# A review of the human exposure-response to amplitude-modulated wind turbine noise: health effects, influences on community annoyance, methods of control and mitigation

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**ABSTRACT**

WSP | Parsons Brinckerhoff led a research project on behalf of the UK Government, reviewing the human exposure-response to amplitude-modulated (AM) wind turbine noise (WTN). The review included identifying the potential effects on health, and recommendation of a scheme for use in development planning to control the potential impact of AM WTN on communities situated near to wind farms. This paper focuses on the findings of the review, including effects on community annoyance and health, with reference to the results of recent field studies. The control scheme for AM is described, and emerging measures for mitigation are discussed. Also examined is the range of non-acoustic factors that influence responses to WTN, and potential future approaches to addressing these complex issues are considered.

## INTRODUCTION

Over the past two decades, anecdotal reports and some studies have linked WTN exposure with a wide range of physiological and psychological health issues, including heart palpitations / tachycardia, nausea, dizziness, stress, anxiety / panic attacks, depression, annoyance, headaches, sleep disturbance, extreme fatigue, tinnitus, hearing problems, nerve abnormalities, pericardial thickening and epilepsy [1, 2, 3, 4]. The effects of wind turbine noise (WTN) have long been a popular subject of mainstream media coverage in the UK, and the characteristic amplitude modulation (AM) in the sound has generated particular concerns, following its identification as a possible factor in complaints previously attributed to low frequency noise [5, 6]. In 2015, the UK Dept of Energy and Climate Change (DECC) commissioned a review of WTN exposure-response research evidence focussed on the effects of AM, with the aim of identifying a potential means of control for use in development planning. The project involved close cooperation with the UK Institute of Acoustics (IOA) Amplitude Modulation Working Group (AMWG), which conducted concurrent independent research, developing an objective method for detecting and rating AM in real WTN signals [7]. An example of measured WTN exhibiting periodic AM is shown in Figure 1, which includes the ratings determined using the AMWG method. Figure 1 also illustrates the characteristics of

AM, including the magnitude (in terms of the level differences between extrema in the level envelope, ie peaks and troughs), the modulation frequency, and the variability in both mean level and AM magnitude over time.

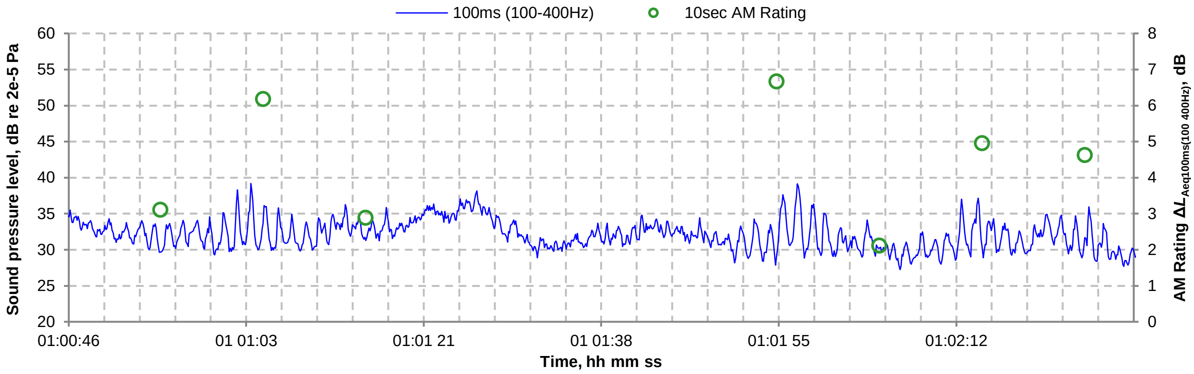


**Figure 1:** Amplitude modulation measured in wind turbine noise signal envelope

The exposure-response review was led by researchers at WSP | Parsons Brinckerhoff, supported by a team of external noise and health consultants. The project team reported to a steering group comprising DECC, the Dept for Environment, Food and Rural Affairs, the Dept for Communities and Local Government, Public Health England, and representatives for the Devolved Authorities. The draft deliverable final report was peer-reviewed by a separate group of wind turbine noise and health experts.

## METHODOLOGY

A systematic approach to the review was adopted and is described in detail within the final report [8]. Search terms and literature repositories were agreed with the steering group during the project design phase [9]. To reduce potential publication bias, searches were carried out in peer-reviewed ('black' literature) databases of both science and health research areas, as well as other sources, such as relevant conference proceedings and industry or government-funded research ('grey' literature). The following information sources were searched:

**Table 1:** Review search sources

| Type | Source |
|---|---|
| Literature databases | Web of Science, PubMed |
| Conference Proceedings | International Commission on the Biological Effects of Noise (ICBEN) Congress<br>International Meeting/Conference on Wind Turbine Noise (INCE Europe)<br>International Meeting on Low Frequency Noise and Vibration<br>International Congress on Sound and Vibration (ICSV)<br>European Congress and Exposition on Noise Control Engineering (Euronoise)<br>International Congress and Exposition on Noise Control Engineering (Inter-noise) |
| Industry publications | RenewableUK AM research reports<br>IOA AMWG reports<br>Reports by the UK Independent Noise Working Group (INWG)<br>Institutional or Government-affiliated research reports on wind turbine noise |

In addition, any suitable papers made known to the team were added. The initial yield lists were sifted by examination of titles and abstracts. The resultant publication database (the 'longlist') was categorised according to the study type: category 1 comprised publications on scaled responses to quantified AM WTN; category 2 comprised other potentially relevant sources, including (2d) epidemiological field studies of WTN (without AM quantification), AM complaint case-studies, exposure-response studies of non-WTN AM, planning issues relating to AM WTN, and any other useful studies of AM in WTN. None of the field studies in category

2d directly linked a quantified degree of WTN AM with effects, and hence did not meet the category 1 criteria; as a result the review of this field research base concentrated on the outputs of existing recent systematic reviews, but also considered large-scale studies that had been conducted subsequently to these reviews. The initial longlist included 134 papers. Further examination of each paper was undertaken and a relevance rating assigned according to the project aims, on the basis of which a shortlist of 69 papers was compiled for the full review. This included 15 papers in category 1 (AM exposure-response), and 12 papers in category 2d, of which 8 were existing reviews from both black and grey sources (inc. 5 independently peer-reviewed journal articles), and 4 publications on the results of 2 recent field studies (in Canada and Japan).

At the inception of the review methodology [9], it was envisaged that a recognised rating system, such as the Newcastle-Ottawa Scale [10], would be employed. During the review process, it transpired that the use of such a scale would not yield useful results, due to the design of the studies with greatest relevance to the main aim of evaluating AM exposure-response (ie category 1, which largely comprised laboratory experiments), and the limited material available. Consequently, a bespoke review template (included as an appendix to ref [8]) was developed for use in reviewing the shortlist, prompting reviewers to extract equivalent information from each paper and to consider the robustness and risks of bias. Each category 1 study was assigned to two reviewers to ensure consistency and reduce potential bias; differences were resolved by discussion. The responses received from reviewers were synthesised and conclusions to be drawn were considered by the research team. During drafting of the output report, two further studies were published that would have met the category 1 selection criteria, and these were also given limited reviews, included as annexes. The initial study recommendations were subject to an external independent peer review, feedback from which was incorporated into the final version of the published report. The potential effects of selection bias (due to the application of relevance ratings and the categorisation processes) are considered unlikely to be significant in the context of the research aims, mainly due to the relatively small number of studies directly addressing the AM WTN exposure-response relationship, i.e. category 1. Suspected duplicates were retained, due to the relatively small number of papers. Category 2 material (including the studies of focus in this article) mainly provided contextual and supporting information, and so bias effects on outputs addressing the main research aims are not expected to be significant.

## REVIEW

### Early work (1980s) – downwind rotor

An early study into WTN exposure-response, which addressed a severe and impulsive form of low-frequency AM in WTN (‘thumping’) attributed to the blade/tower-wake interaction of experimental downwind-rotor turbines[1], is found in the NASA research by Stephens et al [11]. This study identified the potential for noise-related annoyance, and included laboratory tests of perception thresholds, giving advice on the ‘estimated community response’ and consequent action (eg “*widespread complaints*”) expected from varying levels of WTN and AM exposure based on guidance from ISO 1996-1971. This work was followed by a study for the US Dept of Energy [12], also examining perception thresholds in relation to potential annoyance associated with infrasonic / low-frequency impulsive AM from a downwind turbine, which was reported to generate a feeling of ‘unease’ due to the sensation of pressure pulses.

[1] See Appendix for information on the distinction between upwind and downwind-rotor turbines.

## Reviews of major studies (1993+) – upwind rotor

Much of the large-scale field research into WTN and health has been conducted with populations in western mainland Europe. Large projects have more recently also been carried out in eastern Europe, Canada, China, and Japan. Relatively small, limited field studies have been carried out in the UK, New Zealand, Canada, Australia and the US. Figure 2 illustrates the relative sample sizes of the major field research studies conducted around the world since 1990, with a brief summary of specific details and main results in Table 2 (some smaller studies are also listed in refs [13, 14]).

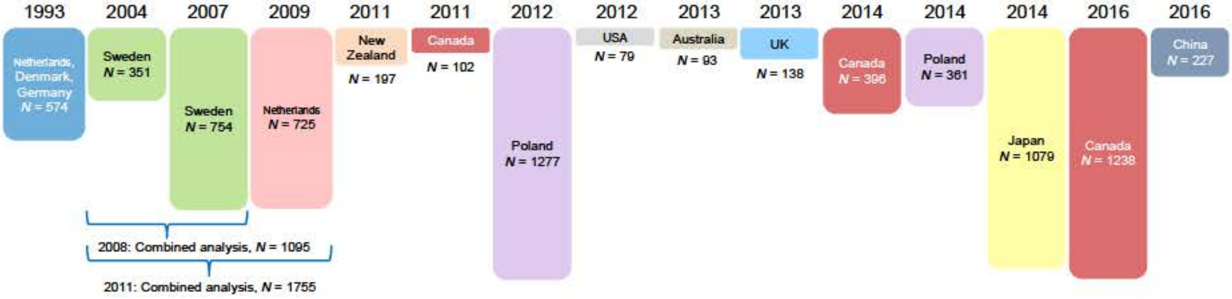


**Figure 2:** Epidemiological field study publications addressing WTN (adapted from ref [15])

Meta-analyses were also conducted on the pooled data from the Swedish and Dutch studies, which showed i) an exposure-response relationship with annoyance (in terms of expected % annoyed or highly annoyed at increasing $L_{den}$ exposure levels), ii) that WTN is considered more annoying than other industrial or transportation sources (by roughly 5-10 dB), and iii) that exposure to visual impacts and having negative attitudes to turbine aesthetics increases the probability of feeling annoyance towards WTN [16, 17].

The conclusions of most reviews of the research on the effects of WTN on health, including those carried out on behalf of Government agencies, confirm that annoyance is caused by WTN, and that AM appears to increase annoyance [2, 13-15, 18-31]. The association of WTN with sleep disturbance appears to be considerably more complex; self-assessment of sleep quality in some cases does seem to be affected by WTN exposure. However, more-consistent results show that sensitivity to noise and feeling annoyed by it are more likely to contribute to poorer perceived sleep quality than the direct exposure to WTN at typical levels. It seems plausible that this is because typical levels of WTN exposure are normally too low to directly intrude into sleeping environments for most people studied (an exception is the Chinese study discussed further below), or that the direct effect of WTN on sleep is small compared with other factors (such as feeling annoyed) – yet the impact of WTN-related annoyance on sleep is of course still a potentially serious problem for people that are affected. Similarly, the evidence for stress tends to indicate that this could in some cases be caused indirectly by annoyance related to WTN, however, recent research has found no evidence linking objective stress indicators with WTN exposure [32]. The definitions used to investigate stress (or 'distress') are sometimes unclear, which makes it more difficult to be conclusive, and limits confidence in the findings of some reviews (for example, ref [27]). The range of other physical and psychological health symptoms that have been suggested as being caused by WTN exposure are not well-supported in the research. The evidence for impacts on quality of life and wellbeing is also conflicting, but it seems reasonable to suppose that for people who feel annoyed by WTN, and perhaps also feel that their sleep is affected, perception of wellbeing is likely to be worsened as well. The reviews also highlight the importance of non-acoustic influences on subjective response to WTN, especially turbine visibility, attitude to wind energy and turbine aesthetics, and economic involvements with wind turbines, as well as exposure to wind energy-related media, neighbourhood land-use, association of perceived sound with wind turbines, and general healthiness; these issues are discussed further below.

**Table 2:** Summary of major epidemiological field research studies into WTN effects on health (publications limited to key papers)

| Publ. year [ref] | Countries | Respondent sample *N* (WTN group *n*) | Turbine power (each) | Health effects studied (method) | Main reported results |
|---|---|---|---|---|---|
| 1993, as reported in [33] | The Netherlands, Denmark, Germany | 574 | Up to 500kW (16 sites) | Annoyance | 6.4% incidence of noise annoyance; stronger correlation for reported noise-related annoyance found with attitude/personality indicators than with WTN exposure levels |
| 2004 [34] | Sweden | 351 | 500-650kW (15/16, 5 sites) | Annoyance; sleep quality (self report) | Significant annoyance response relationship with exposure levels; swishing (AM) of WTN most highly correlated audible characteristic with annoyance; attitude to visual impacts of turbines showed higher correlation than exposure levels (with noise annoyance). |
| 2007 [35] | Sweden | 754 | 500kW - 1.5MW (7 sites) | Annoyance; sleep quality (self-report); chronic illness (self-report) | Significant increasing odds ratios for annoyance and perception of WTN with exposure levels; other factors increasing odds: negative judgments of turbine visual impact; noise-sensitivity; nega ive attitude to turbines; rural/low noise environments. Noise annoyance associated with self-reported sleep disturbance, feelings of iredness and strain. |
| 2009 [36, 37] | The Netherlands | 725 | ≥500kW - 2.5MW (all sites in NED) | Annoyance; sleep quality (self-report); stress (self-report) | Significant annoyance response relationship with exposure levels, comparable with but higher than Swedish studies; WTN more annoying than other environmental sources; noise annoyance associated with sensitivity, negative visual impact, attitude to turbines; economic benefit reduced annoyance incidence. Poorer reported sleep quality related to exposure only at high levels; annoyance associated with sleep quality; stress/distress correlated with exposure. |
| 2011 [38] | New Zealand | 197 (39) | 2.3MW (1 WTN site, 1 control) | Annoyance; HRQoL; sleep quality (self-report); general health (self-report) | Turbine group reported lower sleep quality, physical and environmental HRQoL; noise sensitivity correlated with HRQoL and annoyance. |
| 2011 [2] | Canada | 102 | ? (5 sites) | Sleep quality (self-report); headache; other symptoms (self report) | Significant relationship between distance and reported tiredness; suggested relationships between log-distance and reported sleep quality, tiredness and headache. |
| 2012 [39] | Poland | 1277 | ? | HRQoL | HRQoL higher for residents near wind farms. |
| 2012 [40] | USA | 79 (38 near) | 1.5 MW (2 sites) | Mental health (self-report); sleep quality (self-report) | Subjects nearer to turbines scored poorer on sleep quality and mental health test scales |
| 2013 [41] | Australia | 93 | 3 MW (1 site) | Disturbance /annoyance; tinnitus / ear pain; headache; sleep quality (self-report) | Higher reported night-time annoyance and poorer reported sleep quality for residents nearer the windfarm studied. |
| 2013 [42] | UK | 138 | 0.6-5kW (2 sites) | General health (self-report) | Relationship between perceived noise and negative symptoms found only for individuals high in negative-oriented personality traits. |
| 2014 [43] | Canada | 396 | 1.5-2.3MW (8 sites) | Sleep quality (self-report); tinnitus; headache; mental health (self report); other misc symptoms (self report) | Significantly lower reported sleep quality nearer turbines; significant association of reported ver igo with log-distance; perceived proximity to turbines significantly closer than actual (mean difference: 1.7km). |
| 2014 [44] | Poland | 361 | 100kW - 2.5MW (8 sites) | Annoyance; sleep quality (self-report); chronic illness (self-report) | 33% (outdoor), 21% (indoor) incidence of noise annoyance; annoyance associated with distance to turbine and exposure level; visual impact and general attitude to turbines highly correlated with noise annoyance. Effects on sleep and illness not reported. |
| 2014 [45] | Japan | 1079 (747) | 400kW - 3MW (34 WTN sites, 16 control) | Annoyance; sleep quality (self-report); general health (self-report) | Significant annoyance response relationships with exposure and distance; WTN more annoying at night than other noise; noise sensitivity, visual impacts and negative attitude to turbines increased annoyance; reported sleep quality was poorer for exposure >40 dB(A) only for those respondents also reporting as noise-sensitive. |
| 2016 [32, 46, 47] | Canada | 1238 | 660kW - 4MW | Annoyance; HRQoL; sleep quality (self-report, actimetry); general health (self report); chronic illness (self-report); stress (self report, hormone level, blood pressure, heart rate); other misc symptoms (self-report) | Significant annoyance response relationship with exposure; respondent region influenced annoyance irrespective of WTN level; no relationship between WTN exposure and reported health, QoL, sleep quality, stress or other health symptoms; sleep quality correlated with annoyance. |
| 2016 [48] | China | 227 | 2MW (1 site) | Annoyance; general heal h (self-report); sleep quality (self-report) | Significant response relationships for annoyance and reported sleep quality with exposure; visual impact and noise sensi ivity correlated with annoyance; noise sensitivity and annoyance correlated with sleep quality. |

**More-recently published research (2016+)**

Almost all of the existing WTN research into sleep quality has relied on self-assessment techniques to measure responses. The results of the recent Health Canada study ($N$ = 1238) employed objective measurements of both sleep quality and stress indicators, but found no evidence linking WTN exposure at outdoor levels of up to 46 dB(A) with either [46, 47]. Objective measurements of sleep quality were also used in a small, controlled field study ($N$ = 21, 11 in the exposed group) reported in ref [49], with similar findings. In a related longitudinal study, objective measurements of sleep parameters were made for 16 residents both before and after construction of a wind farm (5×1.8 MW), with noise levels measured outdoors and inside bedrooms. No effect was found on measured sleep for WTN with average indoor levels of 31 dB(A), however, perceived sleep quality worsened following the turbine installation [50]. The poorer perceived sleep quality was related to participants' attitude to wind turbines, the visual impacts of the wind farm, and whether an individual was worried about property devaluation [51]; these factors also contributed to worsened QoL scores [52].

A study conducted in China [48] reported very high rates of annoyance, perceived sleep disturbance and self-assessed ill-health amongst residents around the selected site ($N$ = 227), however this study differed from others due to the very close ranges of the 2MW, 85m hub-height turbines to dwellings – the largest proportion of the subject sample were living within 100-400m of the nearest turbine. Compared with previous studies, WTN levels were higher (44-57 dB(A) at houses within 339m), visibility was greater and residents had (understandably) more negative attitudes to wind turbines and their visual impacts, and higher reported sensitivity to noise. The approach taken to masking the survey intent is not clarified, and may not have been adequate to control bias in the circumstances. Nonetheless, at such high levels, there is no reason to expect that the noise would not disrupt people's sleep.

**Amplitude Modulation**

All of the field studies outlined so far have focussed on the responses to time-averaged WTN exposure levels. In a study of noise emissions from 1.8 MW turbines, it was argued that noise annoyance expressed by residents at 500-1900m distances might be exacerbated by AM, increased levels and low-frequency content occurring in the late evening and night-time. These phenomena were attributed to the stable night-time atmosphere causing high wind shear, and the coincidence of AM patterns from the turbines [53].

An investigation into complaints reported from one site (3×2MW) showed a relationship between recorded annoyance responses and measurements using an indicator of the AM depth, although the sample was small ($N$ = 8), and uncertainty quite large; time-average level was found to be a more important parameter in determining response [54].

Several laboratory studies have been carried out examining details of scaled annoyance responses to quantified AM in WTN (ie category 1). Results from refs [55, 56] are shown[2] in Figures 3 and 4a. Significant relationships were found with time-average level ($L_{\mathrm{Aeq,T}}$) and annoyance; the results for modulation depth (MD) were weaker, with significance typically found only when comparing high and low depth values from the ranges.

Further evidence for the influence of the MD on response has been reported from lab study results in ref [57],as shown in Figure 4b (with MD normalised relative to its maximum value), which exhibit a significant effect of 'relative modulation strength' on rated annoyance ($N$ = 19).

A threshold for perception of the fluctuations in a modulating WTN-like sound has been studied; lab results from ref [58] are shown in Figure 5, which indicate that around 40-50% of

[2] NB. linear regression is shown to aid visibility of trends, but has not been tested as a parametric model for the data displayed.

the participants ($N$ = 17) perceived fluctuation at MDs of 2 dB $\Delta L_{Aeq,100ms(50\text{-}200Hz)}$, increasing to 95-100% at 3 dB $\Delta L_{Aeq,100ms(50\text{-}200Hz)}$[3]. Overall $L_{Aeq,T}$ also appears somewhat related to the likelihood of AM detection, in agreement with other psychoacoustic test results [59].

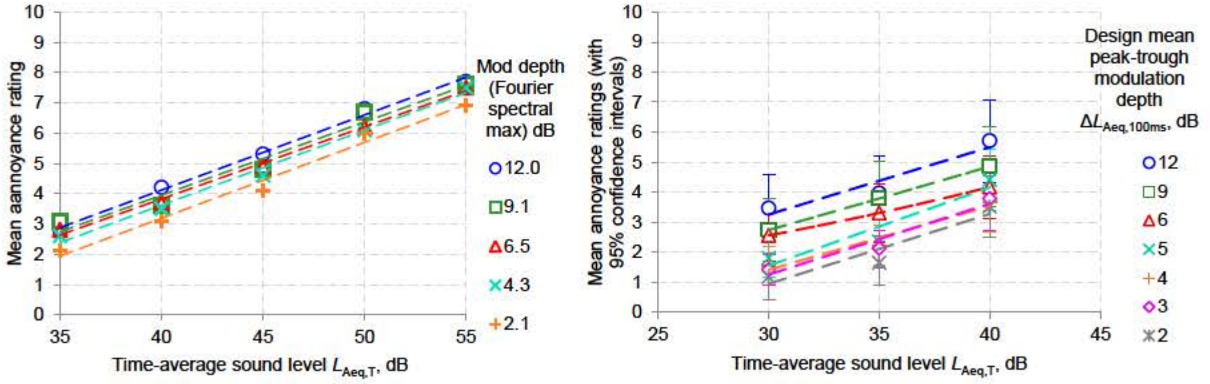


**Figure 3:** AM WTN time-average sound level exposure-response relationships identified in (a, left) ref [55] ($N$ = 30); (b, right) ref [56] ($N$ = 20)

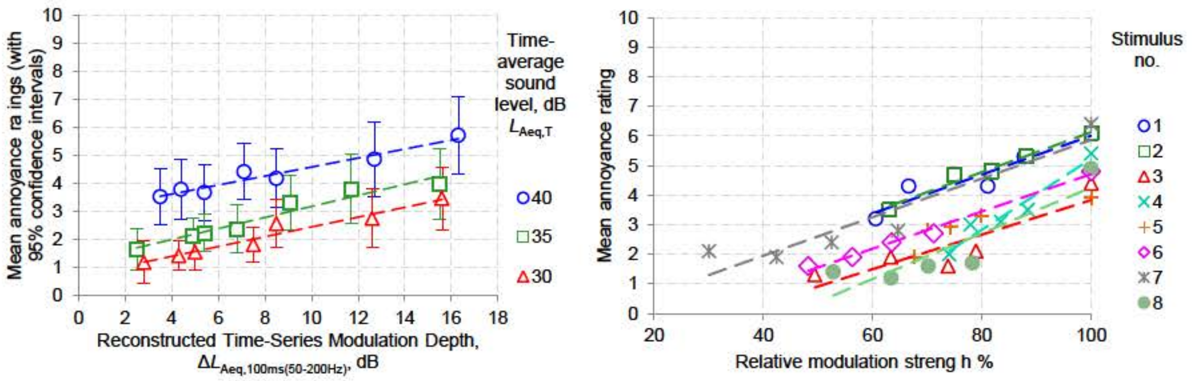


**Figure 4:** AM WTN modulation depth exposure-response relationships identified by (a, left) [adjusted from] ref [56] ($N$ = 20); (b, right) ref [57] ($N$ = 19)

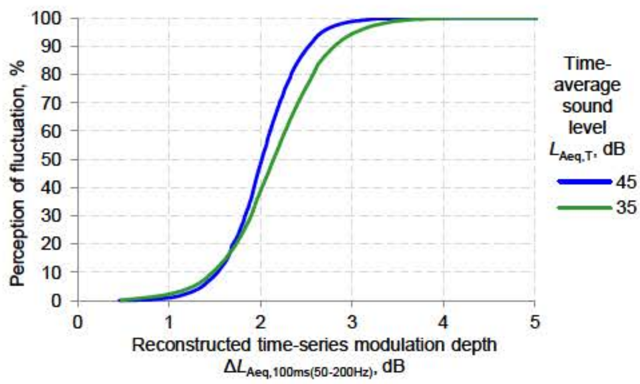


**Figure 5:** WTN AM detection threshold identified by [and adjusted from] ref [58] ($N$ = 17)

Two of the studies directly examined the subjective equivalence of a modulating WTN sound compared with its steady-amplitude counterpart using a method of paired comparison adjustment [56, 58]. The results are shown in Figure 6a; on average, the equivalence between the AM and negligible-AM WTN sounds used was approximately in the range 0-4 dB. The results of an experiment with a larger sample ($N$ = 60) were used to model the probability of

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[3] $\Delta L_{Aeq,100ms(BP)}$ is the indicator for modulation depth developed in ref [7], which evaluates the level difference in the reconstructed bandpass-filtered signal envelope sampled at 100ms intervals. Where possible, results from previous studies have been adjusted to use this metric; details of the adjustments are provided in ref [60].

high annoyance associated with WTN sounds exhibiting i) no significant AM and ii) periodic AM with a varying MD in the range of around 6 to 9 dB [61]; equivalent annoyance probability for periodic AM was approximately 1-3 dB for time-average levels in the range 35-55 dB $L_{Aeq,T}$, in broad agreement with the earlier results of refs [56, 58].

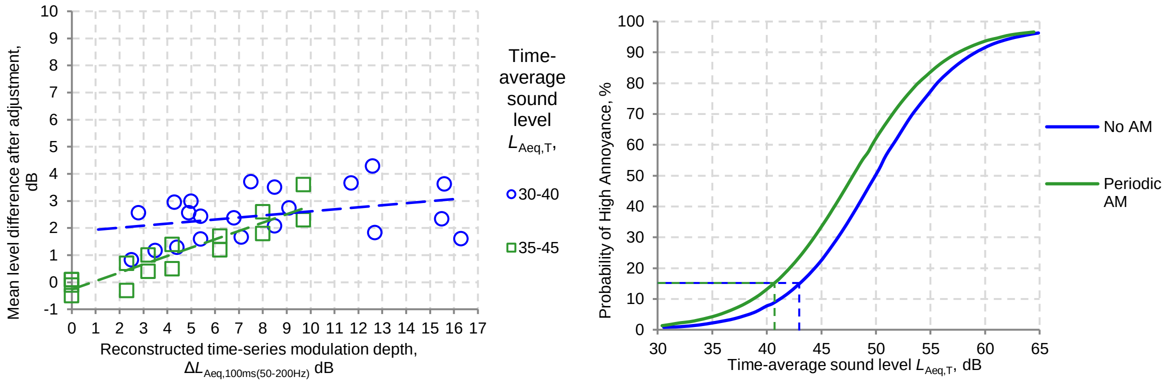


**Figure 6:** AM WTN equivalent response exposure-response relationships (a, left) identified by [adjusted from] (○) ref [56] (*N* = 20) and (□) ref [58] (*N* = 17); (b, right) ref [61] (*N* = 60)

The modulation frequency ($f_m$) of WTN AM has been shown to have some effect on lab ratings of annoyance: ref [57] reported an increasing trend but did not show significance over the range of 0.5 to 2 Hz. Sub-test results presented in ref [56] (*N* = 11) also indicated an increased response to a $f_m$ of 1.5 Hz compared with 0.8 Hz, although, as shown in ref [60], when results are adjusted for differences in $L_{Aeq,T}$ and MD, the effect is small. In both cases the effects of other parameters, such as differences in the audible-range frequency spectra, appeared to be stronger; as mentioned above, low-frequency character in WTN AM has been highlighted as a possible cause of increased annoyance [53]. In a recent laboratory study, Smith et al [62] investigated the effect of AM WTN on objective parameters of sleep (*N* = 6), finding evidence that the night with 'strong, low-frequency' AM at an indoor exposure level of 33 dB $L_{Aeq,1h}$ showed most sleep fragmentation and the least amount of slow wave sleep, compared with the control night. The corresponding outdoor equivalent level was 45 dB(A), though the degree of 'masking sound' in the stimuli (eg from wind/vegetation noise) is unclear. Media reports of adverse impacts from infrasonic emissions in WTN do not appear to be supported by research evidence: in general WTN infrasound levels are well below thresholds of perception [63], and results from a recent lab study (*N* = 72) using real and sham exposures indicated that, whereas high expectation of negative effects from infrasound had a significant influence on symptom reporting, actual exposure to infrasound did not [64].

## Discussion

Issues of potential bias due to study designs (eg lack of masking), the problematic contexts in which some surveys have taken place (eg legal proceedings or complaint investigations) have been raised with many of the existing field studies [13, 15]. That the research is almost all cross-sectional also impedes determination of effects causality. Nonetheless, there is general agreement that WTN can provoke annoyance, and that annoyance could in turn affect sleep. Annoyance tends to be increased when AM is present, and AM tends to be more prevalent (and noticeable) in evening, night and early morning periods, when sensitivity to noise is also likely to be highest. The effects of diurnal variation in AM exposure (duration, intermittency etc), which could be expected to be an important factor in determining responses, are not well-documented in the evidence reviewed, and this area could benefit from further study.

The results from the laboratory-based exposure-response studies are limited by small samples, typically recruited from somewhat unrepresentative populations. However, they offer the advantages of close control and direct examination of the effects of the AM component in WTN, which is much more difficult to achieve in field studies.

The suggestion that psychological factors such as expectation and worry play a significant role in perceived negative health symptoms, such as annoyance, stress, worsened sleep quality, headaches etc is likely to be unpalatable to neighbours of windfarms, but nevertheless, studies have shown that mental attitude, sensitivity and personality traits such as neuroticism, as well as absorption of negative media presentation of wind turbines are likely to influence the effects an individual perceives as being the result of noise exposure [42, 64, 65]. This is far from being a phenomenon unique to wind turbines; worry about safety or health also increases annoyance responses to aircraft and road noise [66], and the decibel equivalence in exposure variation of such moderating factors for a range of sources has been estimated in the research as a broad range of 6 to 26 dB [67].

## PLANNING CONTROL

On the basis of the review and studies considered above, a control for AM has been proposed for use in planning windfarm developments. This control takes as its basis the principle that AM increases annoyance caused by WTN, and that this increase can be characterised by adding a penalty value to the overall WTN level, to equalise it with subjective judgement of a negligible-AM WTN sound. This results of ref [58] suggest that fluctuation in broadband WTN-like sounds will almost certainly be sensed by most people with normal hearing at approximately 3 dB $\Delta L_{\mathrm{Aeq,100ms(BP)}}$, which forms the proposed onset for the penalty. Based on the equivalent response evidence, and in view of existing standardised approaches to noise character penalty adjustments [68], the magnitude for the penalty is given a variable value of 3 to 5 dB over the MD range 3 to 10 dB (and 5 dB thereafter). The AM character penalty scheme as proposed is shown in Figure 7a, with relevant data from the supporting evidence. The result of applying this penalty scheme to the absolute response data from ref [56] is shown in Figure 7b (NB. this is a separate response dataset from the data shown in Figure 7a). As would be expected, the average responses show significant correlation with rating level $L_{\mathrm{Ar,T}}$ with Pearson *r*-value of 0.872 ($p<0.01$), compared with 0.684 for the separated parameters $L_{\mathrm{Aeq,T}}$ and 0.693 for $\Delta L_{\mathrm{Aeq,100ms(50\text{-}200Hz)}}$.

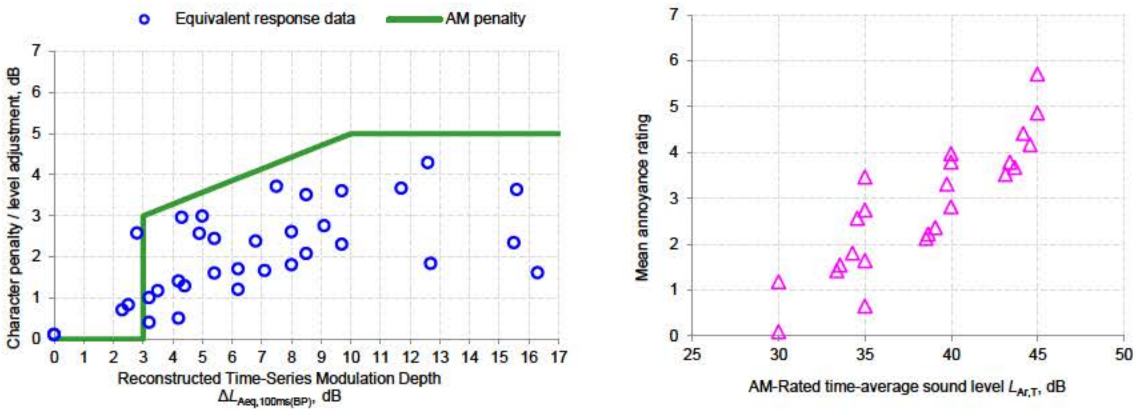


**Figure 7:** AM penalty scheme (a, left) value to be applied and equivalent response datasets [adjusted from] refs [56, 58]; (b, right) application to absolute annoyance response dataset from ref [56] ($N$ = 20)

The possible influence of increased low-frequency content in the AM is addressed by the design of the metric used to rate the magnitude, which employs frequency filtering to ensure the signal is evaluated for the range that produces the maximum AM rating.

The penalty value should be applied to the time-averaged level of WTN before comparison with the noise limits in place, which would form a part of the planning consent. In cases where higher (ie less stringent) night-time limits are in place, the difference in day/night limits should also be added, to ensure protection for the sensitive night period. Where rated levels are above noise limits, and complaint investigations have indicated that impacts are unacceptable, enforcement action should be taken to ensure the additional impact of AM is reduced. Under the principle of the character adjustment penalty scheme proposed, this could either be by reducing incidence or magnitude of AM, or by reducing the overall $L_{\mathrm{Aeq,T}}$, although the former would perhaps be a more favourable outcome.

## CONCLUSIONS

The aims of the project were to review the exposure-response research, and if possible to recommend a planning control for AM. The review found that, of the many health effects attributed to WTN, the weight of the evidence indicates that, at typical community exposure levels (eg 25-45 dB(A) outdoors), the main effect expected is annoyance, and AM can increase that annoyance. Furthermore, it seems that the annoyance some people feel could negatively impact their perceived sleep quality. At higher levels, eg ≥ 45 dB(A) outdoors and ≥ 30 dB(A) indoors, there is some evidence to suggest that sleep quality may be directly affected, and that AM content could have some influence on this. Further research is recommended to more fully understand the levels of WTN and AM that might impact on sleep.

The existing annoyance evidence has been used as a basis for a planning control based on a principle of 'equivalent subjective response' to AM. A character penalty scheme incorporating the main acoustic exposure factors thought to affect response has been recommended for application in planning wind farm developments. Questions remain regarding the extent and prolongation of impacts, and further field research could assist in this regard.

It is hoped that the proposed control will lead to the development of AM mitigation measures.

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## REFERENCES

[1] Alves-Pereira, M and Castelo Branco, N A A (2007). *In-home wind turbine noise is conducive to vibroacoustic disease*. Second International Meeting on Wind Turbine Noise, Lyon, France, 20-21 Sept.

[2] Krogh, C M E, Gillis, L, Kouwen, N and Aramini, J (2011). WindVOiCe, a self-reporting survey: adverse health effects, industrial wind turbines, and the need for vigilance. *Bulletin of Science and Technology*, 31 (4), 334-345.

[3] Frey, B J and Hadden, P J (2012). *Wind turbines and proximity to homes: the impact of wind turbine noise on health – a review of the literature and discussion of the issues* (Independent report).

[4] Castelo Branco, N A A, Alves-Pereira, M, Pimenta, A M and Ferreira, J R (2015). *Low-frequency noise-induced pathology: contributions provided by the Portugese wind turbine case*. 10th European Congress and Exposition on Noise Control Engineering (EuroNoise), Maastricht, the Netherlands, 31 May – 3 Jun, 2015.

[5] Gosden, E. (2014, November 30). Noisy wind farms face ban as ministers launch review into 'annoying' sound levels. *The Telegraph*. Retrieved from.telegraph.co.uk [online], last accessed 18/03/17.

[6] Hayes McKenzie (2006). *The measurement of low frequency noise at three UK wind farms. URN 06/1412.* Department of Trade and Industry.

[7] Bass, J, Cand, M, Coles, D, Davis, R, Irvine, G, Leventhall, G, et al (2016). *IOA Noise Working Group (Wind Turbine Noise) Amplitude Modulation Working Group final report: A method for rating amplitude modulation in wind turbine noise*. Institute of Acoustics.

[8] WSP | Parsons Brinckerhoff (2016). Wind turbine AM review: Phase 2 report. 3514482A-2 V3. Department for Business, Energy and Industrial Strategy. [online]

[9] WSP | Parsons Brinckerhoff (2015) Wind turbine AM review: Phase 1 report. 3514482A-1 V1. Department for Business, Energy and Industrial Strategy. [online]

[10] Wells, G A, Shea, B, O'Connell, D, Peterson, J, Welch, V, Losos, M and Tugwell, P (2014). The Newcastle-Ottawa Scale (NOS) for assessing the quality of nonrandomised studies in meta-analyses, from http://www.ohri.ca/programs/clinical_epidemiology/oxford.asp

[11] Stephens, D G, Shepherd, K P, Hubbard, H H and Grosveld, F W (1982). *Guide to the evaluation of human exposure to noise from large wind turbines*. NASA Technical Memorandum 83288, Langley Research Centre.

[12] Kelley, N D, McKenna, H E, Hemphill, R R, Etter, C L, Garrelts, R L and Linn, N C (1985). *Acoustic noise associated with the MOD-1 wind turbine: its source, impact and control*. Solar Energy Research Institute, US Department of Energy.

[13] Schmidt, J H, Klokker, M (2014). Health effects related to wind turbine noise exposure: a systematic review. PLoS ONE 9(12): e114183.

[14] Onakpoya, I J, O'Sullivan, J, Thompson, M J & Heneghan, C J (2015). The effect of wind turbine noise on sleep and quality of life: a systematic review and meta-analysis of observational studies. *Environment International*, 82, 1-9.

[15] McGunney, R J, Mundt, K A, Colby, D, Dobie, R, Kaliski, K & Blais, M (2014). Wind turbines and health – a critical review of the scientific literature. *Journal of Occupational and Environmental Medicine*, 56 (11), e108-130.

[16] Pedersen, E & Larsman, P (2008). The impact of visual factors on noise annoyance among people living in the vicinity of wind turbines. *Journal of Environmental Psychology*, 28, 379-389.

[17] Janssen, S A, Vos, H, Eisses, A R & Pedersen, E (2011). A comparison between exposure-response relationships for wind turbine annoyance and annoyance due to other noise sources. *Journal of the Acoustical Society of America*, 130 (6), 3746-3753.

[18] van den Berg, F (2011). Effects of sound on people. In: Bowdler, D & Leventhall, G (eds). *Wind Turbine Noise*, ch 6. Brentwood: Multi-Science Publishing.

[19] Knopper, L D & Ollson, C A (2011). Health effects and wind turbines: a review of the literature. *Environmental Health*, 10:78 [online]

[20] von Hünerbein, S, Moorhouse, A, Fiumicelli, D & Baguley, D (2013). *Health impacts of wind turbines.* Scottish Government.

[21] Public Health Wales (2013). *Health impacts of wind turbine noise*. NHS Wales. [online]

[22] Merlin, T, Newton, S, Ellery, B, Milverton, J & Farah, C (2013). *Systematic review of the human health effects of wind farms*. National Health and Medical Research Council.

[23] Jeffery, R D, Krogh, C M E & Horner, B (2014). Industrial wind turbines and adverse health effects. *Canadian Journal of Rural Medicine*, 19 (1), 21-26.

[24] Kurpas, D, Mroczek, B, Karakiewicz, B, Kassolik, K & Andrzejewski, W (2013). *Annals of Agricultural and Environmental Medicine*, 20 (3), 595–605.

[25] Hanning, C D & Evans, A (2012). *Wind turbine noise* (editorial). British Medical Journal, 344 (7853), e1527.

[26] Knopper, L D, Ollson, C A, McCallum, L C, Aslund, M L, Berger, R G, Southweine, K et al (2014). Wind turbines and human health. *Frontiers in Public Health*, 2:63.

[27] Arra, I, Lynn, H, Barker, K, Ogbuneke, C & Regalado, S (2014). Systematic review 2013: association between wind turbines and human distress. *Cureus*, 6 (5): e183.

[28] Hanning, C D (2015). *Wind turbine amplitude modulation and planning control study: work package 3.2 – excessive amplitude modulation, wind turbine noise, sleep and health*. Christopher Heaton-Harris MP.

[29] National Health and Medical Research Council. *Evidence on wind farms and human health*. Australian Government. [online]

[30] Council of Canadian Academies (2015). *Understanding the evidence: wind turbine noise.* The Expert Panel on Wind Turbine Noise.

[31] Cowan, J P (2016). Sound sources associated with negative effects. *The effects of sound on people*, ch 6. Chichester: Wiley.

[32] Michaud, D S, Feder, K, Keith, S E, Voicescu, S A, Marro, L, Than, J et al (2016). Self-reported and measured stress related responses associated with exposure to wind turbine noise. *Journal of the Acoustical Society of America*, 139 (3), 1467-1479.

[33] Pedersen, E (2003). *Report 5308: Noise annoyance from wind turbines - a review.* Swedish Environmental Protection Agency. [online]

[34] Pedersen, E & Persson Waye, K (2004). Perception and annoyance due to wind turbine noise – a dose-response relationship. *Journal of the Acoustical Society of America*, 116 (6), 3460-3470.

[35] Pedersen, E & Persson Waye, K (2007). Wind turbine noise, annoyance and self-reported health and well-being in different living environments. *Occupational Environmental Medicine*, 64, 480-486.

[36] Pedersen, E, van den Berg, F, Bakker, R & Bouma, J (2009). Response to noise from modern wind farms in The Netherlands. *Journal of the Acoustical Society of America*, 126 (2), 634-643.

[37] Bakker, R H, Pedersen, E, van den Berg, G P, Stewart, R E, Lok, W & Bouma, J (2012). Impact of wind turbine sound on annoyance, self-reported sleep disturbance and psychological distress. *Science of the Total Environment*, 425, 42-51.

[38] Shepherd, D, McBride, D, Welch, D, Dirks, K N & Hill, E M (2011). Evaluating the impact of wind turbine noise on health-related quality of life. *Noise and Health*, 13 (54), 333-339.

[39] Mroczek, B, Kurpas, D & Karakiewicz, B (2012). Infuence of distances between places of residence and wind farms on the quality of life in nearby areas. *Annals of Agricultural and Environmental Medicine*, 19 (4), 692-696.

[40] Nissenbaum, M A, Aramini, J J, Hanning, C D (2012). Effects of industrial wind turbine noise on sleep and health. *Noise and Health*, 14 (60), 237-243.

[41] Morris, M (2013). *Waterloo case series preliminary report.* Waubra Foundation. [online]

[42] Taylor, J, Eastwick, C, Wilson, R & Lawrence, C (2013). The influence of negative oriented personality traits on the effects of wind turbine noise. *Personality and Individual Differences*, 54, 338-343.

[43] Paller, C (2014). *Exploring the association between proximity to industrial wind turbines and self-reported health outcomes in Ontario, Canada* (master's thesis). University of Waterloo, Canada.

[44] Pawlaczyk-Łuszczyńska, M, Dudarewicz, A, Zaborowski, K, Zamojska-Daniszewska, M & Waszkowska, M (2014). Annoyance related to wind turbine noise. *Archives of Acoustics*, 39 (1), 89-102.

[45] Kuwano, S, Yano, T, Kageyama, T, Sueoka, S & Tachibana, H (2014). Social survey on wind turbine noise in Japan. *Noise Control Engineering Journal*, 62 (6), 503-520.

[46] Michaud, D S, Feder, K, Keith, S E, Voicescu, S A, Marro, L, Than, J et al (2016). Exposure to wind turbine noise: perceptual responses and reported health effects. *Journal of the Acoustical Society of America*, 139 (3), 1443-1454.

[47] Michaud, D S, Feder, K, Keith, S E, Voicescu, S A, Marro, L, Than, J et al (2016). Effects of wind turbine noise on self-reported and objective measures of sleep. *Sleep*, 39 (1), 97-109.

[48] Song, K, Di, G, Xu, Y and Chen, X (2016). Community survey on noise impacts induced by 2MW wind turbines in China. *Journal of Low Frequency Noise, Vibration and Active Control*, 35 (4), 279-290.

[49] Lane, J D, Bigelow, P L, Majowicz, S E & McColl, R S (2016). Impacts of industrial wind turbine noise on sleep quality: results from a field study of rural residents in Ontario, Canada. *Journal of Environmental Health*, 79 (1), 8-12.

[50] Jalali, L, Bigelow, P L, Nezhad-Ahmadi, M-R, Gohari, M, Williams, D & McColl, R S (2016). Before-after field study of effects of wind turbine noise on polysomnographic sleep parameters. *Noise and Health*, 18 (83), 194-205.

[51] Jalali, L, Nezhad-Ahmadi, M-R, Gohari, M, Bigelow, P, & McColl, S (2016)The impact of psychological factors on self-reported sleep disturbance among people living in the vicinity of wind turbines. *Environmental Research*, 148, 401-410.

[52] Jalali, L, Bigelow, P, McColl, S, Majowicz, S & Gohari, M & Waterhouse, R (2016). Changes in quality of life and perceptions of general health before and after operation of wind turbines. *Environmental Pollution*, 216, 608-615.

[53] van den Berg, G P (2004). Effects of the wind profile at night on wind turbine sound. *Journal of Sound and Vibration*, 277, 955-970.

[54] Bockstael, A, Dekoninck, L, Can, A, Oldoni, D, De Coensel, B & Botteldooren, D (2012). Reduction of wind turbine noise annoyance: an operational approach. *Acta Acustica united with Acustica*, 98, 392-401.

[55] Lee, S, Kim, K, Choi, W & Lee, S (2011). Annoyance caused by amplitude modulation of wind turbine noise. *Noise Control Engineering Journal*, 59 (1), 38-46.

[56] von Hünerbein, S, King, A, Piper, B & Cand, M (2013). *Wind turbine amplitude modulation: research to improve understanding as to its cause and effect. Work package B(2): development of an AM dose-response relationship*, RenewableUK. [online]

[57] Ioaniddou, C, Santurette, S & Jeong, C-H (2016). Effect of modulation depth, frequency, and intermittence on wind turbine noise annoyance. *Journal of the Acoustical Society of America*, 139 (3), 1241-1251.

[58] Yokoyama, S, Kobayashi, T, Sakamoto, S & Tachibana, H (2015). *Subjective experiments on the auditory impression of the amplitude modulation sound contained in wind turbine noise*. 6th International Meeting on Wind Turbine Noise, Glasgow, Scotland, 20-23 April.

[59] Fastl, H (1982). Fluctuation strength and temporal masking patterns of amplitude-modulated broadband noise. *Hearing Research* 8, 59-69.

[60] Perkins, R A, Lotinga, M J (co-lead), Berry, B, Grimwood, C J & Stansfeld, S A (2017). *Development of an approach to controlling the impact of amplitude modulation in wind turbine noise: exposure-response research, application and implementation*. 7th International Conference on Wind Turbine Noise, 2-5 May 2017, Rotterdam, The Netherlands.

[61] Schäffer, B, Schlittmeier, S J, Pieren, R, Heutschi, K, Brink, M, Graf, R et al (2016). Short-term annoyance reactions to stationary and time-varying wind turbine and road traffic noise: a laboratory study. *Journal of the Acoustical Society of America* 139 (5), 2949-2963

[62] Smith, M G, Ögren, M, Thorsson, P, Pedersen, E & Persson Waye, K (2016). Physiological effects of wind turbine noise on sleep. *22nd International Congress on Acoustics*, 5-9 September 2016, Buenos Aires, Argentina.

[63] Jakobsen, J (2005). Infrasound emissions from wind turbines. *Journal of Low Frequency Noise, Vibration and Active Control*, 24 (3), 145-155.

[64] Tonin, R, Brett, J & Colagiuri, B (2016). The effect of infrasound and negative expectations to adverse pathological symptoms from wind farms. *Journal of Low Frequency Noise, Vibration and Active Control*, 35 (1), 77-90.

[65] Crichton, F, Dodd, G, Scmid, G & Petrie, K J (2015). Framing sound: Using expectations to reduce environmental noise annoyance. *Environmental Research*, 142, 609-614.

[66] van den Berg, F, Verhagen, C & Uitenbroek, D (2015). The relation between self-reported worry and annoyance from air and road traffic. *International Journal of Environmental Research and Public Health*, 2015 (12), 2486-2500.

[67] Lercher, P (2007). Environmental noise: a contextual public health perspective. In: Luxon, L & Prasher, D (eds), *Noise and its effects*, ch16. Chichester: John Wiley & Sons.

[68] International Standards Organisation (2016). *ISO 1996-1:2016 Acoustics – description, measurement and assessment of environmental noise – Part 1: Basic quantities and assessment procedures*. ISO.


## Appendix

The distinction between the early downwind-rotor design type of turbine and modern upwind models is indicated in Figure A1; the turbulence in the wake of the tower combined with the slicing of the blades of the downwind-rotor can generate large air pressure variations, which cause the impulsive low-frequency thumping sound and infrasound pulses. This is not the case with the upwind-rotor design, although other mechanisms can contribute to causing a more low-frequency impulsive character to the AM emitted by upwind-rotor turbines.

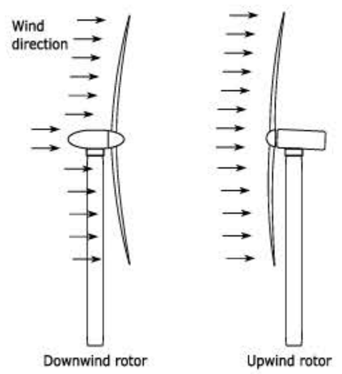


**Figure A1:** Diagram of downwind-rotor and upwind-rotor turbine designs