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Pilot study on perceived sleep acceptability of low-frequency, amplitude modulated tonal noise

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Abstract

The global expansion of wind farm facilities has been associated with community complaints regarding sleep disturbance. This may be related to the presence of amplitude modulation (AM) in wind turbine noise (WTN), which has been shown to result in increased annoyance. However, at present, it is unknown whether acceptability for sleep is judged differently to annoyance or if AM may be more problematic for sleep than other noise types. Previous studies have also focused predominantly on 'swish' noise rather than tonal AM, where the latter has been more consistently measured at several wind farms in South Australia at distances greater than 1 km. Therefore, this study investigated the perceived sleep acceptability of WTN containing low-frequency tonal AM through listening tests involving 13 participants. A total of 13 noise stimuli were synthesised based on real recordings of WTN. The tonal audibility and AM depth were varied within a range relevant to the AM depth measured in field recordings. Participant responses were highly variable, but in self-reported noise-sensitive individuals, an increase in the AM depth at a tonal audibility of 12 dB(A) was associated with lower acceptability for sleep.

Keywords: wind farm noise, low-frequency noise, amplitude modulation, tonal noise, sleep

1 INTRODUCTION

Several important characteristics of wind turbine noise (WTN) account for its potential to disturb humans. These include the dominance of low-frequency components, which have the potential to disturb rest and sleep at relatively low noise levels [1]. Also, the time-varying nature of the noise results in annoying characteristics such as 'swish', 'thumping' and/or 'rumbling' [2][3][4]. Moreover, disturbance can arise due the large contrast between operational and ambient conditions, particularly at night-time, in the normally quiet rural environments where wind farms are usually located in Australia [5].

Previous listening tests have investigated the effect of various WTN components on annoyance. The main focus of these studies has been on signals measured less than 1 km from a wind farm [6][7][8][9], where the noise is dominated by mid-frequency energy. These studies have shown that annoyance ratings increase in response to an increase in sound pressure level (SPL) [10], AM depth [6][7][8][9] and tonal audibility [11]. Listening tests using synthesised WTN based on measurements taken between 100 m and 1 km showed that low-frequency components less than 63 Hz have minimal effect on perceived loudness [8]. However, these results may not extrapolate to all WTN measured at distances greater than 1 km, where the spectrum is dominated by low-frequency energy. One key reason may be that for a specific change in low-frequency content to have an equivalent effect on subjective annoyance as the same change in mid- and high-frequency content, a difference of at least 30 dB between the low-frequency and the mid/high-frequency content is necessary [12]. Another reason may be that the results obtained by Yokoyama *et al.* [8] are only applicable to steady signals and are not representative of WTN containing low-frequency tones and AM.

Results of listening tests investigating other sources of low-frequency noise are also relevant to the study of WTN, particularly where special audible components such as tonality and AM are present. Persson-Waye *et al.* [13] found that low-frequency amplitude modulated tonal noise can adversely affect performance of tasks involving sustained attention and awareness over 30 minutes. However, the noise samples were based on low-frequency ventilation noise containing a tone in the 31.5 Hz 1/3-octave band, which is at least 20 dB higher than tones at the same frequency measured outdoors near a wind farm [14]. Also, the modulation frequency was 2 Hz, which is higher than typical values associated with large modern wind turbines with capacities greater than 2 MW ($<$ 1 Hz). In another study, Persson-Waye *et al*. [15] observed that compared to a reference night with no exposure to noise, participants took nearly twice as long to fall asleep when exposed to low-frequency ventilation noise. The low-frequency ventilation noise investigated included a tone at 50 Hz, which was amplitude modulated at 2 Hz. Similarly to the study by Persson-Waye *et al* [13], the amplitude of the tone was at least 10 dB higher than tonal WTN measured outdoors in this 1/3-octave band and the modulation frequency was higher than that associated with WTN [5]. According to listening tests carried out by Oliva *et al*. [16], penalties for tonality are not required for low-frequency tones at 50 Hz and 110 Hz with tonal audibilities ranging from 5 to 25 dB(A). However, these results may have been influenced by the short sample time of 15 s, which may not have been long enough to capture the extent of annoyance. This may take longer and importantly depend on variable human factors such as attention, concentration, irritability and situational factors at the time. Moreover, results may differ through use of a representative WTN background spectrum rather than a spectrum based on the inverse A-weighting curve.

The majority of studies to date regarding WTN annoyance have investigated relatively short-range noise types dominated by ‘swish’. However, in an Australian context, low-frequency ‘thumping’ or ‘rumbling’ noise appears to be a more significant complaint. This study investigates the human response to this ‘thumping’ or ‘rumbling’ noise that has been mentioned in complaints from residents. A study by the South Australian Environmental Protection Agency in 2013 found that 14 out of 15 residents living at various distances up to 8 km from the Waterloo wind farm (a target of frequent noise complaints in Australia) complained of ‘thumping’ and/or ‘rumbling’. The majority of residents (9 out of 15) also complained about sleep disturbance as a result of exposure to WTN. Their responses were documented in noise diaries that were collected over several weeks. The aim of the present study was to identify which signal characteristics in WTN are deemed more or less acceptable for sleep. This was done through listening tests in a laboratory setting with a sample of WTN-naive individuals that were recruited from the Adelaide Institute for Sleep Health (AISH). The focus was on a low-frequency ($\approx$ 50 Hz), amplitude-modulated (AM) tone, that has been consistently measured at a number of residences located near the Waterloo wind farm [5]. Various combinations of tonal audibility and AM depth were included in the listening test and participants evaluated the acceptability for sleep of each noise sample. A secondary aim was to determine the minimum sample length required for future tests by monitoring when participants stopped adjusting the SPL.

2 METHODOLOGY

2.1 Participants

A total of 13 participants, aged between 21 and 46, took part in the listening tests. As this was a Pilot test, the participants were employees and students at AISH, none of whom have lived near a wind farm. All participants completed the 21-question Weinstein noise-sensitivity scale (WNSS) test [17]. The WNSS focuses on general environmental noise rather than WTN specifically. This study was approved by the Flinders University Social and Behavioural Research Ethics Committee (SBREC project 7536). All participants provided voluntary informed written consent.

2.2 Testing room and instrumentation

Experiments were conducted in a bedroom located in the AISH Nick Antic Sleep Laboratory. The background SPL of the room is 22 dB(A). Participants were instructed to lie flat on a bed and to relax while they were presented with a total of 13 stimuli. The stimuli were 5-minutes long and were played via Bose Quiet Comfort II headphones. Headphones were used to enable faithful reproduction of the signals and to minimise ventilation-noise contamination at low frequencies. The noise signals were created with MATLAB and reproduced via an RME Babyface Pro sound card, which has a flat frequency response, within 0.5 dB, from 0 Hz – 20.8 kHz. The headphones were calibrated using the HEAD acoustics HMS III artificial head and the frequency content adjusted to match the original signal.

2.3 Stimulus design

Synthesised signals were used instead of measured WTN because real signals with various combinations of tonal audibility and AM depth contain different levels and types of background noise, which cannot be standardised. The synthesised signals all contained the same background noise spectrum but the signal-to-noise ratio varied depending on the required tonal audibility.

For the purposes of signal synthesis, WTN with tonal AM was assumed to contain a combination of background noise (BGN) and amplitude modulated (AM) noise, as follows:

$$\mathrm{WTN}_{\mathrm{AM}} = \beta \times (p_{\mathrm{AM}}(t) + \alpha \times \mathrm{BGN}), \tag{1}$$

where the overall SPL is controlled by adjusting β, and the signal-to-noise ratio of the tonal AM, and hence tonal audibility, depends on the value of α.

The BGN spectrum was designed to be representative of WTN measured at a distance of 2.5 km from the Waterloo wind farm, during conditions when WTN was observed to be dominant. The synthesis method is based on the approach described by Lee *et al* [6]. Briefly, the real WTN was transformed to the frequency domain and a moving average filter was applied to extract the general WTN spectrum. The general WTN spectrum was then multiplied with white noise and the resultant signal was transformed back into the time domain using an Inverse Fast Fourier Transform (IFFT).

To synthesise wind turbine AM, a sine wave was used as the modulating signal. For a single-frequency tone, the sound pressure as a function of time that is experienced when the tonal sound of frequency, f, is modulated with a frequency, f_m, is given by,

$$p_{\mathrm{AM}}(t) = A(1 + \mu m(t))\cos(2\pi f t + \phi) \tag{2}$$

where μ is defined as the modulation index [3], ϕ is an arbitrary phase angle that was set equal to zero. The modulation function, $m(t)$, can be represented as a simple cosine function as,

$$m(t) = \cos(2\pi f_m t + \phi_m) \tag{3}$$

where ϕ_m is an arbitrary phase angle that was set equal to zero. The quantity, A is the time averaged value of the amplitude of the signal being modulated and was set equal to 1.

The tonal audibility of the noise samples was calculated using the method outlined in IEC 61400-11 [18] and the parameter α, and hence masking SPL, was adjusted to give the required tonal audibility. The AM depth was calculated using the IOA 'reference method' [19] and the parameter, μ, was varied to give the required AM depth.

2.4 Experimental procedure

The listening test was designed using pre-recorded audio instructions and an inter-stimulus alarm that was kept constant for each participant to minimise possible biases. A representation of the test procedure is provided in Figure 1(a). The noise samples were presented in random order to account for systematic error associated with carry-over effects and sensitisation/de-sensitisation to noise. Each participant underwent a practice test to ensure familiarity with the testing procedures and requirements. The experimenter remained in the room for this phase of the test to answer any questions from participants.

Participants were instructed to lie on a bed and relax for the duration of the test. Lights were turned down to less than 1 lux when the experimenter exited the bedroom and the experimental trial formally commenced. They wore Bose Quiet Comfort II headphones and the Active Noise Control (ANC) feature was switched on to minimise background noise contamination. They were provided with a physical volume control knob that was used to adjust the SPL of noise to the maximum level the participant considered would be acceptable for sleep. The test arrangement is depicted in Figure 1(b). Visual volume cues were not displayed on the control knob, thus adjustment relied solely on auditory input from headphones.

A total of 13 noise samples were presented at various combinations of tonal audibility and AM depth for the 50 Hz tone under investigation, as shown in Figure 1(c) with sample s0 representing the baseline. The total test time was approximately 70 minutes, including instructions.

For each participant, the noise presentation began at a relatively high level of 50 dB(A), with the intention that the majority of participants would wish to reduce the SPL for sleep acceptability (rather than possible non-adjustment if the initial SPL were too low). The SPL adjustment was recorded using the sound card software, which provides a loopback function. This allowed real-time signal information to be sent to MATLAB for later post-processing. Participants could adjust the SPL between a minimum of no noise signal and a maximum SPL of 70 dB(A).

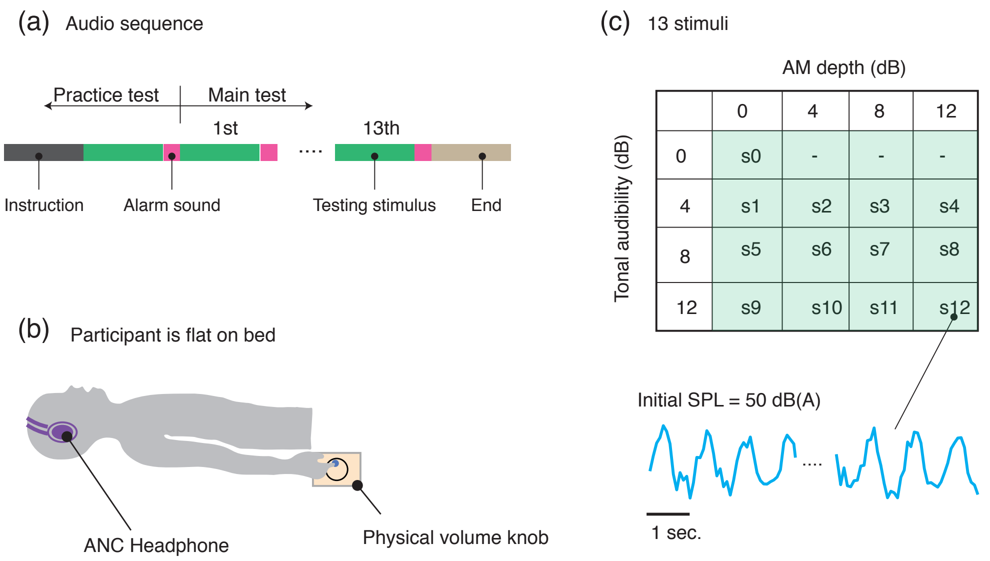

Figure 1. Experimental set-up

3 RESULTS AND DISCUSSION

3.1 Adjustment time for WTN acceptability for sleep

Most participants (85%) reduced the SPL from 50 dB(A) to achieve a level they considered acceptable for trying to fall sleep. A typical plot of the SPL adjustment versus time for a single participant, in response to all 13 samples, is shown in Figure 2(a). A similar plot was constructed for each of the 13 participants and the final mean adjustment time was found by identifying the time at which the adjustment was less than 1 dB over 5 seconds. This was determined by starting from the maximum sample time of 5-minutes and working backwards. The probability density function (PDF) shown in Figure 2(b), which is constructed based on 169 adjustment times recorded for all samples/participants, indicates that most participants were satisfied with their adjustment after 5 seconds but some participants were still making adjustments up to 280 seconds into the noise samples. Therefore, a cumulative distribution function (CDF) was used to find an adjustment time that would be satisfactory for 95% of time, which is 210 seconds, as shown in Figure 2(b). However, closer inspection of the plot indicates that as the slope of the CDF is very small, the sample length could be reduced to 180 seconds and participants would still be satisfied for 94% of the time. Therefore, we propose that an adjustment time of 180 seconds is reasonable for future listening tests involving similar noise samples.

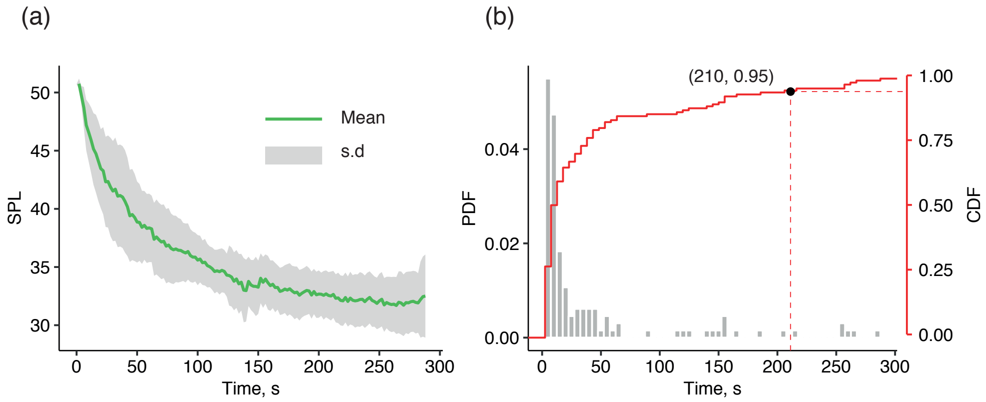

Figure 2. (a) Mean and standard deviation of the sound pressure level (SPL) adjustment as a function of time. (b) Probability density function (PDF) and cumulative distribution function (CDF) of time taken for final adjustment for all samples/participants. The black dot represents the adjustment time that would be satisfactory for 95% of time.

3.2 Noise sensitivity

Each participant's sensitivity to noise was calculated based on the WNSS. From the survey, a sensitivity score ranging from 1 and 105 is obtained, where a higher score denotes higher sensitivity to noise. The sensitivity scores are displayed in Figure 3(a), which shows the distribution of noise sensitivity scores, which followed a normal distribution. In order to test for noise sensitivity effects, the group was arbitrarily divided at the group mean into higher versus lower noise-sensitive groups.

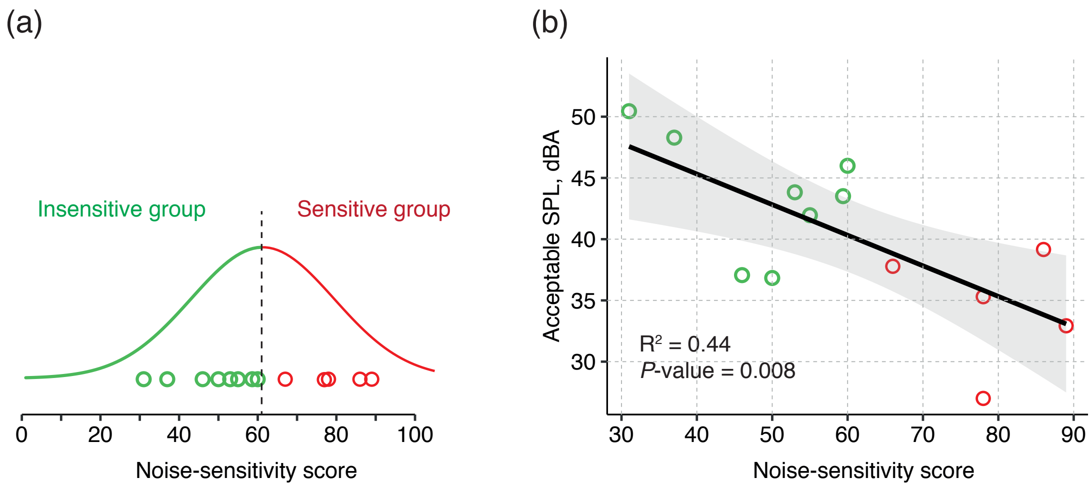

Figure 3. (a) Noise sensitivity scores and associated normal distribution and classification of noise-sensitive or insensitive groups. (b) Relationship between overall acceptable SPL for sleep and the WNSS. A linear regression fit is shown using the solid black line and the 95% confidence interval is indicated by the grey shaded region.

Figure 3(b) shows a strong and statistically significant inverse relationship between the final SPL adjustment and the noise sensitivity score, and indicates that the overall acceptable SPL for sleep varies by over 20 dB(A) between participants.

3.3 Sleep acceptability of an AM tone

The relationship between tonal audibility, AM depth and SPL difference is shown in Figure 4. The y-axis values represent the difference between the final SPL adjustment for the baseline noise sample and samples with tonal AM. A negative value indicates that a penalty may be necessary to ensure that WTN is acceptable for sleep.

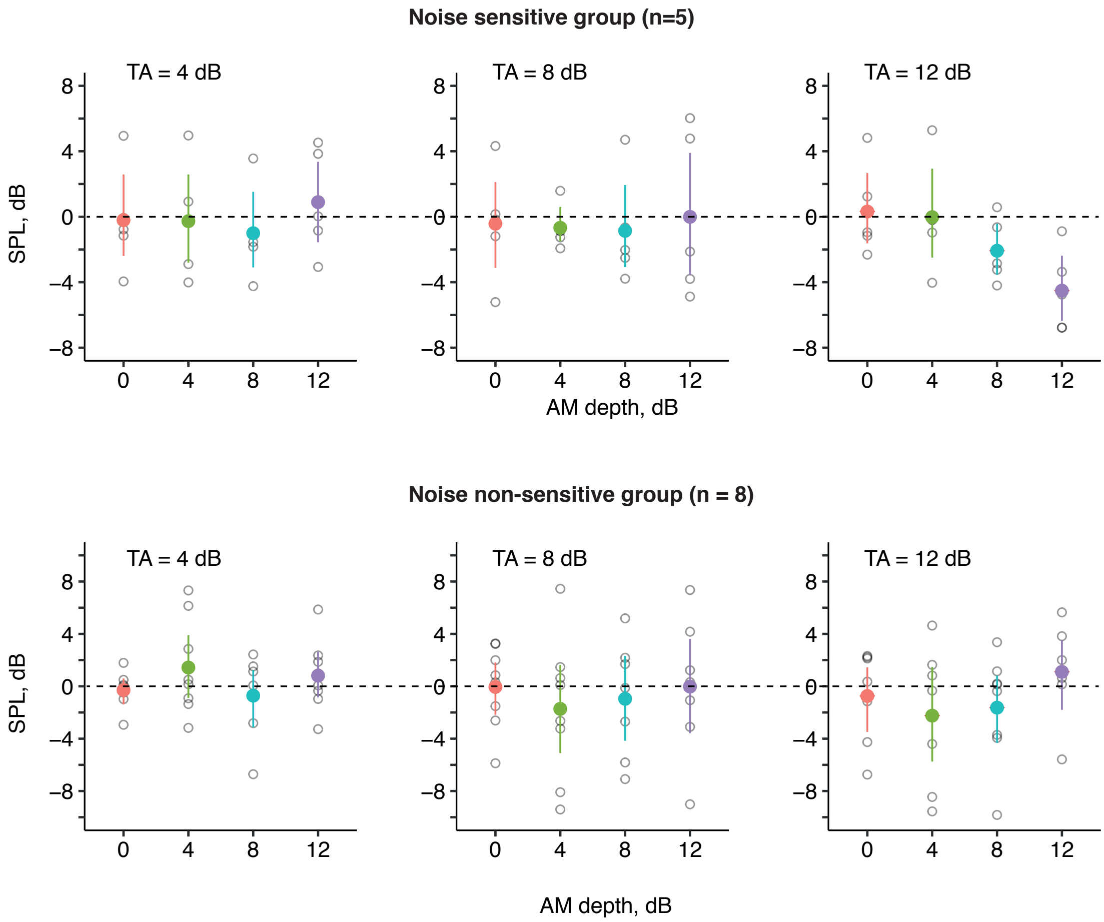

Figure 4. Final SPL adjustment relative to the baseline for (a) noise-sensitive participants, n = 5 and (b) noise-insensitive participants, n = 8.

A clear trend between tonal audibility and AM depth is evident for cases where the tonal audibility was 12 dB(A) and participants were noise-sensitive. The results are consistent with previous studies showing an increased annoyance with increased AM depth [6][7][8][9]. This finding is applicable to around 40% of the sample and suggests that a penalty of up to 5 dB(A) may be required, depending on the AM depth. Further analysis indicated that 62% of the sample reduced the SPL below 40 dB(A) when the tonal audibility and AM depth were 12 dB(A) and 12 dB, respectively. This supports the possible requirement of a penalty for a South Australian wind farm, as the allowable SPL limit is 40 dB(A) [20]. The small sample size is a limitation of this study and studies on larger sample sizes are warranted given these encouraging preliminary results.

The 50 Hz tone had minimal impact on sleep acceptability for all values of tonal audibility in the absence of AM. This finding is similar to the work of Oliva *et al* [16], who showed that no penalty is be required for low-frequency tonal noise at 50 Hz with tonal audibility between 5 and 25 dB(A). In fact, these researchers found a statistically significant negative penalty value for a tonal frequency of 50 Hz and tonal audibility of 18 dB(A), when the overall L_{Aeq} was 25 dB(A). This suggests a reduction in annoyance at low SPLs in the presence of a low-frequency 50 Hz tone. In the present study, some participants found WTN more acceptable for sleep when a 50 Hz tone was present, even when it was amplitude modulated. However, this may be related to the choice of baseline noise sample for which the spectrum shape was based on real WTN. Perhaps a better choice of baseline noise sample would be one that is based on a room criteria (RC) spectrum shape, which is less objectionable [21]. This is particularly true if a penalty is not applied for the presence of low-frequency WTN.

4 CONCLUSIONS

This study shows that the perceived acceptable level of WTN for sleep varies between individuals and is inversely proportional with self-declared noise sensitivity. Noise-sensitive individuals judged WTN containing tonal AM to be less acceptable for sleep when the tonal audibility was 12 dB(A). For the worst-case noise stimulus, which contained a 50 Hz tone with tonal audibility of 12 dB(A) and an AM depth of 12 dB(A), a penalty in the order of 5 dB(A) may be required.

A further aim was to determine an appropriate sample exposure duration to investigate acceptability for sleep. Although it was demonstrated that the majority of participants were satisfied with their adjustment time after 5 seconds, it was also evident that some participants needed more time. Thus, a stimulus time of 3 minutes may be a good conservative choice for future experiments given that this satisfied the study sample for 94% of the time.

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