Wind Turbine Noise Effects on Sleep: The WiTNES study

Michael Smith[1], Mikael Ögren[1], Pontus Thorsson[2], Laith Hussain-Alkhateeb[1], Eja Pedersen[3], Jens Forssén[2], Julia Ageborg Morsing[1], Kerstin Persson Waye[1]

[1] University of Gothenburg, Institute of Medicine, Department of Occupational and Environmental Medicine, Gothenburg, Sweden
[2] Chalmers University of Technology, Department of Civil and Environmental Engineering, Division of Applied Acoustics, Gothenburg, Sweden
[3] Lund University, Department of Architecture and the Built Environment, Lund, Sweden

Corresponding author's e-mail address: michael.smith@amm.gu.se

ABSTRACT

Onshore wind turbines are becoming increasingly widespread globally, with the associated net effect that a greater number of people will be exposed to wind turbine noise (WTN). Sleep disturbance by WTN has been suggested to be of particular importance with regards to a potential impact on human health. Within the Wind Turbine Noise Effects on Sleep (WiTNES) project, we have experimentally investigated the physiological effects of night time WTN on sleep using polysomnography and self-reporting protocols. Fifty participants spent three nights in the sound exposure laboratory. To examine whether habituation or sensitisation occurs among populations with long-term WTN exposure, approximately half of the participants lived within 1km of at least one turbine. The remaining participants were not exposed to WTN at home. The first night served for habituation and one WTN-free night served to measure baseline sleep. Wind turbine noise ($L_{AEq,indoor,night}$=31.9 dB) was introduced in one night. This exposure night included variations in filtering, corresponding to a window being fully closed or slightly open, and variations in amplitude modulation.

INTRODUCTION

Sleep is vital for adequate health and wellbeing, yet by its very definition is reversible. Such reversibility presents the opportunity for external factors, including noise, to disrupt sleep as the brain awakes the body following environmental intrusion. The link between traffic noise and sleep disruption is well established [1], yet the effects of noise from wind turbines is comparatively under-examined, although the body of research is growing. There is some evidence for an association between sleep disturbance and wind turbine noise (WTN) levels, e.g. [2,3], but there has also been recent work finding no link between one-year WTN averages and sleep outcomes [4].

Response to a sound is not wholly dependent on the acoustical characteristics such as level, duration and frequency content. An individual's tolerance and attitude to a certain sound can moderate their response [5], and persistent exposure may lead to an increase or a decrease in reaction. In the case of habituation, repeated exposure over time results in an individual reacting less strongly than previously to an exposure of the same amplitude. For example, long-term behavioural adaptation to noise occurs in fish following repeated motorboat noise exposure following an initial increase in hiding [6]. It is unclear however whether behavioural changes such as these in humans may reflect true habituation, involving synaptic plasticity mechanisms such as long-term depression [7], or if these changes are instead indicative of coping strategies. In the opposite direction to habituation, sensitisation occurs when repeated exposure leads to a stronger response over time. For instance, in the famous example of a dripping tap, the sound may be innocuous at first but can become unbearable after persistent exposure.

Possible habituation or sensitisation to WTN represents a potential explanation for the disparity in findings from research into the effects of WTN on human response. This paper therefore describes a study performed to investigate the physiological impact on sleep from WTN exposure. The Wind Turbine Noise Effects on Sleep (WiTNES) project was performed with the aims of investigating the physiological or psychological impact of WTN on sleep, and whether repeated WTN exposure at home may lead to habituation or sensitisation.

METHODS

Study setting

Our laboratory was equipped to resemble a typical apartment, with a private external entrance, living/dining area, kitchenette fully stocked with breakfast food and drink, lavatories and a shower. Three private bedrooms were furnished with a bed, desk, chairs and bedside cabinets. Participants were free to come and go from the laboratory during the day as they wished. Noise exposure in the bedrooms was introduced though 88 loudspeakers mounted within the ceiling of each room. The background noise level in the bedrooms was <14dBA, so artificial ventilation noise was introduced at L_{AEq}=18 dB.

The study protocol involved three nights in the sound exposure laboratory per participant. The first night was not expected to be representative of typical sleep, and instead served as a habituation period to the environment and the sleep recording equipment. Normal sleep was measured in a WTN-free control night. Simulated wind turbine noise was introduced in an exposure night. To mitigate any possible order effects, the control night and the exposure night altered in order, so that half of the study group experienced the control night first, and the other group the exposure night first (Table 1).

Table 1: Arrangement of study nights across different experimental groups, showing the number of participants from each study group in each arrangement.

Group	1st night	2nd night	3rd night	
			Control	WTN1/2/3/4
Reference	Habituation	Control	-	12
	Habituation	WTN1/2/3/4	14	-
Exposed	Habituation	Control	-	12
	Habituation	WTN1/2/3/4	12	-

Noise exposure

Noise in the WTN exposure night was based on many short- and long-term recordings of WTN in the field. WTN sound files were synthesised based on the amplitude modulation parameters and equivalent frequency spectrum found in the recordings. The amplitude modulation parameters used were frequency-dependent modulation depth and RPM. Random variations in time were also included to mimic the recordings. All WTN sound files were calibrated to represent L_{AEq}=45 dB for the complete sound file as a free field sound level. The equivalent frequency spectrum was chosen to be constant in all WTN sound files.

There were four distinct 2-hour noise scenarios (A-D) over the course of the 8-hour WTN exposure, constructed from a 2×2 arrangement of high and low amplitude modulation strength, and a level and frequency difference corresponding to a filter simulating the bedroom window being fully closed or slightly ajar (Table 2). After 70 minutes in each 2-hour scenario, there was a period of 10 minutes without WTN. The signal to noise ratio between the periods with and without WTN was kept constant at 20 dB independently of the AM strength or window filtering. The order of the scenarios was changed across different noise nights to avoid any ordering or time of night effects. There were hence four different noise exposure nights, WTN1-WTN4, which were counterbalanced between different individuals from both study groups in a Latin square design (Table 1). The alternating scenarios did not affect the 8-hour acoustic measures.

Table 2: Acoustic characteristics of wind turbine noise across 2-hour periods of the WTN nights. Noise levels were measured at the pillow position. AM: amplitude modulation. RPM: Rotations per minute.

Scenario	AM strength	Window filter	$L_{AEq,2h}$	$L_{AF,max}$	Beats	RPM
A	7-9 dB	Closed	29.3 dB	42.6 dB	Yes	13
B	1-2 dB	Closed	29.3 dB	33.5 dB	Yes	13
C	7-9 dB	Slightly open	33.5 dB	44.5 dB	Yes	13
D	1-2 dB	Slightly open	33.4 dB	36.5 dB	Yes	13

The WTN exposure period was 23:00 to 07:00, with noise increasing linearly with time from 22:00 to 23:00 (see Figure 1 for the example of night WTN2). This “lead-in” period was to avoid any startle effects following sudden noise onset at lights-out at 23:00. The 8-hour noise level was $L_{AEq,indoor,night}$=31.9 dB corresponding to an outdoor free field level of slightly less than $L_{AEq,outdoor,night}$=45 dB.

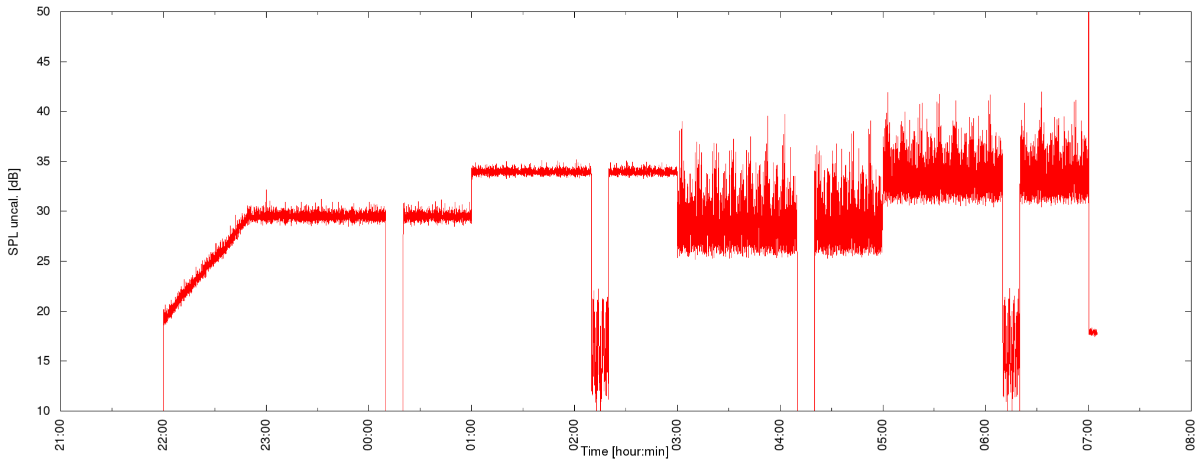

Figure 1: Eight-hour nocturnal noise exposure in WTN2, with additional 1-hour lead-in noise. The noise event at 07:00 was the wakeup alarm call.

Participants

Two study groups were recruited; a group living close to wind turbines and therefore potentially exposed to wind turbine noise at home, hereafter termed *Exposed*, and a control group who did not live close to wind turbines, hereafter termed *Control*. The exclusion criteria were as follows: aged <30 or >70 years; habitual sleep times not comparable to the timings in the laboratory study; self-reported sleep apnoea; sleep medication; BMI>30; poor self-reported auditory acuity. A participant was classed as "exposed" to WTN at home if they lived within 1km of the nearest wind turbine, or reported annoyance or sleep disturbance by WTN at home, for at least one year, although no noise measurements were performed at the dwellings. Applicants rated their attitude towards wind turbines in general, and their impact on the landscape, but these items were not part of the selection criteria. Stress at home was measured prior to arrival at the laboratory, and again on the first study evening, using PSS-10 [8]. Noise sensitivity was scored according to the Weinstein questionnaire [9]. Hearing was measured using pure tone audiometry in the laboratory, and compared against age-dependent norms [10]. Study subjects were financially compensated for participating.

Sleep measurement

The present paper describes the self-reported sleep outcomes, but the study also involved multiple physiological measures of sleep. These physiological measures, which will not be reported here, included polysomnography, wrist actigraphy, heart rate, blood pressure, cortisol awakening response and long-term cortisol from hair samples.

Self-reported sleep quality and day-after effects

Subjective sleep was measured using questionnaires completed each morning within 15 minutes of waking up. The self-report items were as follows: sleep quality (numerical 0-10 scale, and semantic 5-point Likert scale), tired (0)-rested (10), tense (0)-relaxed (10), irritated (0)-happy (10), perceived sleep latency (minutes), number of recalled awakenings, difficulty falling back asleep following awakening (yes/no/did not wake), easy (0)-difficult (10) to sleep, slept better (0)-worse (10) thank usual, slept deep (0)-light (10), did not wake (0)-woke often (10), sleep disturbance by WTN (0-10), WTN causing poor sleep (5-point Likert, not at all-extremely), WTN causing awakenings (5-point Likert, not at all-extremely), WTN causing difficulty sleeping (5-point Likert, not at all-extremely), WTN causing tiredness in the morning (5-point Likert, not at all-extremely), and mood (Pleasantness and Social Orientation, 1-4 [11]).

ANALYSIS

Each self-reported item was analysed individually in an ordinal logistic regression model (STATA, Release 14.1, StataCorp). The model looked at the effect of WTN exposure only (control night vs. WTN night), and accounted for the dependence of repeated measures on the same individuals. The response scales of seven variables were inverted in the analysis so that all scales pointed in the same direction, with an increase in the model estimate from the reference reflecting increased negative effects on the response items. Both mood items were recoded into 3-level categorical variables due to the skewness of their distributions. All variables were checked in a correlation analysis to ensure they did not co-vary.

RESULTS

Participants

Fifty participants spent the full three nights in the study (Table 3). Distribution of sex, age, BMI, health status, medication use, problems with concentration and tension at home were approximately equal between both groups. A higher proportion of the exposed group reported a negative attitude to wind turbines, excessive tiredness and difficulties sleeping. There were no indications of differences in PSS-10 scores measured at home or on the first study evening (paired sample t-test p=0.48, r=0.84).

Table 3: Demographics of study participants from the reference and exposed groups. Data reported as frequencies (n) or means and ±standard deviations.

Variable		Reference	Exposed
Sex (n)	Women	15	12
	Men	11	12
Age (mean years)		50.7±10.5	51.8±9.0
BMI (mean, kg/m^2)		25.6±3.4	25.3±3.1
Health status (n)	Very good	5	4
	Rather good	14	15
	Neither good nor bad	3	3
	Rather bad	1	2
Regular medication use (n)		9	7
General attitude to wind turbines (n)	Very positive	6	3
	Positive	17	7
	Neither positive or negative	3	7
	Negative	0	6
	Very negative	0	1
Attitude to impact on landscape (n)	Very positive	0	0
	Positive	13	1
	Neither positive or negative	12	6
	Negative	1	11
	Very negative	0	6
Excessive tiredness (n)*	Seldom or never	19	10
	Once or several times per month	4	10
	Once or several times per week	0	1
	Daily or almost daily	1	3
Had trouble concentrating (n)*	Seldom or never	14	13
	Once or several times per month	8	7
	Once or several times per week	1	1
	Daily or almost daily	1	3
Felt tense or stressed? (n)*	Seldom or never	7	7
	Once or several times per month	13	10
	Once or several times per week	4	4
	Daily or almost daily	0	3
Difficulties sleeping at home (n)	Rarely or never	14	9
	Several times per month	8	8
	Several times per week	1	5
	Nearly every day	1	1
Annoyance by WTN indoors at home over last month (mean, 1-5)		-	2.5±1.1
Sleep disturbance by WTN at home over last month (mean, 1-5)		-	2.2±1.3
Tiredness in mornings (mean, 0-10)		3.5±2.0	6.3±2.4
Tense in mornings (mean, 0-10)		3.4±1.7	4.5±2.1
Perceived stress at home (mean PSS-10)		12.6±6.5	14.1±7.9
Noise sensitivity score (mean)		74.6±17.2	79.1±13.3

*Selected items from PSS-10

Self-reported outcomes

The results of the models for each outcome, which includes WTN exposure night alone as a predictor, are presented in Table 4. All response items excepting tenseness, perceived sleep depth and social orientation were significantly negatively affected following nights with WTN exposure.

Furthermore, the exposed study group differed from the control group in the majority of the response items, rating their sleep as worse even in the absence of WTN exposure. There was a significant effect of sex for sleep depth and WTN causing difficulty falling back asleep, in both instances with men having worse sleep. Effects of noise sensitivity were seen for WTN causing tiredness and both mood items. Regular sleep difficulties was a significant predictor for around half of all outcomes, including difficulty sleeping, one of the three outcomes for which no effect of WTN exposure was seen. No significant effects of age were found for any of the outcomes, and no WTN exposure × group interactions were observed.

Table 4: Results of the regression models for self-reported sleep outcomes. β=Beta coefficient of model, WTN-free control night as reference category. 95% CI= 95% confidence interval. n.s.=not statistically significant.

Variable	WTN exposure		
	β	p-value	95% CI
Sleep quality (0-10)*	2.25	<0.001	1.16-3.18
Sleep quality (5-point semantic)*	2.17	<0.001	1.17-3.17
Tired-Rested (0-10)*	1.27	<0.01	0.43-2.11
Tense-Relaxed (0-10)*	0.72	n.s.	0.008-1.45
Irritated-Happy (0-10)*	1.3	<0.01	0.48-2.12
Hard to sleep following awakenings? (no/yes)	1.33	<0.05	0.09-2.56
Easy-Difficult to sleep (0-10)	0.88	<0.05	0.13-1.64
Slept better-Worse than usual (0-10)	1.88	<0.001	0.88-2.88
Deep-Light sleep (0-10)	0.67	n.s.	-0.09-1.44
Never woke-woke a lot (0-10)	1.71	<0.001	0.68-2.75
Sleep disturbance by WTN (0-10)	4.31	<0.001	2.29-6.33
WTN impaired sleep quality (5-point semantic)	5.14	<0.001	2.91-7.37
WTN caused awakenings (5-point semantic)	4.09	<0.001	2.28-5.90
WTN making it hard to fall back asleep (5-point semantic)	3.91	<0.001	2.25-5.58
WTN cause tiredness in morning (5-point semantic)	2.92	<0.001	3.52-4.21
Mood: Pleasantness (1-4)* ♪	1.00	<0.05	0.14-1.86
Mood: Social orientation (1-4)* ♫	0.96	n.s.	-0.03-1.94

*Response scale inverted

♪ Converted from continuous data to categories with the following cut-off points: <2.8; ≥2.8 and <3.5; ≥3.5

♫ Converted from continuous data to categories with the following cut-off points: <3.0; ≥3.0 and <4.0; ≥4.0

DISCUSSION

Almost all measures of self-reported sleep were negatively impacted following nights with wind turbine noise. The WTN nights lead to increased sleep disturbance, reduced sleep quality, increased tiredness, increased irritation, awakenings, increased difficulty to sleep, sleeping worse than usual, and decreased mood. Subjects dwelling close to wind turbines, and consequently potentially exposed to WTN at home, repeatedly scored their sleep and restoration lower than the reference group following the WTN nights. However, their baseline sleep and restoration scored after the quiet WTN-free night were also generally scored lower than by the reference group. Although efforts were made during recruitment to obtain as similar a study sample from both the exposed and reference groups, a larger proportion of participants in the exposed group reported excessive tiredness at least once a month (58% vs. 20%) or difficulties sleeping at home at least several times a month (61% vs. 41%). Nevertheless, the effect of WTN exposure on sleep remained even after correcting for regular sleep difficulties and tiredness.

Difficulties sleeping at home, such as those reported by 61% of the exposed group, are not necessarily due to WTN exposure. Stress, stimulants, social commitments, noise from other sources, occupational demands and myriad other factors all have the potential to disrupt sleep. Persons with pre-existing sleep difficulties were more susceptible for negatively impacted sleep in the laboratory, as measured by many of the questionnaire items. Such people might be more readily disturbed from sleep in general, including by WTN, and therefore represent a potentially vulnerable group in the field.

The noise levels in the present study are rather on the high side, and such levels are unlikely to occur regularly if WTN limits are met [12]. Furthermore, the acoustical characteristics of the noise (amplitude modulation and presence of beats) were chosen based on an initial pilot study designed to provide indications on potentially deleterious acoustical characteristics of WTN [13], and as such the exposures in the present study likely represent a worst-case scenario. It is not a simple task to determine any long-term health consequences of infrequent yet acute disturbance, since the body can compensate for poor sleep in subsequent nights [14]. However, when considering noise from aircraft traffic for example, it has been proposed that noise levels insufficient to induce one additional awakening above those that would occur spontaneously represents a suitable night time limit [15].

Despite the limitations of questionnaires and the study design, the present paper provides evidence that a single night of wind turbine noise at indoor levels of $L_{AEq,8h}$= 31.9 dB negatively impacts self-reported sleep. This is in agreement with observations of some cross-sectional field studies [16], but contrary to studies which have found no effects [4]. It may be that any deleterious effects of WTN on sleep depend heavily on a pre-existing susceptibility or a sensitisation among a subgroup of populations. Furthermore, although certain objectively measured sleep and self-reported sleep outcomes may correlate well [17], agreement between the two parameters is often poor. For instance, subjective sleep quality has been shown to worsen among individuals following nearby wind turbine installation, but this was not supported by PSG outcomes where no difference was found [18]. Analysis of the physiological sleep data from the present study will provide further insight into any effects of WTN noise on sleep.

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