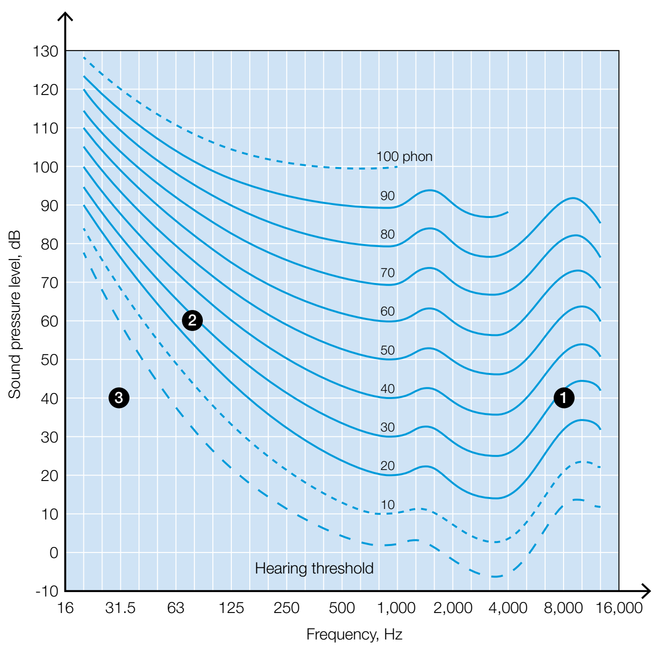
4. How is sound measured and interpreted?

4.1. Measuring sounds of different frequencies

It is very difficult to compare the loudness of sounds when they are of different frequencies. Knowing that a sound has a pressure level of 40 dB, for example, does not tell us how loud it will be. This is because the loudness of the sound depends on its frequency as well as its pressure level.

Figure 2 shows **equal loudness contours** for different levels of loudness, which are expressed in 'phons'. Each line represents different combinations of pressure and frequency which result in the same subjective loudness. Sounds which produce an equal sensation of loudness will have the same phon value.[13] A loudness of 10 phons sounds very soft, while that of 100 phons is very loud. The lowest line on the graph is the **hearing threshold**, so sounds below this line are generally inaudible.

Figure 2: Equal loudness contours and hearing threshold[14]



Examples of two different sounds of the same loudness are marked on the graph below: a high frequency sound of 8,000 Hz, at the level of 40 dB (1), and a low frequency sound of approximately 85 Hz, at 60 dB (2). Both sounds lie on the 30 phon curve, which means that they both sound fairly quiet.

60 dB is a much higher pressure than 40 dB; if the two sounds were at the same frequency the 60 dB sound would seem four times louder than the 40 dB sound (as per Table 2). However, at the two different frequencies in the above example, there is no difference in loudness between the 40 dB and 60 dB sounds.

Furthermore, while sound 1 above is easily audible at 40 dB, another sound of 40 dB could be completely inaudible, for example, if it had a low frequency of 31.5 Hz (sound 3).

4.2. Weighting networks

Instruments used to measure sound may contain *weighting networks*. These electronically adjust for the different responses of the ear to different frequencies. Some of these networks are described below.

4.2.1. A-weighted network (dBA)

This is the most commonly used weighting network. It was designed to approximate the response of the human ear, which is most sensitive to mid and high frequencies[3]. Therefore, sound pressure levels with an A-weighting (written as dBA) generally indicate how loud a sound is to the human ear, regardless of its frequency.

Most sounds have components at many different frequencies, and applying dBA is a way of combining all of these components into one measurement of the overall sound level.

For example, a vacuum cleaner may produce a frequency of 125 Hz with a level of 66 dB, and a frequency of 8,000 Hz with a level of 72 dB, with many other frequencies in between. The overall measurement of the level of sound of the vacuum cleaner is 81 dBA.[15]

Environmental and transportation noise levels are usually measured in dBA. Sound from wind farms is also measured in dBA. Table 3 provides a comparison of A-weighted sound levels for some common environmental noise sources.

Table 3: Typical A-weighted sound levels for different sources (adapted from[4, 16])

Noise source	Sound level (dBA)
Quiet bedroom	20–25
Rural night-time background	20–40
Typical wind farm (at moderate wind speed 7 m/s)	**35–45***
Car at 64 km/h at 100 m	55
Busy general office	60
Pneumatic drill at 15 m	95
Jet aircraft at 50 m	105
Threshold of pain	130

* Based on sound level measurements taken from multiple resident locations near two Victorian wind farms, at distances 500–1,000 m from the nearest turbine

4.2.2. C- and G-weighted networks (dBC and dBG)

Like the human ear, the A-weighted network is less sensitive to low frequencies. Therefore, the C-weighting has been developed to measure sounds with a significant low frequency component, and the G-weighting has been developed to measure sounds in the infrasound range.[17]

4.3. Measuring sound levels over time

Measuring sound in an environment, for example near a wind farm, can be difficult, because there are often different sources of sound and the levels may fluctuate over a wide range and over time.

Therefore, the sound must be measured using a noise descriptor that gives an accurate representation of the sound level over time. L90 and Leq are examples of such noise descriptors, and are described below.

4.3.1. Centile levels (for example, L90 and LA90)

The 90th centile level (L90) is the sound level exceeded for 90% of the measurement period. For example, if sound measurements are taken over 10 minutes, L90 will be the noise level which is exceeded for 9 minutes of that time.

L90 is useful when the noise emissions from a source are constant (for example, from a fan or air conditioner) but the ambient noise level is variable (for example, due to traffic noise).[18] L90 is used for assessing wind farm sound, as it registers the steady, continuous sound typically generated by the turbines, but excludes short peaks in sound levels such as those resulting from gusts of wind.[19]

The 90th centile level can also be written as LA90 (or dBLA90) when the sound is measured in A-weighted decibels, dBA.

Other centile levels are used depending on what is being measured, for example, 10th or 95th centile levels (L10 or L95). L95 is the sound level exceeded for 95% of the measurement period, and it is used in similar circumstances to L90, with very similar results.

LA90 is used in Victoria to measure noise from new wind farms, as directed by the 2010 New Zealand Standard ***Acoustics – Wind farm noise*** **(NZS 6808:2010). LA95** is used for wind farms constructed prior to 2010 under the previous version of the standard, NZS6808:1998 (Section 8.2).

Sections 6.6.3 and 6.7 provide a more detailed description of wind farm noise measurement and assessment under the New Zealand Standard.

4.3.2. Leq and LAeq

The Leq, (or LAeq when measured in A-weighted decibels) is the **equivalent continuous sound pressure level**. As sound levels usually vary over time, this measure converts the varying levels to an equivalent constant level of sound. Loud events can have a significant influence on the overall Leq.

Leq is generally not used for measuring wind farm noise because it takes account of all sounds in the environment, including wind gusts, and other sounds that do not come from the wind turbines themselves.

5. What are the characteristics of low frequency sound?

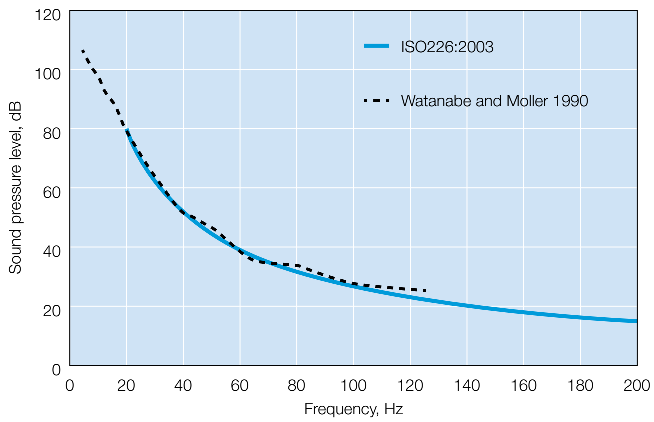
Low frequency sound (including infrasound) has a number of characteristics which differ from mid and high frequency sounds.

5.1. The threshold of hearing is higher for low frequency sounds

Figure 3 is a graph of the hearing threshold for low frequencies. Levels above the line are audible for most people, and those below it are generally inaudible. The graph shows, for example, that we can hear a sound of 200 Hz at the level of just 15 dB, but that a sound of 8 Hz is only audible once it reaches a much higher level of 100 dB.

In other words, the hearing threshold increases as the frequency decreases, particularly below 200 Hz. This is because we are less sensitive to low frequencies than mid and high frequencies. This is also illustrated by the hearing threshold and equal loudness contours in Figure 2.

Figure 3: Hearing threshold levels for low frequency sounds, based on international standard ISO226:2003 and research by Watanabe and Moller, 1990[9]



5.2. Low frequency sounds have a narrow audible range

As described in Section 5.1, low frequencies need to be at higher sound levels than mid and high frequencies to be audible. Once a low frequency sound is audible, the level only needs to increase by a small amount (relative to the increase required at mid and high frequencies) to be considered loud, and only a small amount further again before the loudness increases significantly. There is a smaller range between the threshold of hearing and the threshold of pain for low frequencies compared to higher frequencies; this is called a narrow audible range,[2] and is illustrated by the narrowing of the equal loudness contours (below about 250 Hz) in Figure 2.

Because hearing sensitivity varies between individuals, a slight increase in the level of a low frequency sound can result in a large difference in what people hear. This means that a low frequency sound which is inaudible to some people, may be audible and annoying to others. Further, annoyance increases more rapidly for low frequency sounds, compared to sounds of higher frequencies.[9]

5.3. Low frequency sounds decrease less with distance

All sounds decrease in pressure as they travel away from their source, due to dissipation of sound into the environment. Lower frequencies travel more efficiently and their sound level decreases less than higher frequencies. This means that at a certain distance away from its source, the low frequency content of a sound becomes more prominent than the mid and high frequency content. The larger the distance travelled by the sound, the greater this effect.[17]

For example, when standing next to a road, the higher frequency sounds of the tyre against the road are most obvious. At a distance, the sound which remains from the road is the rumbling low frequency content of the engines.[17]

Low frequency sound is less affected by absorption by the atmosphere, the ground and obstructions as it travels. This is why it is more difficult to insulate against low frequencies, and why bass sounds are often the main component of music heard from next-door neighbours. This may make low frequency components of wind farm noise seem more prominent than higher frequency components inside neighbouring houses, particularly at night under stable atmospheric conditions.[20]

It is important to note, however, that these characteristics do not mean that low frequency sounds from wind farms are *loud*, or even *perceptible*. It depends on the distance involved and the amount of mid to high frequency sound present (either from the wind farm or the ambient environment).[20, 21]

5.4. Characteristics of infrasound

Infrasound is very low frequency sound; it usually refers to sounds with a frequency below 20 Hz.[8] **There is a common misconception that infrasound is always inaudible.** The human ear can in fact perceive sounds in this range if they are at very high levels and therefore above the hearing threshold (Figure 3).

The hearing threshold for infrasound can be approximated using the G-weighted network (Section 4.2.2). 85 dBG is the internationally recognised **audibility threshold** for infrasound. Infrasound above **85 dBG** is generally audible, while infrasound below this level is generally inaudible.[22, 23]

There is no sudden drop in audibility as the frequency drops below 20 Hz. Instead, there is a smooth decrease in audibility from low frequency sound to infrasound.[14] This is clear in Figure 3.

Infrasound is perceived by the ear like other frequencies, so it has to be above the hearing threshold to be detected. However, the sensation of audible infrasound is different to that of higher frequencies. Below 16–20 Hz, the sensation of tone (recognisable pitch of the sound) disappears. The sound may become discontinuous in character and, at very high levels, may feel like pressure at the eardrums.[24] It is also harder to locate the source of infrasound than that of higher frequency sound.[2]

There are many sources of infrasound, as shown in Table 4. Most infrasound is accompanied by sounds at other frequencies so it is unusual to experience pure infrasound.[13]

Table 4: Examples of sources of infrasound

Natural environment	Household and industry	Human body
Waves Wind Waterfalls	Air conditioning Rail traffic Power plants	Breathing Chewing Heart beat Head movement

Infrasound from wind farms has been found to be well below the hearing threshold of 85 dBG, and therefore inaudible, even as close as 185 m from the turbines[22] (Section 6.4.2).

6. What sounds do wind farms produce?

6.1. Source of wind farm sound

Wind turbines generate mechanical and aerodynamic sounds.[22] Mechanical sounds come from the internal machinery and may also be generated from a faulty component. Mechanical sound from turbines has decreased significantly over time as turbine design has improved.[17, 25]

Aerodynamic sound is generated by the rotation of turbine blades through the air, and is the main source of sound from wind farms.

6.2. Variability of wind farm sound

It is hard to generalise about wind farm sound, because the level, character, and frequency of the sound depend on a number of factors.[4, 17] These factors vary within and between farms. They include:

- Distance from the nearest turbine or cluster of turbines
- Number of turbines on the wind farm (or in the nearest cluster, if the farm is very large)
- Model, size and arrangement of the turbines (for example, larger turbines produce higher sound levels)[24]
- Topography of the surrounding land
- Wind speed and direction.

Computer models of wind farms prior to construction take account of all these factors and predict noise levels likely to result from the turbines at different locations. This influences the type of turbines used, the placement of the turbines[26] and their operating conditions.[17] Sound measurements taken after construction can then be compared to predicted measurements.

6.3. Wind farm sound levels

While it is difficult to generalise, the sound pressure levels from wind farms at the distance of most neighbouring residents (for example, 500–1,000 m from the nearest turbine), are **lower than those of many other sources of environmental noise**. This is shown in Table 3 (Section 4.2.1).

6.4. Frequency of wind farm sound

Aerodynamic sound from wind turbines contains many different frequencies. The dominant frequencies are in the 200–1,000 Hz range.[17]

A mid to high frequency intermittent 'swish' is the main sound heard within approximately 300 m of a wind turbine. Low frequency sounds may be at a level just above the hearing threshold, and may become more noticeable than the 'swish' further away from the turbine.[20]

6.4.1. Low frequency sound from wind farms

As described in Section 5.3, low frequency sound from wind farms may be audible at neighbouring residences, and may become more prominent at night under stable conditions. However, while it may be audible, the actual impact of low frequency sound on residents near wind farms is low, because of the low levels produced overall.

For example, the **levels of low frequency sound** 600 m from a large wind turbine, measured both indoors and outdoors, **are lower than in many other environments**, such as light industrial or suburban areas or inside a passenger car.[27]

A UK study measuring noise inside houses near three wind farms in rural areas found that low frequency noise from the wind farms was consistently lower than that produced by local road traffic.[20]

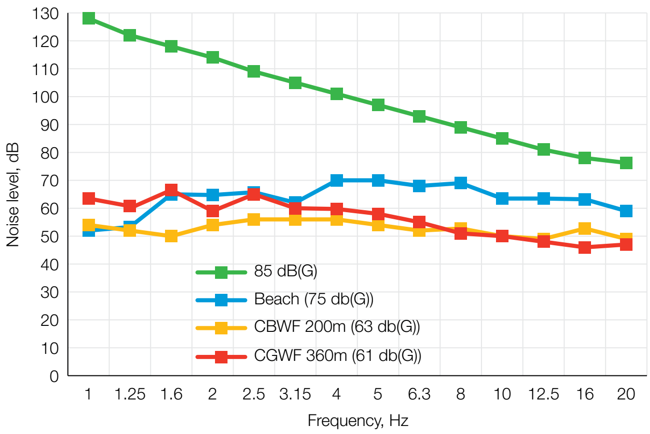
6.4.2. Infrasound from wind farms

Infrasound levels have been measured at close proximity to wind farms in a number of settings (for example, Australia, Japan and Europe) and the measured sound has been found to be in the range of 50–70 dBG.[9, 23, 26–30] This is significantly below the internationally recognised audibility threshold of 85 dBG.

A recent study measuring infrasound near wind farms in South Australia found that infrasound associated with the turbines was insignificant compared to the background levels in the environment. Local wind conditions were identified as the main source of infrasound in a rural environment, regardless of the presence of wind turbines.[23]

This supports the findings of an earlier study, which found that the level of infrasound emitted by wind farms is approximately equivalent to that produced by waves at a beach or background infrasound in an urban environment.[28]

Figure 4: Infrasound measurement results from two Australian wind farms (measured at 61 and 63 dBG) compared against measurement results at a beach (75 dBG) and the internationally recognised audibility threshold of 85 dBG



CBWF: Cape Bridgewater wind farm, 200 m from the base of a turbine (Vic). CGWF: Clements Gap wind farm, 360 m from the base of a turbine (SA).[28]

Figure 4 shows that levels of infrasound from the two wind farms (red and yellow curves) are 20 dBG lower than the audibility threshold (green curve).

In conclusion, there is overwhelming evidence that **infrasound from wind farms is at levels which are too low to be audible, and no higher than background levels in the environment.**[10, 23, 27–31]

6.5. Turbine design

Variations in the make, model and configuration of different wind turbines result in sounds of different frequencies and characteristics.

Larger turbines (2.3–3.6 MW) emit slightly lower frequency sound than smaller turbines. However, the sound produced by large turbines has not been found to be more annoying than that from smaller turbines.[21, 24] There are currently no turbines of this size operating in Victoria, but several projects are planned with larger turbines.

Newer designs aim to reduce the amount of sound produced.[25] For example, larger turbines produce less sound per MW of energy than small turbines.

Modern turbine models, which have the blade in front, are less noisy than older 'downwind' models.[24] Upwind turbines also produce much lower levels of infrasound than downwind turbines.[10, 28] All modern turbines in Australia are designed to be upwind.[†]

6.6. Special audible characteristics (SACs) of wind farms

While sound from wind farms tends to be at lower levels than sources of environmental noise (as in Table 3), there are some aspects of wind farm sound that may be more annoying than predicted by the average of the measured levels.[32] These include 'enhanced' amplitude modulation (regular variation in noise level or pitch), tonality (sounds with a definite pitch) and impulsivity (irregularly timed noises).[33]

6.6.1. Amplitude modulation

As the blades of a wind turbine rotate, they generate a regular rise and fall (or *modulation*) in the level of sound. This normal level of amplitude modulation is expected to occur and **causes the 'swish' sound** described above. It is often inaudible at typical residential distances from wind farms.[17, 34]

Under certain conditions, normal amplitude modulation may be enhanced, so that the swish is louder, and may become a 'beating' or 'thumping' sound. It is unclear what causes this effect, but it may be due to greater variation of wind speed across the rotor area.[24, 34] It is more likely to occur under stable atmospheric conditions, such as at night, when wind speeds at the height of the turbine hub are higher than normal compared to ground-level winds. Because of the stable atmospheric conditions, there are minimal wind-generated background sounds at ground level, so the noise coming from the wind farm can seem relatively louder than usual. It may be more annoying if it occurs at the same time at multiple turbines.[20]

However, 'enhanced' amplitude modulation causing annoyance has only been detected at a small number of wind farms.[34]

† Sinclair Knight Merz Consulting, Personal communication, 2012.

6.6.2. Tonality

Tonality occurs when there is a dominant frequency associated with the noise. It can sound like a hum or whine. High frequency tones can be just as annoying as low frequency tones.[21]

6.6.3. Adjustment of SACs

These special audible characteristics must be specifically assessed, in addition to the measurement of sound levels.[27] Under the wind farm noise standards used in Victoria (NZS 6808:2010 and NZS 6808:1998), **an additional 5 dB penalty applies when SACs are present**. This is quite a significant decrease in sound level; it is equivalent to a doubling of the distance between the turbine and the listener.

According to the standard, wind farms should be designed to minimise special audible characteristics. However this cannot always be predicted, hence the 5 dB limit.[35]

SACs can often be addressed by improved turbine design or changing wind farm operating conditions.[33]

6.7. Measurement of wind farm noise

Wind turbine noise increases with wind speed. When background sound levels are high due to sounds produced by the wind (such as rustling of vegetation), sound pressure levels from the turbines are also high. Noises associated with the wind can mask the noises produced by wind farms, making them less prominent.[36]

Professional acousticians use specific methodologies (including the 90th centile level, Section 4.3.1) to measure wind farm sound that minimises interference by wind and other ambient sounds.

The procedure for assessing whether wind farm noise is compliant with the standard is prescribed by NZS 6808 (Section 8). It involves extensive measurements of wind farm sound levels taken under different conditions to account for changes in wind speed, wind direction and time of day.[19]

Sound measurements need to be taken at multiple locations such as neighbouring residences. This means that any sound experienced is measured directly where the sound impact is likely to be most relevant.

If the sound were simply measured at the turbines, factors such as topography, distance and turbine configuration would not be taken into account, and this would limit the usefulness of the measurements for neighbouring residents.

Measurements need to be correlated with wind speed at the turbines, as well as data on turbine operation, to determine whether sounds measured are attributable to the wind farm or other sources.[33]

Professional acousticians undertake field measurements and recordings which are post processed (known as audio authentication and analysis) in a laboratory and subject to a validation process to ensure that they represent *the source* sound emission, including any SACs, as accurately as possible.[‡]

‡ Sinclair Knight Merz Consulting, Personal communication, 2012.

7. How can noise affect our health?

7.1. Non-auditory health effects of noise

Exposure to unwanted sounds, of any frequency, may cause non-auditory health effects.[§] There is good evidence that environmental or community noise can lead to:

- annoyance
- sleep disturbance
- cardiovascular disease (including high blood pressure and ischaemic heart disease)
- tinnitus
- cognitive impairment in children.[3, 37]

7.2. Cardiovascular disease

There is growing evidence that exposure to road and aircraft noise may increase the risk of high blood pressure. There is weaker evidence of an association with myocardial infarction (heart attack), which is not seen until sound levels become quite high. However, the noise levels associated with these observations are much higher than those near wind farms.[37] Few studies have addressed sources of environmental noise other than transport noise. The mechanisms by which environmental noise may cause cardiovascular disease are unclear, but long term stress is likely to play a role.[3]

7.3. Annoyance and sleep disturbance

These are the key health impacts of noise,[38] together accounting for the vast majority of the burden of disease due to noise.[37]

Annoyance is a broad term used to describe negative reactions to noise. Such negative reactions are more diverse than simply being 'annoyed' or irritated by noise; they may develop into anger, depression, agitation and helplessness, and can thus have a significant impact on quality of life.[37, 39]

Annoyance and sleep deprivation may contribute to a physiological stress response (putting the body into an alert 'fight or flight' mode) that can modify the cardiovascular system and hormone levels in the short term. Stress experience over a long period of time (chronic stress) may contribute to the development of mental illness and cardiovascular disease. Feeling stressed is likely to further impair sleep and increase annoyance, exacerbating the effects of a noise disturbance.[3, 9]

A low level of audible sound, such as that produced by wind farms, is not a problem for most people. However, people may develop a negative reaction to sound due to a number of factors, relating to either the noise itself, or the individual's response to the noise.

7.4. Acoustic factors: factors relating to the noise itself

Acoustic factors which may contribute to annoyance include sound level and the special audible characteristics (SACs) of the sound. Unsurprisingly, a higher sound pressure level is associated with a higher degree of annoyance;[38] that is why there are regulations that set limits on sound levels for different sources of sound (including wind farms).

As described in Section 6.6, SACs of wind farms such as amplitude modulation, tonality and impulsivity may increase the annoyance above that expected for a particular sound level.

§ Auditory effects (i.e. hearing damage) only result from exposure to very high sound levels, much higher than the levels produced by wind farms.

7.5. Non-acoustic factors: an individual's response to noise

Individuals perceive and react to noise very differently. For example, a dripping tap in the night may be unbearable to one person and barely noticeable to another. Non-acoustic factors can contribute more to annoyance and related health effects than the level of the noise itself.[40–43]

The following factors influence how an individual reacts to noise:[9, 41, 43, 44]

- attitude to the source of the noise
- noise sensitivity
- perceived control over the noise and degree of trust in relevant authorities
- history of noise exposure
- existing health and wellbeing.

Figure 5 illustrates the complex ways these factors interact and how they influence annoyance, stress and other health effects.

Because of the importance of non-acoustic factors in the development of annoyance, decreasing the exposure to a noise source does not always decrease the level of annoyance experienced.[43]

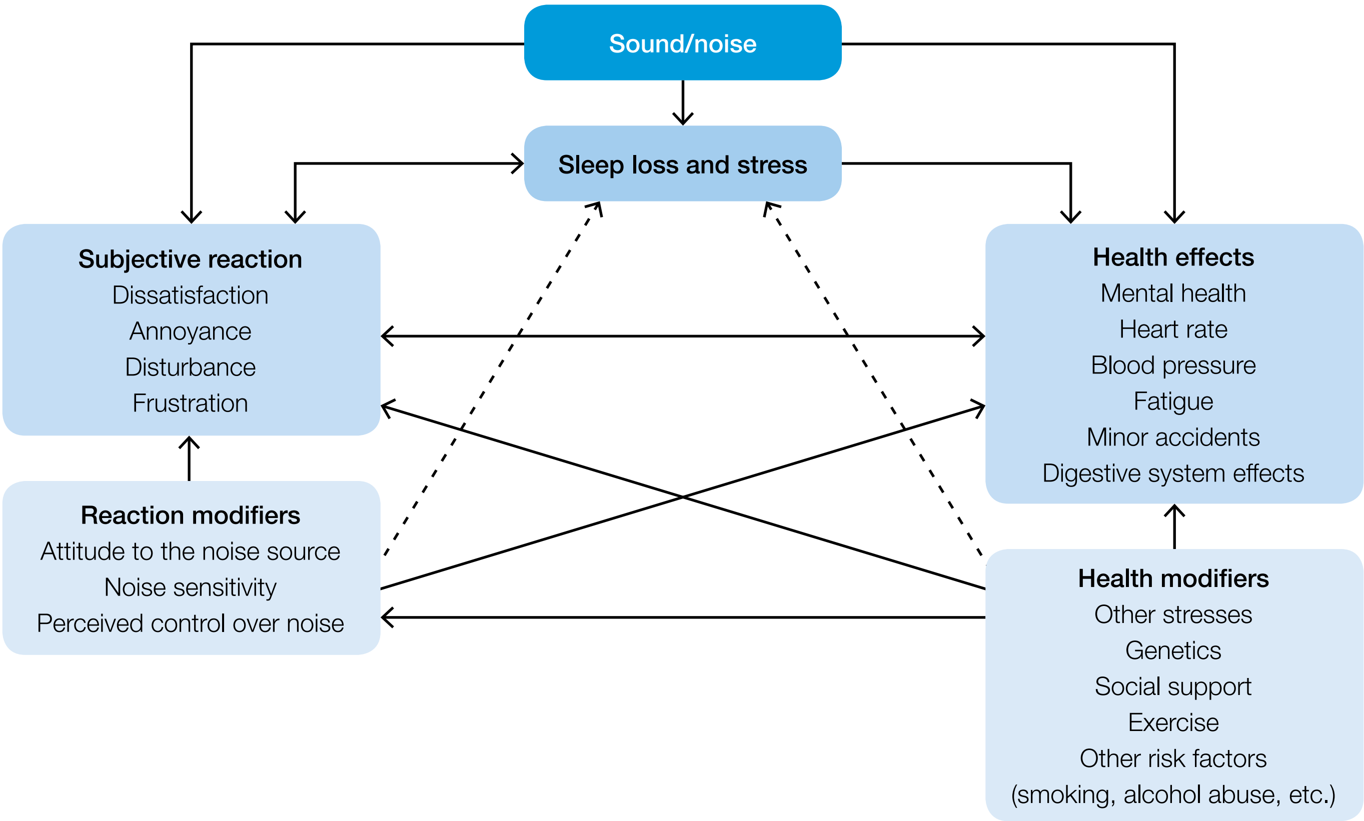
7.5.1. Personal beliefs and attitude

Beliefs about, and attitudes to the sound source, have a significant impact on whether the noises it produces are annoying to the listener.

Values and beliefs about a person's environment, community and landscape are important in how they respond to noise. Community expectations of the environment will influence what people consider to be an acceptable level of noise.[41] It is the overall 'meaning' of the noise which determines how people respond to it.[9]

Exposure to an annoying noise over a long period of time may increase a person's sensitivity to the noise, possibly because they are more focused on the noise and its negative associations. On the other hand, tolerance

Figure 5: A model of the causal connections between noise, community reaction, modifiers and health effects[44]



may develop over time;[9] for example, rail noise which is noticeable upon moving to a new house often becomes less noticeable when the listener becomes accustomed to it.

It is unclear why some people develop increased sensitivity to annoying noise while others develop tolerance, but it is likely related to underlying beliefs and attitudes to the sound source and the degree of control that the listener feels over the sound and their environment generally.

7.5.2. Noise sensitivity

Noise sensitivity refers to how reactive an individual is to noise in general. People may be sensitive to noise for biological reasons (such as natural hearing ability), psychological reasons (such as generalised anxiety or beliefs about noise generally) or external/situational reasons (such as other life stressors or social context).[39]

7.5.3. Low frequency noise sensitivity

Some individuals have a particularly sensitive response to low frequency noise.[10] It is unclear what causes this response, but it is likely to be due to a combination of biological, psychological and social factors.

Some people have biologically sensitive hearing (in other words, a lower than average hearing threshold). However, when tested in the laboratory, few people who are affected by low frequency noise have been found to have particularly sensitive hearing; most have hearing thresholds in the normal range.[9]

Annoyance increases more rapidly for low frequency sounds, and there is greater variation in how individuals perceive them, because of their narrow audible range (Section 5.2). This means that some people's annoyance in response to low frequency noise may not be shared by others. This lack of understanding may make them more frustrated and potentially more 'sensitised' to the sound.[9, 10] Furthermore, once a person has become sensitised to any noise, the slightest elevation over the hearing threshold can be perceived easily and may become unbearable.[10, 20]

Other psychological and social factors, such as anxiety, beliefs about the noise source and the social and environmental context in which the noise occurs, also contribute to annoyance from low frequency noise.[9]

8. How are standards applied to noise?

Noise standards are used not only for environmental noise (such as wind farm and traffic noise) but also for industry and even household appliances.

8.1. Accounting for individual variation

Wide individual variation in the response to noise means that it is very difficult to develop an annoyance threshold for sound levels; this is the case not only for wind farms, but for all sources of noise.

Noise standards are based on protecting the majority of people. Typically, a set proportion of an exposed population will still be affected to some degree by sound levels that meet the relevant standards. A small minority are therefore likely to experience annoyance even at sound levels that are acceptable to the majority.[10, 24]

This is particularly true for **low frequency noises** because of their narrow audible range (described in Sections 5.2 and 7.5.3). Although we are less sensitive to low frequency sounds, once they reach audible levels, individual responses to them are more variable than our responses to sounds of higher frequencies.

8.2. Wind farm noise standard used in Victoria

The New Zealand Standard ***Acoustics – wind farm noise*** **(NZS 6808:2010)** applies to wind farms approved in Victoria since 2010. This standard requires wind farm noise to be **below 40 $dBL_{A90(10\ min)}$, or 5 dBA above the background level, whichever is higher**. The symbol **$dBL_{A90(10\ min)}$** means that multiple measurements in dBA are made using 90th centile levels for 10 minutes each; this should occur over a period of at least 10 days.[35]

There is also a penalty applicable for SACs (Section 6.6.3). Acousticians follow a prescribed procedure to determine whether wind farm noise meets the standard (described in Section 6.7).

The previous version of this standard, NZS 6808:1998, applies to wind farms that were approved prior to 2010. The noise limits are the same under the 1998 standard (i.e. **40 dBA** or 5 dBA above the background level) but the methodology is slightly different; for example, the 1998 standard recommends the use of 95th centile levels (Section 4.3.1).

In special circumstances, NZS 6808:2010 (the most recent standard), allows for a more stringent noise limit for a greater degree of protection of amenity during the evening and night time.

For further information on the application of the standards in Victoria, see the Department of Planning and Community Development's Wind Energy Facilities website: http://www.dpcd.vic.gov.au/planning/planningapplications/moreinformation/windenergy.

9. What are the potential health effects of wind farm noise?

9.1. Symptoms attributed to wind farms

A range of symptoms have been attributed to wind turbines in individual and non-peer-reviewed publications, and have been described as 'wind turbine syndrome'. These symptoms include sleep disturbance, headache, tinnitus, dizziness, nausea, visual blurring, fast heart rate, poor concentration and episodes of panic[45]. These are common symptoms in the community generally and are not unique to those people living near wind farms. They are similar to the symptoms that are known to be produced by a stress reaction to annoying noise.[25, 46]

9.2. Alleged health effects of infrasound

As explained in Section 5.4, audible infrasound produces a different sensation to other frequencies because the ability to detect tonality is lost below 16–20 Hz. This may contribute to annoyance and has resulted in confusion regarding how infrasound is detected.

Some people claim that infrasound may affect health even at an inaudible level. It has been suggested that infrasound can be detected by mechanisms other than hearing, such as touch, vibration and effects on the vestibular system.

However, the available evidence does not support claims that inaudible sounds can have direct physiological effects. **Physiological effects on humans have only been detected at levels that are easily audible.**[9]

Skin receptors can detect sound waves but only at very high levels, well above the hearing threshold. Body vibrations can be felt in response to very high levels of low frequency sound (again, well above the hearing threshold). The chest resonates at 50–80 Hz, so chest vibration can be felt in response to sounds in this low frequency range (at audible levels), but not to sounds in the infrasound range.[9–11, 13, 30]

There is a small possibility that individuals with a specific abnormality of the vestibular system ('superior semicircular canal dehiscence') may experience increased sensitivity to infrasound and low frequency sound. This condition also leads to sound-induced dizziness and imbalance, and unusual sensitivity to everyday sounds. However, this condition is rare and is unlikely to result in perception of the low levels of infrasound produced by wind farms.[9]

Recent research indicates that an expectation of symptoms may lead to increased reporting of health complaints associated with wind turbines.[48]

Infrasound can cause sleep disturbance, but, like sounds in any other frequency range, it will only have this effect at an audible level.[8]

As described in Section 5.4, there are many sources of infrasound in the environment and it is even produced by the human body, at much greater levels than infrasound from external sources such as wind farms.[47] Humans have been exposed to high levels of infrasound throughout our evolution, with no apparent effects.[20, 30]

10. Conclusion

This document has outlined some key concepts in relation to the sounds produced by wind farms and their potential impact on health:

- The predominant sounds produced by wind farms are in the mid to high frequencies. Wind farm sound, including low levels of low frequency sound, may be audible to nearby residents.
- Audible noise from any source, including wind farms, can cause annoyance, resulting in prolonged stress and other health effects. The potential for health impacts depends on acoustic factors (including sound pressure levels and other characteristics of the noise) and non-acoustic factors (including individual noise sensitivity and attitude to the source).
- Infrasound is audible when the sound levels are high enough. The hearing threshold for infrasound is much higher than other frequencies. Infrasound from wind farms is at levels well below the hearing threshold and is therefore inaudible to neighbouring residents.
- There is no evidence that sound which is at inaudible levels can have a physiological effect on the human body. This is the case for sound at any frequency, including infrasound.

References

1. Department of Planning and Community Development. Policy and planning guidelines for development of wind energy facilities in Victoria. State Government of Victoria; 2012.
2. Bellhouse G. Low frequency noise and infrasound from wind turbine generators: a literature review. Wellington NZ: Energy Efficiency and Conservation Authority, 2004.
3. EnHealth. The health effects of environmental noise – other than hearing loss. Canberra: Department of Health and Ageing, 2004.
4. WA Department of Health. Wind farms information sheet. Government of Western Australia; 2012.
5. Cipriani A, Giri M. Electronic Music and Sound Design: Theory and Practice with Max/MSP, Volume 1. Virtual soundcom: ConTempoNet; 2010.
6. Husband G. What's in your music. 1999. http://www.tnt-audio.com/topics/frequency_e.html.
7. Munir B. Voice fundamentals - human speech frequency. 2012. http://www.uoverip.com/voice-fundamentals-human-speech-frequency/.
8. Health Protection Agency. Health effects of exposure to ultrasound and infrasound: report of the independent Advisory Group on Non-ionising Radiation. Oxfordshire, UK, 2010.
9. Leventhall G. Low frequency noise: what we know, what we do not know, and what we would like to know. *Low Frequency Noise, Vibration and Active Control* 2009; **28**(2): 79–104.
10. HGC Engineering. Low frequency noise and infrasound associated with wind turbine generator systems: a literature review: Ontario Ministry of the Environment, 2010.
11. Landstrom U, Bystrom M. Infrasonic threshold levels of physiological effects. *Journal of Low Frequency Noise and Vibration* 1984; **3**(4): 167–73.
12. Egan MD. Architectural Acoustics. Fort Lauderdale, Florida: J. Ross Publishing; 2007.
13. Moller H, Pedersen C. Hearing at low and infrasonic frequencies. (Articles). *Noise and Health 2004;* **6**(23): NA.
14. Leventhall G. What is infrasound? *Progress in Biophysics and Molecular Biology* 2007; **93**(1–3): 130–7.
15. Acoustical Solutions. Noise level chart. 2012. http://www.acousticalsolutions.com/noise-level-chart (accessed 23 August 2012).
16. Scottish Executive. PAN 45: Renewable Energy Technologies. Edinburgh; 2002.
17. Sonus. Wind farms technical paper: environmental noise. Southbank: Clean Energy Council, 2010.
18. NSW Government. Noise guide for local government. Sydney: Department of Environment, Climate Change and Water NSW, 2010.
19. Chiles S. NZS 6808:2010 acoustics – wind farm noise. New Zealand Acoustics 2010; **23**(2): 20–2.
20. Hayes Mackenzie Partnership Ltd. The Measurement of Low Frequency Noise at Three UK Wind Farms: Department of Trade and Industry, UK, 2006.
21. DELTA. EFP-06 project: low frequency noise from large wind turbines: Danish Energy Authority, 2010.

22. Turnbull C, Turner J, Walsh D. Measurement and level of infrasound from wind farms and other sources. *Acoustics Australia* 2012; **40**(1): 45–50.
23. Evans T, Cooper J, Lenchine V. Infrasound levels near windfarms and in other environments: Environment Protection Authority SA, 2013.
24. Moller H, Pedersen CS. Low-frequency noise from large wind turbines. *The Journal of the Acoustical Society of America* 2011; **129**(6): 3727–44.
25. Centre for Sustainable Energy. Common concerns about wind power. Bristol, UK, 2011.
26. Australian Greenhouse Office. Wind farm siting issues in Australia: Sustainable Energy Association of Australia, 2004.
27. DELTA. EFP-06 project. Low frequency noise from large wind turbines: a procedure for evaluation of the audibility for low frequency sound and a literature study. Horsholm, Denmark: Danish Energy Authority, 2008.
28. Sonus. Infrasound Measurements from Wind Farms and Other Sources: Pacific Hydro, 2010.
29. Tickell C. Low frequency, infrasound and amplitude modulation noise from wind farms - some recent findings. *Acoustics Australia* 2012; **40**(1): 64–6.
30. Leventhall G. Infrasound from wind turbines – fact, fiction or deception. *Canadian Acoustics* 2006; **34**(2): 29–36.
31. O'Neal R, Hellweg RJ, Lampeter R. A study of low frequency noise and infrasound from wind turbines: Epsilon Associates Inc, 2009.
32. Pedersen E, Waye KP. Perception and annoyance due to wind turbine noise—a dose—response relationship. *The Journal of the Acoustical Society of America* 2004; **116**(6): 3460–70.
33. EPHC. National wind farm development guidelines (draft): Environment Protection and Heritage Council, 2010.
34. Bullmore A, Jiggins M, Cand M. Wind Turbine Amplitude Modulation: Research to Improve Understanding as to Cause & Effect. Fourth International Meeting on Wind Turbine Noise. Rome; 2011.
35. Standards New Zealand. Acoustics – wind farm noise. Wellington; 2010.
36. EPA. Wind farms: environmental noise guidelines: Environment Protection Authority South Australia, 2009.
37. World Health Organisation. Burden of disease from environmental noise: WHO European Centre for Environment and Health, 2011.
38. Miedema HME, Vos H. Exposure-response relationships for transportation noise. *The Journal of the Acoustical Society of America* 1998; **104**(6): 3432–45.
39. Job RS. Noise sensitivity as a factor influencing human reaction to noise.(Articles). *Noise and Health* 1999; **1**(3): NA.
40. Job RFS. Community response to noise: A review of factors influencing the relationship between noise exposure and reaction. *The Journal of the Acoustical Society of America* 1988; **83**(3): 991–1001.
41. Knopper L, Ollson C. Health effects and wind turbines: a review of the literature. *Environmental Health* 2011; **10**(78).
42. Bakker RH, Pedersen E, van den Berg GP, Stewart RE, Lok W, Bouma J. Impact of wind turbine sound on annoyance, self-reported sleep disturbance and psychological distress. *Science of The Total Environment* 2012; **425**(0): 42–51.
43. Laszlo HE, McRobie ES, Stansfeld SA, Hansell AL. Annoyance and other reaction measures to changes in noise exposure – A review. *Science of The Total Environment* 2012; **435–436**(0): 551–62.
44. Job RFS. The influence of subjective reactions to noise on health effects of the noise. *Environment International* 1996; **22**(1): 93–104.
45. Pierpont N. Wind Turbine Syndrome: K-Selected Books; 2009.
46. Leventhall G. Submission 465: Senate Community Affairs References Committee, 2011.
47. Seligman P. Submission 353: Senate Community Affairs References Committee, 2011.
48. Crichton F., Dodd G., Schmid G., Gamble G. and Petrie Keith J. Can Expectations Produce Symptoms From Intrasound Associated With Wind Turbines? Health Psychology, March 2013.

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