Wind turbine noise: why accurate prediction and measurement matter

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ABSTRACT

On a decibel-for-decibel basis, wind turbine noise is commonly judged as significantly more problematic than most other community noise sources. As a relatively new source of community noise, however, methodological issues remain as to how wind farm noise should be measured, and how data should be collected to afford valid health assessments of turbine noise. Maintaining public health while ensuring that wind farm developments are not unnecessarily blocked has created a tension between the communities asked to host wind farms and those developers wishing to build them. Between them stand local and state regulatory authorities who are increasingly required to judge the risks and benefits of wind farms based on scant data, or technical arguments that go far beyond their expertise. Issues with measurement include, but are not limited to, terrain effects, seasonal and meteorological effects, the validity of averaging, single microphone vs. array recordings, coherent addition of periodic noise sources, level measurements vs. dynamic measurements, selection of frequency weightings, and the effects of thermal stratification on wind shear. Individual responses to wind farm noise are barely related to current acoustical indices and can instead be deconstructed from a set of interacting factors, including noise sensitivity, attachment to place, age, and procedural fairness. A further issue centres on how 'health' should be defined, and the best outcome measures to use when judging the impacts of turbine noise. This paper identifies current and advanced wind turbine noise prediction, measurement and assessment issues and uses examples of individual experiences of turbine noise to emphasise the importance of "getting it right".

INTRODUCTION

The relationship between individuals or groups and their environment can be assessed from one or more perspectives. One approach is Environmental Psychology, which examines the effect of environmental parameters on the environment's inhabitants. Typically, the sorts of parameters scrutinised are those that are problematic in some way, and which adversely affect the well-being of those individuals found residing or operating within the confines of the environment. One example of a commonly cited environmental problem is noise, which traditionally has been judged more of a problem in high-density urban areas than rural or semi-rural (e.g., greenbelt) areas. In the last decade a new source of noise has emerged in many rural and semi-rural areas across the world, noise associated with the operation of wind turbines.

Though considered a 'green' source of renewable energy, wind turbines have their own environmental and social impacts, and need to be sited with care and consideration in relation to the communities hosting them. Communities and individuals opposed to wind turbines argue that their health, amenity, and sense of place are compromised by turbine noise and visual impacts. Wind energy proponents argue that wind turbines provide communities with environmentally-friendly energy and economic opportunities. Missing in all the rhetoric is an explanation of why 'standard' noise measurements fail to 'measure' the sound from wind turbines sufficiently to address the human perception of wind turbine sound.

GETTING SOME NUMBERS TOGETHER

The A-frequency weighted sound pressure level or "sound level" is the most common sound descriptor and is reputedly analogous to our hearing at medium sound levels. This is not strictly true and the A-weighting has a significant restriction in that it does not permit measurement or assessment of low frequency sound. The weighting responses are compared in Figure 1 and it can be seen that the C-weighting is more able to analyse low frequency sounds such as the rumble and thump from wind turbines.

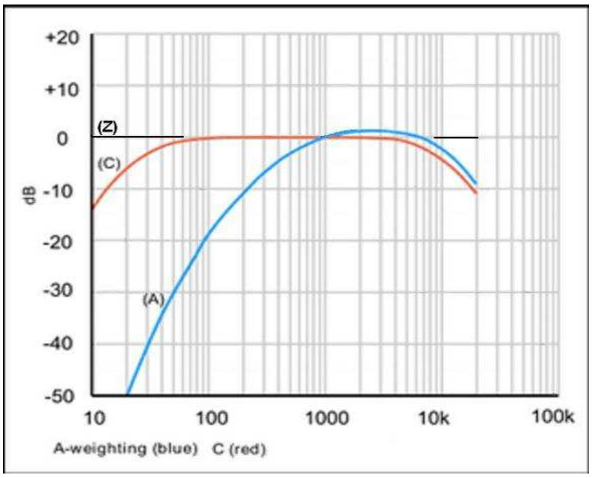


Figure 1. Sound weighting responses

For complex situations where audible or tonal components are significant, procedures for determining tonal adjustment requiring one-third octave band frequency analysis or narrow-band analysis are needed using the C-weighting or the un-weighted (also known as 'Z') response to measure low frequency sound. Both these weightings are essential for the assessment of audibility and human perception (psychoacoustic) response.

Sound emissions from modern wind turbines are primarily due to turbulent flow and trailing edge sound, blade characteristics, blade/tower interaction, mechanical sound and variations in low frequency sound. Air pressure variations fall into the group of ultra-low frequency sound. The sound can be characterised as being audible and, of an impulsive or broadband nature, with tonality or complex tones and modulation.

Sound emissions from individual turbines vary in time (when the wind is blowing), direction (wind direction changes the potential sound character from the turbine) and space (turbines turn into the wind and their individual sound character changes at the same time).

Not all these characteristics can be heard or felt by a person with "normal" hearing as hearing response is unique to an individual and is age-dependent as well as work and living environment-dependent.

The multitude of noise ratings has been thoroughly examined by Schultz (1982), who emphasises the need for a simple and practical rating scheme to characterise community noise. Unfortunately, some sounds and their effects on people cannot always be treated in a simple manner and wind turbine noise emissions are a good example. Thus more complex sound analysis needs to be applied (Zwicker and Fastl, 1999) for measures of what can be simply called 'sound quality'.

Having established the broad framework for sound analysis let us now look at what people at saying about noise and wind farms (Senate Inquiry 2011). The Inquiry received more than 1000 submissions and made seven recommendations. Summaries of the recommendations pertinent to this paper are:

a) Noise standards should include appropriate measures to calculate the impact of low frequency noise and vibrations indoors at impacted dwellings;

b) A study and assessment of the noise impacts of wind farms, including the impacts of infrasound;

c) The initiation of thorough and adequately resourced epidemiological and laboratory studies of the possible effects of wind farms on human health.

UNDERSTANDING THE MEANING OF 'HEALTH'

Before considering any possible impact of wind turbine noise on health a precise definition of health must be adopted. Such a task is not laborious however, as the WHO did precisely that during its formation in 1948. The WHO (1948) defines health as:

> A state of complete physical, mental and social
> well-being and not merely the absence of disease
> or infirmity.

Thus health refers not only to illness and "cuts-and-bruises", but also to well-being, quality of life, and amenity. In its 2008 World Health Report, the WHO recommitted itself to the concept of primary health care and acknowledged that good health exists not in the hospital, but in society at large. At the social level good health can be facilitated not only by the pursuit of healthy lifestyles (e.g., exercise and diet), but also the provision of restful and restorative living environments (e.g., soundscapes). A prominent factor determining the restfulness of a living space is the level of privacy and intrusion by pollutants, including smell, air quality, and noise. In assessing the impacts of wind turbine noise it is important to not only consider the potential of wind turbine noise to induce poor health, but also its potential to compromise good health.

The health of a nation or group may be assessed using morbidity and mortality data, and by using health status and health related quality of life (HRQOL) data. The latter two approaches correlate highly with medical morbidity assessment, but instead of diagnosing particular symptoms or classifying health problems as the medical profession would, this approach has the value and advantage of examining factors that cause and/or result from a health disorder(s). These factors include: physical health, psychological wellbeing, social support and the environment. Such information is important both in the prevention and the treatment of health problems, and in the assessment of treatment outcomes. It is now common practise in health research to incorporate measures of HRQOL, such that the US Food and Drug Administration agency, for example, insists on such assessment in appraising all new pharmaceutical products (Glasgow & Emmons, 2007). Therefore, health status and HRQOL instruments would serve well studies of the effect of wind turbines on the health and wellbeing of nearby residents, and in many ways are more practical and sensitive measures than those applied in medical appraisals.

As an emerging noise source, wind turbines present unique challenges in the assessment of health effects, and as such their impacts are only beginning to emerge in the literature. The recognition of a new disease, disorder, or threat to health usually follows a set pathway. First, doctors and practitioners attempt to fit symptoms into pre-defined diagnostic categories or else classify the complaints as psychosomatic. Second, as evidence accumulates, case studies begin to appear in the literature, and exploratory research is undertaken to obtain better descriptions of the symptoms/complaints. Third, intensive research is undertaken examining the distribution and prevalence of those reporting symptoms, the factors correlating with the distribution and prevalence of those symptoms, and ultimately to cause-and-effect explanations as to why those reporting symptoms may be doing so.

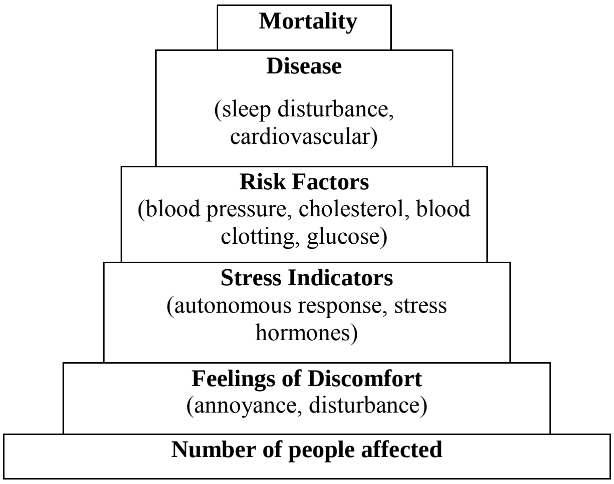
Currently, the health and amenity impacts of wind turbines is only beginning to be elucidated, and is caught somewhere between the first and second stages described above. Case studies (e.g., Harry, 2007; Pierpont, 2009; Krogh et al, 2011) and correlational studies (e.g., Pedersen & Persson-Waye, 2007; Thorne, 2007; Van den Berg et al., 2008) have already emerged in relation to the health effects of wind turbine noise, indicating that wind turbine noise, like traffic or aviation noise, has the potential to impact health and well-being. We can expect that, over the next decade, intensive research will be undertaken enabling more certain decisions to be made regarding wind turbine noise and health, and the mechanisms which mediate the relationships between the two. Until that research is undertaken, however, an absence of data addressing cause-and-effect mechanisms does not equate to an absence of wind turbine noise impact (*viz argumentum ad ignorantiam*).

The WHO Report 'Burden of disease from environmental noise – Quantification of healthy life years lost in Europe', 2011, is a peer-reviewed report with respect to the scientific evidence supporting exposure-response relationships and case studies in calculating burden of disease. The Report is concerned with the effects of environmental noise in all its facets. Although it does not specifically address potential for noise from wind turbines it concludes that:

> There is sufficient evidence from large scale epidemiological studies linking the population's exposure to environmental noise with adverse health effects. Therefore, environmental noise should be considered not only as a cause for nuisance but also a concern for public health and environmental health.

The severity of the relationship between environmental noise, annoyance, sleep disturbance, adverse health effects and disease and number of people affected is summarised in Table 1 derived from Figure 7.1 of the Report:

Table 1: Severity of health effects of noise and number of people affected



The 2011 Report considers sleep disturbance and its potential for adverse health effects:

> In 2009, WHO published the Night noise articles for Europe. This publication presented new evidence of the health damage of night-time noise exposure and recommended threshold values that, if breached at night, would threaten health. An annual average night exposure not exceeding 40 dB outdoors is recommended in the articles.

The WHO Europe (2009) 'Night Noise articles for Europe' identifies in Table 2 the effects of outdoor noise on sleep.

- The WHO recognizes the existence of vulnerable groups and acknowledges the existence of individual differences in noise sensitivity.
- Health begins to be degraded between 30 and 40 dB.
- A $L_{night,outside}$ level of 30 dB is the level that can be considered "safe".
- A $L_{night,outside}$ level of 40 dB and above can be considered as the marker for "unsafe".
- The table is based on a 21 dB noise reduction from outside to inside the residence; a level of 40 dB outside is 19 dB inside
- Supplementary noise indicators (LAmax, sound exposure, etc) may be needed to describe and assess noise for night period protection.

Table 2: WHO Europe (2009) 'Night Noise articles for Europe'.

Average night noise level over a year, $L_{night,outside}$

30 dB $L_{night,outside}$	Although individual sensitivities and circumstances may differ, it appears that up to this level no substantial biological effects are observed.
30–40 dB $L_{night,outside}$	A number of effects on sleep are observed from this range: body movements, awakening, self-reported sleep disturbance, arousals. The intensity of the effect depends on the nature of the source and the number of events. Vulnerable groups (for example children, the chronically ill and the elderly) are more susceptible. However, even in the worst cases the effects seem modest. $L_{night,outside}$ of 40 dB is equivalent to the lowest observed adverse effect level (LOAEL) for night noise.
40–55 dB $L_{night,outside}$	Adverse health effects are observed among the exposed population. Many people have to adapt their lives to cope with the noise at night. Vulnerable groups are more severely affected.
>55 dB $L_{night,outside}$	The situation is considered increasingly dangerous for public health. Adverse health effects occur frequently, a sizeable proportion of the population is highly annoyed and sleep-disturbed. There is evidence that the risk of cardiovascular disease increases.

The WHO's Night Noise articles for Europe' description of the relationship between noise level ($L_{night,\ outside}$) and health are repeated in Table 2. The noise metric used, ($L_{night,\ outside}$), is referenced to the European Environmental Noise Directive (2002/49/EC) with a target of 40 dB ($L_{night,\ outside}$) to protect the public, including the most vulnerable groups such as children, the chronically ill and the elderly. 'Lnight' is the A-weighted long-term average sound level determined over all nights of the year. Night is defined as 23.00 to 0700 hours.

Annoyance criteria, as distinct from the 'sleep' criteria of Table 2, has a different night-time sound level derived from the measured LAeq sound level plus a penalty of 10 dB in the Lden equation (1):

$$L_{den} = 10\lg\frac{1}{24}\left(12*10^{\frac{L_{day}}{10}} + 4*10^{\frac{L_{evening}+5}{10}} + 8*10^{\frac{L_{night}+10}{10}}\right) \quad (1)$$

The relationship, if any, between transportation noise annoyance and wind turbine noise annoyance are still being developed. The use of the various relationships must, therefore, be treated with caution.

NOISE ANNOYANCE

It is important to note that many studies reporting noise annoyance data are laboratory, as opposed to field, studies. If noise guidelines are informed by research predominantly undertaken in laboratories then they themselves lack ecological validity. That is, what is measured in a laboratory may not concord with measurements made in the actual environment. Additionally, older published data on wind turbine noise may involve turbines that are substantially fewer in number, smaller in size, and less noisy than modern wind turbine set ups, and so present findings that cannot be generalised to contemporary technology. Alarmingly, wind turbine noise research (actually non-systematic literature reviews) has been conducted by industrial stakeholders in wind energy (e.g., Colby, 2009), that present results that likewise should be interpreted with caution due to obvious conflicts of interest. Wind turbine noise research, then, should be consulted with qualification and critique when considering wind turbine impacts, and not taken *prima facie*.

To understand ‘wind farm annoyance’ requires a shift in thinking away from the usual ‘noise from transportation’ noise exposure mindset. Man-made noise is not perceived in a social vacuum (Maris et al., 2007).

The characteristics of wind turbine noise have been well described from a social perspective (e.g., Van den Berg et al., 2008: Table 7.23), either as a typical amplitude modulation (i.e., a 3-5 dB modulated “swish”, audible in the near field) or an atypical amplitude modulation (i.e., >5 dB modulated “thump”, audible in the far field). Van den Berg (2004) shows that wind turbines produce noise with an impulsive character, and while the actual cause of the swishing or thumping has not yet been fully elucidated, it has been demonstrated that this swishing or thumping pattern is common with larger turbines (Stigwood, 2008), and may result from a fluctuating angle of attack between the trailing edge of the rotor blade and wind (Siponen, 2011). Furthermore, lower frequencies, which tend to be judged as more annoying than higher frequencies, become more salient during the transitions from swish to thump. In the far field the less common two-bladed turbines, it should be noted, have a different noise profile characterised by an alternating thump without the swish.

Because wind is variable and not constant, wind turbine noise levels are also variable and inconsistent. Furthermore, the cyclic action of the turbine rotors serves to modulate noise level across time, producing a noise that can be perceived as repeating itself several times per second. This is unfortunate, as human senses act as contrast analysers, responding to changes in sound rather than to the absolute level of the sound itself (Laming, 1986). Additionally, we are more sensitive to change in continuous noise (such as impulsive turbine noise) than to discrete auditory events (e.g., a passing car at night). Thus wind variability will bring about noticeable changes in the level of turbine noise, irrespective of the aggregated level of that noise, and these changes in noise level due to wind speed fluctuations can make the noise more noticeable, especially so at night, when ambient sound levels reduce.

Consequently, overall measures of sound level are not in themselves useful in predicting annoyance if those levels are dynamic (i.e., they change over time). In fact, the level of noise only explains 10–25% of an individual’s response to noise (e.g., Pedersen & Persson-Waye, 2008). When considering acoustical characteristics of turbine noise, however, overall noise level is usually chosen as the metric of importance while other aspects of the noise such as periodic amplitude modulation are ignored (Lundmark, 2011). Metrics describing the amplitude modulation characteristics of turbine noise, such as that proposed by Pedersen, Von-Hunerbein, & Legarth (2011) or placed before the Courts (Hulme, 2011), should therefore be considered when judging the appropriateness of turbine placements.

RELIANCE ON OVERSIMPLIFIED MODELS

Though noise level itself explains only a small proportion of the variability found in the response to noise, it invariably carries the greater weighting and emphasis during wind turbine consent processes. Noise level metrics are usually predicted, though on occasion may be reported from other wind farms of a similar nature to that proposed, or directly from the manufacturer’s testing facilities. In relation to predicted levels, there are a number of factors influencing the predictions, and failing to sufficiently account for these factors can potentially produce either under- or overestimates of turbine noise.

Additionally, when the terrain impedes the wind close to dwellings then the wind’s masking effect is reduced, and turbines located on higher ground may become more audible (Appelqvist & Almgren, 2011). Furthermore, thermal effects on atmospheric stratification can induce significant variability in wind gradients. Hence wind speed can differ between ground and turbine hub height. Unfortunately, the most common reference of wind vertical profile used in modelling (IEC 61400-11) is appropriate only for flat terrain containing simple vegetation (Gianni, Bartolazzi, Mariani, and Imperato, 2011). Another important factor effecting noise level is the humidity- and temperature-dependent air absorption coefficient, in which lower values (e.g., 0.003 dB/m) yield more conservative estimates than higher values (e.g., 0.005 dB/m). Though these differences may appear subtle, selecting representative air absorption coefficient values are important as propagation through the air introduces random phase shifts due to atmospheric turbulence, which in turn influences noise levels.

Current approaches to the modelling of sound propagation between multiple turbines assume statistical independence and sum the individual outputs of turbines in order to profile the impact of groups of turbines. Often this involves using manufacturer’s technical data from a single turbine, but does not take into account the fact that multiple deterministic noise sources can add coherently. In the case of wind turbine installations these noise sources include periodic modulating blade noise, low frequency pulsations, and tones emanating from mechanical processes (Walker, 2011). The interactive effects of turbines may produce local “hotspots” or “heightened noise zones” (Bakker & Rapley, 2010) in which turbine noise can be amplified (and elsewhere attenuated) due to the superposition of multiple turbine acoustic waves. Hence, when predicting turbine noise levels using mathematical models, model complexity should not be sacrificed to simplify the calculation process.

CHOOSING THE RIGHT METRIC.

Another important factor when measuring or predicting wind turbine noise level is the range of exposure levels, that is, the minimum and maximum levels that are emitted by wind turbines. Noise measures based on energy summation and expressed as averaged values are not always sufficient when examining the health-related effects of noise.

The WHO has repeatedly emphasised the importance of measuring maximum values of noise fluctuations, rather than averages (1999). The inclusion of maximum levels is important as studies have consistently demonstrated that sleep disturbance is related to peak noise levels rather than aggregated measures (Morrell, 1997). Thus, any measured or predicted noise levels used by acoustic experts must be accompanied by maximum levels, as sensitivity to the peaks of modulating noise waves are likely to better predict annoyance (Walker, 2011). Further debate centres on the type of weighting that should be applied to noise measurements and predictions. Currently, standard practice in the wind turbine industry involves using A-weighted noise level estimates (i.e., dB(A)), though these may underestimate annoyance by failing to account for the degree of temporal variations and low frequency content the measured noise contains. Siponen, (2011), accounting for amplitude modulation and the low frequency noise components in turbine noise, argues that A-weighted noise predictions underestimate the minimum distance required between wind turbines and inhabited dwellings. Instead, he advocates the use of a C-weighting, or else a corrected level based on the difference between C- and A-weightings.

Prior to the approval of a wind farm it is common practice to assess the ambient (or background) sound levels and to compare these to, or combine them with, the predicted levels (Terlich 2011). Even this stage of noise level measurement has issues that require consideration, as extraneous factors such as time of year or equipment type can result in substantial under predictions of wind farm noise levels, up to 13 dBA in one study (PNCC 2010). Seasonal effects such as insect noise can be lessened using weighting algorithms while decreasing the averaging time from the one minute recommended by IEC 61400-11 to around ten seconds can help eliminate data contaminated by bird cries, pedestrian noise, or traffic noise (Ishibashi, 2011). Arguably however, smaller durations around 100 milliseconds should be adopted as best practice, as the 60 second time averaged dB(A) levels recommended by the IEC 61400-11 (but see also its Appendix A5) fail to measure the amplitude modulation inherent in turbine noise (Lundmark, 2011, Hulme 2011).

BE AWARE OF DOSE-RESPONSE RELATIONSHIPS

Many international standards for acceptable levels of community noise are based on the dose-response curve. This approach to establishing acceptable noise levels lacks validity and has been rightly lambasted by acousticians and health researchers alike (Fidell, 2003). The dose-response curve, constructed from dose response data, plots (for example) noise annoyance as a function of noise level. Users of a dose-response curve define a level of noise annoyance that they are willing to accept and then, either graphically or numerically, derive a threshold by determining the level of noise that yields this predefined annoyance level. There are, however, few peer-reviewed studies relating to measured wind farm noise and human perception.

Using dose response curves entails the establishment of an “acceptable harm” threshold, expressed in physical levels of the stimulus. The question is, at what level of noise does one estimate the threshold? In Australia the criterion for aircraft noise is set at a point in which no more than ten per cent of the population would be severely affected. However, such criteria setting reflect a utilitarian approach to public health that is simply not sanctioned by modern society, and are often arbitrary. Would we put an additive in the water that would benefit 90% of citizens and make the other ten percent ill? These values need to be based on scientific validity and medical evidence, but instead are being set to reflect industrial objectives. The notion of acceptable harm then is one that needs to be debated at the societal level, and in relation to wind turbine noise, defined on a case-by-case basis with input from the communities hosting the turbines.

NOISE IS A SOCIAL PROBLEM, SO CONSIDER APPROACHES OTHER THAN SOUND LEVEL

Adopting sound level as the sole criterion of health impact makes little sense, given that 1) sound level is a poor predictor of the human response it elicits, and 2) there has been a systemic failure in the prediction and measurement of wind turbine *noise*, as distinct from *sound*. In relation to the latter, it is apparent that errors of prediction and measurement emerge due to inadequate methodology, which itself has social consequences. For example, many of the wind turbine installations erected in New Zealand’s Manawatu region were initially welcomed by residents who supported renewable energy (Martin, 2008). However, this initial enthusiasm was based upon reassurances from the developers that turbine noise would not intrude into homes. The resulting lack of concordance between the predicted impacts of the noise and the actual impacts of the noise has since led to a rise in resistance to wind turbines in this region.

Recent (2010 and 2011) compliance testing undertaken for the Te Rere Hau wind turbine installation (Palmerston North, New Zealand) indicates that the complaints made by nearby residents regarding noise exposure are justified on the basis of noise level readings. These readings differ from those originally predicted and may not comply with the original resource consent conditions (Lloyd 2010). In 2010 court action against the wind farm operator was initiated by the Palmerston North City Council (PNCC 2010).

Because of the discrepancies between predicted and actual noise levels it may be more prudent, at this point in time, to rely on evidence coming from individuals at established wind turbine installations than mathematical models heavily constrained by assumptions. The conflict between wind farm operators, their advisors (acousticians), regulatory authorities and affected individuals is a problem because none of the parties has common ground and each party only partly understands what the other parties are saying.

The A-weighted 10 minute sound level criterion imposed on most wind farm consents in Australia and New Zealand fails because it is too simple. It does not allow for the type of noise heard by residents. There is ‘no problem’ because, quite simply, the assessment method chosen is almost totally incapable of measuring the noise being heard or felt. Normal complaint systems will also fail because there is no common ground on which to present a case. A more complex system than the A-weighting system is required. This can be simply described as 'sound quality'.

SOUND QUALITY

People are unique in their individual hearing response. A sound audible to one person may be inaudible to another and, therefore, a method is needed to define measure and assess "audible sound". A sound is said to be audible if it can be heard within the ambient sound (soundscape) of the locality. That is, the sound under investigation is not masked by the soundscape. This is a signal-to-noise phenomenon and can be defined in terms of sound detectability.

Audibility can be considered as a psychophysical quantitative relationship between physical and psychological events:

- the physical relationship is considered as being the role of signal detection
- the psychological or behavioural and perceptive reactions of an individual are considered as psychoacoustical or sound quality relationships

The audibility of noise sources is a function of the relationships between signal-to-noise ratio and frequency that govern detectability of acoustic signals by human observers to:

- Predict the frequency region of a spectrum that is most detectable in any given sound environment
- Quantify the degree of detectability of the signal in question
- Estimate reduction in signal-to-noise ratio necessary to render the signal undetectable

Just-noticeable differences (jnd) are the smallest difference in a sensory input that is perceivable by a person. Just-noticeable changes in amplitude, frequency and phase are an important feature for the assessment of low amplitude sound in a quiet background, where slight changes in frequency or amplitude can be readily noticed as a change in ambience. The characteristic of the sound is its absence; that is, the sound is not noticed until it has gone. It is the absence of the sound that defines its degree of intrusion and potential annoyance.

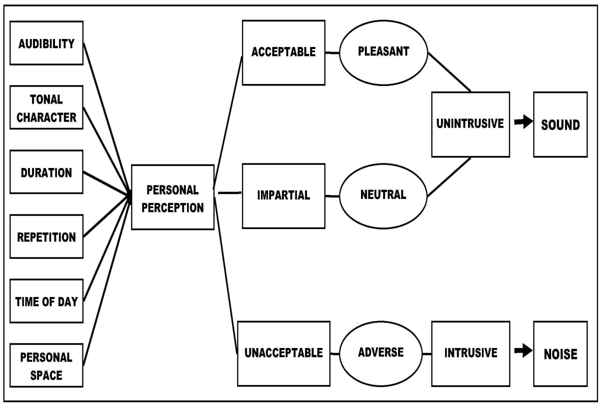


Figure 2. Subjective decision processes to differentiate between sound and noise

An individual's comfort within an environment and sensitivity to noise are affected by that individual's exposure and habituation to different types of sounds. The subjective component of the methodology (Thorne 2007) outlined in Figure 2 above presents the various indicators a person may subconsciously perceive and apply when listening to a sound. The criterion 'personal space' includes an individual's emotional state and sensitivity to a particular sound. Acoustical analysis has little meaning to a person unless it is has a real relationship with an individual's responses to intrusive sound and can be described or explained in a way that the individual understands. Individuals understand intuitively what "noise" is to them personally, and this distinction may change day-by-day even to the same sound. Individual amenity is assessed as an *intrinsic* value reflecting personal noise sensitivity, personal and cultural attitudes to sound in the environment, the environment itself, and habituation effects. The *extrinsic* values that affect individual amenity are presented as community values that may have potential effect on the individual.

Having heard a sound and made an instantaneous value of that sound, an individual immediately characterises the sound as pleasant or unpleasant, acceptable or unacceptable, a sound that can be accommodated or intrusive noise. The same sound does not always provoke the same intensity of disturbance or annoyance at different times in the same individual. The processes presented in Figure 2 are common features in how an individual responds to a sound and makes perceptive choice that the sound is "good", "annoying but can be lived with" or "intrusive – get rid of it". A person can change his or her perception about a sound but tends towards a stable response with a set "value" for the sound. That is, ultimately, the sound is either accepted or rejected as a nuisance.

The perception of environmental sound, as well as the objective and subjective analysis of intrusive noise, has been reported by Thorne (2007). Various real-world and constructed soundfiles were evaluated by review panels in New Zealand and Australia. Measures of sound quality and personal noise sensitivity were investigated. The research was in two parts (1) to determine objective measures for an individual to assess a sound and (2) to determine whether variance in character is perceived adversely compared to the character of the environment in the absence of that sound. The objective of the research was to develop a methodology incorporating a decision-support system to integrate perceived noise with noise performance indicators, annoyance criteria and individual noise sensitivity. The character of the sound was tested for audibility, dissonance, duration, fluctuation, impulsiveness, loudness, roughness, sharpness, and tonality. Zwicker's unbiased annoyance (UBA) concept was tested during the research and modified as a primary measure for noise assessment.

The measure was modified as an outcome of the research to unbiased annoyance (UBA*m*). This measure includes loudness (10%), sharpness (Aures) and a modified approach to fluctuation (Sethare's Tonal Dissonance, *TD(S)* in *sets*) to account for frequency as well as amplitude fluctuation. The UBA*m* measure has an effect on soundfile measured values by emphasising the contribution of dissonance and tonalness. Equation (2) calculates the measure in 'intrusion units, *iu*':

$$UBAm = d(N10)^{1.3} \cdot \left\{ 1 + 0.25(S-1) \cdot \lg(N10+10) + 0.3TD(S) \cdot \frac{1+N10}{0.3+N10} \right\} \qquad (2)$$

UBA*m* is modified for night-time. The value of '*d*' in the equation for the day is 1, for night-time the value of $d = 1 + (N_{10}/5)^{0.5}$. The expression 'lg' means '$\log_{10}$'.

The UBA*m* measure has been studied and tested in both green-fields and wind-farm noise affected locales. The research indicates that a rural environment unaffected by commercial or industrial noise has a high degree of positive amenity. The rural environments have modified unbiased annoyance values of less than 20 intrusion units. In comparison, the rural and urban environments that have wind farm noise overlaid have modified unbiased annoyance values in the range of 40-50 intrusion units. Sound perceived as being unpleasant and annoying has modified unbiased annoyance values of approximately 150-500 intrusion units.

As a result of the research it is concluded that the UBA*m* measure incorporating measures of sound quality is a useful measure for the purposes of environmental sound analysis, assessment of annoyance and perception. The measure is not suitable for music analysis, however.

CONCLUSION

Currently, environmental agencies, planning authorities and policy makers in many parts of the world are demanding more information on the possible link between wind turbine noise and health in order to legislate permissible noise levels or setback distances. Concurrently, larger and noisier wind turbines are emerging, and consent is being sought for progressively larger wind turbine installations to be placed even closer to human habitats. However, the stimulus-response approach demanded by the bulk of these decision makers is misguided, and neither noise levels nor setback distances used in isolation are likely to be acceptable by society at large. While noise standards can effectively and fairly facilitate decision-making processes if developed properly, the current standards on offer suffer severe conceptual difficulties. All this points to a need to incorporate social perspectives into the decision making processes - although how this process can be standardised remains a challenge to be addressed.

We have listed a number of important considerations that need to be addressed by environmental agencies currently deciding on the location of wind turbine installations. These various considerations can be grouped into broader categories, such as the credibility of procedures and players involved with standard development, the use of research to inform standards, critique of current approaches inherent in contemporary noise standards, and broader social factors. Ultimately, however, man-made noise is not perceived in a social vacuum, and acceptable levels of wind turbine noise should be as much a societal as a technological decision.

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