The Effect of Wind Turbine Noise on Objective and Subjective Sleep and Next-Day Mood, Anxiety and Cognitive Performance

By

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DEDICATION

I would like to dedicate this thesis to my number one supporter, Dan.

We did it.

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SUMMARY

Sleep is essential for optimal daytime functioning and good physical and mental wellbeing. Chronically inadequate or poor-quality sleep contributes to a range of physical and mental health impacts, such as insomnia, poor daytime functioning, irritability and increased risks of accidents and adverse health outcomes. Thus, chronic sleep problems are an important cause of potentially avoidable morbidity, mortality and economic costs to the community.

Environmental noises, such as traffic noise, are well known to impact sleep. However, high quality, objective evidence to evaluate the impact of wind turbine noise (WTN) on sleep is limited. Furthermore, the currently available literature is dominated by cross-sectional and observational field studies that show mixed findings and where causation remains equivocal. Given the increasing reliance on wind power generation with continued growth in wind farm developments and ongoing community complaints regarding WTN related sleep disturbance, it is important to investigate potential impacts of WTN on sleep. Therefore, the primary aim of the work presented in this thesis was to investigate the impact of WTN on objective and subjective measures of sleep as well as next-day mood, anxiety, and cognitive performance under carefully controlled experimental conditions in a laboratory environment. A further aim was to examine if WTN exposure effects differ amongst different population groups, including young healthy adults without prior WTN exposure, residents living near a wind farm who do and do not report WTN related sleep disruption, rural residents without WTN exposure and urban residents reporting road traffic noise (RTN) related sleep disruption. A third aim was to gain an understanding of the possible psychological versus physiological contributions to possible WTN effects on sleep by comparing wake only versus sleep only presentations of WTN. These different modes of WTN presentations are detailed in Chapters 4 and 5. This was to

investigate if residents living near wind farms and self-reporting WTN related sleep disturbance potentially exhibit a conditioned insomnia response to nocturnal WTN in a carefully controlled laboratory environment. Whilst Chapter 2 and Chapter 3 are independent studies, Chapter 4 and Chapter 5 investigate the same sample and same study design but different outcomes.

In the second Chapter, the first comprehensive systematic literature review and meta-analysis is presented to evaluate the available evidence to date regarding WTN effects on sleep from validated objective and subjective sleep assessment tools. Nine studies were eligible for review and five studies were meta-analysed. Combined data from five objective studies comparing WTN to quiet background noise conditions showed no significant effects on the most widely used objective markers of sleep including sleep latency, total sleep time, wake after sleep onset and sleep efficiency. Subjective sleep outcomes were not sufficiently uniform for combining data or comparisons between studies, but appeared to support that insomnia severity, sleep quality and daytime sleepiness can be impacted by WTN exposure in comparison to quiet background noise. This review highlighted the limited knowledge and data in this area and the need for further carefully controlled experimental studies using ecologically valid WTN as well as objective and psychometrically validated sleep assessments to provide more conclusive evidence regarding the impact of WTN on sleep.

In the third Chapter, the effect of WTN on polysomnographically (objective) and sleep diary determined (subjective) sleep latency was assessed in a pilot study of 23 healthy sleepers living in urban residences away from wind turbines. Participants were exposed, in counterbalanced order, to one night of background noise alone (23 dB(A)) as a control, and another night of WTN at 33 dB(A) (i.e., the upper end of expected indoor values) up until the time of sustained sleep in a sleep laboratory. No significant differences in objective or subjective sleep latency were found between WTN exposure versus control

nights. Whilst undetected small effects could not be ruled out, these results do not support the position that WTN increases sleep latency in individuals without prior WTN exposure.

In the fourth Chapter and a separate study and sleep laboratory, objective and subjective sleep macrostructure parameters were assessed in a large carefully controlled laboratory study in four population groups. Participants included two groups habitually exposed to WTN at night, one group with (n = 14) and one without (n = 18) self-reported WTN related sleep disruption, another group of rural residents without WTN exposure (n = 18) and a group of urban residents who reported RTN related sleep disruption (n = 18). All participants were exposed in randomised order to: (1) a quiet control night with background noise only (19 dB(A)); (2) a full night of WTN exposure at 25 dB(A); (3) WTN exposure only during established sleep periods; and (4) WTN exposure only during wake periods. The 25 dB(A) WTN was similar to median indoor night-time WTN levels recorded over a full-year observation period for distances from 1-3 kilometres from a wind farm to illustrate representative WTN levels in the field. All study participants (n = 68) underwent full in-laboratory polysomnography during the four exposure nights. No significant main effects of noise condition or group-by-noise condition interaction effects on objective or subjective sleep efficiency, total sleep time, sleep latency, wake after sleep onset, number of awakenings or any sleep stage outcomes were found.

This controlled laboratory study suggests that WTN exposure at a level similar to median indoor WTN levels does not appear to significantly impact key objective or subjective sleep macrostructure parameters or show any wake- versus sleep-dependent effects within or between population groups with varying prior noise exposure and self-reported noise related sleep disruption (i.e., WTN-sleep disturbed, WTN-non sleep disturbed, rural control or RTN-sleep disturbed). Whilst effects of WTN at higher noise exposure levels cannot be ruled out, these findings do not support the idea that residents living near wind turbines and who report WTN related sleep disruption display consistent

conditioned responses to nocturnal WTN exposure in a carefully controlled laboratory environment.

Similar to sleep disturbance, experimental studies to investigate the impact of nocturnal WTN on next-day mood, anxiety or cognitive performance outcomes remain lacking. Whilst the work of previous Chapters showed no significant impacts of WTN on objective and subjective markers of sleep time and quality, the potential for WTN to impact subsequent daytime functioning warranted specific investigation. For example, traditional sleep scoring metrics reported in Chapter 4 may not be sufficiently sensitive to detect more subtle sleep disruption that could contribute to daytime functioning impairments. Alternatively, psychological effects without necessarily any detectable sleep disruption could also potentially influence subsequent daytime performance and behavioural outcomes. Thus, in a separate analysis, reported in Chapter 5, next-day mood, anxiety and cognitive performance outcomes were assessed in the same controlled laboratory study. There was a marginal statistically significant noise condition main effect for digit span forwards recall, with greater recall occurring in the WTN-Continuous versus WTN-Sleep condition (p=0.048). However, this finding is difficult to explain and is in the reverse direction expected of noise disruption effects, particularly given no evidence of any differences compared to the no noise control. Thus, Type-1 error seems most likely. There were no further significant noise condition, or group-by-noise condition interaction effects to indicate any systematic differences in any other mood, anxiety, or cognitive performance outcomes. Given no consistent evidence of poorer outcomes in the presence of WTN compared to control conditions, WTN exposure at 25 dB(A) in a carefully controlled environment does not appear to impact mood, anxiety or daytime cognitive performance outcomes the day following nocturnal WTN exposure.

The work presented in this thesis suggests that WTN exposure at 25 dB(A) in a carefully controlled laboratory environment does not appear to significantly impact

objective or subjective sleep, next-day mood, anxiety or cognitive performance when assessed via traditional sleep scoring methods of polysomnography and psychometrically validated measures of sleep, mood and anxiety and objective daytime cognitive performance measures. These findings were consistent across different populations including those residing close to wind farms and report sleep disruption from WTN. These studies make an important contribution to understanding the impact of WTN on objective and subjective sleep macrostructure, as well as next-day mood, anxiety, and cognitive performance.

DECLARATION

I certify that this thesis:

1. does not incorporate without acknowledgment any material previously submitted for a degree or diploma in any university; and
2. to the best of my knowledge and belief, does not contain any material previously published or written by another person except where due reference is made in the text.

Signed.....Tessa Liebich..... Date.....28/04/2022.....

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GLOSSARY OF ABBREVIATIONS

BMI	Body Mass Index
CBTi	Cognitive Behaviour Therapy for insomnia
CI	Confidence Interval
dB	Decibels
dB(A)	A-weighted decibels
dB(G)	G-weighted decibels
df	Degrees of freedom
DSM-V	Diagnostic and Statistical Manual of Mental Disorders – Fifth Edition
DSST	Digit Symbol Substitution Test
EEG	Electroencephalographic
EMG	Electromyography
EOG	Electrooculography
ESS	Epworth Sleepiness Scale
Hrs	Hours
Hz	Hertz
IQR	Interquartile Range
ISI	Insomnia Severity Index
km	Kilometres
L_{AEq}	Equivalent continuous sound pressure level
$L_{AEq, 8h}$	Eight-hour equivalent continuous sound pressure level
M	Mean
m	Metres
Mins	Minutes
ms	Milliseconds
N / n	Sample size / number of participants

NREM	Non-Rapid Eye Movement Sleep
POMS	Profile of Mood States
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
PSG	Polysomnography
PSQI	Pittsburgh Sleep Quality Index
PVT	Psychomotor Vigilance Task
REM	Rapid Eye Movement Sleep
RTN	Road Traffic Noise
SD	Standard Deviation
SE	Standard Error
SOL	Sleep Onset Latency
SPL	Sound Pressure Level
SPLs	Sound Pressure Levels
STAI	State-Trait Anxiety Inventory
STROBE	Strength the Reporting if Observational studies in Epidemiology
TST	Total Sleep Time
WASO	Wake After Sleep Onset
WFN	Wind Farm Noise
WiTNES	Wind Turbine Noise Effects on Sleep
WTN	Wind Turbine Noise

**In this thesis the following terms are used interchangeably:*

1. *'Sleep onset latency' and 'sleep latency'*
2. *'Subjective' and 'self-reported'*
3. *'Objective' and 'polysomnography'*
4. *'Sleep disturbance' and 'sleep disruption '*

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Liebich, T., Micic, G., Zajamšek, B., Hansen, K., Lack, L., Dunbar, C., Lechat, B., Decup, F., & Catcheside, P. The effect of worst-case wind farm noise on self-reported and polysomnographically measured sleep onset latency: A pilot study. *Flinders University DocFest 2019*, 30th August – 6th September 2019, Adelaide: Australia.

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Liebich, T., Catcheside, P., Lack, L., Hansen, K., Zajamšek, B., Lovato, N., & Micic, G. A systematic review and meta-analysis of wind farm noise effects on sleep using validated objective and subjective sleep assessments. *Flinders University DocFest, 2020,* 8th – 11th September 2020, Adelaide: Australia.

Liebich, T., Catcheside, P., Lack, L., Hansen, K., Zajamšek, B., Lovato, N., & Micic, G. An evaluation of wind farm noise effects on sleep using validated objective and subjective sleep assessment: a systematic review and meta-analysis. *The European Sleep Research Society Congress 2020,* 22nd – 25th September 2020, Spain: Europe (presented virtually).

Liebich, T., Micic, G., Hansen, K., Zajamšek, B., Lovato, N., Catcheside, P., ... & Lack, L. The effect of wind farm noise on subjective and polysomnographically measured sleep onset latency: a pilot study. *The European Sleep Research Society Congress 2020,* 22nd – 25th September 2020, Spain: Europe (presented virtually).

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Liebich, T., Lack, L., Hansen, K., Zajamšek, B., Lovato, N., Catcheside, P., & Micic, G. A meta-analysis on the impact of wind turbine noise on sleep using validated objective sleep assessments. *9th International Conference on Wind Turbine Noise,* 18th – 21st May 2021, Ireland: Europe (presented virtually).

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CHAPTER 1. INTRODUCTION TO WIND TURBINE NOISE AND ITS POTENTIAL IMPACT ON SLEEP

1.1 Overview

In 2015, there were 76 operating wind farms across Australia, which expanded by 24% to 94 operating wind farms in the three years to 2018 (Australian Renewable Energy Agency, 2019; Clean Energy Council, 2015). With ongoing expansion of wind farm developments, it is pertinent to investigate and clarify the impact that wind farms could have on health and in particular sleep, given current community complaints surrounding sleep disturbance attributed to wind turbine noise (WTN: the noise emitted by wind farms, i.e., one or more wind turbines). For simplicity, the present thesis will use WTN to label this noise with no implication as to the exact source (e.g., blades, generator, gears, structural filtering etc.) of what will become clear later is a very complex noise. Irrespective of the many advantages associated with wind farms, such as their clean energy, sustainable and economically profitable nature, community complaints nevertheless exist. These complaints include nausea, headaches, cognitive and psychological impairment, as well as sleep disturbance, which is one of the most commonly reported complaints by individuals living near wind farms (Basner et al., 2014; Krogh, Gillis, Kouwen, & Aramini, 2011; Muzet, 2007; World Health Organization, 2011). Concurrently, other residents live within similar distances but report no sleep disturbance complaints (Chapman, St. George, Waller, & Cakic, 2013; Hessler, Leventhall, Schomer, & Walker, 2017; Michaud et al., 2016). Despite anecdotal community complaints, the evidence surrounding WTN impacts on sleep is scarce, inconsistent, and under-researched, indicating a need for carefully controlled experimental studies to evaluate the impact of WTN on both objectively and subjectively measured sleep. Thus, the work in this thesis aimed to investigate the impact of nocturnal WTN on objective and subjective measures of sleep time and quality, as well as next-day mood, anxiety, and cognitive performance under carefully controlled experimental

conditions. This work sought to better understand the nature and potential mechanisms underpinning reports of WTN related sleep disturbance to help inform the possible need for future guideline refinements in Australia and internationally. This will aid in further understanding the mechanisms behind reported WTN related sleep disturbance and help inform future guidelines surrounding wind turbines and wind farms both inside and outside of Australia.

1.2 Wind turbine noise characteristics

The terms noise and sound are sometimes used interchangeably but noise is typically used to refer to unwanted sound. Noise frequency and sound pressure level (SPL) are important characteristics when describing WTN. In the context of noise, frequency refers to the periodicity of vibrations associated with compression and rarefaction of the medium transmitting sound, such as air, and is measured in cycles per second or Hertz (Hz). SPL is a characteristic of the overall amplitude or intensity of noise, typically measured on a logarithmic scale of decibels (dB) (Department of Health Australia, 2018). Low frequency noise is present in many environmental sources such as natural noise (e.g., wind, storms, waves, and tremors), residential and industrial noise (Broner, 1978, 2010), and is also produced by wind turbines. However, WTN has unique low frequency noise components with the potential to contribute to sleep disturbance. WTN arises from both mechanical and aerodynamic noise. Mechanical noise is often minimal relative to aerodynamic noise which typically dominates to give WTN broadband and dynamic noise characteristics (i.e., variable and time-varying SPL and noise frequencies) ranging from a fundamental frequency around 0.8 Hz to 1.5 kHz (Hansen, Doolan, & Hansen, 2017; Hansen, Zajamšek, & Hansen, 2015b). These dynamic characteristics include trailing edge noise, or ‘swish’ which contains high frequency components typically more prominent at closer distances to wind turbines and further time-varying SPLs due to

the movement of the turbine blades and blade-tower aerodynamic interactions at the blade-pass frequency of 0.5-1.5 Hz, which gives rise to prominent amplitude modulation components. In Australia, the closest wind turbines to nearby residences is typically at least one kilometre away and therefore, trailing edge noise is less dominant due to attenuation through atmospheric absorption of higher frequencies leaving more prominent lower frequency ‘rumbling’ amplitude modulation potentially more likely to contribute to community complaints and annoyance in an Australian context (Environmental Protection Authority South Australia, 2013; Hansen et al., 2017; Micic et al., 2018).

This ‘rumbling’ type of amplitude modulation is highly dependent on extraneous environmental factors including weather conditions, wind speed, wind shear, the number and size of turbines in the area, local topography, flora conditions and the residential distance from wind turbines. For example, Öhlund and Larsson (2013) suggested that changes in weather alone can lead to a 7-14 dB variability in SPL and that the highest and most noticeable intensity of amplitude modulation often exists when wind and weather conditions are unstable and thus variable. This ‘rumbling’ type of amplitude modulation is often reported as more disruptive during the evening and at night, when atmospheric conditions are typically more stable than during the day, and when background noise is lowest, resulting in amplitude modulation becoming more dominant and likely to be more intrusive in normally quiet rural areas (Hansen et al., 2015b). Background noise levels in quiet rural areas where wind farms are often commissioned is also much lower compared to urbanised environments with much higher background noise levels (>40 dB(A)) due to greater human activity including traffic and industrial noise (Griefahn, Marks, & Robens, 2006; Hansen, Hansen, & Zajamšek, 2015a; King, Roland-Mieszkowski, Jason, & Rainham, 2012). Road traffic noise (RTN) is also relatively ubiquitous, expected and predictable, particularly in suburban areas where most people are living (Clark et al., 2006). Therefore, individuals in urban environments may more easily habituate to higher

background noise levels expected in urban environments where road traffic is typically substantially reduced and more sporadic at night compared to individuals in rural environments where lower background noise levels are expected, particularly at night (<30 dB(A)). Thus, persistent and likely more prominent time-varying fluctuations in SPL at night may make habituation to WTN inherently more difficult compared to other environmental noise types (Bolin, Bluhm, & Nilsson, 2014; Hansen et al., 2015a; Micic et al., 2018; Pedersen, Hallberg, & Persson Waye, 2007).

Another WTN characteristic is infrasound, which is typically defined as noise <20 Hz (Hessler et al., 2017). Infrasound from WTN is generated when the wind turbine blades pass the turbine tower, which creates a noise pulse that is made up of the blade-pass frequency and harmonics in the infrasonic region below 20 Hz (Cooper, 2021; Zajamšek et al., 2019). Infrasound is generally considered to be below the average hearing threshold for humans and is often described as ‘sub-audible’ (Leventhall, 2007), although this is not necessarily always true given considerable inter-individual variability in low frequency hearing acuity and that equal loudness contours are more compressed at low frequencies (Møller, 1987). Previous research has shown that for infrasound to be audible, SPL typically needs to reach at least 110 dB(A) (Dommes et al., 2009). In a study by Tachibana, Yano, Fukushima, and Sueoka (2014) they found that at distances greater than 300 metres, infrasound levels were between 49-56 dB(A), well below levels expected to be audible. Evans, Cooper, and Lenchine (2013) also suggest that for those living >1.5 kilometres from a wind turbine (commonly the distance from the nearest wind turbines and residences in Australia (Hansen et al., 2017), infrasound exposure is no greater than what would be generated by local wind conditions alone with no turbines. Despite these findings, wind turbine infrasound peak levels can exceed the hearing threshold at some frequencies for some individuals (Zajamšek, Hansen, Doolan, & Hansen, 2016). For example, Jakobsen (2005) has shown that wind turbine infrasound levels that generate

infrasound of 60-70 dB(G) (dB(G): G-weightings based on frequencies <20 Hz and independent of frequencies in the normal audible frequency range of 20 to 20,000 Hz, i.e., A-weighted scales (Salt & Hullar, 2010; Salt & Kaltenbach, 2011)) has the potential to stimulate the outer hair cells in the human ear, leading to the possibility of sleep disruption to occur. In addition, other studies have shown that these levels may be higher or lower for some individuals (Shepherd & Hubbard, 2018). Therefore, it is possible that inter-individual differences in hearing acuity around infrasonic frequencies could contribute to sleep disruption (Hansen, Zajamšek, & Hansen, 2014a; Jung, Cheong, Shin, & Cheung, 2008; Marcillo, Arrowsmith, Blom, & Jones, 2015; Zajamšek et al., 2016). Given the unusually low frequency and dynamic time-varying characteristics of WTN, it is important to investigate the relationships between environmental WTN exposure, which includes full-spectrum WTN characteristics (i.e., infrasonic and likely more relevant audible features), and potential impacts on sleep.

1.3 Wind turbine noise guidelines

Typically, the decibel scale is A-weighted, to help linearise the otherwise curvilinear relationship between frequencies over the normal range of human hearing from 20 to 20,000 Hz, and SPL. The World Health Organization (1999) (WHO) state that continuous indoor noise >30 dB(A) is likely to impair sleep. The World Health Organization (1999, 2011) do however state that SPLs <30 dB(A) may be disturbing depending on the individual and noise source. Whilst noise limits vary between states in Australia, in general WTN levels should not exceed 35-40 dB outside and that the WTN should not exceed the background noise by more than 5 dB(A) (Song & Yorke, 2009). These limits also assume a 10-15 dB(A) outdoor-to-indoor noise attentuation and lower night time versus daytime limits (Hansen et al., 2015b; Micic et al., 2018). However, these guidelines are based largely on positive associations between dB(A) and annoyance levels to RTN (Guski, Schreckenberg, & Schuemer, 2017), which has more prominent mid-to-high frequencies,

within the 200-2000 Hz range, compared to WTN. Therefore, low frequency noise has the potential to attenuate to a lesser extent over distance compared to higher frequency noise (World Health Organization, 1999). Overall, it is possible for sleep disruption to occur when indoor WTN is <30 dB(A). Consequently, a key aim of the work described in this thesis was to test if WTN at a SPL <30 dB(A) most relevant to real-world exposure has the potential to impact sleep and daytime functioning.

1.4 The importance of sleep

Sleep is essential for optimal daytime functioning and maintaining good physical and mental health. Adequate or restorative sleep allows the brain and other physiological processes to recuperate, adapt and reorganise functions in preparation for the following wake period. Insufficient or unrefreshing sleep overtime can lead to adverse health impacts including decreased daytime alertness with associated increased accident risks, as well as mood disturbance and reduced quality of life. Chronic poor sleep can lead to a clinically recognised diagnosis of insomnia, which is associated with significant negative impacts to individuals and the broader community. For example, in 2010, the total economic cost of sleep disorders in Australia was estimated to be approximately $36 billion per annum (Hillman & Lack, 2013). In 2016-2017, the estimated annual cost of inadequate sleep in Australia was estimated to equate to around $8,968 per person (Deloitte Access Economics, 2017). Given the individual and societal consequences of poor sleep, it is important to examine the potential impact of WTN on sleep.

1.4.1 Normal sleep

A common misperception of normal good sleep is that individuals enter into one long ‘valley’ of unconsciousness with minimal night-time awakenings until the final awakening in the morning (Figure 1.1) (Bruck, Dolan, & Lack, 2015). However, a more accurate description of sleep uses the analogy of a ‘rollercoaster’ of multiple sleep cycles

through the four major recognised stages of sleep, also depicted in Figure 1.1 (Wright & Lack, 2019). Figure 1.1 shows that normal adult sleep is characterised by four to six 90-minute cycles of both non-rapid eye movement (NREM) and rapid eye movement (REM) sleep, with several brief awakenings across the night, despite self-reported awakenings often being severely under-reported (Wright & Lack, 2019). Furthermore, there is often an awakening threshold during sleep, which is much lower during the second half of the sleep period and therefore in the second half of the night, individuals might be more susceptible to awakenings from external stimuli (Rosenthal et al., 1996).

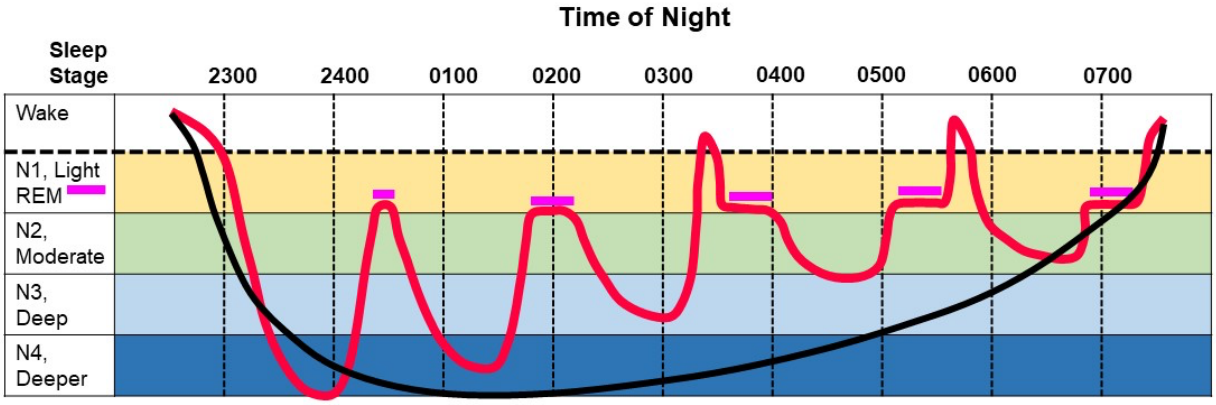

Figure 1.1 A normal adult sleep pattern depicting five 'sleep cycles' of roughly 90 minutes in the red line compared to the common misperception of normal sleep in the black line.
Note. Figure developed by author based on Wright and Lack (2019).

NREM sleep is characterised by three different stages of N1-N3 sleep (Berry et al., 2012), which have superseded four classically defined stages of 1-4 sleep (Kales & Rechtschaffen, 1968) by collapsing stage 3 and 4 sleep into a single stage of N3. In a normal adult, N1 sleep involves light, transitional sleep and comprises approximately 5% of the sleep period. N2 sleep is characterised by the presence of frequent transient electroencephalographic (EEG) K-complexes and sleep spindles on a background of EEG frequencies slower than in wake (Figure 1.2), and typically accounts for around 50% of sleep. N3 sleep is often described as slow wave sleep as it is characterised by large amplitude slow waves in EEG activity, which typically comprises around 20-25% of sleep. REM sleep, which accounts for a further 20-25% of the sleep, is characterised by sawtooth

waves and high frequency wake-like brain activity, but with bursts of rapid eye movements likely associated with dream activity along with profoundly reduced muscle activity (hypotonia). REM is theorised to facilitate memory consolidation processes (Altevogt & Colten, 2006; Jones, 2005).

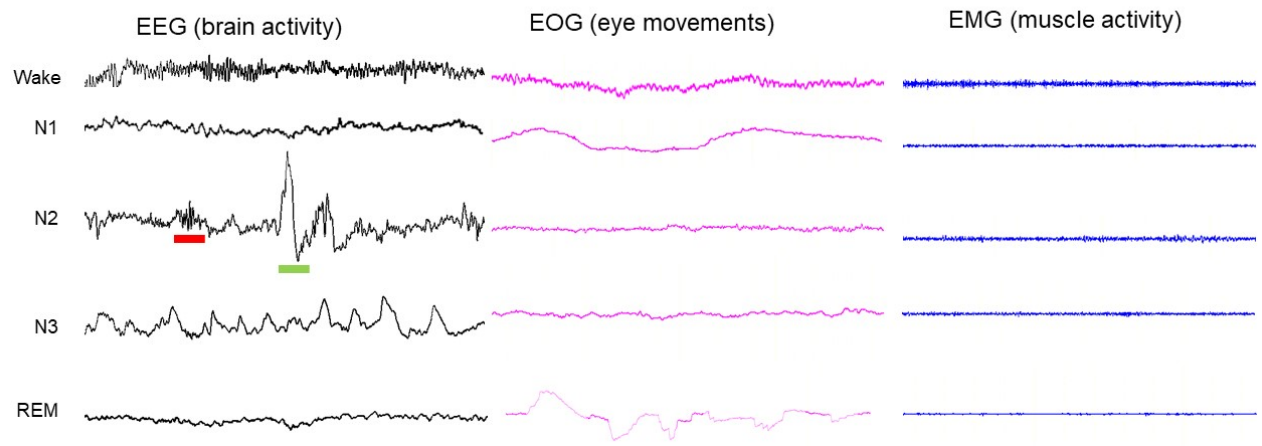

Figure 1.2 EEG, EOG and EMG activity changes across the different stages of sleep.

Note. The green bar indicates a K-complex and the red bar indicates a sleep spindle. Figure developed by author.

1.4.2 Insomnia

The most recent Diagnostic and Statistical Manual of Mental Disorders Fifth Edition (DSM-V), classifies insomnia based on having a difficulty initiating sleep, maintaining sleep or experiencing premature morning awakenings without being able to return to sleep, which has been present for a minimum of three months, for at least three nights per week (American Psychiatric Association, 2013, 2020). In addition, individuals also need to have reported that the sleep disturbance also causes clinically significant distress or impairment in social, occupational, educational, academic, behavioural, or other important areas of functioning, as well as being present despite an adequate opportunity for sleep. Short-term insomnia is common within the general population, where approximately 50% of individuals experience insomnia annually. Insomnia usually begins with a life stressor that might then cause worry and anxiety surrounding the experience of sleep interruption. This can then lead to maladaptive coping strategies such as spending more time in bed, which typically leads to increases in wake time in bed at night and may

then reinforce a conditioned response of worry and anxiety associated with the bed environment to create a self-reinforcing and sustaining vicious cycle. Most of the time, individuals are able to recover from a stressful period with a return of sleep to normal. However, for some, even after the life stressor passes, the sleep environment (i.e., the bedroom, bed, pyjamas, lying down, closing eyes etc.) through frequent association with poor sleep, extended wakefulness, anxiety and worry, may trigger recurrent anxiety and poor sleep which may develop into long-term chronic insomnia (Harvey & Tang, 2012). Thus, it is possible that WTN could impact sleep through similar mechanisms (Micic et al., 2018). For example, based on the behavioural model of insomnia, WTN could trigger insomnia via a conditioned emotional response (Perlis, Giles, Mendelson, Bootzin, & Wyatt, 1997). More specifically, WTN may be an aversive noise to some individuals thus contributing as a precipitating or trigger factor to keep some residents awake at night. This could lead to residents adopting maladaptive coping strategies to make up for lost sleep, such as spending excessive time in bed, staying in bed whilst awake or counter-productive napping during the day which can reduce sleep drive to make sleep more difficult to achieve at night. Extended opportunities for unhelpful cognitions could also arise in addition to possible heightened arousal, noise sensitivity and more negative attitudes and beliefs regarding wind farms (involving the WTN itself or visual WTN effects such as the warning lights on the wind turbine nacelle). In combination, these factors could promote a conditioned emotional response while attempting sleep in a WTN exposed environment and become a vicious cycle that maintains insomnia and sleep disruption (Figure 1.3).

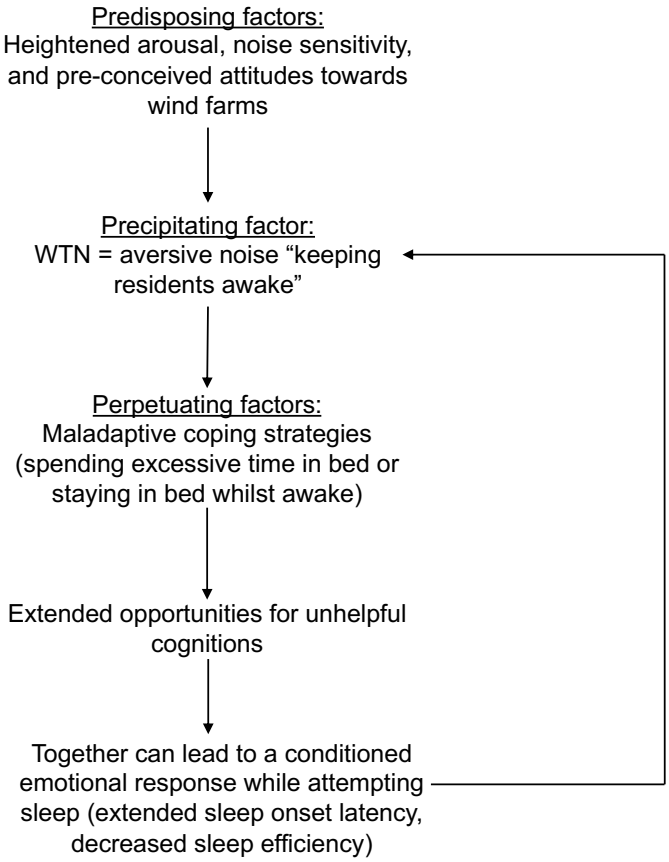

Figure 1.3 An example of how WTN might lead to a conditioned emotional response based on the behavioural model of insomnia.

Note. Figure developed by author based on (Perlis et al., 1997). WTN=Wind Turbine Noise.

Chronic insomnia can severely impact an individual's quality of life due to an increase in fatigue, lack of energy, decreased mood, irritability as well as memory and cognitive impairments (Lovato, Lack, Wright, & Kennaway, 2014; Sweetman, Lack, Lambert, Gradisar, & Harris, 2017). These daytime functional impairments are often considered to be the most important consequence of sleep disruption and are often the primary reason for patients to seek treatment (Morin, LeBlanc, Daley, Gregoire, & Merette, 2006). Insomnia is frequently comorbid and thus co-occurs with other mental disorders and if left untreated, can contribute to depression and anxiety (American Psychiatric Association, 2013; Morin et al., 2006). Along with complaints about sleep disturbance,

some residents living near wind farms have also reported increased anxiety, stress and impairments in memory and concentration (Krogh et al., 2011; Pierpont, 2006). This is perhaps not surprising given that feelings of exhaustion, mood disturbance, concentration and learning issues often stem from poor sleep (Pierpont, 2006). However, previous literature evaluating mood, anxiety and daytime impairments in the presence of WTN is sparse, and like sleep disturbance, is reliant on self-reported survey data or anecdotal case reports of daytime impairments without psychometrically validated questionnaires or objective daytime performance assessments (Jalali et al., 2016a; Jalali, Nezhad-Ahmadi, Gohari, Bigelow, & McColl, 2016b; Nissenbaum, Aramini, & Hanning, 2012), and thus the conclusions and interpretation surrounding the effect of WTN on daytime functioning should be interpreted with caution. Objective evidence for memory and cognitive impairments even between good sleepers and individuals with insomnia is mixed and unconvincing (Lovato, Lack, Wright, Cant, & Humphreys, 2013) so extrapolation to individuals who do and do not self-report WTN related daytime impairments is problematic. Given that a bout of poor sleep can, over time, lead to the development of chronic insomnia and potentially other mental health difficulties, it is important to investigate if and by what mechanisms, WTN could potentially impact sleep and next-day functioning. Thus, the purpose of the work presented in **Chapters 4 and 5** was specifically to investigate if, how much and through what mechanisms, WTN exposure impacts on human sleep. An understanding of the magnitude and nature of sleep problems is important to guide the need for potential strategies needed to mitigate environmental noise impacts on sleep, such as through noise abatement strategies and education and cognitive behavioural strategies potentially needed to help treat psychological elements of sleep problems such as insomnia.

1.4.3 Cognitive behaviour therapy for insomnia

Cognitive behaviour therapy alone focuses on thoughts, feelings, and behaviours

with an underlying aim of helping individuals to understand the relationship between their thoughts and behaviours using a goal-oriented approach (Beck, 2011). Sessions often involve psychoeducation surrounding the link between thoughts, feelings, and behaviours and how this may contribute to vicious cycles, challenging unhelpful thinking styles and undergoing behavioural experiments to test these unhelpful thinking styles and re-establish effective coping strategies. Similarly, cognitive behaviour therapy for insomnia (CBTi) involves applying these techniques to address precipitating and perpetuating factors of insomnia and is considered the first-line treatment for insomnia (Lovato et al., 2014). Specific CBTi techniques involve sleep education surrounding sleep hygiene practices, cognitive restructuring and behavioural techniques including sleep restriction therapy, stimulus control therapy and elements of relaxation therapy. CBTi has strong efficacy and is also effective for comorbid mental health conditions including chronic pain, post-traumatic stress disorder, depression, and tinnitus (Manber et al., 2008; Marks, McKenna, & Vogt, 2019; McCrae, Curtis, Staud, Berry, & Robinson, 2019; Taylor et al., 2018). Furthermore, Leventhall, Pelmear, and Benton (2003) suggest that teaching individuals the appropriate skills to re-establish control over their lives can help in reducing the personal impact of low frequency noise disruption, given ‘loss of control’ is a core symptom reported by individuals reporting low frequency noise disruption. Therefore, CBTi or elements of cognitive behaviour therapy in conjunction with sleep aids such as foam insert earplugs could be considered effective treatments for WTN sleep disruption if insomnia symptoms are present.

1.5 Sleep assessment methods

1.5.1 Actigraphy

A common objective measurement of sleep is actigraphy monitoring, which involves wearing a wrist-worn motion sensor device to infer sleep and wakefulness based

on gross body movements, sometimes complemented with ambient light exposure levels to help infer darkness typically also present during the sleep period (Stone & Ancoli-Israel, 2017). Actigraphy is commonly used as an objective measure in sleep studies due to its wide availability, relatively low cost, and reduced participant burden compared to other methods, as individuals are able to wear an 'actiwatch' in their home, instead of sleeping away from their home in an experimental laboratory. Actigraphy monitoring is beneficial as, unlike questionnaire assessments, it is not impacted by recall bias, sleep misperception or misattribution of awakenings or participant expectations, which even PSG is not void of (Martin & Hakim, 2011). Actigraphy can also be used to assess sleep over many nights in the individual's normal bedroom environment to obtain a more representative evaluation of typical sleep than from a single night of laboratory-assessed sleep, which may also be impacted by the unfamiliar laboratory environment. Whilst actigraphy shows very high sensitivity (around 95%) for detecting periods of EEG confirmed sleep, it has poor specificity (around 36%) given that the lack of gross body movements is not specific to sleep and can also arise during periods of wake without movement (Marino et al., 2013; Sivertsen et al., 2006), thus negatively impacting the accuracy of sleep parameters such as sleep onset latency, total sleep time and wake after sleep onset derived from actigraphy.

1.5.2 Polysomnography

Polysomnography (PSG) is the gold-standard direct measurement for sleep and overcomes the key limitations of actigraphy by directly assessing sleep-related changes in electroencephalography (EEG; brain activity), electrooculography (EOG; eye movements) and electromyography (EMG; muscle activity) (Figure 1.4) (Martin & Hakim, 2011; Van de Water, Holmes, & Hurley, 2011). PSG is frequently also used to examine respiratory, electrocardiography and pulse oximetry for the assessment of breathing problems in sleep such as obstructive sleep apnoea. Scoring of PSG recordings against international

standard sleep classification criteria, typically in 30-second Epochs are then used to quantify sleep-wake timing and sleep macrostructure parameters typically including sleep onset latency, total sleep time, wake after sleep onset, number of awakenings, sleep efficiency, N2, N3 and REM latency, and time or proportion of time spent in each stage of sleep. Whilst PSG requires extensively trained sleep technicians to setup, read, score and analyse sleep data, it is recognised as the most accurate way of measuring sleep disturbance and thus the impact WTN could have on sleep. Given the scarcity in the literature of objective, carefully controlled studies employing PSG, PSG was chosen as the main objective sleep assessment method used in the experimental chapters presented in this thesis (**Chapter 3, 4, and 5).** However, subjective, or self-reported sleep is also equally important to investigate, particularly given that insomnia-related disorders are based primarily on self-reported sleep difficulties in combination with daytime symptoms, where PSG assessed sleep can be normal despite self-reported problems with insomnia. Thus, how individuals perceive their sleep to be following a night of noise disturbance is also important irrespective of PSG measurements and is often a contributing factor to the development of insomnia (Mercer, Bootzin, & Lack, 2002).

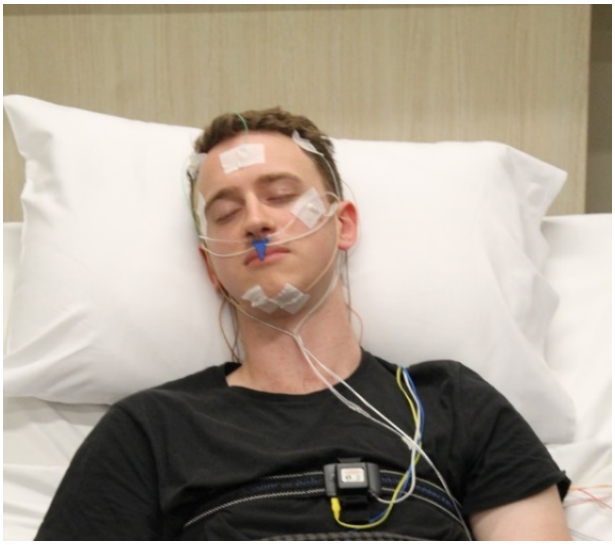

Figure 1.4 Polysomnography (PSG) setup in the sleep laboratory for the assessment of brain activity (EEG), eye movements (EOG) and muscle activity (EMG).

Note. Image owned by the author. EEG=electroencephalography. EOG=electrooculography. EMG=electromyography. PSG=polysomnography.

1.5.3 Psychometrically validated sleep questionnaires

The Consensus Sleep Diary is the most widely recommended tool for assessing subjective sleep parameters (Carney et al., 2012; Maich, Lachowski, & Carney, 2018). The Consensus Sleep Diary allows for the assessment of perceived sleep outcomes including time spent in bed, sleep onset latency, number of awakenings, wake after sleep onset, time of final awakening, time out of bed and sleep quality. In addition, psychometrically validated sleep questionnaires such as the Insomnia Severity Index (ISI) and the Pittsburgh Sleep Quality Index (PSQI) are further useful retrospective measures that ask about typical sleep habits and can be used to gain a rapid understanding of an individual's sleep quality and sleep difficulties. As a result, these sleep questionnaires and the Consensus Sleep Diary are the main subjective sleep measurements used in this thesis work **(Chapter 3, 4 and 5).**

1.6 Daytime functioning assessment methods

1.6.1 Mood

The Profile of Mood States (POMS) is a 65-item self-report measure of psychological distress. It is a widely accepted and reliable tool used in clinical and non-clinical populations and shows moderate internal consistency across subscales (Cronbach's α =0.67 to 0.95) (Curran, Andrykowski, & Studts, 1995). In the study reported in Chapter's 4 and 5 of this theses, the POMS was given to each participant the morning after each night and asked them to rate the degree to which each item (i.e., mood symptom) describes their mood at the current time using a 5-point Likert response format from 0 (not at all) to 4 (extremely). Total mood disturbance scores were calculated by summing overall scores of tension, depression, anger, fatigue and confusion and subtracting overall vigour scores. Total mood disturbance scores range from -32 to 200, with higher scores indicating greater mood disturbance.

1.6.2 Anxiety

Anxiety is often referred to as an emotional 'state' that consists of feelings of tension, apprehension, nervousness, worry and heightened autonomic nervous system activity but can also be viewed as a personality 'trait', indicating a potential anxiety disposition. The State-Trait Anxiety Inventory is a reliable and brief self-report measure of both state and trait anxiety and has been used extensively in both research and clinical practice (Spielberger, Gonzalez-Reigosa, Martinez-Urrutia, Natalicio, & Natalicio, 1971). The 'State' scale consists of 20 statements that ask individuals to rate the degree or magnitude of their current feelings (e.g., I feel calm), on a 4-point response format from 1 (not at all) to 4 (very much so). Similarly, the 'Trait' scale also consists of 20 statements, which ask individuals how they feel in general (e.g., I feel pleasant) on a 4-point response format from 1 (almost never) to 4 (almost always). Weighted scores are generated based on some items needing reverse-scoring, which are then totalled to indicate a total 'State' and total 'Trait' anxiety score. Total scores range from 20 to 80, with higher scores indicating greater state and trait anxiety.

1.6.3 Cognitive performance

For the purposes of this thesis, cognitive performance consisted of measures of alertness, sustained attention, associative learning, visual-spatial skills, processing speed and short-term and working memory, which have been previously found to be sensitive to sleep disruption (Wilhelmsen-Langeland et al., 2013).

1.6.3.1 Alertness and sustained attention

Alertness and sustained attention were assessed using the Psychomotor Vigilance Task (PVT) which is a 10-minute task that involves participant's responding with a button press to a visual LED-digital counter stimulus, that is presented at randomly timed delays of 2-10 seconds following a previous response (Loh, Lamond, Dorrian, Roach, & Dawson,

2004). Median and Mean Reaction Time, number of errors made and number of lapses (i.e., failure to respond in <500 milliseconds) are measured for each 10-minute task. The PVT is a sensitive measure of sleep disruption and is regarded as an objective and widely used measure of cognitive impairment (Lee, Bardwell, Ancoli-Israel, & Dimsdale, 2010).

1.6.3.2 Associative learning and processing speed

Associative learning and processing speed was assessed via the Digit Symbol Substitution Test (DSST). The DSST is based on the Coding subtests of the Wechsler Intelligence Scale for Children – Fifth Edition (WISC-V) (Wechsler, 2014) and the Wechsler Adult Intelligence Scale – Fourth Edition (WAIS-IV) (Wechsler, 2008). The DSST used in this thesis was a computerised 2-minute task that required individuals to view a digit-symbol key and match as many symbols with their corresponding number as fast and accurately as possible. The DSST has high discriminant validity and high sensitivity in identifying cognitive impairment (Jaeger & Domingo, 2016).

1.6.3.3 Short-term and working memory

Short term and working memory were assessed using the Digit Span task, which is based on the Digit Span subtest of the WISC-V (Wechsler, 2014) and WAIS-IV (Wechsler, 2008). Individuals were required to watch the computer screen when a series of digits is presented and to recall the digits in the correct order (either in forwards or backwards order). The number of digits presented increased progressively until two consecutive failed attempts of the same digit length occurred. The Digit Span task demonstrates moderate-high internal consistency (de Paula, Malloy-Diniz, & Romano-Silva, 2016) and has been previously shown to be impaired with sleep disruption (Bastien et al., 2003; Richardson et al., 2018).

1.7 Noise and sleep mechanisms

The reticular activating system in combination with other brainstem centres is the primary system responsible for the determination of wake and sleep periods and responses to sensory stimuli presented during sleep (Jones, 2005). The reticular activating system importantly determines whether sleep is preserved, or higher brain functions are re-engaged through cortical reactivation through arousal in the presence of sensory stimuli during sleep. In terms of noise disruption, reticular activating system responses may evoke no or minimally discernible EEG and other (e.g., cardiovascular activation) responses, a shift to a lighter stage of sleep, a brief arousal (i.e., a 3-15 second change in EEG frequency) or a full awakening (i.e., ≥15 second change in EEG frequency to wake like EEG) to noise (Kingshott, Cosway, Deary, & Douglas, 2000). The response elicited is dependent on the type and intensity of the noise and an individual's sleep stage. For example, louder stimuli are often needed to elicit an arousal or awakening in deeper stages of sleep (Catcheside et al., 2002; Lechat et al., 2021a).

The behavioural model of insomnia (Perlis et al., 1997) suggests that one crucial factor in both acute and chronic insomnia is the persistent heightened arousal that becomes conditioned over time to a generalised state of alertness when trying to cope with psychosocial stressors (e.g., aversive noise) prior to and during sleep (Hamida, Penzel, & Ahmed, 2015). Support for this concept includes observations of increased high-frequency EEG activity suggestive of heightened cortical activity and alertness in insomniacs compared with good sleepers during the sleep onset period as well as during sleep itself (Milner, Cuthbert, Kertesz, & Cote, 2009). In addition, individuals with insomnia also show evidence of enhanced sensory processing with impaired sensory gating and thus an inability to reduce cortical processing during pre-sleep wake periods (Milner et al., 2009). Therefore, it is possible that by virtue of a lower hearing threshold and greater alertness when attempting to initiate and maintain sleep, that WTN exposure during the sleep period

could reinforce heightened arousal to contribute to subjective and/or objective sleep disturbance and insomnia symptoms via cumulative conditioned emotional responses over time (Riemann et al., 2010). Investigation of these mechanisms formed the basis of the noise interventions described in **Chapters 4 and 5**.

Subjective factors, including noise sensitivity also have the potential to predispose and contribute to insomnia symptoms via psychological activation and stress during the sleep period (Pedersen, 2011; Van den Berg, Pedersen, Bouma, & Bakker, 2008). Noise sensitivity is a stable personality trait that describes one's predisposition to assess sounds as aversive (i.e., noise) and is considered important in the investigation of noise related disturbance (Stansfeld, 1992; Stansfeld, Sharp, Gallacher, & Babisch, 1993; Sung et al., 2017). Inter-individual differences in noise sensitivity and/or attitudinal bias such as annoyance (i.e., the extent to which noisy events are evaluated unfavourably) or other emotional responses towards WTN are likely to be key factors underpinning variable responses between individuals (Stansfeld, 1992; Stansfeld et al., 1993). For example, whilst WTN exposed individuals have been shown to be more sensitive to noise and to report more noise-related sleep disturbance than non-exposed individuals, not all individuals living near wind turbines report sleep disturbance (Michaud et al., 2016; Shepherd, McBride, Welch, Dirks, & Hill, 2011; Shepherd, Welch, Dirks, & Mathews, 2010). Stansfeld (1992) reported that noise-sensitive individuals exhibit greater attention to noise, perceive noise as more of a threat, are more reactive to noise and habituate to noise more slowly than less noise sensitive individuals. In addition, Persson Waye et al. (2002) showed that noise sensitive individuals exposed to low frequency noise were more likely to report annoyance than less or non-noise sensitive individuals. Therefore, it is possible that individuals who live in close proximity to wind farms and subjectively report WTN related sleep disturbance to WTN or noise sensitivity, are likely to pay more attention to WTN, perceive it as more problematic and may not habituate to noise as easily as

individuals less sensitive to noise and WTN disturbance. In addition, increased noise sensitivity has also been shown to be associated with greater annoyance to noise, greater sleep disruption and impaired daytime functioning (Evandt et al., 2017; Jakovljević, Belojević, Paunović, & Stojanov, 2006; Marks & Griefahn, 2007). Therefore, perceived noise sensitivity could be a key factor that may help to explain apparent relationships between WTN and perceived and potentially objectively measured sleep disruption. Thus, part of the aim of the work presented in **Chapter 4** was to explore if potential relationships between WTN exposure and both subjective and objective markers of sleep disruption are influenced by noise sensitivity and prior WTN exposure effects.

1.8 Addressing the knowledge gap

There is already a large body of established literature to support negative effects of common sources of environmental noise such as traffic, air and rail noise on sleep (Basner, Müller, & Elmenhorst, 2011; Department of Health Australia, 2018; Jakovljević et al., 2006; Miedema & Vos, 2007). For example, Basner et al. (2011) conducted a double-blind experimental study using polysomnographic sleep measurements in 72 healthy participants who spent 11 nights in a sleep laboratory and were exposed to nights of varying noise exposures including air, road and rail noise at SPLs ranging from 45 to 65 dB(A). These experiments showed small but significant changes in sleep macrostructure, including increased latency to slow wave sleep, decreased slow wave sleep and increased stage one sleep during RTN exposure compared to control background noise.

However, significant uncertainty remains regarding the impact of WTN on sleep quality and health. The Australian National Health and Medical Research Council (2015, February) have stated that the body of direct evidence is small and of poor quality, that there is no consistent evidence that wind farms cause adverse health effects in humans and that there is a need for high quality research into possible health effects of wind farms. Previous systematic reviews have focused on the broad impact of WTN on health,

including sleep and quality of life (Onakpoya, O'Sullivan, Thompson, & Heneghan, 2015; Schmidt & Klokker, 2014). However, these reviews were based on observational studies that used various researcher-developed questionnaires and items targeting perceived sleep disturbance that often included limited items examining the presence or absence of reported sleep disturbance or rating scales based on the frequency or degree of experienced sleep disturbance, thus making comparisons between studies challenging and likely contributing to inconsistent findings amongst studies.

For example, Pedersen and Persson Waye (2004) conducted a cross-sectional study in Sweden and surveyed 351 individuals living within 150-1199 metres of a wind turbine and exposed to varying WTN SPLs that were calculated for each participant's dwelling based on sound propagation models including <30 dB(A), 30-32.5 dB(A), 32.5-35 dB(A), 35-37.5 dB(A), 37.5-40 dB(A) and >40 dB(A). The questionnaire included items surrounding housing and satisfaction with the living environment (including annoyance experienced outdoors and indoors, noise sensitivity), perception and disturbance from wind turbines (including visual, and auditory aspects of wind turbines, frequency of disturbances, weather conditions, perception and annoyance), health aspects (such as chronic illnesses, general wellbeing and sleep habits), and employment and working hours. Sleep items included normal sleep habits, sleep quality, noise induced sleep disturbance and sleeping conditions. There were no reports of WTN related sleep disturbance in individuals exposed to SPLs of <35 dB(A), but for those exposed to SPLs of >35 dB(A), 16% (95% CI: 11-20%) reported sleep disturbance. In a second cross-sectional study using the same survey methodology as Pedersen and Persson Waye (2007), 754 individuals living in seven different wind turbine areas in Sweden with an overall mean distance of 780 metres from the nearest wind turbine were surveyed. There were no significant associations between WTN SPL, estimated using sound propagation models and sleep disturbance. A subsequent cross-sectional study by Van den Berg et al. (2008)

also using the same questionnaire as Pedersen and Persson Waye (2004, 2007) was conducted on 1,948 individuals (with a response rate of 37%, n = 725) in the Netherlands living within 2.5 kilometres of a wind turbine, and WTN SPL estimated to range from 24-54 dB(A) also based on sound propagation models. Sleep disturbance was a specific focus and was assessed using two items (i.e., *"How often have you had difficulties falling asleep in your home?"* and *"How often is your sleep interrupted by sound?")* and was scored on a 5-point Likert scale from 'almost never' to 'almost daily'. There was a positive association between sleep disturbance and WTN SPL, where individuals exposed to >45 dB(A) were more likely to report interrupted sleep than individuals exposed to levels <30 dB(A). This finding could potentially be confounded by self-selection bias, whereby the residents with higher exposure levels and experiencing sleep disruption may have been more likely or motivated to respond to the questionnaire than residents exposed to lower WTN levels. A further analysis by Bakker et al. (2012) from the Van den Berg et al. (2008) study found that 66.8% of the survey sample reported no sleep disturbance, 15.2% reported sleep disturbance from traffic and mechanical noise, 13.4% reported sleep disturbance from people or animals and only 4.7% attributed sleep disturbance to WTN. Therefore, perhaps WTN is not the sole contributor of reported sleep disruption and that other environmental noise, such as RTN, animals or people could also contribute to sleep disruption. This study also suggested that for participants who did not notice WTN, there was no significant relationship between SPL and sleep disruption, and therefore, indicates that for those who do notice WTN and perhaps evaluate it unfavourably or as a potential "threatening" stimulus, WTN could possibly lead to increases in sleep disruption.

Kuwano, Yano, Kageyama, Sueoka, and Tachibana (2014) and Kageyama, Yano, Kuwano, Sueoka, and Tachibana (2016) also used self-report rating scales to investigate the relationships between WTN exposure and self-reported sleep disturbance in individuals living both near (n = 747) and far (n = 332) from a wind farm. WTN levels were

estimated from a previous field study during the same time period (Tachibana et al., 2014). Sleep disturbance was assessed in terms of how frequent any of the four following conditions were experienced: (1) difficulties initiating and maintaining sleep; (2) premature awakenings; (3) feelings of light sleep; and (4) daytime sleepiness, each rated on a 1 to 3 scale (1 = more than three times a week to 3 = occasionally). Insomnia was classified if participants had one or any combination of the four conditions occurring >3 times per week. 1.2% of participants (n=13) were defined as having insomnia (which is below the general prevalence data for insomnia), but there were no significant differences in the prevalence of insomnia between wind farm and control participants. However, of these 13 'insomniacs', 11 individuals lived near a wind turbine site, and attributed their sleep disruption to WTN (Kageyama et al., 2016). Both these studies also showed that when WTN exceeded 40 dB(A), self-reported insomnia was more prevalent than lower WTN SPLs (Kageyama et al., 2016; Kuwano et al., 2014). Whilst these data are informative, insomnia is more typically defined on the basis of self-reported difficulty initiating or maintaining sleep or early awakening in combination with daytime problems associated with inadequate or poor-quality sleep. Thus, any one self-report sleep problem without necessarily daytime impacts may not be sufficiently specific for inferring likely insomnia and could include a range of other sleep problems unrelated to noise exposure.

Pawlaczyk-Luszczynska, Dudarewicz, Zaborowski, Zamojska-Daniszewska, and Waszkowska (2014) also used a rating scale to evaluate sleep in 156 individuals living between 235-2470 metres from a wind farm. SPLs (dB(A)) were calculated based on sound propagation models and distance related estimates. Sleep was assessed via a 7-point rating scale that asked about sleep quality (difficulty falling asleep and waking feeling unrefreshed) with response items ranging from never to everyday. 26.3% of participants reported difficulty falling asleep and approximately 36% reported waking up feeling unrefreshed. In addition, 80.8% of participants also reported rarely experiencing insomnia.

26% of participants rated their insomnia as occurring every day, almost every day or a few times a week in the 40-45 dB(A) noise category compared to 10.2% in the 35-40 dB(A) noise category (p<0.05).

Radun, Hongisto, and Suokas (2019) also conducted a cross-sectional survey in 318 participants living within two kilometres of a wind turbine to study the potential impact of WTN (predicted using sound propagation modelling) on sleep via one item asking "*has the sound from the wind turbines woken you up or kept you awake during the night?*" which was rated on a 6-point rating scale (1= never to 6 = every day). 10.9% of participants rated sleep disturbance ≥3 and sleep disturbance was positively correlated with SPL (r = 0.33, p=0.01). In another study Song, Di, Xu, and Chen (2016) conducted a cross-sectional study that evaluated 251 individuals living much closer to wind turbines than previous studies (between 79 and 1155m from a wind turbine). Sleep disturbance was measured via a 5-point rating scale asking, "*when at home, how often is your sleep disturbed by ambient noise?*" where 1 referred to almost never and 5 referred to almost daily. 93.4% of respondents reported sleep disturbance with scores ≥3 (i.e., at least once a month), which the authors considered to be disruptive to sleep. However, given the difficulty in comparing data between studies of varying designs and measurement methodologies, the body of available evidence from these studies remain inconclusive as to whether residents living near wind farms are to some extent impacted by environmental noise disruption to sleep, thus calling for experimental, laboratory-based studies using gold-standard objective and subjective sleep measurement.

In summary, the available evidence regarding WTN impacts on sleep shows mixed findings with varying percentages of reported sleep disturbance derived from a range of different questions and scales based almost exclusively on self-reported data from researcher-developed questionnaire items. A significant limitation of self-reported survey

data is the risk of participation bias, where those who choose to complete questionnaires might reflect the views of those with strong opinions regarding wind farms and WTN and thus may not be representative of the total population of interest. Nevertheless, subjective measures of sleep remain important given that insomnia complaints rely on self-reported sleep disturbance. However, reliable evaluation of self-reported sleep requires the use of psychometrically validated sleep questionnaires with established psychometric and test-retest characteristics and standardised outcomes more comparable between studies than individual researcher-developed sleep items.

More recently, several studies have evaluated the impact of WTN on sleep using objective measures (i.e., PSG and actigraphy), thus calling for an updated literature search (Ageborg Morsing et al., 2018; Jalali et al., 2016a; Lane, Bigelow, Majowicz, & McColl, 2016; Michaud et al., 2016; Smith et al., 2020). **Chapter 2** of this thesis presents an updated systematic review and meta-analysis (conducted in early 2020) of the recent literature investigating the impact of WTN on sleep using objective and psychometrically validated sleep assessment tools.

WTN is a problem for at least some individuals living in wind farm areas and in some instances have reportedly been sufficiently severe for some individuals in Australia to abandon their properties due to perceived noise and health impacts (Hansen et al., 2017; Jeffery, Krogh, & Horner, 2013; Krogh et al., 2011). However, anecdotal reports and observational studies may be biased by other factors and are not sufficient to conclude underlying causal mechanisms or that significant problems necessarily exist. Given the lack of high-quality evidence in this area, further carefully controlled studies using both gold-standard PSG measures of sleep and psychometrically validated self-reported sleep measures are needed to clarify the nature and level of WTN impacts on objective and subjective markers of sleep quality and next day impacts.

1.9 Thesis aims

The aims of the work presented in this thesis were, for the first time, to investigate how nocturnal WTN impacts objective and subjective sleep and next-day mood, anxiety and cognitive performance in a carefully controlled laboratory setting. The primary aim of this thesis was to examine the impact of ecologically relevant WTN exposure on conventional polysomnography (objective)- and sleep diary determined (subjective) sleep parameters in a carefully controlled laboratory environment. This study also aimed to elucidate possible effects of prior noise exposure on WTN responses by recruiting participants living near wind farms who do and do not report WTN related sleep disruption, as well as two control groups: residents of rural communities with no wind farms nearby and participants reporting RTN related sleep disruption. Furthermore, to help investigate potential wake-dependent psychological effects versus sleep-dependent WTN effects, four different noise exposure conditions were examined in randomised order across separate nights, including: continuous WTN exposure during wake and sleep (WTN-Continuous); WTN exposure only during established N2, N3 and REM sleep (WTN-Sleep); WTN exposure only during periods of wake and very light transitional N1 sleep (WTN-Wake); and no WTN exposure (i.e., quiet background noise (control)). A final aim was to investigate whether varying WTN exposures during the sleep period (continuously, wake periods and sleep periods) impacts next-day mood, anxiety, and cognitive performance outcomes in comparison to no WTN exposure and to examine if responses differ between individuals who report WTN or RTN related sleep disturbance compared to those without self-reported environmental noise related sleep disruption.

1.9.1 Justification of methodology

Although some residents living near wind turbines report WTN related sleep disturbance, objective evidence to support the nature and magnitude of sleep disruption remains lacking. This at least in part likely reflects that WTN is difficult to study in the field

and to replicate and use in carefully controlled research settings, which requires high-quality sound engineering and recording systems to faithfully reproduce WTN and an effectively controlled setting to avoid a range of confounding factors that variably occur in the environment such as WTN characteristics and levels depending on local wind and weather conditions and potential confounding from other noise sources.

Following a pilot study included in the work presented in this thesis, a separate and larger group of participants were exposed to four different nightly conditions in a carefully controlled and sound attenuated sleep laboratory. These nights included a background noise control night, a night of continuous WTN exposure from lights off to lights on, a night of WTN exposure only during established sleep periods (N2, N3 and REM sleep) and a night of WTN exposure only during wake and non-established sleep periods (W, N1 sleep). The WTN stimulus used in the main investigation was referred to as 'full-spectrum' WTN, which included infrasound at 68 dB(G), dominance of low frequency content and amplitude modulated tones at multiple frequencies between 25 and 63 Hz. The SPL chosen was 25 dB(A) based on the results of a year-long field measurement of WTN in South Australia by acoustic engineers on the project (Nguyen, Hansen, Catcheside, Hansen, & Zajamšek, 2021), that showed a median SPL of 26 dB(A) at distances within 3 kilometres from the nearest wind turbine. At the commencement of the current study, these data were not available, but the measurements were done at a similar distance (~3 kilometres) from the same wind farm as the measurements associated with the sample selected for this study. For these data the median SPL was 26 dB(A). The SPL associated with the sample selected for this study was 17 dB(A) and thus, an increase to 25 dB(A) was considered reasonable to ensure that the SPL was sufficiently high above the ambient background to be detectable. Whilst the SPL was relatively low, it is important to consider that the infrasound and low-frequency amplitude modulated tones were at worst-case levels. It is well-known that noise with special audible characteristics such as these is not

accurately characterised using the A-weighted SPL (Persson Waye & Ohrstrom, 2002). Thus, prior to this investigation, there was no evidence to suggest that this noise sample would not invoke clinically meaningful sleep disturbance and overall, the aim of the exposure nights discussed in this study was to focus on WTN exposures representative for the South Australian field setting.

By exposing participants to WTN only during wake/light sleep periods, potential wake-dependent subjective/ psychological effects of WTN whilst initially attempting sleep and re-initiating sleep after awakenings were investigated. By also exposing participants to WTN only during established sleep periods on another night, direct physiological effects of WTN on established sleep without potential wake-dependent exposure effects were also investigated. In the presence of only an indirect wake-dependent effect of WTN on sleep and next day outcomes, then WTN-Wake and WTN-Continuous nights would be expected to produce similar and greater levels of self-reported sleep disruption and increased wake time compared to WTN-Sleep and control nights. In the presence of only a direct, physiological sleep-dependent WTN effect, then WTN-Sleep and WTN-Continuous nights would be expected to show similar and greater levels of sleep disruption compared to WTN-Wake and control nights. Furthermore, in the presence of a combined direct and indirect effect of WTN on sleep and daytime outcomes, then the WTN-Continuous condition would be expected to show greater levels of sleep disruption compared to the control condition.

Furthermore, it was predicted that the effect of these conditions, would ultimately depend on participant characteristics and more specifically, habitual WTN or RTN exposure and self-reported WTN/RTN related sleep disturbance. Therefore, four different participant samples were recruited: (1) individuals living near wind farms who self-report WTN related sleep disturbance; (2) individuals living near wind farms who do not self-report WTN related sleep disturbance; (3) individuals in urban areas who do self-report

RTN related sleep disturbance; and (4) individuals in quiet rural areas who acted as our control group.

By recruiting these four groups, the possible interaction effects between groups and the four noise conditions on sleep and next-day mood, anxiety, and cognitive performance could be investigated. Additionally, this allowed for a determination of whether a potential insomnia or conditioned emotional response may exist in residents living near wind turbines and with self-reported WTN related sleep disturbance. For example, it was postulated that if the WTN-sleep disturbed group showed increased wake time when exposed to WTN during wake periods but not during established sleep periods, this would support the presence of insomnia and a conditioned emotional response to WTN. In this context wake-dependent psychological responses to WTN exposure could be a primary cause of sleep disruption rather than direct WTN sleep disruption effects. In this case, reliable evidence-based information and education in combination with psychological therapies, such as cognitive behaviour therapy or CBTi would likely be indicated. On the other hand, if all participant groups showed consistent sleep disruption effects during WTN exposure during the established sleep condition compared to control, then direct sleep disruption effects would be indicated. In this context, effective mitigation strategies would likely be to limit the proximity of wind farms to residences and to promote more effective noise abatement through improved WTN locations and residential building design.

This project was amongst the first and largest carefully controlled in-laboratory study to directly evaluate the impact of WTN on both objective and subjective sleep using current gold-standard measures of sleep and the psychometrically validated Consensus Sleep Diary. This work sought to aid the understanding of the nature and mechanisms underpinning reports of WTN related sleep disturbance, and to help explain why some residents report noise impacts while others do not. Ultimately these data remain needed to help guide the need for and design of effective and appropriate intervention options for

individuals with self-reported WTN related sleep disturbance. The remainder of this thesis is presented in six Chapters briefly outlined below.

1.9.2 Chapter 2

This recently published work was the first systematic review and meta-analysis to focus on the existing literature evaluating WTN effects on sleep using validated objective and subjective sleep assessment tools (Liebich et al., 2021). This paper outlined the gaps in the available evidence and emphasised the need for further carefully controlled laboratory-based studies to provide more conclusive evidence regarding the impact of WTN on both objectively and subjectively measured sleep. This led to the rationale, development, and implementation of an initial pilot study and later a larger, 7-night laboratory-based study to more specifically examine the impact of WTN on sleep.

1.9.3 Chapter 3

This pilot study investigated whether objective and subjective sleep latency and latency to N2 sleep were significantly impacted by WTN exposure during the sleep initiation period compared to background noise alone without WTN in young, healthy individuals from urban residences and naïve to WTN.

1.9.4 Chapter 4

On the basis of the pilot work outlined in Chapter 3, a larger randomised controlled laboratory study was undertaken and reported in Chapters 4 and 5. The primary aim of Chapter 4 was to investigate the impact of WTN on objective and subjective sleep macrostructure parameters in a carefully controlled laboratory environment using current gold-standard PSG measures of sleep and the psychometrically validated Consensus Sleep Diary. This chapter also aimed to investigate the impact of wake- versus sleep-dependent WTN exposures (continuously, only during sleep periods and only during wake

periods) on sleep, in groups of individuals with and without reports of prior WTN related sleep disturbance. This Chapter also examined the impact of perceived noise sensitivity on objective and subjective sleep outcomes.

1.9.5 Chapter 5

Given that poor sleep can also have impacts on next-day mood, anxiety and cognitive performance outcomes, and that some wind farm residents have reported daytime impairments from WTN, this Chapter aimed to examine the impact of prior night WTN exposures during sleep and wake periods and the impact of previous self-reported WTN related sleep disturbance on next-day mood and anxiety symptoms and cognitive performance. This study also considered the possibility that WTN could have a detrimental effect on sleep and subsequent daytime functioning without necessarily showing discernible changes in traditional measures of sleep. This is a particularly important consideration given that daytime symptoms of functional impairment are an important defining criteria for a diagnosis of insomnia; one of the potentially most relevant and potential impacts of WTN on residents who live near a wind farm (Dolan-Sewell, Riley, & Hunt, 2005; Shekleton, Rogers, & Rajaratnam, 2010).

1.9.6 Chapter 6

Chapter 6 presents a summary and discussion of the overall findings and how these findings address some of the knowledge gaps regarding the impact of WTN on objectively and subjectively measured sleep parameters. Also presented is a consideration of the role of psychological awareness of WTN exposure during periods of wake on both objective and subjective sleep and on next-day mood, anxiety, and cognitive performance outcomes. This Chapter also discusses the implications of the thesis findings on suggested directions for future research surrounding WTN effects on sleep.

CHAPTER 2. A SYSTEMATIC REVIEW AND META-ANALYSIS OF WIND TURBINE NOISE EFFECTS ON SLEEP USING VALIDATED OBJECTIVE AND SUBJECTIVE SLEEP ASSESSMENTS

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Author Contributions

TL was the primary author of the manuscript, conducted the literature search and review process and conducted all statistical analyses. KH, BZ, NL, LL & PC contributed to results interpretation and manuscript preparation. GM contributed to study design, literature search, statistical analysis, results interpretation, and manuscript preparation.

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ABSTRACT

Little is known about the potential impacts of wind turbine noise (WTN) on sleep. Previous research is limited to cross-sectional studies reporting anecdotal impacts on sleep using inconsistent sleep metrics. This meta-analysis sought to comprehensively review studies evaluating the impact of WTN using widely accepted and validated objective and subjective sleep assessments. Search terms included: “wind farm noise”, “wind turbine noise”, “wind turbine sound”, “wind turbine noise exposure” AND “sleep”. Only original articles published in English published after the year 2000 and reporting sleep outcomes in the presence of WTN using polysomnography, actigraphy or psychometrically validated sleep questionnaires were included. Uniform outcomes of the retrieved studies were meta-analysed to examine WTN effects on objective and subjective sleep outcomes. Nine studies were eligible for review and five studies were meta-analysed. Meta-analyses (Hedges’ *g*; 95% Confidence Interval [CI]) revealed no significant differences in objective sleep onset latency (0.03, 95% CI −0.34 to 0.41), total sleep time (−0.05, 95% CI −0.77 to 0.67), sleep efficiency (−0.25, 95% CI −0.71 to 0.22) or wake after sleep onset (1.25, 95% CI −2.00 to 4.50) in the presence versus absence of WTN (all *p*’s >0.05). Subjective sleep estimates were not meta-analysed because measurement outcomes were not sufficiently uniform for comparisons between studies. This systematic review and meta-analysis suggests that WTN does not significantly impact key indicators of objective sleep. Cautious interpretation remains warranted given variable measurement methodologies, WTN interventions, limited sample sizes, and cross-sectional study designs, where cause-and-effect relationships are uncertain. Carefully controlled experimental studies using ecologically valid WTN, objective and psychometrically validated sleep assessments are needed to provide conclusive evidence regarding WTN impacts on sleep.

KEYWORDS: objective sleep, polysomnography, psychometrically validated assessment, sleep disruption, subjective sleep, wind turbine noise.

A systematic review and meta-analysis of wind turbine noise effects on sleep using validated objective and subjective sleep assessments.

2.1 Overview

There are many economic and eco-friendly advantages associated with wind turbines given the long-term sustainability of this clean energy source. However, adverse health effects have also been reported by residents who live near wind turbines (Thorne, 2011), with sleep disturbance one of the most prominent and commonly reported concerns (Basner et al., 2014; Crichton et al., 2014; Janssen, Basner, Griefahn, Miedema, & Kim, 2011a; Krogh et al., 2011; Muzet, 2007; World Health Organization, 2011). However, other residents living at similar distances to wind turbines report no sleep disturbance or ill health effects (Thorne, 2011), thus the prevalence, severity, and impacts of potential sleep disturbance effects remain unclear.

Good sleep is essential for health and quality of life, as well as for achieving optimal neural development, learning, memory and emotional regulation (Frank et al., 2013). Insufficient sleep (i.e., difficulty initiating and maintaining sleep) can result in daytime alertness and functional impairments, mood disturbance and reduced quality of life (Jalali et al., 2016a; Janssen et al., 2011a; Micic et al., 2018). Pre-existing psychosocial stress and aversive noise (e.g., environmental noise) have the potential to impair one's ability to initiate and maintain sleep, which can over time lead to maladaptive coping strategies such as spending increased time in bed awake and ruminating on the noise keeping them awake, thus developing conditioned responses to the noise, such as, increased alertness (Perlis et al., 1997). This can contribute to the development of insomnia, which can have a severe impact on an individual's quality of life via fatigue, lack of energy, decreased mood, irritability, as well as memory and cognitive impairments (Lovato et al., 2014; Sweetman et al., 2017). Given that environmental noise, such as

WTN, has the potential to be a psychosocial stressor and thus result in poor sleep (Evandt et al., 2017; Perlis et al., 1997; Riemann et al., 2010), it is important to consider and review the available findings to date regarding whether WTN impacts individual objective and subjective sleep.

Sleep disturbance from common environmental noise sources (e.g., road traffic and aircraft noise) is well established (Eberhardt & Akselsson, 1987; Kuroiwa et al., 2002; Marks & Griefahn, 2007). For example, in the presence of traffic noise, aircraft noise, and rail noise at A-weighted SPLs of 39, 44 and 50 dB(A), compared to control nights of 32 dB(A) background noise, total sleep time and sleep quality have been shown to be reduced and latency to slow wave sleep has been shown to be prolonged (Griefahn et al., 2006). A-weighting is frequently applied to noise measurements and is similar to the hearing response of the human auditory system as it is most sensitive in the mid-frequency ranges (200–2000 Hz) compared to the lower (<200 Hz) and higher frequencies (>2,000 Hz) (Leventhall, 2004). Whilst WTN is another environmental noise source, limited research has examined its effects on human sleep and physiology. Furthermore, WTN has some acoustic features that could make it more problematic for sleep compared to other noise types.

WTN occurs predominantly in low frequencies, which can propagate substantially longer distances and penetrate building structures more readily, and thus could potentially be more problematic for sleep compared to higher frequency noises. In addition, WTN can also exhibit substantial amplitude modulation, where noise amplitude varies with time continuously with each turbine blade-tower passage and sometimes more sporadically depending on external factors, such as, variations in the weather, wind speed, wind shear, the number and size of the turbines in the area, local topography, vegetation, and the distance between turbines and residences receiving the noise (Hansen et al., 2017; Hansen, Nguyen, Zajamšek, Catcheside, & Hansen, 2019). As a result of low frequency

noise predominance, the time-varying nature of amplitude modulation, and low background noise of rural areas where wind turbines are typically installed, there is the potential for sleep disruption to occur. The aim of the present review was to meta-analytically gather all recent evidence to date (i.e., papers published after the year 2000) to quantitatively assess and systematically review WTN impacts on objective and psychometrically validated subjective sleep.

Previous literature reviews have focussed on the correlates of WTN on annoyance and health effects rather than the specific impact of WTN on sleep (Basner & McGuire, 2018; Schmidt & Klokker, 2014). To our knowledge, only one systematic review has specifically investigated the impact of WTN on sleep (Onakpoya et al., 2015). That review was based on studies that used self-reported assessments of sleep alone, many of which involved researcher-developed sleep questionnaires, often consisting of limited items addressing the presence versus absence of self-reported sleep disturbance, rather than outcomes from psychometrically validated questionnaires that have undergone extensive reliability and validity testing. Without the use of standardised, psychometrically validated tools, limited conclusions can be drawn regarding the impact of WTN on subjective sleep. Psychometric validity of questionnaires in research demonstrates that the questionnaires systematically measure what they are designed to measure. Using standardised questionnaires is useful and necessary for allowing comparisons between studies. More recently, several experimental studies have examined the effects of WTN on sleep using PSG, the “gold-standard” measure of sleep, as well as actigraphy and validated questionnaires. The present review aimed to use systematic and meta-analytic approaches to describe and provide a quantitative summary of data on this topic. Where possible, the present review also aimed to quantify the strength of evidence around the impacts of WTN on objective (PSG and actigraphy) and psychometrically validated self-reported measures of sleep.

2.2 METHOD

2.2.1 Design

This systematic review and meta-analysis was written in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) Statement (Moher, Liberati, Tetzlaff, & Altman, 2010).

2.2.2 Data sources and search strategies

A systematic literature search was performed between January and April 2020. Electronic searches were conducted in PubMed, Scopus, Science Direct, Cumulative Index to Nursing and Allied Health Literature (CINAHL), PsycARTICLES, Web of Science and the Medical Literature Analysis and Retrieval System Online (MEDLINE) databases. Search terms were “wind farm noise”, “wind turbine noise”, “wind turbine sound”, “wind turbine noise exposure” AND “sleep” [Title/Abstract]. See Appendix 1 for the specific database search strategies used. The search was also expanded by manually identifying relevant publications from the reference lists of retrieved literature after discussion with co-authors.

2.2.3 Study selection criteria

Duplicate articles were removed, and the rest were screened by the primary author (TL) according to the selection criteria presented in Table 2.1. The retrieved studies were also reviewed by GM in an unblinded manner. GM also helped manually identify any relevant publications that were not retrieved from database searching.

An initial search was implemented in each database, which involved searching for studies that had been published before 2000 and investigated the impact of WTN on sleep using objective and/or psychometrically validated subjective sleep assessments. Given previous reviews and a lack of relevant publications before 2000, the selection criteria were designed to capture more recent studies published after 2000, that used objective

sleep measures (i.e., PSG or actigraphy), and/or psychometrically validated subjective sleep measures. These included, but were not limited to sleep diaries, the PSQI, ISI and the ESS.

Table 2.1 Study selection criteria.

Article Criteria
Original, full text, peer-reviewed article
Contains terms “wind farm noise” OR “wind turbine noise”, OR “wind turbine noise exposure”, OR “wind turbine sound” and “sleep” in the title/abstract
Written in English
Published after 2000
Sample Characteristics Criteria
Adults, ≥18 years of age
Reportedly living/working within 15 kilometres from a wind farm or exposed to WTN as part of the study procedure
Primary Outcome Criteria
Evaluated the impact of WTN on any of the following objective and/or psychometrically validated subjective sleep parameters: • Sleep onset latency (SOL), total sleep time (TST), wake after sleep onset (WASO), sleep efficiency. • Global scores of PSQI, ISI and/or ESS.
Meta-analysis Criteria
Examined the presence versus absence of WTN on any of the aforementioned objective and/or psychometrically validated subjective sleep parameters (i.e., included a control group/condition and WTN exposure condition).

Note. SOL = Sleep Onset Latency; TST = Total Sleep Time; WASO= Wake After Sleep Onset; ESS = Epworth Sleepiness Scale; ISI = Insomnia Severity Index; PSQI = Pittsburgh Sleep Quality Index. WTN=wind turbine noise.

2.2.4 Objective sleep measurement

2.2.4.1 PSG

PSG is the current “gold-standard” used for objective sleep measurement, as it uses direct EEG measurements and widely accepted scoring criteria to comprehensively describe sleep–wake timing, sleep stages, sleep onset latency (SOL; the time taken to fall asleep, in minutes), wake after sleep onset (WASO; the total time spent awake between the first and last epoch of sleep, in minutes), TST (in minutes), sleep efficiency (the total

time spent asleep expressed as a percentage of time available for sleep between lights out and arising from sleep), and brief arousals from sleep (Martin & Hakim, 2011). PSG is often scored in 30-second Epochs and is used to classify cortical activity including sleep staging, arousals, awakenings, sleep spindles, and K-complexes according to standards developed and maintained by the American Academy of Sleep Medicine (Berry et al., 2012; Iber, Ancoli-Israel, Chesson, & Quan, 2007). Eligible PSG studies required the use of the international 10–20 system for electrode placement on both an experimental night (a night with WTN exposure) and a control night (a quiet, WTN-free night), and thus report the traditional gold-standard metrics of sleep quality described above. Studies using PSG under these conditions were considered for eligibility and no other factors, such as sampling and filter frequencies or maximum impedance values, impacted study eligibility.

2.2.4.2 Actigraphy

Actigraphy is a wrist-worn motion sensor device that algorithmically infers sleep and wakefulness from gross body movements, often across 1-min Epochs (Smith et al., 2018). Actigraphy provides information on sleep patterns including estimates of the timing and duration of sleep and awakenings from which sleep onset latency, total sleep time, wake after sleep onset, and sleep efficiency is inferred. Actigraphy is minimally intrusive and thus enables longer-term inferences of sleep patterns not practical via PSG (Martin & Hakim, 2011). In addition, actigraphy provides an objective marker of sleep that can be easily used in an individual's home and does not need trained personnel to set up and implement. Whilst it does require some manual scoring, actigraphy does not require rigorous and time-consuming scoring after an overnight recording unlike PSG. Actigraphy is also less impacted by recall bias, sleep misperception or misattribution of awakenings than subjective self-report measures (Martin & Hakim, 2011). However, actigraphy relies on motion without directly assessing sleep via cortical activity. This approach has high sensitivity, but low specificity for detecting sleep, with frequent misclassification of inactivity

as sleep when EEG demonstrates wake. This can result in an overestimation of sleep and an underestimation of wakefulness during the night (Marino et al., 2013; Martin & Hakim, 2011; Sivertsen et al., 2006). In addition, because the Epoch length of actigraphy is one minute, only longer duration awakenings can be captured in comparison to PSG that can capture shorter awakenings.

Eligible actigraphy studies required the use of actigraphy as an objective measure of sleep and thus allowed for the reporting of traditional sleep metrics (e.g., sleep onset latency, total sleep time, wake after sleep onset, sleep efficiency). Eligible actigraphy studies also needed to have a control condition (e.g., non-exposed individuals or no-WTN exposure) to be considered in the meta-analysis. Studies using actigraphy under these conditions were considered for eligibility and no other factors, such as, manually verified scoring or specific actigraphy devices or scoring algorithms, impacted study eligibility to maximise the number of eligible studies.

2.2.5 Subjective sleep assessment

Sleep perception (i.e., the individual's own account of how long it takes them to go to sleep, how many hours of sleep they received, how much time they spent awake etc.) is important, particularly when assessing the possibility of insomnia (Maich et al., 2018; Morgenthaler et al., 2007). Self-reported sleep quality assessment using sleep diaries and sleep questionnaires is central to an insomnia diagnosis and treatment and requires psychometrically validated instruments for meaningful between-group comparisons and for tracking improvements and recovery (American Psychiatric Association, 2013). For instance, using psychometrically validated questionnaires makes it possible to combine studies that have used the same questionnaires and thus strengthen and broaden research findings.

2.2.5.1 Sleep diary

Sleep diaries are psychometrically validated for measuring sleep perception night-to-night (Carney et al., 2012; Maich et al., 2018). Individual questions are used to calculate common sleep parameters including time in bed, sleep onset latency, number of perceived awakenings, wake after sleep onset, time of final awakening, and time out of bed. More comprehensive versions may also assess day-by-day sleep medication use, naps, caffeine, and alcohol use (Maich et al., 2018).

2.2.5.2 Insomnia Severity Index (ISI)

The ISI is a 7-item self-report assessment of difficulty initiating and maintaining sleep, sleep satisfaction, and daily functioning (Morin, 1993). The total score ranges from 0 to 28, whereby higher scores indicate greater insomnia severity. Clinical score cut-offs are 0–7 = absence of insomnia, 8–14 = subthreshold insomnia, 15–21 = moderate insomnia, and 22–28 = severe insomnia. The ISI demonstrates adequate internal consistency for identifying both clinical (Cronbach's $\alpha = 0.91$) and community samples (Cronbach's $\alpha = 0.90$); hence, is considered to be a reliable tool for assessing insomnia severity (Morin, Belleville, Bélanger, & Ivers, 2011).

2.2.5.3 Pittsburgh Sleep Quality Index (PSQI)

The PSQI is a 19-item questionnaire that assesses sleep duration, sleep latency and the frequency/severity of specific sleep-related problems (Buysse, Reynolds, Monk, Berman, & Kupfer, 1989). Individual items are scored into seven main components that are then summed to provide an aggregate global score. Global PSQI scores range from 0 to 21, where higher scores represent worse sleep quality and PSQI scores of >5 indicate poor sleep quality. The PSQI has good internal consistency (Cronbach's $\alpha = 0.83$), good test–retest reliability ($r = 0.85$), adequate validity to distinguish between poor and healthy sleepers (89.6% sensitivity and 86.5% specificity), and good construct validity ($r = 0.69$) (Buysse et al., 1989).

2.2.5.4 Epworth Sleepiness Scale (ESS)

The ESS is an 8-item scale that assesses habitual daytime sleepiness or the likelihood of sleeping in particular situations (Johns, 1991). It has high test–retest reliability (r = 0.82) and internal consistency (Cronbach's α = 0.88) (Johns, 1992). Total ESS scores range from 0 to 24, with higher scores indicating higher daytime sleepiness. Clinical cut-offs of ≥10 indicate excessive daytime sleepiness. However, worthy of note is that the ESS does not capture momentary sleepiness, where instead momentary sleepiness would be captured by the Karolinska Sleepiness Scale (KSS) (Åkerstedt & Gillberg, 1990).

2.2.6 Statistical analysis

2.2.6.1 Data extraction and quality assessment

Relevant data fields for extraction were identified by TL and are shown in Tables 2.2 and 2.3. In the case that data were not available for analysis in the retrieved studies, TL contacted the appropriate authors for such data. The statistics reported in the retrieved articles included mean (SD; standard deviation) or mean (SE; standard error) from which pooled variances were determined where possible.

The reporting quality of the included studies was assessed via the adapted Strengthening the Reporting of Observational studies in Epidemiology (STROBE) Checklist (Von Elm et al., 2007) at the study level. The adapted STROBE checklist was chosen to measure study quality because this is the checklist that has been used by the only other systematic review and meta-analysis that has investigated the impact of WTN on sleep (Onakpoya et al., 2015). Therefore, it was assumed that a larger proportion of the identified studies in the present review and meta-analysis would also be observational, and thus, it was considered appropriate to still use the adapted STROBE checklist. This involved an assessment of the recruitment and sampling technique (e.g., did they detail their techniques and was the recruited sample representative of the interested population

and sampled in an adequate way?), response rate, relevant outcome measures, appropriate statistical analyses, and any limitations and biases. Based on the identified limitations and risk of selection bias, reporting bias, detection bias, and attrition/response rate if applicable; a risk of bias judgement (i.e., low risk, some concerns, and high risk) was also made and is shown in Table 2.4. The reporting quality and risk of bias judgement were assessed independently by TL in an unblinded manner and reviewed by GM. Differential judgements by TL and GM were resolved by a third author (PC).

2.2.6.2 Meta-analyses

All analyses were conducted using Meta-Essentials: Workbooks for meta-analysis, version 1.5 (Hak, van Rhee, & Suurmond, 2016) for estimation of pooled mean effects and 95% Confidence Intervals (95% CIs) using random-effects models. Hedges' *g* is the appropriate effect size to use when analysing group differences (i.e., between an experimental versus control group) and when sample sizes are small (Borenstein, Hedges, Higgins, & Rothstein, 2011). The present review also reported on prediction intervals (PI), which involve the range in which 95% of future studies are predicted to fall and the assessment of heterogeneity and potential for publication biases. Meta-analyses were conducted on all eligible retrieved studies that used uniform objective or self-reported measures of sleep to investigate the impact of the presence versus absence of WTN exposure on sleep outcomes (sleep onset latency, total sleep time, wake after sleep onset, sleep efficiency, PSQI, ISI and/or ESS scores).

2.2.6.3 Heterogeneity and risk of biases

The Q-statistic (Cochrane's Q) was also reported to indicate the average variability of the effect size for each sleep parameter. A significant Q-statistic suggests that the variability in the effect size is greater than expected by chance (Hak, van Rhee, & Suurmond, 2016). The Q-statistic is limited as it can be impacted by sample size biases between studies and thus should be interpreted with the I^2 statistic, which indicates the

proportion of variance of real differences in effect sizes (Hak et al., 2016). In the present meta-analyses, I^2, the Q-statistic, and the significance level are reported. In the event of a high I^2 (>50%), a subgroup analysis will be sought, as this indicates that the meta-analysed studies are less likely to be of the same population.

In addition, funnel plots of the effect size in comparison to the standard error for each sleep parameter were used to assess the potential for publication bias. Symmetrical funnel plots are strongly indicative of minimal bias. A further assessment of bias in individual studies is provided in Table 2.4.

2.3 RESULTS

2.3.1 Selection of studies

Figure 2.1 illustrates the PRISMA flow diagram, outlining the study selection process at each stage of screening. The database search strategy identified 451 records and seven additional records through consultation with co-authors to identify pertinent articles not captured by the search strategy and screening reference lists of included articles. In all, 324 records remained after removing duplicates and 49 remained after abstract screening. Full-text screening excluded 41 studies, mainly due to absence of key outcomes, leaving eight studies that met the inclusion criteria (Figure 2.1). One of the eligible studies reported on two separate pilot studies and, therefore, this was treated as two separate records, making nine eligible studies for qualitative synthesis after abstract screening. For quantitative synthesis, four studies were excluded for reasons detailed in Figure 2.1. Studies that did not uniformly or comparably measure objective and subjective outcomes and thus could not be meta-analysed were discussed separately. Ageborg Morsing et al. (2018a, 2018b) had three different WTN exposure nights [at outdoor SPLs of 40, 45, 50 dB equivalent continuous SPL (L_{AEq})]. In this case, the 45 dB L_{AEq} conditions were chosen as the WTN condition to be included in the meta-analysis. This was due to the World Health Organization stating that at night, outdoor SPLs should not exceed 45 dB

L_{AEq} (Bergland & Lindvall, 1995). Additionally, Ageborg Morsing et al. (2018a, 2018b) did not report wake after sleep onset in their studies and therefore, TL contacted the primary authors of these studies to obtain wake after sleep onset data for inclusion in this review and meta-analysis.

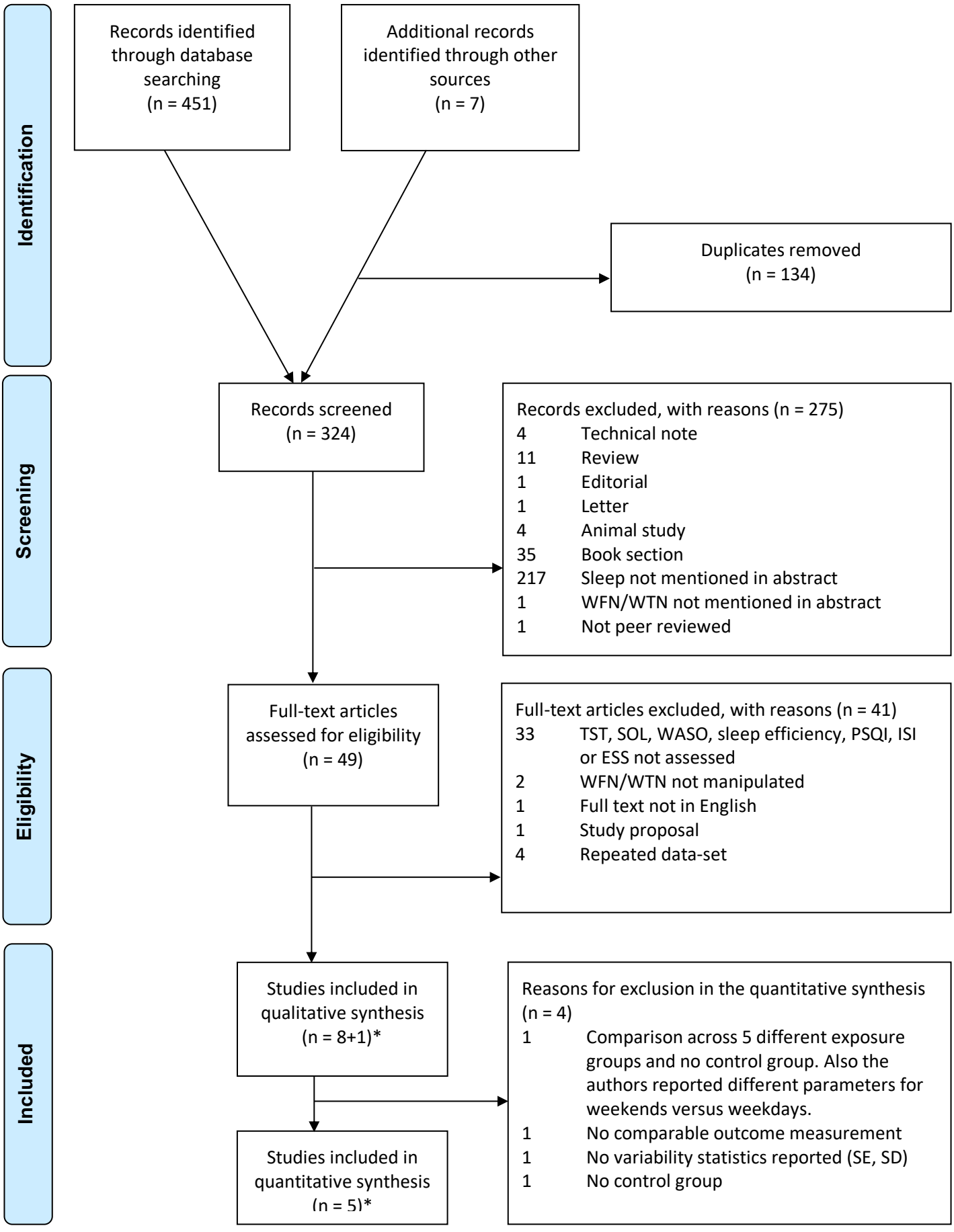

Figure 2.1 PRISMA flow diagram showing the process for inclusion.

Note. *1 additional study was included as one record conducted and analysed two separate studies.

2.3.2 Study demographics

Table 2.2 summarises the sample and testing characteristics and Table 2.3 summarises the outcomes, tools used to assess each outcome, and the study findings. In all, 1,517 participants were assessed in the nine included studies. Three experimental laboratory studies were conducted in Sweden (Ageborg Morsing et al., 2018a, 2018b; Smith et al., 2020), two cross-sectional and two longitudinal studies in Canada (Jalali et al., 2016a; Jalali et al., 2016b; Lane et al., 2016; Michaud et al., 2016) one cross-sectional study in Iran (Abbasi, Monazzam, Akbarzadeh, Zakerian, & Ebrahimi, 2015) and one cross-sectional study in the USA (Nissenbaum et al., 2012). Topography varied between the non-laboratory studies, with two study locations being in mountainous areas, (Abbasi et al., 2015; Nissenbaum et al., 2012) and four Canadian studies in rural areas with flat, open fields (Jalali et al., 2016a; Jalali et al., 2016b; Lane et al., 2016; Michaud et al., 2016). The mean (*SD*, range) age across all studies was 41.3 (15.0, 22–56) years. The distance from wind turbines ranged between <50 metres and 11.2 kilometres and outdoor SPLs ranged from <25 to 83 dB(A). It is worth noting that studies included not only individuals who lived near wind turbines, but also individuals with no prior exposure to WTN and those who worked on wind farms. Three studies used synthesised WTN recordings, (Ageborg Morsing et al., 2018a, 2018b; Smith et al., 2020), four studies used 8–10 hour recordings of WTN measured inside participants' homes (Abbasi et al., 2015; Jalali et al., 2016a; Jalali et al., 2016b; Lane et al., 2016), and two studies used estimations/predictions of WTN using International Organisation for Standardisation (ISO) models (Michaud et al., 2016; Nissenbaum et al., 2012). Five of the nine studies assessed sleep onset latency, total sleep time, wake after sleep onset and sleep efficiency using objective measures of sleep, which included one actigraphy-based study and four PSG studies that were included in the meta-analysis (Ageborg Morsing et al., 2018a, 2018b; Jalali et al., 2016a; Lane et al., 2016; Smith et al., 2020).

Table 2.2 Study characteristics including sample and testing characteristics.

Study	Location/ Environment	Sample Size	Mean age (years)	Design	SPL of WTN exposure	Method of SPL Measurement	Distance measurements
Ageborg Morsing et al. (2018a)	Sweden, laboratory	6	22.2	Experimental laboratory study	29.5 dB L_{AEq}, 34.1 dB L_{AEq}, 33.7 dB L_{AEq} indoor WTN (with varying frequencies and amplitude modulation characteristics)	Three 8-hour night-time synthesised WTN exposures with varying filtering, frequency bands and amplitude modulation beats.	N/A
Ageborg Morsing et al. (2018b)	Sweden, laboratory	6	24	Experimental laboratory study	32.8 dB L_{AEq}, 32.8 dB L_{AEq}, 30.4 dB L_{AEq} indoor WTN (with varying frequencies and amplitude modulation characteristics)	Three 8-hour night-time synthesised WTN exposures with varying filtering, frequency bands and amplitude modulation beats.	N/A
Jalali et al. (2016a)	Canada, open flat agricultural fields	16	55.9	Pre-post field study	Time 1: 36.55 dB(A); Time 2: 36.50 dB(A)	10-hour noise measurements at two participant's residences for 16 nights before and 16 nights after wind turbine operation.	10 individuals <1000m from a turbine and 6 individuals >1000m from a turbine.
Lane et al. (2016)	Canada, rural matched areas	32	Exposed group: 60.4; Unexposed group: 41.4 (adjusted mean age = 50.9)	Cross-sectional field study	N/A	8-hour equivalent A-weighted sound level ($L_{AEq,\ 8h}$) from 23:00 and 7:00 in one participant per group for five nights.	Exposed group mean distance of 794.6m (SD = 264.1m) from a turbine. Unexposed group mean distance of 2,931m (SD = 1,015.6m) from a turbine.
Jalali et al. (2016b)	Canada, rural area with flat agricultural fields	37	54.25	Pre-post field study	Time 1: 31.52 dB(A); Time 2: 31.23 dB(A)	10-hour noise measurements at two participant's residences for 16 nights before and 16 nights after wind turbine operation.	22 individuals <1000m from a turbine and 15 individuals >1000m from a turbine.
Nissenbaum et al. (2012)	USA, tree covered island and mountainous topography	79	N/A	Cross-sectional field study	WTN ranging from 32-61 dB L_{AEq}	Predicted noise levels at various distances from both wind turbine sites.	Near group: 375-1400m; far group: 3.3-6.6km.
Abbasi et al. (2015)	Iran, mountainous topography	53	30.8	Cross-sectional field study	83 dB(A), 66 dB(A), 60 dB(A)	8-hour equivalent sound levels ($L_{AEq,\ 8h}$) according to ISO 9612:2009.	0-50m, 50-100m, >150m.
Michaud et al. (2016)	Canada	1238	N/A	Cross-sectional field study	Calculated outdoor SPLs at dwellings reached 46 dB(A) (M=35.6, SD=7.4) and background night-time levels ranged between 35-61 dB(A). Ontario and Prince Edward Island residents were grouped into SPL categories of <25 dB(A), 25-<30 dB(A), 30-<35 dB(A), 35-<40 dB(A) and 40-46 dB(A)	Estimation using ISO 9613-1 (ISO,1993) and 9613-2 (ISO,1996). Long-term 1-year A-weighted equivalent continuous outdoor SPLs (L_{AEq}).	Ontario and Prince Edward Island residents at varying distances from a wind farm (<550m, 550m-1km, 1-2km, 2-5km, >5km).

Study	Location/ Environment	Sample Size	Mean age (years)	Design	SPL of WTN exposure	Method of SPL Measurement	Distance measurements
Smith et al. (2020)	Sweden, laboratory	50	51.2	Experimental laboratory study	32 dB L_{AEq} indoor WTN including amplitude modulation	Continuous synthesised WTN based on short and long-term recordings including amplitude modulation. This was played from 22:00 to 07:00. Participant's scheduled sleep opportunity was 23:00-07:00 and thus participants were aware of the WTN exposure. All sound was calibrated to reflect a max 45 dB L_{AEq}.	Exposed group = resided <1km from a turbine or reported sleep disturbance or annoyance from wind turbines in the past month; unexposed group.

Note. M=Mean; *SD*=Standard Deviation; dB(A)=A-weighted decibel; dB L_{AEq}=Equivalent Continuous Sound Pressure Level; SPLs=Sound Pressure Levels; SOL=Sleep Onset Latency; TST=Total Sleep Time; WASO=Wake After Sleep Onset. ISO=International Organisation for Standardisation; WTN=Wind Turbine Noise. m=metres. km=kilometres. N/A=not available. h=hour.

Table 2.3 Study outcomes and the tools used to assess these outcomes and the main findings of included studies.

Study	Outcomes	Tools used to assess outcomes	Study Findings
Ageborg Morsing et al. (2018a)	Objective SOL, sleep efficiency, TST, subjective sleep outcomes	PSG, morning questionnaire	No significant effect of SOL between control night (*M*=23.3, *SD*=20.6), 29.5 dB L_{AEq} WTN (*M*=20.4, *SD*=13.2), 34.1 dB L_{AEq} WTN (*M*=16.0, *SD*=7.2) or 33.7 dB L_{AEq} WTN (*M*=13.7, *SD*=8), *p*>0.01. No significant effect of TST between control night (*M*=425.9, *SD*=32.5), 29.5 dB L_{AEq} WTN (*M*=444.9, *SD*=13.8), 34.1 dB L_{AEq} WTN (*M*=429.2, *SD*=32.4) or 33.7 dB L_{AEq} WTN (*M*=448.6,*SD*=8.4), *p*>0.01. No significant effect of sleep efficiency between control night (*M*=90.0, *SD*=6.8), 29.5 dB L_{AEq} WTN (*M*=93.2, *SD*=2.5), 34.1 dB L_{AEq} WTN (*M*=90.3, *SD*=6.4) or 33.7 dB L_{AEq} WTN (*M*=93.6, *SD*=1.6), *p*>0.01. WASO data was not analysed in this study*. No significant effect of subjective SOL or number of perceived awakenings.
Ageborg Morsing et al. (2018b)	Objective SOL, sleep efficiency, TST, subjective sleep outcomes	PSG, morning questionnaire	No significant effect of SOL between control night (*M*=10.3, *SD*=8.4), 32.8 dB L_{AEq} WTN with window gap filtering and high frequency amplitude modulation beats (*M*=17.5, *SD*=10.6), 32.8 dB L_{AEq} WTN with window gap filtering and low frequency amplitude modulation beats (*M*=17.0, *SD*=11.4) or 30.4 dB L_{AEq} WTN with window closed filtering and low frequency amplitude modulation beats (*M*=21.3, *SD*=25.5), *p*>0.01. No significant effect of TST between control night (*M*=455.2, *SD*=9.2), 32.8 dB L_{AEq} WTN with window gap filtering and high frequency amplitude modulation beats (*M*=447.5, *SD*=14.7), 32.8 dB L_{AEq} WTN with window gap filtering and low frequency amplitude modulation beats (*M*=442.7, *SD*=9.9) or 30.4 dB L_{AEq} WTN with window closed filtering and low frequency amplitude modulation beats (*M*=440.8, *SD*=34.4), *p*>0.01. No significant effect of sleep efficiency between control night (*M*=94.8, *SD*=1.9), 32.8 dB L_{AEq} WTN with window gap filtering and high frequency amplitude modulation beats (*M*=93.2, *SD*=3.1), 32.8 dB L_{AEq} WTN with window gap filtering and low frequency amplitude modulation beats (*M*=92.2, *SD*=2.1) or 30.4 dB L_{AEq} WTN with window closed filtering and low frequency amplitude modulation beats (*M*=91.8, *SD*=7.2), *p*>0.01. WASO data was not analysed in this study*. No significant effect of subjective SOL or number of perceived awakenings.
Jalali et al. (2016a)	Objective SOL, sleep efficiency, TST, WASO, subjective sleep outcomes	Ambulatory PSG, sleep diary	No significant difference between SOL at Time 1 (*M*=14.9, *SD*=17.7) and Time 2 (*M*=11.1, *SD*=16.9), *p*=0.371. No significant difference between TST at Time 1 (*M*=380.3, *SD*=68.8) and Time 2 (*M*=402.1, *SD*=36.4), *p* =0.226. No significant difference between WASO at Time 1 (*M*=34.8, *SD*=26.0) and Time 2 (*M*=34.4, *SD*=26.9), *p*=0.950. No significant difference between sleep efficiency at Time 1 (*M*=88.5%, *SD*=7.1) and Time 2 (*M*=89.4%, *SD*=6.9), *p*=0.634. No significant differences in subjective TST, number and length of awakenings or SOL at Time 1 compared with Time 2 (all *p*'s >0.05).

Study	Outcomes	Tools used to assess outcomes	Study Findings
Lane et al. (2016)	Objective SOL, sleep efficiency, TST, WASO, subjective sleep outcomes	Actigraphy, sleep diary	No significant differences in SOL for exposed individuals (*M*=6.8, *SD*=1.8) and unexposed individuals (*M*=7.3, *SD*=2.3), *p*=0.22. No significant differences in sleep efficiency for exposed individuals (*M*=88.5, *SD*=5.4) and unexposed individuals (*M*=91.0 *SD*=4.1), *p*=0.17. No significant differences in TST for exposed individuals (*M*=436.7, *SD*=53.6) and unexposed individuals (*M*=413.7, *SD*=47.7), *p*=0.34. No significant differences in WASO for exposed individuals (*M*=44.0, *SD*=1.7) and unexposed individuals (*M*=30.6, *SD*=1.9), *p*=0.16.
Jalali et al. (2016b)	Subjective sleep quality	PSQI, ESS, ISI	PSQI scores increased from Time 1 (*M*=4.1, *SD*=2.1) to Time 2 (*M*=6.2, *SD*=3.9), *p*=0.006. ESS scores also significantly increased from Time 1 (*M*=4.7, *SD*=3.2), to Time 2 (*M*=7.1, *SD*=5.3), *p*=0.002. ISI scores also significantly increased from Time 1 (*M*=3.1, *SD*=3.6), to Time 2 (*M*=6.4, *SD*=6.7), *p*=0.005.
Nissenbaum et al. (2012)	Subjective sleep quality	PSQI, ESS	PSQI scores were significantly greater in the near group (*M*=7.8) than the far group (*M*=6.0), *p*=0.046. ESS scores were also significantly greater in the near group (*M*=7.8), than the far group (*M*=5.7), *p*=0.032.
Abbasi et al. (2015)	Daytime sleepiness	ESS	Significant differences between ESS and occupational group, where maintenance/repair workers had the greater ESS scores (*M*=10.5, *SD*=1.7) than security (*M*=6.0, *SD*=1.4) and office administration staff (*M*=4.0, *SD*=0.9), *p*<0.001.
Michaud et al. (2016)	Objective SOL, sleep efficiency, TST, WASO and self-reported sleep quality	Actigraphy, PSQI	No significant difference between SOL (*p*=0.02), sleep efficiency (*p*=0.05), WASO (*p*=0.36) or TST (*p*=0.74), across the different exposure levels. No significant differences between mean PSQI scores across different exposure levels (*p*=0.75). (means+SD not reported here).
Smith et al. (2020)	Objective SOL, sleep efficiency, TST, WASO and self-reported sleep quality	PSG, morning questionnaire	No significant effect of SOL between control night (*M*=21.3, *SE*=3.5), and WTN night (*M*=25.3, *SE*=3.7), *p*=0.165. No significant effect of TST between control night (*M*=415.6, *SE*=5.5) and WTN night (*M*=402.9, *SE*=8.6), *p*=0.543. No significant effect of sleep efficiency between control night (*M*=86.6, *SE*=1.2), and WTN night (*M*=84.2, *SE*=1.7), *p*=0.483. No significant effect of WASO between control night (*M*=45.2, *SE*=5.3) and WTN night (*M*=52.3, *SE*=7.5), *p*=0.50.

Note. M=Mean; *SD*=Standard Deviation; dB(A)=A-weighted decibel; dB L_{AEq}=Equivalent Continuous Sound Pressure Level; SPLs=Sound Pressure Levels; SOL=Sleep Onset Latency; TST=Total Sleep Time; WASO=Wake After Sleep Onset; ESS=Epworth Sleepiness Scale; ISI=Insomnia Severity Index; PSQI=Pittsburgh Sleep Quality Index; WTN=Wind Turbine Noise. PSG=Polysomnography. *denotes no WASO data was analysed in the study. The primary author, TL contacted the authors of these studies to obtain M(SD) to be included in the meta-analysis.

2.3.3 Reporting quality

Despite three of the retrieved studies being experimental studies, the STROBE Checklist was still used as a measure of reporting quality and bias given the larger proportion of studies still being cross-sectional in nature. Table 2.4 summarises the reporting quality of all nine included studies. As shown in Table 2.4, all studies used appropriate statistical methods to compare groups and associations, and used relevant and appropriate, objective or psychologically validated self-report outcome measures, as per the study selection criteria (Table 2.1). Four of the studies used the gold-standard PSG to assess sleep outcomes objectively (Ageborg Morsing et al., 2018a, 2018b; Jalali et al., 2016a; Smith et al., 2020), two used actigraphy to assess sleep objectively (Lane et al., 2016; Michaud et al., 2016), and the remaining three used psychometrically validated subjective sleep questionnaires including the PSQI, ESS and ISI (Abbasi et al., 2015; Jalali et al., 2016b; Nissenbaum et al., 2012). One of the actigraphy based studies also used the PSQI to assess self-reported sleep quality (Michaud et al., 2016) and the other actigraphy study also used a sleep diary to assess self-reported perception of sleep in addition to objective sleep outcomes (Lane et al., 2016). The four remaining objective studies (Ageborg Morsing et al., 2018a, 2018b; Jalali et al., 2016a; Smith et al., 2020) also used a sleep diary or morning questionnaire to assess self-reported sleep outcomes.

Recruitment and sampling strategies varied from appropriate to low quality. For cross-sectional studies, recruitment and sampling strategies included questionnaires, door-to-door recruitment, face to-face/telephone interviews, random sampling, a computer-assisted personal interviewing technique and the use of census data (Onakpoya et al., 2015; Von Elm et al., 2007). For the two longitudinal studies (Jalali et al., 2016a; Jalali et al., 2016b), recruitment involved door-to-door recruitment for those meeting specified criteria including being aged ≥18 years, healthy, good sleepers, no sleep medication, no hearing loss, and no other significant sources of noise disruption (such as traffic or rail

noise). Sampling strategies for the longitudinal studies involved selecting residents living within two kilometres of a pre-operational wind farm to reflect a baseline control condition (Jalali et al., 2016a; Jalali et al., 2016b). The three experimental studies (Ageborg Morsing et al., 2018a, 2018b; Smith et al., 2020) also utilised advertising and detailed exclusion/inclusion criteria, and all adopted a counterbalanced design. Smith et al. (2020) in particular, provided detailed information regarding their recruitment and sampling strategies in their supplementary analyses.

However, some of these criteria/strategies have the potential to introduce bias, particularly without random sampling to minimise potential attitudinal biases around perceived annoyance and sleep impacts. Multiple additional factors could also confound WTN effects on sleep, such as, hearing loss with ageing populations or industrial noise exposure, and common pre-existing sleep problems. Excluding participants with hearing loss or sleep apnea could help to avoid confounding but might not adequately represent rural residents surrounding wind farms or wind turbines. For example, heightened low frequency hearing acuity, increased wake across the night, conscious noise exposure or pre-existing sleep problems, can all impact sleep quality and by excluding participants that do not experience these factors, may impact the generalisability of study findings.

Furthermore, only one study (Michaud et al., 2016) reported sample size (power) calculations and only four of the nine studies provided response rates, from which the mean (SD) response rate across the studies was 54.5 (20.3)% (Jalali et al., 2016b; Lane et al., 2016; Michaud et al., 2016; Nissenbaum et al., 2012).

Based on the biases summarised in Table 2.4, the overall reporting quality was classed as “low” according to the STROBE checklist and identified limitations and biases. In terms of the risk of bias judgements for each study, four of the nine studies identified had a high risk of bias, and another four had some concerns of bias, with only one having a low risk of bias.

Table 2.4 Reporting quality and risk of bias within identified studies using an adapted version of the STROBE checklist (Onakpoya et al., 2015).

Study	Country	Study Design	Appropriate Recruitment Strategy?	Appropriate Sampling Technique?	Response Rate if applicable	Representative Sample?	Relevant Outcome Measures?	Power Calculation (yes/no)	Appropriate Statistical Analysis?	Limitations/Biases	Risk of Bias Judgement
Ageborg Morsing et al. (2018a)	Sweden	Experimental laboratory study	Somewhat-advertising and detailed exclusion criteria	Yes - Participants were counterbalanced to receive all conditions (within-subjects cross-over design)	N/A	Yes - noise sensitive individuals	Yes - objective SOL, sleep efficiency, TST, WASO*	No	Yes - Non-parametric tests – Friedman tests, and Wilcoxon signed-rank tests.	Low sample size and representativeness of the sample, WTN noise was above recommended outdoor levels for Sweden. Significance levels were $p<0.01$ rather than 0.05. Individual non-significance levels were not reported for $M\pm SD$ across nights (= risk reporting bias). Some counterbalancing was used (Nights 3-5), but control night was always on night 2. No reports on blinding of participants or researchers mentioned (although a blind sleep scorer was used).	Some concerns
Ageborg Morsing et al. (2018b)	Sweden	Experimental laboratory study	Somewhat-advertising and detailed exclusion criteria	Yes - Participants were counterbalanced to receive all conditions (within-subjects cross-over design)	N/A	Yes - noise sensitive individuals	Yes - objective SOL, sleep efficiency, TST, WASO*	No	Yes - Non-parametric tests – Friedman tests, and Wilcoxon signed-rank tests.	Low sample size and representativeness of the sample, WTN was above recommended outdoor levels for Sweden. Significance levels were $p<0.01$ rather than 0.05. Individual non-significance levels were not reported for $M\pm SD$ across nights (= risk of reporting bias). Some counterbalancing was used (Nights 3-5), but control night was always on night 2. No reports on blinding of participants or researchers mentioned (although a blind sleep scorer was used).	Some concerns
(Jalali et al., 2016a)	Canada	Pre-post field study	Uncertain - inclusion criteria for home sleep assessment	Unclear - Residents who lived within 2000m from a proposed wind farm	N/A	Yes - residents living within 2000m of a post-turbine erection site but in the pre-operational stage	Yes - objective SOL, sleep efficiency, TST, WASO	No	Yes - Paired sample t-test, McNemar tests, Spearman's rank correlations.	Identifies lack of control in field designs (WTN exposure levels, wind speed variation), order effects and general issues with WTN exposure. Participants not blinded to study aims (although a blind sleep scorer was used). Unclear whether random sampling was used (=risk of selection bias). No indication of attrition.	High risk

Study	Country	Study Design	Appropriate Recruitment Strategy?	Appropriate Sampling Technique?	Response Rate if applicable	Representative Sample?	Relevant Outcome Measures?	Power Calculation (yes/no)	Appropriate Statistical Analysis?	Limitations/Biases	Risk of Bias Judgement
Lane et al. (2016)	Canada	Cross-sectional field study	Yes - door to door recruitment	Yes - Randomly sampled	50%	Yes - individuals living near wind farm areas and a demographically matched rural control area.	Yes - objective SOL, sleep efficiency, TST, WASO	No	Yes - T-tests and Wilcoxon-Mann Whitney tests.	Notes the limitations of low statistical power and low estimates of exposure due to calm weather. Random sampling used (=less risk of selection bias). Response rate stated. Actigraphy scored based on algorithm (=less risk of detection bias).	Some concerns
Jalali et al. (2016b)	Canada	Pre-post field study	Uncertain - letters of advance notice delivered to door and door to door recruitment	No - Residents who lived within 2000m from a proposed wind farm	30%	Yes - residents living within 2000m of a post-turbine erection site but in the pre-operational stage	Yes - PSQI, ISI and ESS	No	Yes - Wilcoxon signed rank tests, Mann-Whitney tests, independent t-tests, chi-square tests, and Spearman's rank correlations.	Identifies lack of control in field designs (WTN exposure levels, wind speed variation), order effects and non-response biases. Participants not blinded to study aims (= risk of selection bias). No random sampling was used (=risk of selection bias). Low response rate (30% = risk of selection bias).	High risk
Nissenbaum et al. (2012)	USA	Cross-sectional field study	Yes - questionnaire face to face or telephone interview	Yes - Random sampling	59% for the near group - no response rate for far group	Yes - residents living in close proximity to a wind turbine (375-1400m) and far from a wind turbine (3000-6600m)	Yes - PSQI, ESS	No	Yes - Descriptive and multivariate analyses.	Reporting and selection biases due to both areas involving residents that benefit financially from wind turbines. Reducing property value fears, visual impacts and attitudes impacting results. No *SD*/variability measures reported. Lack of variability estimates (= risk of reporting bias). Response rate only provided for near group (=risk of reporting bias). Participants not blinded to study aims. Principle investigator was blind to outcome assessment.	High risk
Abbasi et al. (2015)	Iran	Cross-sectional field study	Uncertain - based on job type, questionnaire sent	Unclear - Census	N/A	Unclear - individuals working on a wind farm (no control group as the individuals furthest away was still >150m)	Unclear - ESS is not used to diagnose sleep disorders	No	Yes - MANOVA, Pillai's Trace test, Scheffe's post-hoc test, multivariate regression.	Used ESS to identify sleep disorder, fear of responding truthfully due to job. Unclear in terms of whether sampling was random (=risk of selection bias). No response rate indicated (= risk of selection bias). Participants unlikely blinded to study aims. No indication of blind outcome assessment/data handling at any stage (= risk of selection bias and detection bias).	High risk

Study	Country	Study Design	Appropriate Recruitment Strategy?	Appropriate Sampling Technique?	Response Rate if applicable	Representative Sample?	Relevant Outcome Measures?	Power Calculation (yes/no)	Appropriate Statistical Analysis?	Limitations/Biases	Risk of Bias Judgement
Michaud et al. (2016)	Canada	Cross-sectional field study	Yes - computer-assisted personal interviewing technique	Yes - Computer assisted random selection method	78.9%	Yes - individuals at varying distances from a wind farm (<550m, 550m-1km, 1-2km, 2-5km, >5km)	Yes - PSQI, objective SOL, sleep efficiency, WASO, TST, number of awakenings, time in bed, rate of awakenings per one hour in bed	Yes	Yes - Cochran Mantel-Haenszel chi-square test, univariate logistic regression models, multiple regression models, stepwise regression analyses, generalised estimating equation methods, Poisson distributions.	Describes the use of actigraphy as an objective measure of sleep, as well as the timing of objective versus subjective measures of sleep (7-day actigraphy versus PSQI over the year and 30 days). Also identifies night to night variation in outdoor WTN levels and the possibility that wind turbine operators altered the output of their turbines to produce desirable effects. Considered the difference in objective sleep variables from weekdays to weekends. Masked the true aim of the study (= less risk of selection bias). Actigraphy scored based on algorithm (=less risk of detection bias). Random sampling (= less risk of selection bias). Adequate response rate.	Low risk
Smith et al. (2020)	Sweden	Experimental laboratory study	Yes - postal mailings, phone calls, advertising, experimental exclusion criteria considered	Yes - Participants were counterbalanced to receive all conditions (within-subjects cross-over design)	N/A	Yes - individuals living <1000m from a turbine and those not living near a turbine	Yes - objective SOL, sleep efficiency, TST, WASO and subjective morning questionnaire	No	Yes - Mixed effects regression models.	Acknowledges self-selection bias, self-report habitual sleep times, lower ecological validity due to being in a laboratory. Participants not blinded (although a blind sleep scorer was used) (=risk of selection bias). Counterbalanced WTN and control night. Reported outcome variables.	Some concerns

Note. SOL=Sleep Onset Latency; TST=Total Sleep Time; WASO=Wake After Sleep Onset; WTN=Wind Turbine Noise; ESS=Epworth Sleepiness Scale; ISI=Insomnia Severity Index; PSQI=Pittsburgh Sleep Quality Index; MANOVA=Multivariate Analysis of Variance; N/A=not available. m=metres. km=kilometres. *WASO data was requested by TL.

2.3.4 Meta-analysis of objectively measured sleep parameters

Whilst six studies used objective measures of sleep (four PSG and two actigraphy), only five used uniform outcomes (four PSG and one actigraphy) and thus were included in the meta-analysis. The actigraphy study by Michaud et al. (2016) compared five different exposure groups in the field, the lowest exposure being <25 dB(A) and thus did not have a control no-WTN exposure condition. Whilst 25 dB(A) could be argued to reflect a control condition, participants were still exposed to WTN and thus could invalidate participant responses who are exposed to this level of WTN. Four objective sleep parameters were comparable across the five objective studies that assessed the impact of WTN exposure on sleep relative to control no-WTN exposure. These included sleep onset latency, total sleep time, wake after sleep onset and sleep efficiency.

As there are known limitations of actigraphy versus PSG measures, meta-analyses were initially run without the actigraphy study (Lane et al., 2016) to minimise the potential for biases associated with actigraphy compared to PSG. However, the overall results remained unchanged with versus without this study included (all *p's* >0.05), and thus all five studies that used objective measures of sleep (PSG and actigraphy) were meta-analysed together.

2.3.4.1 Sleep onset latency, total sleep time, sleep efficiency and wake after sleep onset meta-analytic results

Figure 2.2 shows the mean differences between the presence and absence of WTN exposure in sleep onset latency, total sleep time, sleep efficiency, and wake after sleep onset of the five included studies. The Hedges' *g* (95% CI) and associated meta-analytic statistics are shown in Table 2.5. Individual study mean (*SD*) values are displayed in Table 2.3. When all available studies were combined, there were no statistically significant effects of WTN exposure on sleep onset latency, total sleep time, sleep efficiency, and wake after sleep onset compared to no-WTN exposure. As shown in Table

2.5, heterogeneity between studies was low and not statistically significant for sleep onset latency, total sleep time and sleep efficiency, but was high for wake after sleep onset, suggesting that wake after sleep onset effects cannot be considered to be generalisable across studies. A meaningful subgroup analysis was not possible with only five studies, but when the actigraphy study was removed from the meta-analysis, heterogeneity in wake after sleep onset decreased from 89.77% (p<0.001) to 12.82% (p=0.328), whereby the heterogeneity was no longer significant. Overall, this suggests that for wake after sleep onset, the meta-analysed studies are likely not considered to be of the same population.

With only five included studies, evaluating the risk of bias across studies was difficult to assess and thus these results should be interpreted with caution. Figure 2.3 shows the funnel plots that were constructed for each sleep parameter in the meta-analysis. Upon visual inspection of each funnel plot, sleep onset latency, total sleep time, sleep efficiency and wake after sleep onset appeared symmetrical, indicating minimal publication bias across studies. The Duval and Tweedie “Trim and Fill” method was used to determine the presence of any missing unpublished studies and where they would likely fall within the funnel plot as well as calculating an adjusted, combined effect size after including any missing studies in the analysis (Duval & Tweedie, 2000). This method was used as it allows for filling each plot by including any trimmed studies on the right-hand side and the imputed studies on the left side of the mean. By using this method, no studies were deemed missing in any of the funnel plots (a–d) and thus no data points were imputed into Figure 2.3 and all adjusted combined effect sizes remained identical to the unadjusted combined effect sizes.

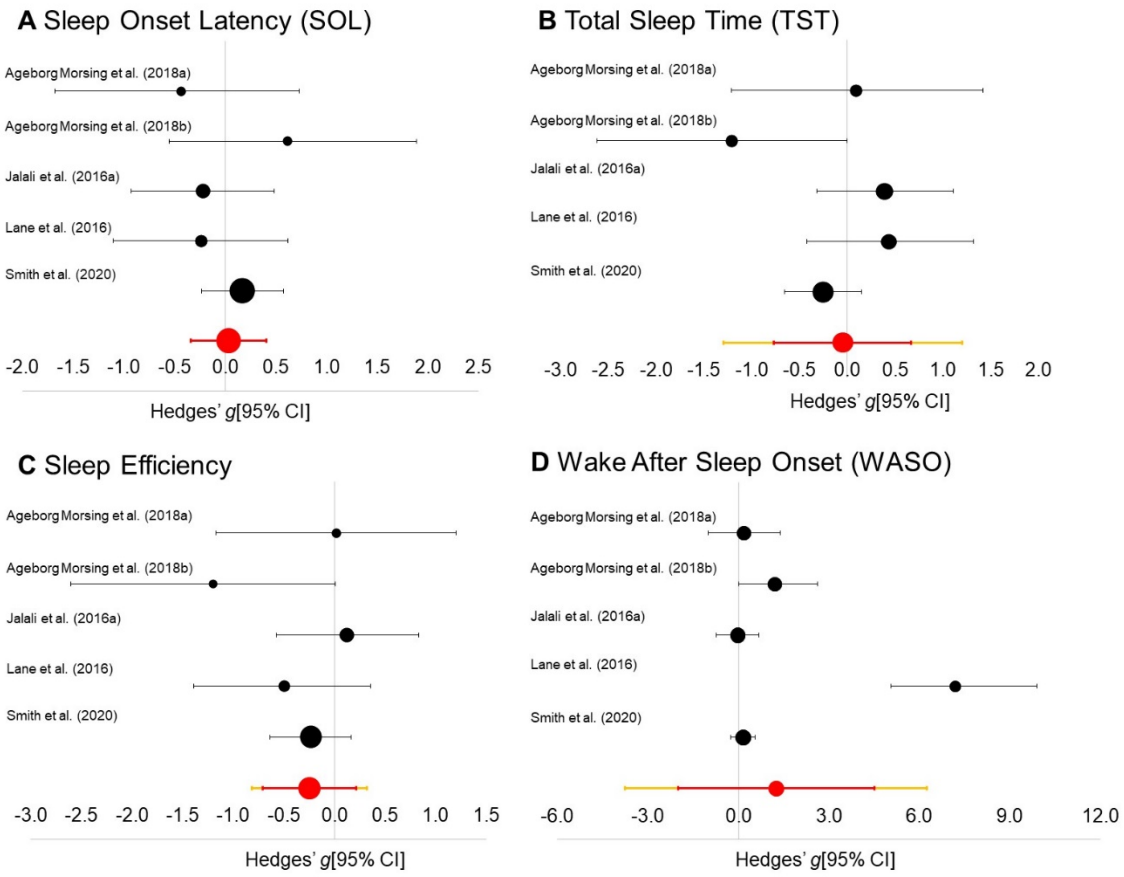

Figure 2.2 Graphical representation of pooled mean effects (effect sizes) for sleep onset latency (a), total sleep time (b), sleep efficiency (c) and wake after sleep onset (d) in the presence and absence of WTN exposure.

Note. Negative values on the *x* axis indicate a shorter sleep onset latency, less total sleep time, lower sleep efficiency, and a lower amount of wake after sleep onset in the presence of WTN exposure, while positive values indicate a longer sleep onset latency, greater total sleep time, greater sleep efficiency, and a higher amount of wake after sleep onset in the presence of WTN exposure, compared to control, no WTN exposure. The relative size of the point estimates indicates the study's weighting in the generation of the meta-analytic result. Red error bars represent 95% confidence intervals (CI). The orange error bars indicate 95% predicted interval estimates of where 95% of future studies are predicted to lie. In (a), no orange error bars are present as the 95% prediction intervals are identical to the 95% CI. All studies which evaluated sleep onset latency, total sleep time, sleep efficiency and wake after sleep onset were included in these figures.

Table 2.5 Hedges' g [95% CI] and associated meta-analytic statistics.

Objective Sleep Parameter	**Range of Hedges' *g* between studies**	**Combined Hedges' *g* (95% CI)***	***p*-value**	**95% Prediction Interval (PI)****	**Heterogeneity (*Q*, I^2, *p*-value)**
Sleep onset latency (mins)	-0.44-0.62	0.03 (-0.34 to 0.41)	p=0.806	-0.34 to 0.41	Q = 3.29, I^2 = 0%, p=0.510
Total sleep time (mins)	-1.21-0.43	-0.05 (-0.77 to 0.67)	p=0.849	-1.30 to 1.20	Q = 7.81, I^2 = 48.8%, p=0.099
Sleep efficiency (%)	-1.20-0.13	-0.25 (-0.71 to 0.22)	p=0.139	-0.82 to 0.32	Q = 4.4, I^2 = 9.16%, p=0.354
Wake after sleep onset (mins)	-0.02-7.19	1.25 (-2.00 to 4.50)	p=0.284	-3.48 to 5.99	Q =39.09, I^2 = 89.77%, p<0.001

Note. *95% CI=95% Confidence Interval; **PI=95% prediction interval; 95% of future studies effects are predicted to fall within this range. mins=minutes.

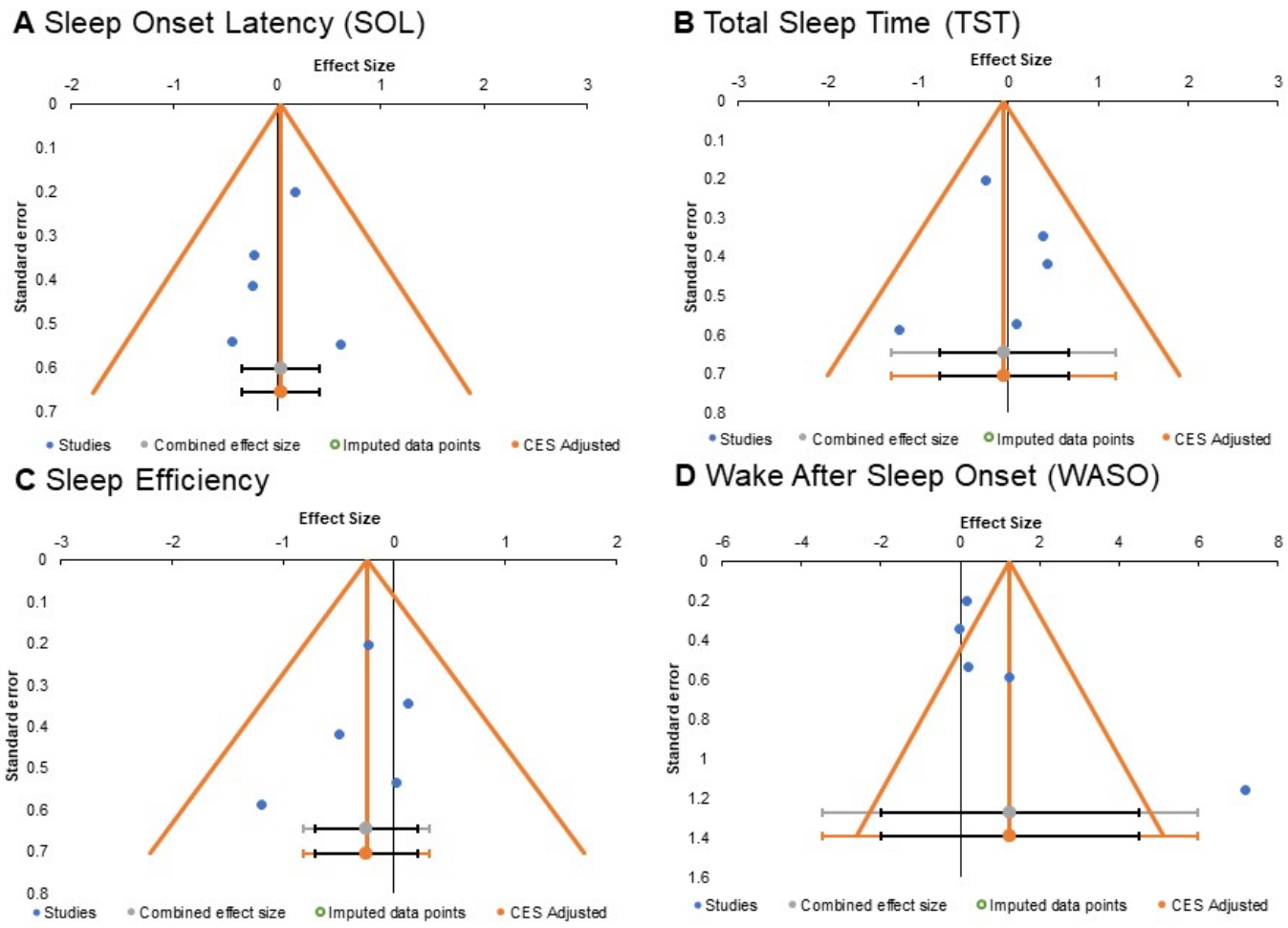

Figure 2.3 Graphical representation of each funnel plot for sleep onset latency (A), total sleep time (B), sleep efficiency (C) and wake after sleep onset (D).

Note. These four plots indicate that sleep onset latency, total sleep time, sleep efficiency and wake after sleep onset appear symmetrical, suggesting minimal publication bias. CES: combined effect size.

2.3.5 Systematic narrative review of objectively and subjectively measured sleep parameters

2.3.5.1 Actigraphy

Two studies used actigraphy to assess the impact of WTN on sleep (Lane et al., 2016; Michaud et al., 2016). One of these cross-sectional studies was initially based on weekdays versus weekend sleep data but was then adjusted using least squares mean (95% CI) to account for province and day of the week (Michaud et al., 2016). Table 2.6 shows the adjusted results of this actigraphy study of 1,238 participants, which found no significant differences between WTN exposure levels in sleep onset latency, total sleep time, sleep efficiency or wake after sleep onset (Michaud et al., 2016). Lane et al. (2016) assessed sleep using actigraphy in 12 WTN exposed individuals and 10 WTN non-exposed individuals and also found no evidence to support that WTN significantly impacted objectively assessed sleep parameters including sleep onset latency, total sleep time, sleep efficiency, wake after sleep onset, time in bed or number of awakenings.

Table 2.6 Results of a cross-sectional study by Michaud et al. (2016) depicting the measured sleep outcome in comparison to each WTN exposure (dB(A)).

SPL, dB(A)	**Sleep Parameter, Least Squares Mean (95% CI)**			
	Sleep onset latency, mins	Total sleep time, mins	Sleep efficiency, %	Wake after sleep onset, mins
<25 dB(A)	9.9 (6.2, 13.6)	447.9 (422.6, 473.2)	84.0 (81.9, 86.0)	60.9 (54.2, 67.6)
25-30 dB(A)	4.4 (1.4, 7.5)	442.7 (412.8, 472.6)	86.0 (84.1, 88.0)	58.6 (50.6, 66.6)
30-35 dB(A)	8.1 (5.3, 11.0)	438.5 (416.4, 460.6)	82.8 (80.8, 84.8)	62.7 (57.1, 68.2)
35-40 dB(A)	8.5 (6.2, 10.8)	444.4 (423.1, 465.7)	83.9 (82.2, 85.6)	60.8 (55.6, 66.0)
40-46 dB(A)	9.9 (7.4, 12.4)	438.5 (416.1, 460.9)	83.5 (81.7, 85.3)	64.1 (57.8, 70.3)
p	*p*=0.1783	*p*=0.7348	*p*=0.0519	*p*=0.3596

Note. Permission for reproduction of this table has been approved by Michaud et al. (2016). SPL=Sound Pressure Level. dB(A)=A-weighted decibel. 95% CI=95% Confidence Interval.

2.3.5.2 PSG in field versus laboratory settings

The four PSG studies included in the present review and meta-analysis involved both ambulatory PSG in the field and three PSG laboratory studies, for which there were varying results. Jalali et al. (2016a) found no significant differences between objective sleep parameters (including but not limited to sleep onset latency, sleep stage distribution, wake after sleep onset, and total sleep time) from the pre- to post-operational stage of a wind farm. However, average A-weighted WTN exposures were also not significantly different between pre- versus post-operational stages [mean (*SD*) Time 1: 36.5 (4.2) dB(A) versus Time 2: 36.5 (4.2) dB(A), p=0.959].

The two experimental pilot studies by Ageborg Morsing et al. (2018a, 2018b) used PSG and a morning questionnaire to examine objective and self-reported sleep parameters in six participants who had not had prior exposure to WTN. Participants spent five nights in the sleep laboratory and were exposed to various types of WTN and 18 dB L_{AEq} control background noise. Results showed some significant impacts of WTN on sleep, which are summarised in Table 2.7. Overall, these two studies found some evidence that wakefulness increases with strong amplitude modulation and lower frequencies, that deep sleep is reduced in the presence of higher frequencies and stronger amplitude modulation, and that light sleep increases with higher frequencies and stronger amplitude modulation. No other significant effects were found in terms of objective sleep parameters in either study. It is worth noting that these two studies used a WTN level that represented worst-case weather conditions designed to increase the likelihood of showing noise effects compared to control.

Table 2.7 Two experimental pilot studies by Ageborg Morsing et al. (2018a, 2018b) depicting mean (SD), statistical significance and Cohen's d (95% CI) for each experimental night.

PILOT STUDY A					
	Control 18 dB L_{AEq}	**50 dB L_{AEq} outdoors; 33.7 dB L_{AEq} indoors (window closed filtering)**	**40 dB L_{AEq} outdoors; 29.5 dB L_{AEq} indoors (window open filtering)**	**45 dB L_{AEq} outdoors; 34.1 dB L_{AEq} indoors (window open filtering)**	**Post-hoc comparisons (*p*, Cohen's *d* (95% CI)**
Awakenings (n/hour)	1.75 (0.63)	2.47 (0.66)	1.69 (0.63)	1.58 (0.75)	[a]*p*=0.046, *d*=1.12 (-0.10 to 2.33) [b]n.s. [c]n.s. [d]*p*=0.028, *d*=1.21 (-0.02 to 2.44) [e]n.s. [f]*p*=0.028, *d*=1.26 (0.02 to 2.50)
PILOT STUDY B					
	Control 18 dB L_{Aeq}	**40 dB L_{AEq} outdoors; 32.8 dB L_{AEq} indoors (window open filtering, high amplitude modulation)**	**50 dB L_{AEq} outdoors; 30.4 dB L_{AEq} indoors (window closed filtering, low amplitude modulation)**	**45 dB L_{AEq} outdoors; 32.8 dB L_{AEq} indoors (window open filtering, low amplitude modulation)**	**Post-hoc comparisons (*p*, Cohen's *d* (95% CI)**
N3%	22.8 (4.9)	21.7 (5.3)	22.0 (4.0)	18.0 (3.7)	[a]n.s. [b]*p*=0.043, *d*=-0.22 (-1.35 to 0.92) [c]n.s. [d]*p*=0.046, *d*=-0.06 (-1.20 to 1.07) [e]n.s. [f]n.s.
	Control 18 dB L_{AEq}	**40 dB L_{AEq} outdoors; 32.8 dB L_{AEq} indoors (window open filtering, high amplitude modulation)**	**50 dB L_{AEq} outdoors; 30.4 dB L_{AEq} indoors (window closed filtering, low amplitude modulation)**	**45 dB L_{AEq} outdoors; 32.8 dB L_{AEq} indoors (window open filtering, low amplitude modulation)**	**Post-hoc comparisons (*p*, Cohen's *d* (95% CI)**
First Awakening (mins)	39.8 (30.0)	58.8 (51.4)	57.3 (59.6)	26.3 (34.7)	[a]n.s. [b]n.s. [c]n.s. [d]*p*=0.028, *d*=-0.64 (-1.80 to 0.52) [e]*p*=0.028, *d*=-0.74 (-1.91 to 0.43) [f]n.s. [g]n.s.
	Control 18 dB L_{AEq}	**50 dB L_{AEq} outdoors; 30.4 dB L_{AEq} indoors (window closed filtering, low amplitude modulation)**	**45 dB L_{AEq} outdoors; 32.8 dB L_{AEq} indoors (window open filtering, low amplitude modulation)**	**40 dB L_{AEq} outdoors; 32.8 dB L_{AEq} indoors (window open filtering, high amplitude modulation)**	**Post-hoc comparisons (*p*, Cohen's *d* (95% CI)**
Maximum Continuous N2 (mins)	38. 3(8.0)	26.9 (5.7)	36.1 (9.0)	27.7 (6.6)	[a]*p*=0.027, *d*=-1.64 (-2.95 to -0.33) [b]*p*=0.027, *d*=-1.45 (-2.72 to -0.18) [c]n.s. [d]n.s. [e]*p*=0.046, *d*=-1.06 (-2.27 to 0.15) [f]*p*=0.028, *d*=-1.22 (-2.45 to 0.01)

Note. dB L_{AEq}=equivalent continuous sound pressure level; mins=minutes. n=number. n.s.=non-significant comparison (p>0.05). Superscript letters indicate the following paired comparisons: [a]control versus 50 dB L_{AEq} outdoors; [b]control versus 40 dB L_{AEq} outdoors; [c]control versus 45 dB L_{AEq} outdoors; [d]40 dB L_{AEq} outdoors versus 50 dB L_{AEq} outdoors; [e]40 dB L_{AEq} outdoors versus 45 dB L_{AEq} outdoors; [f]50 dB L_{AEq} outdoors versus 45 dB L_{AEq} outdoors. *Permission for reproduction of this table has been approved by Ageborg Morsing et al. (2018a, 2018b).*

Lastly, in an experimental study of 50 individuals living within one kilometre of a wind turbine and/or reporting annoyance or sleep disturbance by WTN over the past month compared to individuals living further away from wind turbines, Smith et al. (2020) found a significant difference in the percentage of N3 sleep (p=0.034), where the maximum continuous N3 duration in the exposed group was 6.8 minutes (estimated marginal mean) longer than in the reference group. Smith et al. (2020) also found a significant main effect of study night on the latency to REM sleep and percentage of REM sleep, with an 11.1-minute reduction in REM sleep time and a 16.8-minute extension of REM latency in the WTN exposure night compared to the control night. No other significant interactions between study night (WTN; 32 dB L_{AEq} with varying filtering and amplitude modulation depth, control; 13 dB L_{AEq} background noise) and study group (reference, exposed) were found for the remaining PSG outcomes investigated.

2.3.5.3 Sleep diaries

All five objective studies used some form of sleep diary to assess subjective sleep parameters, (Ageborg Morsing et al., 2018a, 2018b; Jalali et al., 2016a; Lane et al., 2016; Smith et al., 2020), but only Jalali et al. (2016a) reported quantitative sleep diary-based subjective sleep parameters. Jalali et al. (2016a) showed no significant impacts of WTN on total sleep time (p=0.472), number of awakenings (p=0.126), length of awakenings (p=0.062) or sleep onset latency (p=0.942) from pre- to post-wind farm operation. Lane et al. (2016) used an adapted version of the Pittsburgh Sleep Diary to assess the impact of WTN on exposed versus non-exposed individuals' self-reported sleep. This involved asking participants what time they got into bed, time they fell asleep, their wake-up time, and sleep quality on a 6-point rating scale. Lane et al. (2016) did not specifically report subjective sleep onset latency, total sleep time, number of awakenings, length of awakenings, or wake after sleep onset, but reported that noise-exposed participants went to bed significantly earlier than the non-exposed participants (p=0.02) and went to sleep

significantly earlier than the unexposed group (p=0.03). No other significant differences in subjective sleep quality were reported.

Ageborg Morsing et al. (2018a, 2018b) used morning questionnaires to assess subjective sleep parameters in the presence versus absence of WTN exposure in a controlled sleep laboratory, in addition to their objective measures of sleep (PSG) on noise-sensitive individuals. The sleep items involved 11-point numerical scales and 5-point descriptive scales (i.e., “very good” to “very bad”). It was also reported that the questionnaire asked about perceived sleep latency and number of awakenings. Ageborg Morsing et al. (2018a) found no significant differences in any of the subjective sleep variables, whereas Ageborg Morsing et al. (2018b) found greater difficulty falling asleep with 32.8 dB(A) indoor WTN exposure (window gap filtering and high amplitude modulation frequency) and with 30.4 dB(A) indoor WTN exposure (closed window, low amplitude modulation frequency) compared to a control night (p=0.032). No other significant effects were found between the three WTN exposure nights and the control night including sleep onset latency and number of awakenings.

In addition to objective sleep measures, Smith et al. (2020) also used morning questionnaires to assess subjective sleep parameters in the presence and absence of WTN exposure on 50 individuals. Smith et al. (2020) found no significant interactions between study night and study group but found significantly lower sleep quality, greater difficulty falling back to sleep after an awakening, increased difficulty sleeping, sleeping worse than usual, and waking more frequently after the WTN exposure night compared to the control night. Similarly, Smith et al. (2020) also found that noise-exposed participants rated their sleep quality as being more negative than the control group after both nights.

2.3.5.4 ISI

The pre–post field study on 37 individuals before and after the operation of wind turbines was the only study that reported on insomnia severity scores and found that self-

reported insomnia symptoms were significantly higher from pre- to post-operational wind turbines [mean (*SD*) score 3.1 (3.6) versus 6.4 (6.7), *p*=0.005], with a moderate effect size (Cohen's *d*=0.62) (Jalali et al., 2016b). Whilst there was a notable increase in ISI scores, it is important to note that these scores are below levels considered to reflect subthreshold insomnia (ISI >7). These findings also showed that 45.9% of the 37 participants had a negative attitude, 18.9% had a neutral attitude, and 32.4% had a positive attitude towards wind turbines. Jalali et al. (2016b) further reported that changes in ISI scores from Time 1 to Time 2 were strongly associated with negative attitudes to WTN (*p*=0.003).

2.3.5.5 PSQI

Three studies used the PSQI to assess the impact of WTN on perceived sleep quality (Jalali et al., 2016b; Michaud et al., 2016; Nissenbaum et al., 2012). Jalali et al. (2016b) showed that self-reported sleep quality was significantly poorer following compared to prior to WTN exposure [mean (*SD*) score 6.2 (3.9) versus 4.1 (2.1), *p*=0.006] with a moderate effect size (Cohen's *d*=0.67). PSQI scores of >5 are considered to indicate poor sleep, so these results support a shift from good to poor sleep with WTN exposure. Jalali et al. (2016b) also found that almost 50% of participants had a negative attitude towards wind turbines and that changes in PSQI scores from Time 1 to Time 2 were strongly associated with negative attitudes (*p*=0.002). Nissenbaum et al. (2012) conducted a cross-sectional field study in 79 individuals showing similar results, whereby participants living near a wind turbine (375–1,400 metres) showed poorer sleep quality than participants living further away (3,000–6,600 metres) from a wind turbine (mean score 7.8 versus 6.0, *p*=0.046). However, variance was not reported so effect sizes could not be calculated, and A-weighted noise levels were variable ranging from 32–61 dB L_{AEq}. Lastly, Michaud et al. (2016) reported no significant relationships between PSQI scores and model estimated WTN exposure levels.

2.3.5.6 ESS

Three studies used the ESS and consistently reported significant associations between daytime sleepiness and WTN exposure (Abbasi et al., 2015; Jalali et al., 2016b; Nissenbaum et al., 2012). Jalali et al. (2016b) showed that self-reported daytime sleepiness of residents was significantly greater following the post-operation of wind turbines compared to pre-operational wind turbines [mean (*SD*) score 7.1 (5.3) versus 4.7 (3.2), p=0.002], with a moderate effect (Cohen's d=0.56). However, daytime sleepiness did not reach the clinical cut-off indicative of excessive daytime sleepiness. Nissenbaum et al. (2012) showed similar results, whereby participants living 375–1,400 metres from a wind turbine showed greater ESS scores (mean 7.8) than participants living 3,000–6,600 metres away from a wind turbine (mean 5.7; p=0.032). Again, effect sizes could not be calculated as variance was not reported. In addition, Abbasi et al. (2015) showed significantly greater ESS scores for wind farm maintenance staff than security staff and administrative staff. In addition, the maintenance staff showed clinically relevant ESS scores (>10), indicating significant daytime sleepiness. However, while ESS scores of >10 indicate excessive daytime sleepiness, attribution to necessarily indicate the presence of a sleep disorder and/or sleep disturbance is problematic.

2.4 DISCUSSION

We examined existing literature to evaluate and meta-analyse the potential impact of WTN on sleep using objective and/or psychometrically validated subjective measures of sleep. To our knowledge, only one systematic review and meta-analysis has previously examined this question, and was limited to self-reported, cross-sectional study outcomes available at that time (Onakpoya et al., 2015). Several more recently published studies have included objective measures and more validated questionnaires widely used in sleep research to assess sleep outcomes in the presence versus absence of WTN. Nine studies met eligibility criteria and of those, six used objective sleep measurement (PSG or

actigraphy) and three used psychometrically validated questionnaires. Included objective studies varied in methodologies and outcome measures (field, laboratory, PSG, actigraphy); however, five of the six objective studies uniformly reported key sleep outcomes including sleep onset latency, total sleep time, wake after sleep onset, and sleep efficiency. The meta-analysis of five studies found no evidence to support that objectively measured sleep latency, sleep efficiency, time spent asleep and awake during the night are significantly different in the presence versus absence of WTN exposure.

However, it is worth noting that Jalali et al. (2016a) and Jalali et al. (2016b) reported that average A-weighted WTN exposure was not significantly different between pre- versus post-operational stages and thus it is perhaps not surprising that objective sleep outcomes were not impacted. Furthermore, findings by Smith et al. (2020) were also not surprising, given they assessed perceived sleep disturbance in a group who were already self-reporting sleep disturbance or presenting with annoyance towards WTN in comparison to a general sample of unexposed individuals.

Field studies are the most ecologically valid and most representative of real-world WTN conditions in comparison to in-laboratory studies. However, field studies lack control over extraneous variables such as changes in wind speed, wind direction, atmospheric turbulence, topography, study blinding, nocebo effects, trial design quality, and other environmental factors including visual impacts that also have the potential to impact objective and subjective sleep disturbance (Aziz, 2017; Micic et al., 2018). For example, many of these factors can influence the airflow, turbulence and propagation of WTN leading to variability in amplitude modulation, infrasound, tonality and swish components, and thus could play a part in reports of sleep disturbance. Study design differences and the way in which noise exposure is conducted could importantly influence different findings across studies (Micic et al., 2018).

Whilst actigraphy is an objective measure, unlike PSG it does not directly

monitor cortical activity so relies on sleep–wake inferences based on pre-defined activity thresholds. Thus, actigraphy has poor specificity for discriminating wake from sleep when activity is low (Marino et al., 2013). Actigraphy is also unreliable for detecting micro-arousals, which may or may not be associated with gross body movements. In addition, whilst actigraphy is able to record data across the day, the algorithms that are used during sleep periods at night may not directly translate to detecting sleep during the day. Further shortcomings of actigraphy involve the fact that manual scoring is at times still used, which can introduce human error, inter- and intra-scorer variability (Driller, McQuillan, & O'Donnell, 2016). Whilst, computerised scoring algorithms help to reduce human error, automatic scoring algorithms are still faced with limitations, due to heavily relying on the estimation of sleep parameters rather than the actual activity measurement (de Souza et al., 2003) and the possibility of the off-wrist detection being mis-scored as sleep (Grandner & Rosenberger, 2019).

In contrast, whilst PSG is technical, intrusive, expensive and still subject to inter- and intra-scorer variability given the need for study setup, supervision and manual scoring by skilled sleep technicians with extensive training in scoring EEG activity (Van de Water et al., 2011); experimental laboratory-based studies using PSG do allow for substantially superior control of most extraneous variables that may confound sleep outcomes (Aziz, 2017). PSG also allows for the measurement of more fine-grain microstructural changes and sleep stage changes that extend beyond basic sleep architecture (Aziz, 2017). Ultimately, carefully controlled experimental laboratory studies are needed to definitively establish the impact of WTN on sleep. Few recent controlled experimental studies evaluating WTN exposure effects compared to quiet control conditions using PSG sleep assessment and a repeated measures design have shown some significant impacts of WTN on the timing of the first awakening, frequency of awakenings per hour, reductions in deep sleep, less continuous time spent in N2 sleep,

prolonged REM latency, and decreased REM sleep percentage (Ageborg Morsing et al., 2018a, 2018b; Smith et al., 2020). Whilst these repeated measures designs have not shown significant effects on the standard sleep metrics (sleep onset latency, total sleep time, wake after sleep onset and sleep efficiency), these results do suggest that some more detailed changes in cortical activity, sleep stage changes, and physiology in sleep can become impacted by WTN. Whilst two of the experimental laboratory-based studies had limited samples (e.g., six each), finer-grained analyses of sleep outcomes beyond basic sleep architecture are warranted in future PSG studies to investigate impacts of WTN on sleep using larger sample sizes. On the other hand, participants in these studies were also likely aware of the WTN exposure before falling asleep and during night-time awakenings as the noise exposure was present from lights out time and played until lights on in the morning. This could have potentially biased not only participant's self-reported responses, but also their objective sleep quality. Given the difficulties in controlling extraneous factors in field studies, between-subjects designs, and with participant awareness and potential attitudinal biases; the interpretation of sleep findings from field studies is particularly problematic. Thus, future repeated measures, laboratory-based PSG experimental studies, using study protocols designed to compare the presence versus absence of psychological awareness of noise exposure are needed. For example, methodologies including WTN exposure only during sleep versus wake versus continuously throughout the night could allow for a deeper exploration of both psychological and physiological factors that may influence WTN noise effects on objective and subjective sleep measures.

Three of the nine studies only used psychometrically validated sleep questionnaires, and the six objective studies also used psychometrically validated sleep questionnaires in addition to either PSG or actigraphy. Findings based on self-reported sleep perception were mixed, likely partly reflecting the use of different assessment tools

assessing somewhat different sleep outcomes. Studies including items that assessed self-reported sleep parameters including sleep onset latency, wake after sleep onset, total sleep time, and number of awakenings found no significant impacts of WTN in comparison to control background noise without WTN. Jalali et al. (2016b), Michaud et al. (2016) and Nissenbaum et al. (2012) all used the PSQI to assess sleep quality in the presence of WTN and produced mixed findings. Jalali et al. (2016b) found poorer PSQI and ISI scores post- compared to pre-operational WTN exposure. These results could have been impacted by the absence of study blinding, as participants were fully aware of the impending turbine presence and noise exposure, for which participant attitude and expectation bias risks are high, particularly for self-report outcomes (Jalali et al., 2016a; Jalali et al., 2016b). For example, given no significant differences in pre–post WTN exposure levels, these results suggest that being aware of a wind farm beginning operation may have contributed to increased ISI scores. Visual impacts and awareness of wind turbine existence and attitudes towards wind farms, instead of the WTN itself could also play a role. Furthermore, the study by Jalali et al. (2016b) also showed that almost 50% of participants had a negative attitude towards wind turbines, thus, attitudinal effects appear likely to help explain why participants self-reported poorer sleep quality and insomnia symptoms following the operation of the wind turbines. The between-groups study by Nissenbaum et al. (2012) was based on a combination of both predicted and measured WTN and found significantly poorer PSQI scores in participants who lived near wind turbines, compared to unexposed residents. Michaud et al. (2016) also assessed PSQI scores based on five WTN exposure levels and found no significant relationship between PSQI scores and WTN exposure. However, given the large-scale cross-sectional study design, these authors were reliant on WTN exposure estimates from sound propagation models rather than direct noise measurements, which may not necessarily adequately capture difference in noise exposures between regions and groups.

Abbasi et al. (2015), Jalali et al. (2016b) and Nissenbaum et al. (2012) assessed daytime sleepiness using the ESS. Although methods varied, consistent associations between WTN exposure and daytime sleepiness were found. Jalali et al. (2016b) showed significantly stronger associations in daytime sleepiness after wind farm operation. Likewise, Nissenbaum et al. (2012) showed that exposed individuals living close to wind turbines showed significantly greater daytime sleepiness than unexposed people living further away from wind turbines. Abbasi et al. (2015) assessed three wind farm worker groups (maintenance, security, and administrative staff) during wind farm operation, which were used to manipulate the relative distance and thus SPLs of WTN exposure. Abbasi et al. (2015) used 8-hour equivalent sound levels in their study. Results showed a dose-response relationship, whereby those working closer to wind turbines showed greater daytime sleepiness than those working further away. These results do not provide support for a particular wind farm worker job type being associated with sleep disturbance/sleep disorder presence or even momentary daytime sleepiness. These results rather speak to wind farm workers' habitual daytime sleepiness symptoms, and thus may not necessarily indicate sleep disturbance or sleep disorder presence. However, cross-sectional associations of daytime exposure levels between different worker types are inherently problematic. This is because group differences could potentially be confounded by uncontrolled factors such as differential participant characteristics (age, gender) and risk factors for sleep problems unrelated to daytime noise exposure presumably away from the usual sleep environment.

2.4.1 Strengths and limitations

This is the first systematic review and meta-analysis that has investigated the impact of WTN on key sleep outcomes. The review used a robust search strategy to identify pertinent articles and underwent a reporting quality assessment based on an adapted version of the STROBE checklist (Von Elm et al., 2007). A limitation of this

review was that there were only a small number of identified studies included with varied methodologies and outcome variables, which prevented a more comprehensive meta-analysis of quantifiable sleep measures. In addition, although a second author did review the retrieved studies for eligibility and reporting quality, only TL initially screened abstracts for eligibility and reporting quality. Furthermore, this review and meta-analysis treated WTN exposure as a binary outcome (i.e., exposed versus unexposed to WTN), despite the differences in WTN levels and acoustical characteristics between and within the different studies.

Studies also used mixed methods with variable measurement and model-based estimates of noise exposure levels and differing WTN exposures including worst-case WTN with characteristics that could be particularly problematic (e.g., amplitude modulation, infrasound, tonality) through to more typical WTN. Given inevitable variability in weather and local conditions known to influence WTN, carefully controlled laboratory studies are needed to more specifically determine WTN effects on sleep.

In addition, despite the use of objective and psychometrically validated subjective sleep measures; selection and response biases, as well as the absence of study blinding may importantly influence both objective and subjective sleep measures. For example, strong negative or positive attitudes towards wind turbines and awareness of study conditions or interventions appear likely to impact study participation, self-reported and potentially objective sleep parameters through expectation effects on abilities and times taken to fall asleep, remain asleep versus awake overnight, and to wake following sleep. With the exception of Smith et al. (2020) who reported that participants were not blinded in their study, all other studies did not report nor consider blinding. As blinding is inherently difficult and not considered or reported by the large majority of these studies, the results should be interpreted with caution. Therefore, based on the aforementioned

limitations and risk of biases, the strength of the present evidence surrounding the impact of WTN on objective and psychometrically validated sleep is lacking.

Overall, the results of the present systematic review and meta-analysis do not support the position that WTN significantly impacts the main objective markers of sleep quality including sleep onset latency, total sleep time, wake after sleep onset, and sleep efficiency, but does appear to impact some subjective sleep outcomes; which supports the notion of WTN being an environmental psychosocial stressor that has the ability to contribute to self-reported sleep disturbance, and in some instances, as well as impact some sleep stage shifts and number of awakenings per hour. However, future experiments should consider including WTN exposures only during wake versus only during established sleep (e.g., ≥N2 sleep) to help separate potential psychological versus physiological influences of WTN on sleep. Only exposing participants to WTN during established sleep periods would help to avoid potential participant expectation biases to more specifically investigate the impact of WTN on objective and subjective measures of sleep in a carefully controlled laboratory environment. Similarly, comparisons between WTN versus quiet control exposures during wake periods may also be needed to more specifically test for wake-dependent psychological awareness and bias effects on sleep propensity that also strongly influence both objective and subjective sleep.

2.4.2 Conclusion

In summary, the present review used a systematic and meta-analytic approach to investigate WTN effects on objective and subjective sleep outcomes. Nine studies using objective and/or psychometrically validated subjective sleep measures were identified and included. To date, various methodologies, noise measurements, and outcome assessments have been used and shown mixed findings. Assessments of WTN impacts on sleep using gold-standard PSG assessment are starting to emerge and the present review provides an update and summary of these findings. This meta-analysis suggests

that key indicators of objectively measured sleep macrostructure (i.e., sleep onset latency, sleep efficiency, total time spent asleep and awake) under carefully controlled laboratory conditions and in the field are not significantly impacted by WTN compared to no-WTN noise control conditions. However, studies that have used a repeated measures design with small sample sizes, under controlled laboratory conditions have shown some significant changes in more detailed measures of cortical activity and sleep stages. This apparent discrepancy between some PSG measures and conventional macro-sleep measures suggests further carefully controlled PSG studies on larger sample sizes are needed to resolve WTN impacts on sleep.

Whilst PSG is the most objective and most direct way to measure physiological impacts of WTN on sleep; self-report measures are also needed to assess perceived sleep quality, particularly for evaluating insomnia. Overall, few studies have used psychometrically validated subjective measures of sleep. Due to inconsistent findings and mixed methodologies, a meta-analysis of subjective sleep outcomes was not possible (e.g., sleep quality, insomnia severity, and daytime sleepiness). However, available data support that insomnia symptom severity, sleep quality, and daytime sleepiness are impacted by WTN exposure in comparison to no WTN exposure, whereas sleep diary parameters, including self-reported sleep onset latency, total sleep time, wake after sleep onset, and sleep efficiency show less consistent findings. Future studies should more strongly consider potential confounding through selection and response biases and study blinding effects in their design, and also consider noise stimuli representative of typical WTN exposure, as well as the less common WTN features such as amplitude modulation, infrasound and swish characteristics. Finally, methodologies that expose individuals to WTN only during sleep versus wake periods may be important to help separate subjective versus objective sleep effects and the likelihood that psychological awareness, attitudinal, and/or noise-sensitivity factors could also impact sleep.

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Conflict of interest

KH has research funds from the Australian Research Council. PC has research funds from the National Health and Medical Research Council. BZ has research funds from the National Health and Medical Research Council. LL is a shareholder in Re-time Pty. Ltd. And has received royalties from Retime, which is unrelated to the submitted work. TL, NL and GM have no conflicts of interest to declare.

Authors contributions

All authors contributed to the manuscript as follows: TL: conceptualisation, methodology, software, formal analysis, data curation, writing – original draft preparation, writing – review and editing, visualisation. PC*:* writing – review and editing, supervision. LL*:* writing– review and editing, supervision. KH: writing – review and editing. BZ: writing – review and editing, visualisation. NL: writing – review and editing. GM*:* conceptualization, methodology, writing – review and editing, supervision. All authors have read and approved the final manuscript.

CHAPTER 3 THE EFFECT OF WIND TURBINE NOISE ON POLYSOMNOGRAPHICALLY-MEASURED AND SELF-REPORTED SLEEP LATENCY IN WIND TURBINE NOISE NAÏVE PARTICIPANTS

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TL contributed to study design, data collection, analysis and interpretation and manuscript preparation. LL, GM, KH, BZ, NL & PC contributed to conception and study design, interpretation of the data and drafting of the manuscript. CD, BL & FD contributed to data collection, data interpretation and drafting of the manuscript. HS & DPN contributed to data analysis, data interpretation and drafting of the manuscript.

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ABSTRACT

Study Objectives: Wind turbine noise exposure could potentially interfere with the initiation of sleep. However, effects on objectively assessed sleep latency are largely unknown. This study sought to assess the impact of wind turbine noise on polysomnographically-measured and sleep diary-determined sleep latency compared to control background noise alone in healthy good sleepers without habitual prior wind turbine noise exposure.

Methods: Twenty-three wind turbine noise naïve urban residents (mean±standard deviation age: 21.7±2.1 years, range 18-29, 13 females) attended the sleep laboratory for two polysomnography studies, one week apart. Participants were blind to noise conditions and only informed that they may or may not hear noise during each night. During the sleep onset period, participants were exposed to counterbalanced nights of wind turbine noise at 33 dB(A), the upper end of expected indoor values; or background noise alone as the control condition (23 dB(A)).

Results: Linear mixed model analyses revealed no differences in $\log_{10}$ normalised objective or subjective sleep latency between the wind turbine noise versus control nights (median [interquartile range] objective 16.5 [11.0 to 18.5] versus 16.5 [10.5 to 29.0] minutes, p=0.401; subjective 20.0 [15.0 to 25.0] versus 15.0 [10.0 to 30.0] minutes, p=0.907).

Conclusions: Although undetected small effects cannot be ruled out, these results do not support that wind turbine noise extends sleep latency in young urban dwelling individuals without prior wind turbine noise exposure.

Keywords: environmental noise, wind turbine noise, health impacts, sleep, perception.

Statement of Significance

Tightly-controlled experiments to investigate the impact of wind turbine noise on objective and subjective sleep latency (time taken to fall asleep) are remarkably limited. This study found no evidence to support that wind turbine noise extends objective or subjective sleep latency compared to quiet background noise. However, further studies remain needed to examine potential wind turbine noise effects on sleep latency in residents habitually exposed to wind turbine noise, especially those reporting impacts of wind turbine noise on their sleep. Direct measures of noise impacts on sleep are essential to inform evidence-based noise guidelines designed to effectively mitigate potential wind turbine noise impacts on nearby residences in normally quiet rural and remote communities.

The effect of wind turbine noise on polysomnographically-measured and self-reported sleep latency in wind turbine noise naïve participants.

3.1 INTRODUCTION

While some wind turbine facilities have operated for many years with few noise complaints, the rapid global expansion of wind turbine generators has been associated with community concerns around noise amenity and the potential for sleep disturbance (Basner et al., 2014; Crichton et al., 2014; Janssen et al., 2011a; Krogh et al., 2011). Wind turbine noise (WTN) has several unique characteristics that could potentially make it intrusive and problematic when attempting sleep. Wind farms are often installed in quiet rural areas where the ambient SPL at night is substantially lower compared to urban environments. Unlike many environmental noise sources that are typically more sporadic (e.g., vehicle pass-bys) and reduce diurnally at night when human activity is diminished, wind turbines can operate continuously throughout the day and at night when atmospheric and wind conditions are often more stable and remain favourable for power generation. Thus, noise emissions from wind turbines may be particularly obvious and problematic at night when ambient noise levels from other sources are typically lowest (Hansen et al., 2019) and when individuals typically need to and wish to sleep.

Furthermore, perceived noise sensitivity and individual attitudes towards noise may also influence sleep latency (Janssen, Vos, Eisses, & Pedersen, 2011b; Van den Berg et al., 2008). For example, individuals who self-report high noise-sensitivity appear more likely to react more negatively to noise (e.g., with annoyance) compared to individuals with low noise sensitivity (Weinstein, 1978), especially when attempting to sleep. By its nature, annoyance is likely to promote alertness and impair sleep through more indirect mechanisms (Hamida et al., 2015; Perlis et al., 1997). Other studies have found with controlled laboratory listening tests that WTN is consistently rated as more annoying than

RTN at the same SPL (Schaffer et al., 2016). Therefore, WTN has the potential to disrupt the initiation of sleep, perhaps more so than other common environmental noise sources, such as traffic, rail and aircraft noise at equivalent SPLs. However, much of the currently available evidence relies on self-reported data alone and often from WTN exposed individuals with potentially complex and variable prior experiences, beliefs and expectations regarding WTN annoyance and associated sleep disruption. Very few studies have objectively measured sleep in the presence of WTN in individuals without prior overnight exposure and thus reduced risk of potential biases that may further influence WTN effects on human sleep. This includes sleep latency, a key indicator of an individual's ability to sufficiently relax to initiate sleep, where the time taken to achieve sleep is importantly influenced by both physiological sleep "drive" and psychological factors that may facilitate or inhibit the successful transition from wake into EEG confirmed sleep.

WTN has been reported to interfere with sleep initiation by some individuals living near wind turbines (Jalali et al., 2016a; Jalali et al., 2016b; Nissenbaum et al., 2012; Pawlaczyk-Luszczynska et al., 2014; Pohl, Gabriel, & Hübner, 2018; Song et al., 2016). However, the meta-analysis in Chapter 2 of the current thesis found only five published studies to date that have evaluated objective sleep latency in the presence versus absence of WTN (Liebich et al., 2021). These studies included uncontrolled field studies (Jalali et al., 2016a) and actigraphy-based objective estimates of sleep (Lane et al., 2016; Michaud et al., 2016). However, actigraphy devices are known to systematically under-estimate PSG-derived sleep latency due to misclassification of sleep during the relatively immobile wakefulness before EEG confirmed sleep initiation (Blood, Sack, Percy, & Pen, 1997; Sadeh & Acebo, 2002). Additionally, uncontrolled external factors such as wind speed and direction, topography, air temperature and noise transmission characteristics of building structures amongst many other factors all influence noise characteristics and limit inferences that can be drawn from field studies regarding noise-specific effects on sleep.

To our knowledge, only two previous reports from the Wind Turbine Noise Effects on Sleep (WiTNES) study have evaluated the impact of WTN based on direct EEG assessment of sleep parameters, including sleep latency, in a carefully controlled laboratory environment (Ageborg Morsing et al., 2018; Smith et al., 2020). Two within-subject experimental laboratory-based pilot studies assessed the effect of three WTN exposure nights of varying sound frequencies and SPLs compared to a quiet control night on objective and subjective sleep in six healthy individuals (Ageborg Morsing et al., 2018). In both studies, there were no significant differences in objective or subjective sleep latency between the three WTN exposure nights compared to the control night. Another in-laboratory study investigated WTN exposure and prior exposure effects on objective and subjective sleep latency in 24 participants with prior WTN exposure and 26 participants with no prior exposure to WTN (Smith et al., 2020). Participants were exposed to a night of synthesised continuous WTN exposure (32 dB L_{AEq} [equivalent continuous sound pressure level]) and a quiet control night. The synthesised WTN exposure involved 2-hour periods of varying WTN characteristics (including changes in amplitude modulation, window open versus closed filtering). No significant effects of WTN exposure or group were found in objective sleep latency, but both groups reported that it was significantly more difficult to fall asleep as measured on a 10-point Likert scale (0 = easy, 10 = difficult) on the WTN night compared to the control night without WTN.

In terms of subjective sleep latency, previous studies have inconsistently utilised sleep questionnaires, many of which involve researcher-developed questionnaires instead of more widely used sleep questionnaires (Liebich et al., 2021). Although a recent systematic review and meta-analysis reported in Chapter 2 found no systematic effects on sleep latency and other sleep outcomes in previous reports, objective and subjective sleep measurements were difficult to ascertain due to inconsistent methodologies, variable outcome and WTN measures and limited sample sizes (Liebich et al., 2021). Thus, more

controlled experimental studies remain needed to better understand the impact of WTN on direct EEG derived measurements of sleep.

Overall, current evidence regarding the impact of WTN on objective and subjective sleep latency is limited and conflicting. Considering the importance of sleep for optimal health and daytime functioning, a clearer understanding of environmental effects on sleep (in this case, the effects of WTN) remains needed. Thus, the primary aim of this study was to examine the effects of WTN on PSG and sleep diary determined sleep latency compared to control background noise in a carefully controlled laboratory setting in WTN naïve individuals not habitually exposed to WTN and with normal sleep and hearing. We reasoned that if this group took longer to achieve sleep when exposed to WTN at realistic exposure levels, then these data would strongly support a sleep impairment effect independent of more complex factors (such as pre-existing insomnia, prior exposure and more firmly established personal views and expectations regarding noise effects on sleep) that may more variably influence sleep latency in other groups. It was hypothesised that objective and subjective sleep latency would be longer when participants were exposed to WTN compared to quiet background noise during the sleep onset period.

3.2 METHODS

3.2.1 Study design and setting

This study used a within-subjects randomised controlled design that was part of another study that also investigated noise impacts after sleep initiation involving noise samples of different characteristics and intensities that have greater potential to disrupt sleep (Lechat et al., 2021a). Consequently, the effect of WTN could only be examined during the initial sleep onset period in this study. Sleep latency was chosen as the primary outcome because sleep latency is the main marker of an individual's ability to attain sleep,

which reflects a combination of physiological need and drive for sleep and a range of environmental and psychological factors that may promote or inhibit sleep, such as the level of comfort of the sleeping environment and an individual's ability to sufficiently physically and mentally relax to achieve sleep.

In-laboratory PSG and morning self-report sleep diaries were administered to assess objective and subjective sleep latency in the presence of WTN during the sleep onset period on one night versus control background noise on another night, scheduled one week apart in random order. Participants were instructed that they may or may not hear noise during each night but remained unaware of the randomisation of WTN versus quiet background noise exposure during the sleep onset period for this study.

3.2.2 Participants

Participants were recruited via flyers posted on university campus, word of mouth, and social media. Data collection occurred between May and September 2018, during the Southern Hemisphere winter. The study was approved by the Flinders University Social and Behavioural Ethics Committee and all participants provided informed consent in writing. Upon full completion of the experiment, participants were reimbursed $300 AU for the time associated with study participation.

3.2.2.1 Inclusion and exclusion criteria

Interested individuals were screened using the Insomnia Severity Index; ISI (Morin, 1993; Morin et al., 2011), the Epworth Sleepiness Scale; ESS (Johns, 1991), and the Pittsburgh Sleep Quality Index; PSQI (Buysse et al., 1989), to select healthy sleepers on the basis of standardised cut-offs of ISI scores <8, ESS <10 and PSQI <6. Further inclusion criteria included habitual sleep latency <30 minutes, total sleep time ≥8 hours per night and sleep efficiency ≥85%, as reported on the PSQI. To avoid the potential for circadian misalignment to impact study outcomes, participation also required habitual

bedtimes between 21:00 and 00:00 hours and wake up times between 06:00 and 09:00 hours, with ≤2-hour discrepancy in both wake up and bedtimes on weekends and weekdays.

Exclusion criteria included age <18 years, any hearing difficulties, consumption of >5 cups of caffeinated beverages per day or >10 standard alcoholic drinks per week, a history of substance abuse in the past six months, use of any medications known to affect sleep, engagement in night shift work (any shift between 22:00 and 08:00 hours), travel across two time zones within the last two months, pregnancy or lactating within the past two months, or a body mass index (BMI) outside the normal range (<18 and >32 kg/m²).

Eligibility criteria also included a requirement for normal hearing thresholds (within <20 dB of normal values) for all test frequencies spanning 125-8000 Hertz (Schaette & McAlpine, 2011). In addition to an initial audiology screening, participants underwent separate and more extensive hearing assessment by an independent audiologist to confirm normal hearing, including normal hearing thresholds between 125-8000 Hertz and normal ear tympanometry, otoscopy, and acoustic reflexes.

3.2.3 Measures

3.2.3.1 Noise sensitivity

To allow for the exploration of potential relationships between noise sensitivity and changes in objective or subjective sleep latency in the WTN compared with the control condition, perceived noise sensitivity was assessed via the Weinstein Noise Sensitivity Scale, a 21-item scale that assesses self-reported sensitivity to noise. Weinstein Noise Sensitivity scores range from 1 – 105, where higher scores indicate greater sensitivity to noise (Stansfeld et al., 1993; Weinstein, 1978).

3.2.3.2 Noise stimulus

To faithfully reproduce WTN, original noise samples were recorded at a residence located 3.3 kilometres from a wind farm in South Australia (Hansen, Zajamšek, & Hansen, 2014b). The recordings included an amplitude modulated tone at 46 Hz which has been described by some residents as “rumbling”, “thumping” and/or “pulsing”. The measured night-time background noise in the sleep laboratory was 23 dB(A) and the WTN stimulus was played at 33 dB(A), 10 dB(A) above background noise in the laboratory, both measured at the participant’s head location (Hansen et al., 2015a). A WTN level of 33 dB(A) is close to the maximum level of WTN that residents who do not host a turbine on their land would experience in their home and approximates most guidelines on maximal night-time WTN limits (Alamir, Hansen, & Catcheside, 2021). WTN was reproduced using a RME Babyface Pro sound card, LabGruppen C 10:4X amplifier and Krix Pheonik V2.1 speaker in an unvented case (950(H) x 195(W) x 295(D) millimetres) positioned approximately one metre from the foot of the participants’ bed.

3.2.3.3 Sleep environment

The study was conducted in the Flinders University College of Education, Psychology and Social Work sleep laboratory with the bedroom temperature set to 23 degrees Celsius via an air conditioning system with the fan speed set to the lowest available setting, which produced a consistent overnight background noise level of 23 dB(A).

3.2.3.4 PSG

Objective sleep parameters were determined via PSG (Grael 4K and ProFusion 4 EEG software, Compumedics Ltd., Abbotsford, Vic) to record frontal, central and occipital EEG via gold-cup electrodes placed on the scalp at Fz, F3, F4, C3, C4, O1, and O2 sites referenced to mastoids (M1 and M2), and with ground and reference electrodes placed on

the clavicle and the forehead respectively. Chin EMG and left and right EOG were used to assess skeletal muscle activity and eye-movements respectively. EEG electrode impedances were (mean±SD) 3.0±0.7 kOhms.

A single trained sleep technologist, who remained blind to participant identity and noise conditions, scored sleep latency according to the American Academy of Sleep Medicine scoring criteria as the first 30-second Epoch of sleep (Iber et al., 2007), which was always NREM N1 sleep in this study. A second criteria for PSG sleep latency was also applied to identify the onset of more consolidated sleep from the first of ≥10 consecutive epochs of N2 or deeper (N3 or REM). Given ongoing noise-presentations throughout the remainder of the night for another study, further sleep parameters beyond objective sleep latency were not assessed.

3.2.3.5 Sleep diary

To assess subjective sleep latency, an online version (via Qualtrics software) of the Consensus Sleep Diary was completed by participants each morning. Participants self-reported how many minutes it took them to fall asleep initially (Carney et al., 2012).

3.2.4 Study protocol

One week prior to their first scheduled laboratory stay, participants attended the sleep laboratory for consent and familiarisation to the protocol and equipment. During this meeting, participants were provided with the online sleep diary, actigraphy monitor and screened for normal hearing by trained personnel using a calibrated audiometer and conventional auditory threshold-hunting method. Participants then completed the online sleep diary (Carney et al., 2012; Maich et al., 2018) and wore actigraphy devices (Actigraphy 2 actiwatch, Phillips Respironics, USA) in the week leading up to their first overnight laboratory visit. The sleep diary and actigraphy device was administered to assess their typical sleep in terms of bedtime, time spent in bed, sleep latency, total sleep

time, number of awakenings, wake after sleep onset, time of final awakening and time out of bed. These data were used to monitor and confirm participants' sleeping patterns prior to each overnight stay in the laboratory and to determine appropriate lights out time for each subsequent overnight in-laboratory study.

On each night of the study, participants arrived at the sleep laboratory at least two hours before their habitual bedtime. Participants were set up for PSG and given time to relax prior to sleep in dim light at <10 lux. To account for each participant's usual sleep time, lights out time was calculated based on the previous week's average attempted sleep time from their sleep diary and actigraphy device data (Kerkhof & Van Dongen, 1996; Lavie, 2001; Zavada, Gordijn, Beersma, Daan, & Roenneberg, 2005).

Prior to lights out time, participants were informed that they may or may not hear noises during the night and to try and sleep as they would in their own bed. This was to reduce any hypervigilance and rumination to/from WTN during the sleep onset period. Wake up times were self-selected by the participants prior to lights out time. Prior to lights out time, the noise in the bedroom was at background level (23 dB(A)). At lights out time, participants were exposed in random order to either WTN at 33 dB(A) (10 dB(A) above background noise) or control background noise (23 dB(A)) until 10 consecutive epochs of N2 or deeper sleep was established, after which another experimental noise battery commenced as part of another study (Dunbar et al., 2021; Lechat et al., 2021a). In the morning following each study, subjective sleep latency, in minutes, was evaluated using the Consensus Sleep Diary item "how long did it take you to fall asleep?" after which participants were discharged from the laboratory (Carney et al., 2012). One week later and following ongoing sleep diary and actigraphy assessments, participants returned to the laboratory for the remaining noise exposure condition.

3.2.5 Statistical analysis

A meaningful *a priori* power analysis was not available given an absence of published studies reporting within-subject standard deviation of sleep latency across >1 night. Consequently, the target sample size of 25 participants was chosen based on previous studies that assessed objective sleep latency in various patient groups of approximately 20-30 participants (Baker, Maloney, & Driver, 1999; Scott, Whitelaw, Canty, Lovato, & Lack, 2021; Smith & Trinder, 2000).

All statistical analyses were performed using IBM Statistical Package for Social Sciences (SPSS; Version 25). The primary outcomes of objective sleep latency, latency to N2 sleep, and subjective sleep latency failed normality tests and were subsequently $\log_{10}$ normalised for further statistical analyses. Consequently, all data are presented as median and IQR unless otherwise specified. Linear mixed effects model analyses, on $\log_{10}$ normalised data where necessary, were used to assess fixed and interaction effects of noise exposure condition (WTN versus background noise) and condition order (WTN first or second night) and a separate model including night number to test and control for potential order or first night effects on objective and subjective sleep latency. Each model used a first-order autoregressive covariance structure, with noise exposure condition specified as repeated measures within-subjects and subject as a random effect, each with their own intercept. Statistically significant interactions and/or main effects were further examined using Sidak adjusted pairwise comparisons within each linear model. *P* values <0.05 were considered statistically significant. Cohen's *d* was calculated and interpreted according to standard benchmarks (Cohen, 1992). Spearman's rank correlations (r_s) and Bland-Altman analyses were also conducted to assess potential relationships, bias and levels of agreement between objective and subjective sleep latency (Bland & Altman, 1986).

Fisher's exact tests were calculated to test for differences in the proportion of individuals within each noise exposure condition (WTN, control background noise) who took >30 and >20 minutes to fall asleep. Thirty minutes was selected as it is a common cut-off to discriminate healthy sleepers from poor sleepers, including those with insomnia (American Academy of Sleep Medicine, 2014; Lichstein, Durrence, Taylor, Bush, & Riedel, 2003; Lineberger, Carney, Edinger, & Means, 2006). Twenty minutes was also examined as it has also been used previously (Jalali et al., 2016a; Jalali et al., 2016b).

Given that N1, N2 and subjective sleep latency failed normality tests, Spearman's rank correlations (r_s) were used to explore the relationships between perceived noise sensitivity and changes in objective and subjective sleep latency in the presence of WTN versus background noise.

3.3 RESULTS

3.3.1 Baseline demographics

From 50 individuals responding to study advertisements, 27 were excluded (9 declined to participate and 18 did not meet the study criteria for healthy sleepers). Reasons for exclusion included bedtimes >00:00 hours (n = 8), >2-hour circadian misalignment on weekdays versus weekends (n = 3), use of medication known to affect sleep (n = 4), sleep onset latencies >30 minutes (n = 1) and total sleep time <8 hours (n = 2). The remaining 23 eligible healthy volunteers that consented to participate were aged 18-29 years, lived in suburban residences away from wind turbines, exhibited normal hearing and completed the study. Participant demographics are presented in Table 3.1 and sleep characteristics obtained at screening and the baseline week before each laboratory night are presented in Table 3.2. Thirteen individuals were randomised to the WTN exposure condition on their first overnight laboratory visit and 10 individuals were

randomised to the control background noise condition on their first overnight. All available data were included in analysis, except data from one participant because of a noise reproduction versus sleep recording time-matching problem whereby the onset of noise within the PSG could not be accurately determined (analysis n = 22). N1 objective and subjective sleep latency data from two further participants were excluded due to premature discontinuation of noise prior to N1 scored sleep (n = 20), and N2 sleep onset data were excluded from three participants due to premature discontinuation of the noise prior to consolidated N2 sleep onset (n = 19).

Table 3.1 Participant demographics.

Characteristic	***Mean±SD***
Females:Males N (%)	13:10 (57:43%)
Age (years)	21.7±2.1
BMI (kg/m²)	20.4±2.9
ESS	4.0±2.3
ISI	3.9±2.5
PSQI	4.1±2.0
PSQI-Sleep Efficiency (%)	91.5±9.1
Weinstein Noise Sensitivity Scale	51.0±11.1

Note. N = 23 participants. SD=Standard Deviation, BMI=Body Mass Index, ESS=Epworth Sleepiness Scale (range of scores: 0-21, >10 indicates excessive daytime sleepiness) (Johns, 1991), ISI=Insomnia Severity Index (range of scores: 0-28, >7 subthreshold insomnia, >14 insomnia) (Morin, 1993), PSQI=Pittsburgh Sleep Quality Index (range of scores: 0-24, >5 poor sleep quality) (Buysse et al., 1989), Weinstein Noise Sensitivity Scale range of scores: 1-105, higher scores indicate greater sensitivity to noise (Weinstein, 1978).

Table 3.2 Participant screening sleep characteristics and baseline sleep diary parameters.

Self-reported sleep parameters	Screening[a]	WTN baseline week[b]	Control baseline week[b]
Total sleep time (mins)	478.1±40.5	486.2±63.3	472.8±7.8
Wake up time (hrs/24)	7.6±1.0	8.0±1.1	7.8±1.0
Lights out time (hrs/24)	22.7±1.0	23.5±1.0	23.4±0.9
Sleep efficiency (%)	91.2±9.1	95.2±4.8	93.9±9.4
Sleep latency (mins)	19.7±12.1	18.2±20.9	22.0±40.9
Wake after sleep onset (mins)	*	6.3±4.9	7.4±5.4
Number of awakenings	*	0.8±0.8	0.7±0.6
Time in bed (mins)	529.8±1.2	510.5±59.8	502.2±52.1
Evening circadian misalignment (hrs)	0.7±0.6[c]	*	*
Morning circadian misalignment (hrs)	1.3±0.8[c]	*	*

Note. Values are mean±standard deviation. *variable not measured. [a]PSQI derived sleep estimates. [b]Sleep diary-derived sleep estimates. [c]Health and Lifestyle derived estimates. All *p*'s >0.05. WTN=Wind Turbine Noise. mins=minutes. hrs=hours.

3.3.2 WTN exposure and sleep latency

Figure 3.1 illustrates individual and group (condition) responses to background noise (control) compared to WTN on N1, N2 and subjective sleep latencies. There were no statistically significant noise condition, order or interaction effects on N1 sleep latency (noise effect, $F(1, 17.66) = 0.74$, $p=0.401$, Figure 3.1a), latency to N2 sleep (noise effect, $F(1, 15.99) = 0.36$, $p=0.559$, Figure 3.1b) or subjective sleep latency (noise effect, $F(1, 18.26) = 0.01$, $p=0.907$, Figure 3.1c). There were also no statistically significant noise condition, night number or interaction effects on N1, N2 or subjective sleep latency.

There were no significant differences in the proportions of participants with objective or subjective sleep onset latencies >30 minutes during WTN compared to background noise exposure (N1: 1/20 (5%) vs 4/20 (20%), $p=0.342$; N2: 2/18 (11.1%) vs 6/19 (31.6%), $p=0.232$; Subjective sleep latency: 2/20 (10%) vs 1/20 (5%), $p>0.999$). Similarly, there were no differences in the proportions of participants with objective sleep latencies >20 minutes.

A greater proportion of participants with control sleep latencies below the median (<15 minutes) appeared to show more prolonged N1 sleep latency in the presence of WTN (8/9: 88.9%), compared to participants with control N1 sleep latencies above the median (>15 minutes) who showed a reduction in sleep latency in the presence of WTN (9/11: 81.8%, Fisher's exact $p=0.005$, Figure 3a(i)). However, Spearman's rank correlations revealed no significant correlations between N1 sleep latency in the control condition, compared with the WTN condition, $r_s(20) =0.298$, $p=0.201$ and linear mixed model analyses showed no significant sub-group effect on the WTN minus control difference in N1 sleep latency (mean difference [95% CI] 4.6 [-4.9 to 14.1] in the <15 minutes group versus -7.2 [-15.0 to -0.6] in the >15 minutes group $F(1,16) = 4.13$, $p=0.059$). Furthermore,

there were no consistent noise condition effects on N2 latency or subjective sleep latency (Figure 3.1b(i) and 3.1c(i)).

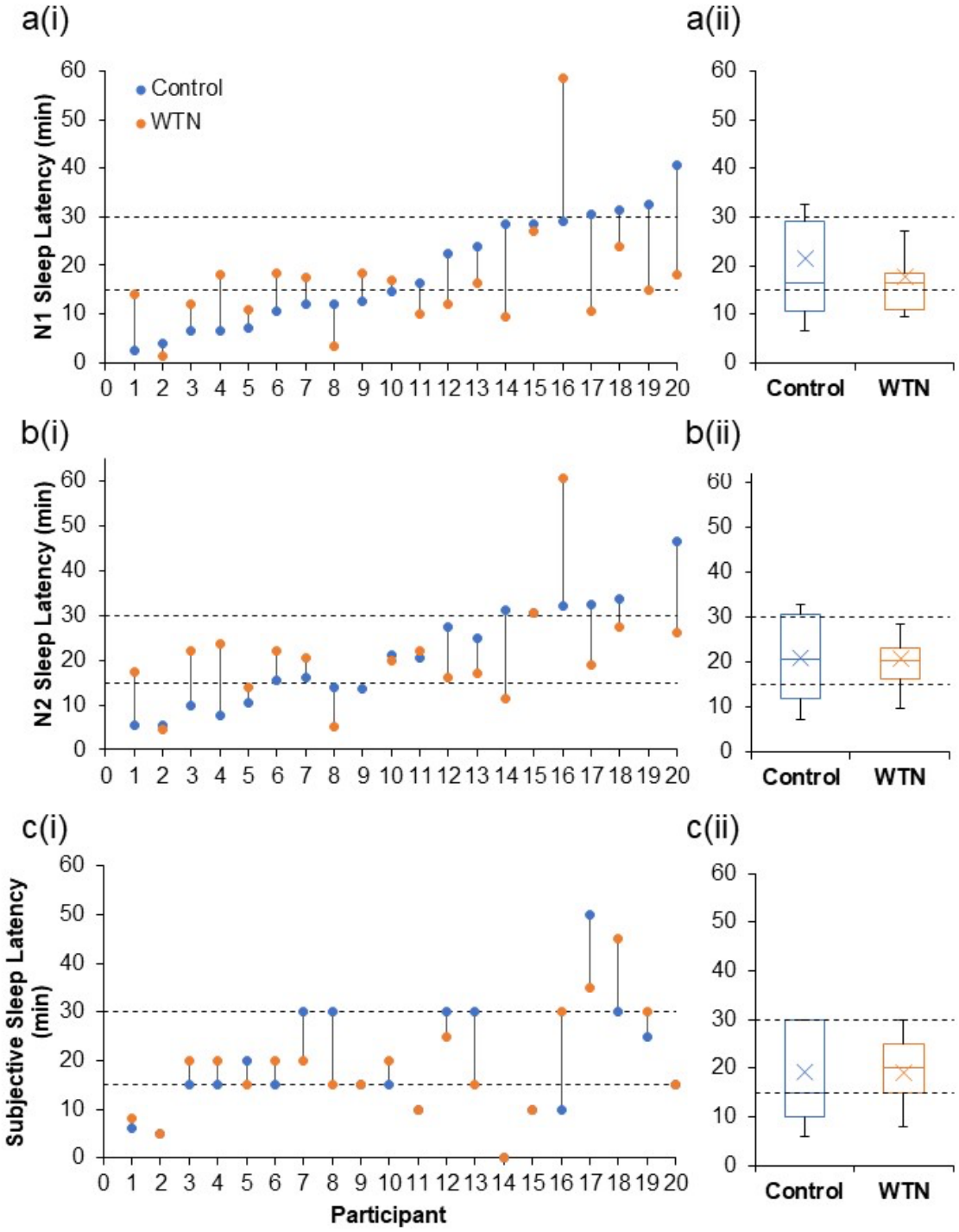

Figure 3.1 Waterfall plots on the left (a-c(i)) depict the individual discrepancies between each noise exposure condition (WTN and control background noise) and the corresponding box-and-whisker plots shown on the right (a-c(ii)) present the overall group differences in objective N1 sleep latency (a(i) and a(ii)), N2 latency (b(i) and b(ii)) and subjective sleep latency (c(i) and c(ii)) when exposed to WTN compared to control background noise.

Note. WTN=Wind Turbine Noise.

3.3.3 Objective versus subjective sleep latency

Figure 3.2 shows Bland-Altman plots of mean sleep latency versus objective minus subjective sleep latency, which showed no evidence of a differential bias between control background noise versus WTN nights in this normal, healthy sleeper sample, with wide limits of agreement of approximately 30 minutes. Furthermore, as shown in Figure 3.3, there were no significant correlations between objective and subjective N1 sleep latency in the control background noise condition or WTN condition. Furthermore, no significant correlations between N2 latency and subjective N1 sleep latency were also found in the control background noise condition or WTN condition (Figure 3.3).

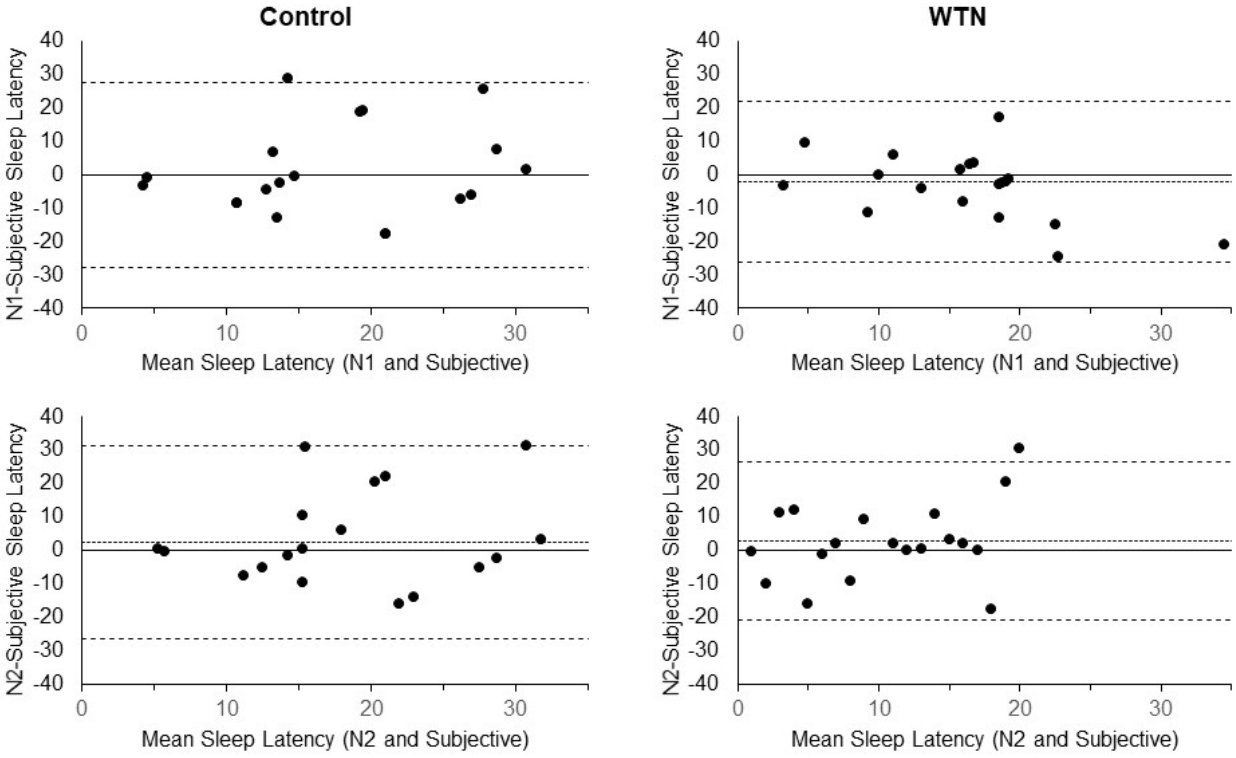

Figure 3.2 Traditional Bland Altman plots assessing the systematic bias present between objective (N1 and N2) and subjectively measured sleep latency in the presence versus absence of WTN exposure.

Note. WTN=Wind Turbine Noise.

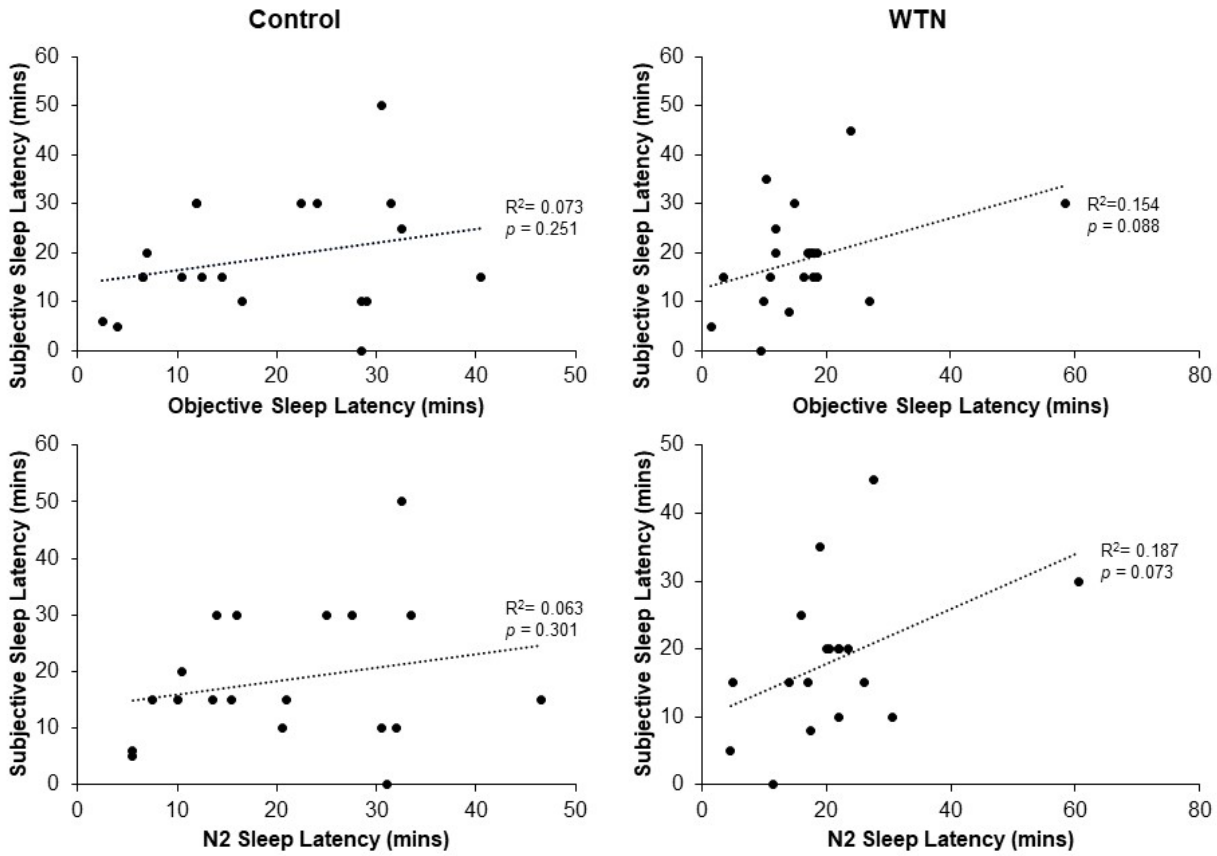

Figure 3.3 Scatterplots depicting the Spearman's rank correlations between objective (N1 and N2) and subjectively measured sleep latency in the presence versus absence of WTN exposure.

Note. WTN=Wind Turbine Noise.

3.3.4 Perceived noise sensitivity and sleep latency

Perceived noise sensitivity scores were within the mid-range (mean±SD 51.0±11.4; range: 35-75) of noise-sensitivity scores for the Weinstein Noise Sensitivity Scale. There were no significant correlations between Weinstein Noise Sensitivity scores and increases in N1 ($r_{s(20)}$ = 0.282, p=0.229), N2 ($r_{s\,(18)}$ = 0.322, p=0.192) or subjective sleep latency ($r_{s\,(20)}$ = 0.186, p=0.433) on WTN nights compared with control nights. Furthermore, objective sleep latency difference scores (WTN-control) were not correlated with PSQI ($r_{s\,(20)}$ = -0.107, p=0.654), ISI ($r_{s\,(20)}$ = -0.019, p=0.938) or ESS ($r_{s\,(20)}$ = 0.013, p=0.958) scores. There were also no significant correlations between PSQI, ISI and ESS and N2 or subjective sleep latency (all p's >0.05).

3.4 DISCUSSION

This study investigated the impact of WTN at 33 dB(A) (10 dB(A) above background noise) on objective and subjective sleep latency in individuals from urban residences studied in a carefully controlled laboratory environment. These findings do not support the position that either objective or subjective sleep latency are impacted by WTN in young, healthy, good sleepers not habitually exposed to WTN. Although these findings could potentially reflect a Type II error, modest systematic effects of WTN on sleep latency are unlikely to have been missed in this study. Given a pooled within-subject SD in N1 sleep latency of 11.3 minutes (N2 11.7, subjective 11.1 minutes), 20 participants should provide 80% power, with a two-tailed significance level of 0.05, to detect changes in sleep latency in the order of 10 minutes, or less given that undetected WTN effects would be expected to inflate within-subject SD. Nevertheless, smaller systematic effects could have been missed. These findings do not rule out significant effects in individuals with prior WTN exposure in a typically quiet rural environment, or those more sensitive and prone to noise annoyance effects on sleep. Nevertheless, findings from normal hearing healthy good sleepers are important for evaluating impacts of realistic WTN exposure levels on sleep latency in humans.

Furthermore, there was some evidence that habitual sleep onset time and WTN may interact given that participants with the shortest (<15 minutes) control background noise N1 sleep latency showed more frequent sleep onset delays with WTN compared to shorter latencies in participants with N1 sleep latency >15 minutes. However, given the smaller divided sample and ranking, this might simply reflect Type I error or regression to the mean. Nevertheless, this does not rule out the possibility of an interaction between noise and sleep latency for those who show shorter versus longer habitual sleep latencies. This may warrant further investigation and consideration in future studies.

Overall, these results are consistent with the WiTNES study (Ageborg Morsing et al., 2018), the only other in-laboratory study to date, which found no significant differences in objective or self-reported sleep latency with versus without exposure to WTN at 29.5 dB(A), 34.1 dB(A), 33.7 dB(A) 32.8 dB(A) and 30.4 dB(A) with various window open and closed filtering and amplitude modulation frequencies between 80-315 Hz and 160-500 Hz in six healthy participants (Ageborg Morsing et al., 2018). These findings are also consistent with the larger WiTNES study (Smith et al., 2020), which also found no WTN effects compared to a control night on objective sleep latency in 26 participants who did not live close to wind turbines (reference group) or 24 participants who lived close to a turbine and reported annoyance or sleep disturbance within the past month (exposed group). However, the WiTNES study did find that both study groups reported more difficulty getting to sleep during the WTN versus control night (Smith et al., 2020). The current study used the more common Consensus Sleep Diary to assess subjective sleep latency (minutes), whereas the WiTNES study used a 10-point Likert scale (0 = easy, 10 = difficult) to assess the level of difficulty in achieving sleep and did not report subjective sleep latency (minutes). The Consensus Sleep Diary is a standardised tool for measuring sleep perception and is psychometrically validated against other objective measures of sleep, including actigraphy (Liebich et al., 2021; Maich et al., 2018). The Consensus Sleep Diary also allows for the direct estimate of perceived time taken to fall asleep, whereas the 10-point Likert scale used in the WiTNES study assessed the level of difficulty taken to fall asleep, rather than sleep latency itself (which can imply a psychological effort or impairment component), rather than an estimate of the time taken to fall asleep.

Another key difference between the current study and the WiTNES study is that the WiTNES study used four different synthesised WTN samples that had different noise levels and frequency content (Smith et al., 2020). Due to the randomisation used in the WiTNES study, the noise sample played during the sleep onset period differed. The

current study used a more ecologically valid real-world recorded WTN sample with fixed characteristics (33 dB(A)) to ensure that all participants were exposed to the same WTN characteristics from lights off time. Furthermore, the WiTNES study used a tapered noise onset which may introduce problems of defining when noise is likely to have first become audible to participants, which will also likely vary between individuals according to hearing acuity. This approach also risks more variable noise-exposure times in the sleep onset period, including the potential for sleep onset prior to exposure to the specified noise level, rendering noise effects on sleep latency problematic to evaluate. Hence, the current study played the noise at 33 dB(A) from noise onset with no tapering. Regardless, similar findings in both studies more strongly support that realistic WTN exposure levels over the sleep onset period do not have detectable effects on objective or subjective sleep latency in the selected study groups.

No differences were found in terms of the percentage of individuals who took longer than 20 or 30 minutes to fall asleep when exposed WTN compared to background noise alone. These results are consistent with a previous study that found no significant differences in objective sleep latency pre- versus post-operational WTN exposure (Jalali et al., 2016a). This previous study found only two participants that had sleep latencies >20 minutes under post operational WTN exposure conditions, perhaps due to higher noise sensitivity. However, they also found no differences in WTN levels pre- versus post-operational conditions, so these participants appeared not to have been exposed to detectably increased noise levels (Jalali et al., 2016a).

In addition, 75% of participants in the study (n=12) by Jalali et al. (2016a) were classified as not or slightly noise sensitive compared to 12.5% (n=2) that were classified as rather or very noise sensitive. In comparison, no participants in our study were classified as noise sensitive as assessed by the Weinstein Noise Sensitivity Scale (i.e., participants scoring within the upper quartile of the Weinstein Noise Sensitivity Scale score – 78-105).

Future studies should therefore include individuals with higher noise sensitivity scores to examine if noise sensitivity may help explain relationships between WTN and self-reported sleep problems. Ideally, future studies would also recruit individuals who reside near wind turbines and report sleep disturbances and sensitivity to noise.

Another potential explanation for the study findings is that the majority of the recruited suburban sample may habitually experience background noise levels above 23 dB(A) when attempting to sleep. Previous reports have hypothesised that individuals living in areas with higher background noise levels may have a higher tolerance to noise than individuals who habitually receive low rural noise levels before the construction of nearby wind farms (Hansen et al., 2015a). Although dependent on the proximity to main roads and surrounding industry, individuals in urban areas can be exposed to outdoor background noise levels >36 dB(A) (Gjestland, 2008). Whereas, in quiet rural areas where wind farms are typically situated, individuals are exposed to much lower indoor background noise levels, compared to urban areas (Gjestland, 2008; Griefahn et al., 2006; Hansen et al., 2015a; King et al., 2012). Participants were not asked about their perceived usual sleep noise exposure levels in the current study and therefore, future studies should include measures of perceived noise exposure in the home environment to help elucidate the potential role of habituation in modulating relationships between environmental noise and sleep disruption.

3.4.1 Study limitations

This experimental study investigated the presence versus absence of WTN during the initial sleep onset period. However, sleep latency and latency to N2 sleep are only two sleep parameters to consider when examining the impact of WTN on sleep macrostructure. All other sleep parameters in the current study were potentially impacted by ongoing noise manipulations throughout the remainder of sleep on both control and

WTN exposure nights, as part of another study to investigate the impact of WTN compared to RTN on sleep reported elsewhere (Dunbar et al., 2021; Lechat et al., 2021a). However, given a 1-week washout period and no evidence of significant carry-over effects between conditions, potential bias associated with additional noise exposures beyond the sleep onset period investigated in this study are unlikely. Regardless, the current study addressed an important gap in the literature and supports that WTN at realistic environmental exposure levels does not impair the ability of WTN naïve urban residents to initiate sleep or alter their perceptions of sleep latency. Whilst these are important findings, responses in healthy young volunteers without potentially more complex demographic and prior habitual WTN exposure influences (e.g., age-related sleep quality effects, hearing acuity differences, prior noise exposure, established beliefs and expectations regarding WTN and potential financial factors), may not be generalisable to individuals living in rural areas exposed to WTN. Therefore, further research remains needed to investigate WTN impacts in more relevant environmental noise exposure groups, such as in rural residents with and without prior WTN exposure and WTN related sleep disturbance. Further investigations using full-night exposures to a range of WTN levels compared to no-noise controls are also warranted to further evaluate the effect of WTN on the full range of sleep parameters. Experiments incorporating WTN exposure during established sleep periods, wake periods and continuously throughout the night would also be useful to investigate and help differentiate between possible psychological, attitudinal, and physiological mechanisms that could all influence objective and subjective sleep quality. Lastly, we selected a more practical and lower cost randomised controlled cross-over design without a habituation night. Although we found no evidence to support significant night or order effects, sleep latency could to some extent have been influenced by first night effects. Future studies including a habituation night would help to reduce potential confounding by first night effects.

3.4.2 Conclusions

WTN effects on objective and subjective sleep latency were assessed via a two-night sleep study in a controlled sleep laboratory setting using PSG and sleep diary measures in a sample of healthy sleepers not typically exposed to WTN. No differences were found in objective or subjective sleep latency when WTN at 33 dB(A) was presented during the sleep onset period compared to control background noise at 23 dB(A). Furthermore, no differences were found in latency to N2 sleep, nor in the proportion of individuals who took >20 or >30 minutes to fall asleep in the presence versus absence of WTN. Given participants were not sensitive to noise nor habitually exposed to WTN, these findings should be interpreted with caution as habitual noise exposure conditions may importantly influence sleep latency in other sub-populations. Future studies should include individuals living near wind farm areas who report noise sensitivity and/or sleep disturbance attributed to WTN, as well as non-exposed and non-noise sensitive individuals as controls, to further test for possible effects of WTN on sleep.

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Non-financial Disclosure: None.

Data availability statement

The data underlying this article will be shared on reasonable request to the corresponding author.

CHAPTER 4 AN EXPERIMENTAL INVESTIGATION ON THE IMPACT OF WIND TURBINE NOISE ON POLYSOMNOGRAPHICALLY-MEASURED AND SLEEP DIARY-DETERMINED SLEEP OUTCOMES

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Author Contributions

TL contributed to study design, data collection, analysis and interpretation and manuscript preparation. LL, KH, BZ, GM, & PC contributed to conception and study design, interpretation of the data and drafting of the manuscript. BL, CD, DPN & HS contributed to data collection, data-analysis, data interpretation and drafting of the manuscript.

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ABSTRACT

Introduction: Carefully controlled studies of wind turbine noise (WTN) and sleep are lacking, despite anecdotal complaints from some residents in wind farm areas and known detrimental effects of other noises on sleep. This laboratory-based study investigated the impact of overnight WTN exposure on objective and self-reported sleep outcomes.

Methods: Sixty-eight participants (38 females) aged (mean±SD) 49.2±19.5 were recruited from four groups; N=14, living <10km from a wind farm and reporting WTN related sleep disruption; N=18, living <10km from a wind farm and reporting no WTN sleep disruption; N=18, reporting road traffic noise related sleep disruption; and N=18 control participants living in a quiet rural area. All participants underwent in-laboratory polysomnography during four full-night noise exposure conditions in random order: a quiet control night (19 dB(A) background laboratory noise), continuous WTN (25 dB(A)) throughout the night; WTN (25 dB(A)) only during periods of established sleep; and WTN (25 dB(A)) only during periods of wake or light N1 sleep. Group, noise condition and interaction effects on measures of sleep quantity and quality were examined via linear mixed model analyses.

Results: There were no significant noise condition or group-by-noise condition interaction effects on polysomnographic or sleep diary determined sleep outcomes (all *p*'s >0.05).

Conclusion: These results do not support that WTN at 25 dB(A) impacts sleep outcomes in participants with or without prior WTN exposure or self-reported habitual noise-related sleep disruption. These findings do not rule out effects at higher noise exposure levels or potential effects of WTN on more sensitive markers of sleep disruption.

Keywords: sleep disruption, sleep disturbance, sleep quality, wind farm, wind turbine, environmental noise.

This study was prospectively registered on the Australian and New Zealand Clinical Trial Registry.

Clinical Trial name: Establishing the physiological and sleep disruption characteristics of noise disturbances in sleep.

URL: https://www.anzctr.org.au/

Registration: ACTRN12619000501145, UTN U1111-1229-6126

Statement of Significance

Carefully controlled laboratory studies to investigate the effect of wind turbine noise (WTN) on polysomnographically and sleep diary determined sleep outcomes are limited. This study found no evidence to support that overnight WTN exposure levels similar to average year-long indoor WTN levels significantly impact key objective or subjective sleep outcomes, including in residents habitually exposed to WTN. However, sleep disturbance effects at higher worst-case noise exposure levels or more subtle microstructural sleep effects cannot be ruled out so further studies remain warranted.

An experimental investigation on the impact of wind turbine noise on polysomnographically-measured and sleep diary-determined sleep outcomes

4.1 INTRODUCTION

A rapid ongoing shift away from fossil fuels to renewable energy generation includes the expansion of wind turbines in reliable wind exposure areas, often with existing near-by residences. Therefore, it is important to clarify whether WTN has detrimental health effects and through what mechanisms in order to help inform the need for and design of potential mitigation strategies.

Chronic exposure to environmental noises (e.g., road, rail, and aircraft noise), of sufficient sound pressure levels (SPLs which govern the overall amplitude/intensity of the noise) are known to negatively impact sleep (Basner et al., 2011; Jakovljević et al., 2006; Miedema & Vos, 2007). However, only a limited number of studies have examined the impact of WTN on sleep, and these have shown inconsistent and inconclusive findings. This potentially reflects a combination of factors such as more modest sound levels, lower frequency content, variable exposure levels and a reliance on self-report and cross-sectional study designs, which may make WTN effects difficult to reliably detect.

WTN has several prominent and acoustically unusual features compared to other environmental noises known to affect sleep, such as RTN. Unlike RTN, which typically reduces in SPL at night because of reduced road traffic, WTN SPLs and acoustic characteristics are largely dependent on atmospheric and wind conditions, which are often more stable and favour more prominent noise at night when background noise levels are typically lowest; especially in rural areas where wind turbines are typically located. Consequently, residents living near wind turbines, who are likely to be accustomed to very low background noise levels at night, may be susceptible to WTN disruption when attempting sleep at night. Despite limited high-quality evidence, consistent reports of sleep

complaints support that sleep disruption is problematic for some residents living close to wind turbines (Basner et al., 2014; Crichton et al., 2014; Janssen et al., 2011b; Krogh et al., 2011). Therefore, it is possible that WTN has direct physiologically disruptive effects on sleep and on subsequent daytime functioning and health. In that context, the most effective mitigation strategies would likely be to limit the proximity of wind farms to residences, to promote more effective noise abatement through improved WTN locations and residential building design or potentially to mask WTN noise.

However, sleep disruption can also manifest as self-reported difficulties initiating and maintaining sleep and/or experiencing un-restorative sleep without necessarily a specific sleep disruption trigger, such as what occurs with insomnia (Thorpy, 2012). Thus, a combination of WTN and other factors including knowledge, attitudes, noise sensitivity and beliefs around WTN exposure could also produce psychological responses with indirect detrimental effects on sleep. If residents attribute sleep disruption to WTN and symptoms are left untreated, individuals could develop chronic insomnia, via conditioned responses when attempting sleep including maladaptive sleep behaviours and cognitions, which may subsequently impact on daily function, well-being and potentially health (Bolin et al., 2014; Hansen et al., 2015a; Micic et al., 2018; Ohayon, 1997; Pedersen et al., 2007; Perlis et al., 1997; Roehrs, Zorick, Sicklesteel, Wittig, & Roth, 1983; Thorpy, 2012). In this context, reliable evidence-based information and education along with psychological therapies would likely be indicated. Therefore, experimental investigations to help clarify the effects of WTN on sleep through direct sleep disruption and indirect psychological effects are important.

To date, three studies have utilised experimental designs in carefully controlled laboratory settings to investigate the impact of WTN on PSG-assessed sleep (Ageborg Morsing et al., 2018; Liebich et al., 2022; Smith et al., 2020). Ageborg Morsing et al. (2018) conducted two pilot studies (N = 6 in both) where participants were exposed to

three WTN exposure nights with varying frequencies, amplitude modulation characteristics and dB L_{AEq} SPLs (L_{AEq} referring to A-weighted equivalent continuous SPLs; See Bergland and Lindvall (1995) for more details). SPLs used in Ageborg Morsing et al. (2018) ranged from 29.5 to 34.1 dB L_{AEq} in one study and 30.4 to 32.8 dB L_{AEq} in another study, with a quiet control night (18 dB L_{AEq}) for comparison in both. There were no significant effects of noise exposure level on self-reported or PSG sleep outcomes, including total sleep time, sleep latency, sleep efficiency or wake after sleep onset. However, given the small sample sizes, and associated Type II error risk, these findings warrant cautious interpretation. Chapter 3 discussed a recent larger study in 23 urban residents without habitual WTN exposure and found no significant effects of WTN exposure at 33 dB(A) on one night compared to background noise at 23 dB(A) on another night on PSG derived latency to N1 or N2 sleep or self-reported sleep latency (Liebich et al., 2022). However, these urban residents may have been more tolerant of higher noise levels, (e.g., road traffic), during the sleep period, particularly as these urban residents were also not overly noise sensitive, were healthy sleepers and did not report RTN related sleep disruption at home (Liebich et al., 2022).

In the largest experimental study to date, Smith et al. (2020) studied 50 participants, including a group of individuals living near wind farms and another group without prior WTN exposure, during a control background noise only night at 13 dB and a night of indoor WTN exposure at 32 dB L_{AEq}. REM sleep latency was significantly increased, and REM duration reduced on the WTN noise exposure compared to the control night, but no other PSG-derived sleep parameters changed including sleep latency. However, self-reported sleep quality, measured on a 5-point scale from “very good” to “very bad” was significantly reduced on the WTN night compared to the control night. This effect was larger for participants previously exposed to WTN versus participants previously unexposed to WTN. However, as discussed in Chapter 3, potential participant awareness

of WTN exposure prior to falling asleep and during night-time awakenings with continuous noise exposures from lights out until lights on has the potential to influence and bias self-reported responses (e.g., the expectation of taking longer to fall asleep on WTN nights), particularly in participants with strongly established attitudes, beliefs and expectations regarding WTN effects on sleep (Liebich et al., 2022). Therefore, further studies to test for effects of WTN exposure more specifically during periods of wake versus sleep are needed to help separate potential wake-dependent psychological effects from sleep-dependent effects of WTN on objective and subjective measures of sleep difficulties and quality.

Accordingly, the primary aim of this study was to examine the impact of audible WTN, including prominent infrasound and low-frequency amplitude modulated tones, on conventional PSG (objective)- and sleep diary determined (subjective) sleep parameters in a carefully controlled laboratory environment. This study was part of a larger study that included two separate study nights for evaluating dose-response characteristics of WTN compared to RTN presented during established sleep. However, the current study, which involved four separate study nights, was specifically designed to examine the effect of realistic levels of audible WTN, including prominent amplitude modulated tones and infrasound (which are often inaccurately characterised using A-weighted SPL (Persson Waye & Ohrstrom, 2002; World Health Organization, 1999), on the ability of participants to initiate and maintain sleep. We reasoned that if audible WTN including prominent amplitude modulation and infrasound is problematic for initiating and/or returning to sleep following awakenings, then these effects should be wake-dependent and apparent with audible WTN above background noise, particularly in individuals reporting WTN-related sleep difficulties.

To investigate potential wake-dependent psychological effects versus sleep-dependent WTN effects, four different noise exposure conditions were examined in a

randomised order across separate nights, including: continuous WTN exposure during wake and sleep (WTN-Continuous); WTN exposure only during established N2, N3 and REM sleep (WTN-Sleep); WTN exposure only during periods of wake and transitional stages of N1 sleep (WTN-Wake); and no WTN exposure (i.e., quiet background noise (control)). A further aim was to elucidate possible effects of prior noise exposure on WTN responses, by recruiting participants living near wind farms who did and did not report WTN related sleep disruption, as well as two control groups: residents from rural communities with no wind farms nearby and participants reporting RTN related sleep disruption.

It was hypothesised that PSG and sleep diary outcomes would be more disrupted (i.e., more wake and less sleep) on the WTN-Continuous night compared to the control night due to direct sleep-dependent WTN effects, indirect wake-dependent psychological effects, or both. If only wake-dependent psychological effects were operating, then WTN-Wake and WTN-Continuous nights would be expected to show reduced sleep compared to the WTN-Sleep and control nights. In the presence of sleep-specific WTN disruption effects, WTN-Sleep and WTN-Continuous nights would be expected to show greater sleep disruption than both the WTN-Wake and control nights. Furthermore, in the presence of prior exposure and potential noise sensitisation effects, greater levels of sleep disruption were anticipated in residents living near wind turbines and reporting WTN related sleep disruption compared to other groups.

4.2 METHODS

4.2.1 Study setting and design

The study was conducted at the Adelaide Institute for Sleep Health, Nick Antic Sleep Laboratory. For seven consecutive nights, study participants spent the night in one of two fully private, heavily sound-attenuated bedrooms (background noise level 19 dB(A))

with their own ensuite and a shared lounge area. Bedroom temperatures were set to 23°C and participants were provided with light bed covering and additional bed covering if requested.

A four group (WTN-sleep disturbed, WTN-non sleep disturbed, rural control, RTN-sleep disturbed) by four noise condition (WTN-Sleep, WTN-Wake, WTN-Continuous, Control) single-blind study design was used to investigate the effect of WTN exposure on PSG and sleep diary outcomes. The first night was an acclimatisation night, after which participants were randomised to six different noise exposure conditions over the remaining nights, of which, only four nights are relevant and reported in this thesis.

The primary outcomes were PSG measured sleep efficiency (i.e., the total amount of sleep time divided by total time spent in bed), the most widely used objective measure of overall sleep quality and sleep diary determined sleep efficiency (Lemola, Ledermann, & Friedman, 2013). Secondary outcomes were PSG and sleep diary derived sleep latency, total sleep time, wake after sleep onset, number of awakenings and time spent in bed, as well as PSG derived total wake time, time and proportion spent in each sleep stage and latency to N2, N3 and REM sleep. Prior to lights out, participants were only instructed that “they may or may not hear noise during the night” and that noise exposure could include a range of noise samples including WTN. Thus, participants remained unaware of specific noise conditions each night, but by study design and use of audible noise, were most likely aware of noise presentations during wake.

Sleep technicians manually commenced and paused noise play-back according to allocation night and observed sleep stages across each study night (sleep, wake, or played continuously) so could not be blinded to noise condition. However, an independent sleep scientist undertook all subsequent sleep staging and arousal scoring analysis blinded to noise exposure conditions.

4.2.2 Participants

Potential participants were recruited via print advertising on community noticeboards, word of mouth and online social media advertising (Facebook and Gumtree) (See Appendix 2 for the recruitment poster used). This study was approved by the Southern Adelaide Clinical Human Research Ethics Committee (Protocol number 343.18) and was prospectively registered on the Australian and New Zealand Clinical Trials Registry (ACTRN12619000501145, UTN U1111-1229-6126). All participants provided written and informed consent and were financially compensated for study participation and travel costs (total reimbursement: $1300 AUD for rural participants and $1000 AUD for urban participants).

4.2.2.1 Inclusion and exclusion criteria

Study participants were adults recruited from different noise exposure areas and were considered for inclusion based on residential location and questionnaire responses indicating either the presence or absence of self-reported WTN or RTN related sleep disruption. Participants in the WTN-non sleep disturbed and WTN-sleep disturbed group lived <10 kilometres from a wind turbine and reported 1 and >1 respectively on a 5-point Likert scale (1 = not at all, 2 = mildly, 3 = moderately, 4 = severely, 5 = very severely) which involved one item asking, “Thinking about the last 12 months or so, when you are at home, does the noise from wind turbines bother, disturb or annoy you while you are in bed trying to sleep?” based largely on the ISO-15666-2003 standard, but with a non-standard “very severely” instead of “extremely” highest response option (Internal Organisation for Standardization, 2003). Participants in the RTN-sleep disturbed group reported >1 on an equivalent question regarding RTN related sleep disruption. Rural control participants lived in a rural or remote area classified by the Rural, Remote and Metropolitan Area

Classification (Australian Government, 1991) and reported 1 to both WTN and RTN related sleep disruption items.

Study exclusion criteria included age <18 years; any use of sedative medications; any history of substance use in the past six months; night shift work within the last two months (i.e., any shift between 22:00 and 08:00 hours); or travelled across ≥2 time-zones within the past two months.

4.2.3 Intervention

4.2.3.1 Noise reproduction

Experimental noise stimuli were faithfully reproduced via a RME BabyFace Pro sound card, a Krix KX-4010s non-vented subwoofer speaker with a 25 centimetre driver positioned approximately three metres from the foot of the participant's bed and a Crown DC-300 power amplifier with a flat frequency response down to 0 Hz (Nguyen, Hansen, Zajamšek, Micic, & Catcheside, 2019; Crown, n.d.).

4.2.3.2 Noise stimulus

The WTN stimulus was recorded indoors at a residence located 3.3 kilometres from a wind farm in South Australia. A 3-minute sample was then extracted from the measured data and was played on a repetitive loop (See Hansen et al. (2014b) for further details regarding wind farm layout, properties and measurement setup). The temporal profile of the WTN included a ramp in of approximately 2.5 seconds and a very minimal ramp out (approximately 300 milliseconds) to ensure abrupt cessation in the event of awakenings on WTN-Sleep only nights.

The measured recordings generated WTN at an indoor SPL of 25 dB(A) (dB(A) referring to A-weighted decibels, which involves a linearised logarithmic scale of frequencies and SPL over the normal range of human hearing from 20 to 20,000 Hertz)

and included an amplitude modulated tone at multiple frequencies in 1/3-octave bands centred at 31.5 and 63 Hertz and infrasound at the blade-pass frequency of 0.8 Hertz and harmonics (Figure 4.1a). Due to limitations with the loudspeaker, the spectral contents below 1.6 Hertz could not be reproduced as shown in Figure 4.1a. The selection of 25 dB(A) was based on the results of a year-long measurement of WTN that showed that the median indoor SPL at night was between 25 and 30 dB(A) for distances from 1-3 kilometres (Figure 4.1b) (Nguyen et al., 2021). Furthermore, the WHO guidelines (World Health Organization, 1999, p xiii) also state that "when noise is continuous, the equivalent SPL should not exceed 30 dB(A) indoors if negative effects on sleep are to be avoided and for noise with a large proportion of low frequency sound, a lower guideline value is recommended". Therefore, choosing a SPL based on median SPLs measured over a year-long period was considered to be more representative of long-term WTN exposure rather than exposure to louder and less common events. Also, the reproduced noise level was approximately six dB(A) above the background noise level in the sleep laboratory, which is clearly perceivable by normal hearing subjects (Song & Yorke, 2009; Zwicker & Fastl, 2013).

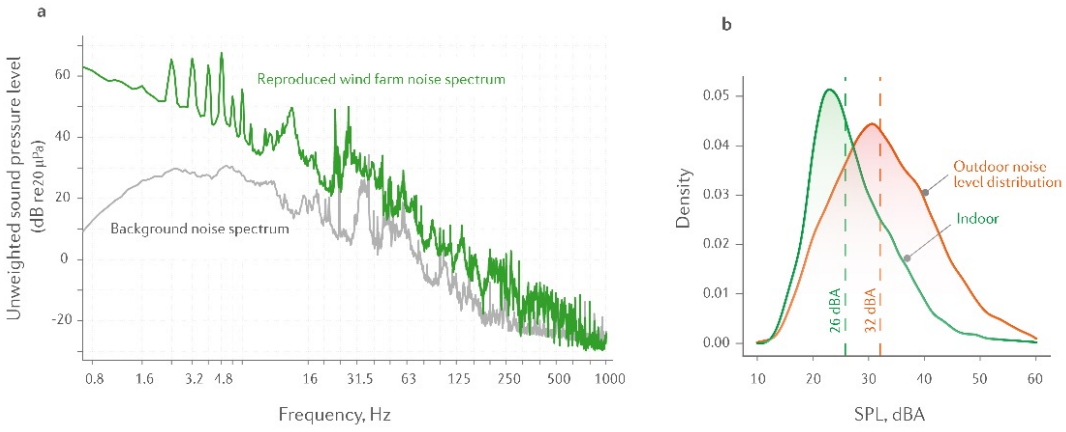

Figure 4.1 Selected noise stimulus frequency and SPL characteristics. ***(a)*** *Bedroom background noise and reproduced full-spectrum WTN measured in the current study.* ***(b)*** *Density distributions of outdoor and indoor noise levels during a separate year-long study (Nguyen et al., 2021).*

Note. Dashed lines in **(b)** indicate median indoor and outdoor SPLs from Nguyen et al. (2021). This shows that the WTN level used in the current study (25 dB(A)) was similar to median indoor SPLs measured over a year-long study (26 dB(A)).

4.2.3.3 Noise Intervention

In the control condition, the only noise present was background noise at 19 dB(A). In the WTN-Continuous condition, 25 dB(A) WTN was played continuously from lights out time to lights on time to investigate the combination of potential sleep- and wake-dependent WTN effects. In the WTN-Sleep condition, 25 dB(A) WTN was played during established sleep periods (N2, N3, REM sleep) and paused during wake and light/transitional sleep periods (N1), to test for potential sleep-specific effects of WTN, with reduced opportunity for noise awareness when participants were attempting to initiate and return to sleep following an awakening. Finally, in the WTN-Wake condition, 25 dB(A) WTN was played during wake and light/transitional sleep periods (N1) and paused during established sleep periods (N2, N3, REM sleep) to test for potential wake-dependent psychological effects of WTN exposure whilst participants attempted to initiate and return to sleep. The sleep technicians continuously monitored sleep stage throughout each night so that WTN could be stopped and started as appropriate and in accordance with the American Academy of Sleep Medicine scoring criteria (Iber et al., 2007).

4.2.4 Measures

4.2.4.1 PSG

Objective sleep parameters were assessed via PSG (Grael 4K, Compumedics Ltd., Abbotsford, Vic) and scored by a single trained scorer blinded to noise exposure conditions and acoustic data, which were recorded separately. PSG signals included electroencephalograms recorded from gold-plated electrodes placed at Fz, F3, F4, C3, C4, O1, and O2 sites referenced to contralateral mastoids (M1 and M2), and ground and reference electrodes on the clavicle and forehead respectively. EMG, EOG, electrocardiography, pulse oximeter and leg movement signals were also recorded.

4.2.4.2 Sleep and daytime questionnaires

Subjective sleep parameters were assessed using an online morning sleep diary based on the Consensus Sleep Diary (Carney et al., 2012). The Consensus Sleep Diary asks questions pertaining to time in/out of bed and minutes awake/asleep in bed per night, enabling the calculation of time in bed, sleep latency, number and duration of awakenings, wake up time and total sleep time (Carney et al., 2012) (See Appendix 3 for the 22-item online sleep diary used in the current study). The Consensus Sleep Diary is well-validated and shows high agreement compared to PSG (kappa = 0.87) and high sensitivity (92.3%) and specificity (95.6%) (Rogers, Caruso, & Aldrich, 1993).

Participants also completed several questionnaires regarding their usual sleep and noise sensitivity prior to their laboratory visit, including insomnia symptoms [ISI] (Morin, 1993), sleep quality [PSQI] (Buysse et al., 1989), daytime sleepiness [ESS] (Johns, 1991), and noise sensitivity [Weinstein Noise Sensitivity Scale] (Weinstein, 1978).

4.2.5 Procedure

For two weeks prior to their scheduled 7-night stay, participants completed a paper-based version of the Consensus Sleep Diary. Upon arrival to the sleep laboratory, participants were given a tour and reminded of the study procedures. On all nights following dinner (approximately 6:30pm), participants were set up for PSG recording. Prior to bed, participants were reminded that they may or may not hear noises during the night and to try to sleep as normal. Lights-out time was their habitual bedtime (average bedtime during baseline reported on the sleep diary).

Wake-up times were self-selected by participants prior to lights out time on each night. Following morning awakening at the prescribed time, participants completed the online sleep diary and responded to questions about noise-related sleep disruption, which took on average 5-10 minutes to complete. Participants were then free to have breakfast

and leave the laboratory (around 9:00-10:00am) until 5:30pm that evening for the next study night. On one occasion during the 7-night laboratory stay, participants also underwent an extensive hearing assessment by an independent audiologist to assess hearing thresholds via pure tone audiometry between 125-8000 Hertz in each ear in an audiology booth.

4.2.6 Data and statistical analysis

Statistical analyses were conducted with IBM Statistical Package for Social Sciences (SPSS; Version 25). Based on the primary outcome of sleep efficiency and previous reports of relatively low between- (SD approx. 10% (Levendowski et al., 2009)) and within-subject variability over consecutive nights (approx. 3% (Zheng et al., 2012)), we estimated that a repeated measures design with four groups of approximately 17 participants would have approximately 80% power to detect an absolute difference in sleep efficiency in the order of 4.5% between groups and 1.8% between noise conditions. Thus, a target sample size of 20 participants per group was selected to allow for some study technical failures and attrition.

Variables that failed normality tests were transformed ($\log_{10}$ or a Box-Cox selected transform if required) prior to further statistical analyses and *p*-values indicated with an * indicate results based on transformed data.

Group differences in demographics and baseline sleep characteristics were analysed firstly, using linear mixed model analyses with a first-order autoregressive covariance structure and subject specified as a random effect, each with their own intercept. Given statistically significant age differences between groups, age was also included as a covariate and a random effect, statistically significant group effects were examined using Sidak adjusted pairwise comparisons.

For all linear mixed model analyses, the acclimatisation night (night 1) was initially included in the analysis to test for potential 'first-night effects' and then excluded to control for such effects in follow-up analyses. For all primary and secondary outcomes, effects of noise condition, group and prior night noise exposure condition were analysed using linear mixed model analyses using a first-order autoregressive covariance structure, noise condition and prior night condition specified as a repeated measure within-subjects, and subject ID as a random effect, each with their own intercept. Alternative covariance structures including (scaled identity, unstructured and diagonal) were examined using Akaike's Information Criterion and for the most part demonstrated that AR(1) consistently provided the best model fit. Given statistically significant age and hearing threshold differences between groups, age and hearing threshold were included as a covariate and random effect. The prior night noise condition was included to test for potential carry-over/order effects between nights and adjusted for when significant order effects were present. Statistically significant main or interaction effects were examined using Sidak adjusted pairwise comparisons within each linear model following adjustment for significant order effects when present.

Spearman's rank correlations (r_s) were used to explore associations between perceived noise sensitivity and changes in PSG and sleep diary determined sleep efficiency in the presence of WTN-Continuous versus control conditions. Spearman's rank correlations (r_s) were also used to explore associations between noise sensitivity and sleep efficiency in the control condition alone. These analyses were also carried out for PSG and sleep diary determined total sleep time, wake after sleep onset, sleep latency, number of awakenings, time in bed as well as PSG sleep stage outcomes.

Bland-Altman analyses were also conducted to assess for potential bias between the primary and secondary PSG and sleep diary parameters listed above. Pearson chi-square tests were used to test for differences in proportions of individuals within each

group with different characteristics, including sleep efficiencies <85% and sleep latencies of >30 and >20 minutes in the WTN-Continuous and control conditions. This was to allow for comparisons with previous studies using commonly used cut-offs for discriminating good sleep from poor sleep (American Academy of Sleep Medicine, 2014; Jalali et al., 2016a; Lichstein et al., 2003; Lineberger et al., 2006). Pearson chi-square tests were also used to test for differences in the proportion of individuals within each group who had high perceived noise sensitivity scores (>78) (Weinstein, 1978). In a secondary analysis, perceived noise sensitivity was also included as a covariate along with age to test and adjust for potential effects on PSG and sleep diary determined sleep efficiency.

Finally, paired samples t-tests were used to determine if participant's self-reported sleep efficiency, sleep latency, total sleep time and wake after sleep onset two weeks prior to their sleep study at home differed compared to self-reported sleep in the laboratory during the control and WTN-Continuous conditions, and for each participant group separately. All data are presented as median (IQR) unless otherwise specified. *p* values <0.05 were considered statistically significant.

4.3 RESULTS

4.3.1 Study participants

Figure 4.2 shows a CONSORT (Consolidated Standards of Reporting Trials) diagram of the number of individuals screened from which 68 participants aged 18-80 years participated in the study. From 240 individuals responding to study advertisements, 172 were excluded (104 declined to participate, 65 did not meet the study criteria and three resided interstate and were unable to travel given extended COVID-19 border restrictions). Further reasons for exclusion included urban residents not reporting RTN

related sleep disruption and faster recruitment into the RTN-sleep disturbed group risking group imbalance away from the primary WTN exposure groups of interest.

Demographics and baseline sleep characteristics of the study participants are presented in Table 4.1. The majority of participants (61/68 or 89.7% of the overall sample) were of Caucasian/European descent, with no differences in proportions between groups. On average, participants in the WTN-sleep disturbed and WTN-non sleep disturbed groups lived between 2-4 and 4-6 kilometres from the nearest wind turbine respectively. All rural and RTN-sleep disturbed participants indicated living >10km from a wind turbine. The WTN-sleep disturbed group lived on average 0.9 kilometres from the nearest road traffic noise source, compared to 0.4 kilometres, 0.4 kilometres and 0.2 kilometres for the WTN-non sleep disturbed group, rural control, and RTN-sleep disturbed group respectively.

There were significant age differences between groups, where the WTN-sleep disturbed group was significantly older than the rural control (mean [95% CI] difference 19.6 [4.1 to 35.0] years, p=0.006) and RTN-sleep disturbed group (32.8 [17.4 to 48.2] years, p<0.001) and the WTN-non sleep disturbed group was significantly older than the RTN-sleep disturbed group (20.7 [6.3 to 35.2] years, p=0.001) (Table 4.1). Given age differences, all further analyses were adjusted for age. After age adjustment, the WTN-sleep disturbed group showed significantly higher ESS, ISI, PSQI, perceived noise sensitivity scores and hearing thresholds for frequencies 125-1000 Hertz compared to the rural control group, and higher ISI and PSQI scores than the RTN-sleep disturbed group (Table 4.1). The WTN-non sleep disturbed group had significantly greater BMI scores compared to the RTN-sleep disturbed group. Noise sensitivity scores were also higher in the WTN-sleep disturbed group versus the rural control group (Table 4.1).

By participant selection design, there was significantly greater self-reported WTN related sleep disruption in the WTN-sleep disturbed group, in the moderate-severe

disruption range, versus the three other groups. There was also significantly greater, and moderate-to-severe, self-reported RTN related sleep disruption in the RTN-sleep disturbed versus the three other groups who reported no or mild disruption. However, there were no further differences in baseline measures of sleep time or quality between groups (Table 4.1).

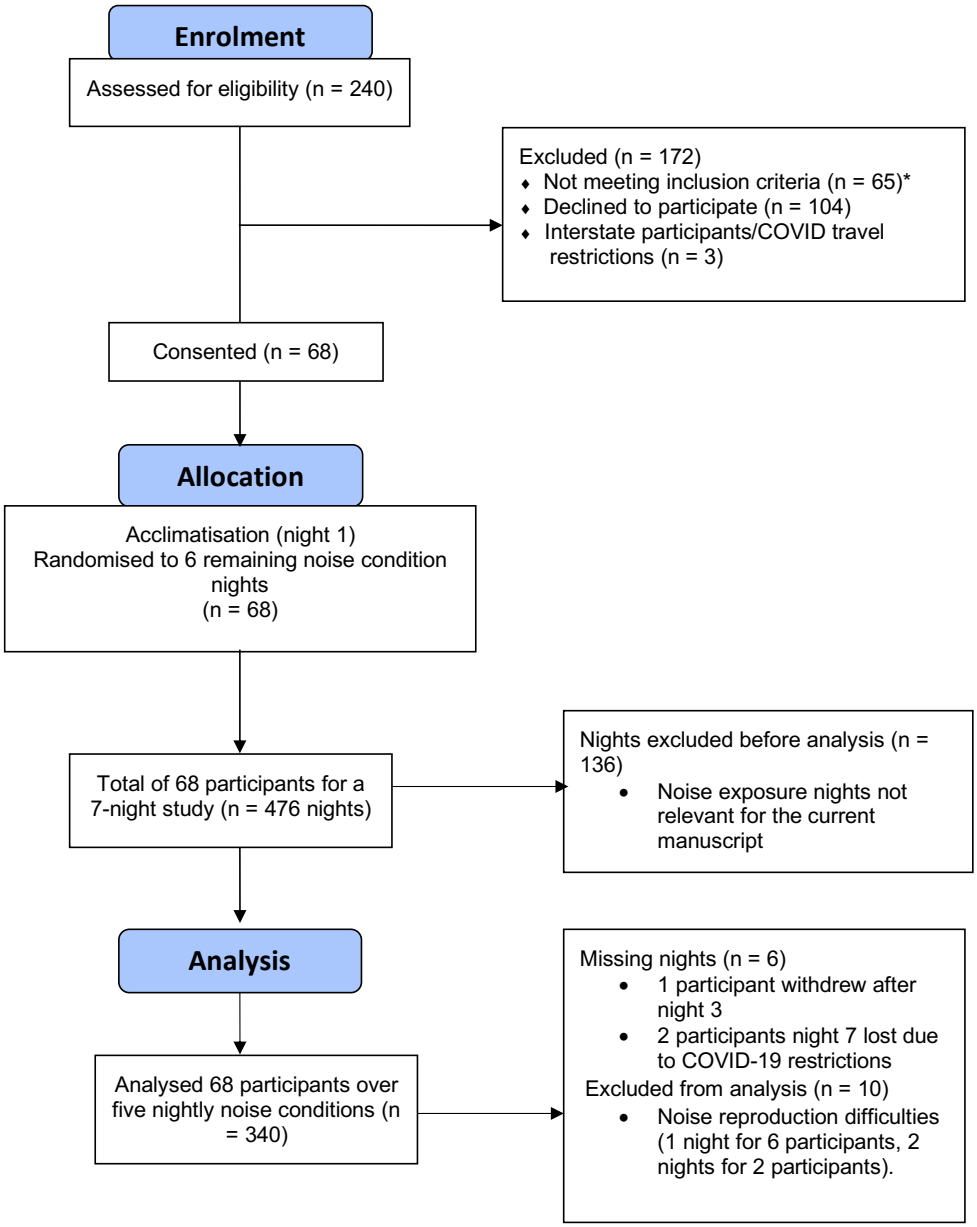

Figure 4.2 CONSORT flow diagram showing the process from enrolment into the study to analysis (Schulz, Altman, & Moher, 2010).

Note. *Reasons for exclusion included urban residents not reporting RTN related sleep disruption or recruitment capacity reached for the RTN-sleep disturbed group. RTN=Road Traffic Noise.

Table 4.1 *Participant demographics and baseline at-home sleep monitoring.*

Characteristic	WTN-Sleep Disturbed	WTN-Non Sleep Disturbed	Rural Control	RTN-Sleep Disturbed	*p*-value
Demographics					
Females:Males N (%)	7:7 (50:50%)	9:9 (50:50%)	14:4 (78:22%)	8:10 (44:56%)	0.092
Age (years)	66.3±6.9	54.2±16.3	46.7±20.7*	33.5±15.1*‡	<0.001
BMI (kg/m^2)	27.7±3.4	29.9±5.0	27.9±5.8	24.8±5.9‡	0.039
ESS	9.4±4.2	5.5±4.0	4.6±2.8*	6.3±5.2	0.014
ISI	12.6±5.9	7.8±5.1	6.3±3.2*	6.5±4.3*	0.003
PSQI	10.9±3.5	7.5±3.7	6.2±3.1*	6.2±3.2*	0.001
Weinstein Noise Sensitivity[a]	70.9±14.1	61.6±18.8	52.9±13.6*	65.4±17.4	0.019
Degree of WTN related sleep disruption[b]	3.7±1.3	1.0±0.0*	1.0±0.0*	1.0±0.0*	<0.001
Degree of RTN related sleep disruption[b]	1.6±1.2	1.5±0.9	1.3±0.5	3.5±0.8*‡†	<0.001
Hearing Level 125Hz-1000Hz (dB HL)[c]	15.7±14.5	10.0±10.1	8.3±11.2	6.1±6.3*	0.031
Baseline At-Home Self-Reported Sleep Monitoring					
Habitual bed time (hrs:mins)	22:42±1:30	22:36±3:42	22.48±2:36	23:18±2:24	0.193
Habitual wake time (hrs:mins)	6:30±1:0	7:18±1:30	7:06±1:18	7:30±1:54	0.208
Total sleep time (hrs)	7.0±1.5	7.2±1.4	7.3±1.3	7.6±1.6	0.109
Sleep latency (min)	17.2±25.7	24.7±30.7	19.3±20.4	23.0±25.6	0.740
Sleep efficiency (%)	95.6±21.6	93.6±20.1	199.0±465.4*	96.7±20.8	0.364
Wake after sleep onset (min)	39.2±44.7	30.9±45.5	27.9±40.0	23.1±30.8	0.304
Number of awakenings	2.1±1.4	2.1±1.8	1.7±1.5	1.8±1.6	0.474

Note. N=68. Values are M±SD. All *p* values reflect untransformed data. WTN=Wind Turbine Noise. RTN=Road Traffic Noise. BMI=Body Mass Index. ESS=Epworth Sleepiness Scale. ISI=Insomnia Severity Index. PSQI=Pittsburgh Sleep Quality Index. dB=decibel. HL=Hearing Level. [a] Cut-offs for the Weinstein Noise Sensitivity Scale= >78 indicates high noise sensitivity, scores <26 indicate low noise sensitivity based on upper and lower quartiles of the original study (Weinstein, 1978). [b] scored on a 5-point Likert scale (1 = not at all, 2 = mildly, 3 = moderately, 4 = severely, 5 = very severely) regarding “noise from wind turbines/road traffic bother, disturb or annoy you while you are in bed trying to sleep within the last 12 months”. [c] Normal hearing range <20 dB HL. $p<0.05$ *versus WTN-sleep disturbed group, ‡versus the WTN-non sleep disturbed group, †versus the rural control group. *Sleep efficiency calculation illustrates participants inaccurate reporting time in bed and total sleep time.

4.3.2 First-night effects

There were significant differences between nights for PSG total sleep time (p=0.005), time in bed (p=0.039), time spent in REM sleep (p<0.001), N1 % (p=0.003), N2 % (p<0.001), N3 % (p<0.001), REM latency (p=0.016) and total wake time (p=0.034).

Pairwise comparisons revealed significantly lower PSG total sleep time in the acclimatisation night compared to the control night (p=0.019), the WTN-sleep night (p=0.005) and the WTN-Continuous night (p=0.037). Furthermore, there was significantly lower PSG time in bed in the acclimatisation night compared to the WTN-Sleep (p=0.033) night and significantly lower time spent in REM, N1 %*, N2 % and N3 % in the acclimatisation night compared to all four noise exposure conditions (all p's<0.05). REM latency was also significantly longer on the acclimatisation night compared to the control night (p=0.010). Total wake time was also significantly greater in the acclimatisation night compared to the WTN-Sleep night (p=0.044).

There were no other significant differences between nights for any other PSG or sleep diary determined sleep parameters. First night effects were controlled by acclimatisation night inclusion and randomisation of subsequent nights, so the acclimatisation night (night 1) was excluded in further analyses.

4.3.3 Group-by-noise condition interaction effects

Figure 4.3(A) shows PSG and sleep diary determined sleep efficiency during the background noise (control), WTN-Continuous, WTN-Sleep and WTN-Wake exposure conditions within each group as well as the overall group effect irrespective of noise condition (combined) and shaded plots that indicate the overall noise condition effect irrespective of group. Figure 4.3(B) shows change in PSG sleep efficiency and sleep diary sleep efficiency from the control condition for each noise condition including a combined noise condition effect within each group and the overall noise condition effect irrespective

of group (shaded plots). Tables 4.2 and 4.3 show the descriptive statistics for PSG and sleep diary determined sleep outcomes for each group and across each noise condition respectively and Table 4.4 shows the descriptive statistics for PSG sleep stage outcomes for each group and across each noise condition. As indicated by Figure 4.3(A) and Figure 4.3(B), there were no significant group-by-noise condition interaction effects on PSG or sleep diary determined sleep efficiency. Furthermore, Tables 4.2, 4.3 and 4.4 show no significant group-by-noise condition interaction effects on PSG or sleep diary determined sleep latency, wake after sleep onset, total sleep time, time in bed, number of awakenings or any PSG determined sleep stage outcomes (see Appendices 4-7 for further details).

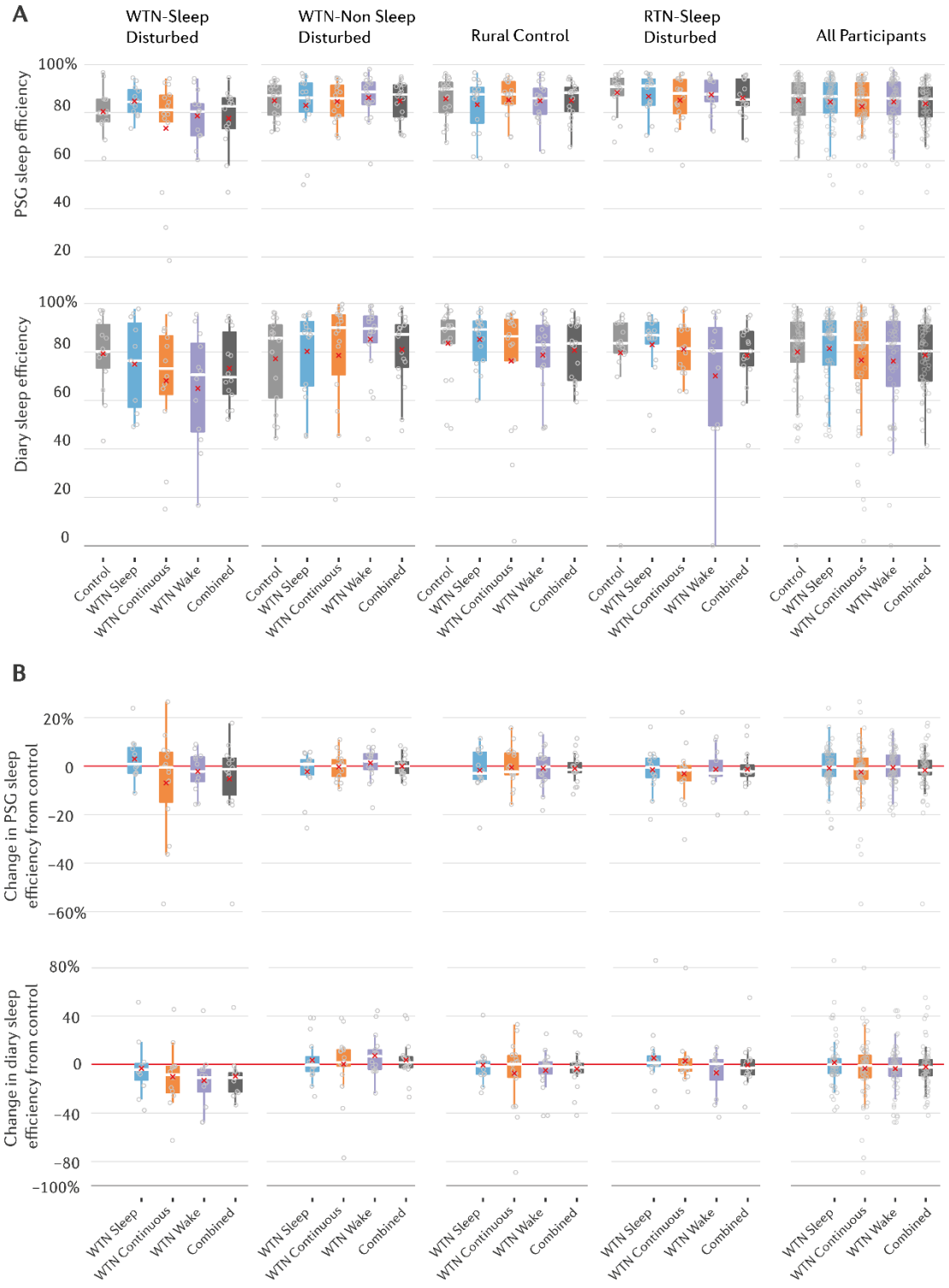

*Figure 4.3 Box and whisker plots showing **(A)** PSG sleep efficiency (%) (upper panel) and sleep diary determined sleep efficiency (%) (second panel) across groups and noise conditions and **(B)** difference scores from control (for each WTN condition) for PSG and sleep diary determined sleep efficiency for each group.*

Note. Plots depict group mean (X) and median (gaps) for each group (WTN-sleep disturbed, n=14; WTN-non sleep disturbed, n=18; rural control, n=18; RTN-sleep disturbed, n=18; and across all participants, n=68) and under each noise condition (control background noise, WTN-continuously across the night, WTN-only during sleep periods, WTN-only during wake period exposures and combined across all noise conditions). The box bounds the IQR divided by the median. Whiskers are Tukey-style (extend to a maximum 1.5 x IQR beyond the box as described in Krzywinski and Altman (2014). Circles indicate individual data points. PSG=Polysomnography. WTN=Wind Turbine Noise. RTN=Road Traffic Noise.

Table 4.2 Median [IQR] PSG sleep outcomes for each group and noise condition.

Group	Noise condition	Sleep Efficiency (%)	Sleep Latency (mins)	Total Sleep Time (mins)	Wake After Sleep Onset (mins)	Time Spent in Bed (mins)	Number of Awakenings (n)
WTN-Sleep Disturbed	Control	79.8 [76.3 to 85.5]	5.3 [3.1 to 11.9]	430.3 [398.3 to 439.3]	97.8 [66.8 to 116.9]	509.3 [488.1 to 535.4]	31.5 [24.5 to 44.0]
	WTN-Continuous	81.1 [76.2 to 87.1]	7.3 [6.1 to 13.6]	407.3 [339.6 to 452.5]	85.3 [48.8 to 126.6]	494.8 [455.1 to 548.0]	34.0 [19.0 to 40.3]
	WTN-Sleep	84.4 [80.2 to 89.4]	6.0 [3.5 to 10.9]	438.0 [414.6 to 458.5]	67.5 [55.0 to 89.4]	510.8 [480.3 to 539.9]	30.5 [23.8 to 35.3]
	WTN-Wake	80.4 [70.5 to 83.5]	10.0 [6.5 to 16.5]	418.0 [383.5 to 428.0]	79.0 [52.0 to 143.0]	526.5 [467.0 to 539.0]	27.0 [26.0 to 32.0]
WTN-Non Sleep Disturbed	Control	87.1 [79.1 to 91.2]	10.8 [9.3 to 19.9]	439.0 [396.9 to 466.5]	46.3 [31.5 to 80.8]	513.0 [473.0 to 541.3]	31.0 [27.3 to 45.0]
	WTN-Continuous	85.9 [78.6 to 91.2]	13.3 [5.5 to 17.0]	440.3 [394.9 to 477.0]	60.5 [26.3 to 82.8]	518.8 [473.0 to 531.8]	35.0 [22.3 to 47.3]
	WTN-Sleep	86.2 [80.4 to 92.2]	10.0 [6.5 to 19.0]	430.5 [384.8 to 482.0]	51.0 [22.8 to 92.8]	506.5 [462.3 to 537.5]	29.0 [24.0 to 31.0]
	WTN-Wake	88.6 [83.5 to 92.5]	11.8 [8.8 to 16.9]	444.8 [403.0 to 476.1]	38.5 [29.5 to 68.0]	509.5 [471.0 to 543.5]	33.5 [23.0 to 39.8]
Rural Control	Control	89.8 [80.1 to 92.5]	15.5 [8.6 to 34.1]	446.3 [411.5 to 467.9]	33.5 [19.5 to 64.9]	510.5 [494.8 to 555.6]	30.5 [20.5 to 38.8]
	WTN-Continuous	87.6 [83.6 to 92.8]	18.0 [8.9 to 22.5]	439.3 [396.0 to 497.4]	52.0 [18.9 to 70.4]	513.8 [467.9 to 539.4]	31.5 [18.3 to 42.0]
	WTN-Sleep	87.6 [75.7 to 90.4]	12.8 [8.8 to 22.0]	425.8 [386.1 to 478.0]	49.0 [23.1 to 125.8]	512.3 [476.5 to 542.6]	30.0 [20.8 to 40.0]
	WTN-Wake	86.0 [79.4 to 89.9]	17.5 [7.9 to 22.9]	431.5 [416.0 to 474.3]	48.5 [20.0 to 75.4]	506.3 [482.1 to 534.8]	30.0 [21.3 to 37.5]
RTN-Sleep Disturbed	Control	90.7 [87.2 to 94.2]	16.3 [9.8 to 41.0]	410.5 [391.6 to 452.4]	19.5 [11.3 to 32.8]	477.3 [430.0 to 527.8]	22.0 [20.0 to 24.0]
	WTN-Continuous	88.0 [79.7 to 93.6]	17.3 [10.1 to 21.5]	447.5 [405.3 to 493.5]	37.3 [15.4 to 56.1]	525.5 [469.6 to 569.1]	31.5 [20.8 to 37.5]
	WTN-Sleep	91.1 [83.2 to 93.8]	15.0 [7.9 to 24.1]	447.5 [372.8 to 492.0]	24.3 [15.3 to 58.1]	513.0 [444.6 to 566.9]	27.5 [26.8 to 30.3]
	WTN-Wake	87.6 [84.8 to 93.3]	19.0 [9.0 to 37.0]	427.5 [392.0 to 468.0]	20.5 [12.0 to 48.0]	509.0 [420.0 to 527.5]	27.0 [17.0 to 35.0]

Note. Values represent Median [IQR] for each participant group (WTN-sleep disturbed, n=14; WTN-non sleep disturbed, n=18; rural control, n=18 and RTN-sleep disturbed, n=18) under each noise condition. WTN=Wind Turbine Noise. RTN=Road Traffic Noise. mins=minutes. n=number.

Table 4.3 Median [IQR] sleep diary determined sleep outcomes for each group and noise condition.

Group	Noise condition	Sleep Efficiency (%)	Sleep Latency (mins)	Total Sleep Time (mins)	Wake After Sleep Onset (mins)	Time Spent in Bed (mins)	Number of Awakenings (n)
WTN-Sleep Disturbed	Control	80.2 [73.4 to 91.3]	20.0 [11.3 to 27.5]	405.0 [360.0 to 448.8]	75.0 [18.8 to 112.5]	517.5 [482.5 to 558.8]	3.0 [1.3 to 3.0]
	WTN-Continuous	73.2 [62.5 to 86.6]	30.0 [18.8 to 60.0]	420.0 [285.0 to 431.8]	120.0 [48.8 to 165.0]	540.0 [507.3 to 577.5]	2.5 [2.0 to 3.8]
	WTN-Sleep	76.4 [57.3 to 91.8]	30.0 [10.0 to 60.0]	420.0 [330.0 to 457.5]	60.0 [18.8 to 135.0]	550.0 [495.0 to 576.0]	3.0 [2.0 to 5.0]
	WTN-Wake	70.6 [47.1 to 83.6]	30.0 [15.0 to 70.0]	365.0 [262.5 to 426.3]	120.0 [30.0 to 180.0]	550.0 [472.5 to 566.3]	3.0 [2.0 to 5.0]
WTN-Non Sleep Disturbed	Control	85.7 [61.1 to 91.1]	20.0 [15.0 to 35.0]	450.0 [360.0 to 490.0]	60.0 [20.0 to 150.0]	540.0 [520.0 to 585.0]	2.0 [1.0 to 4.0]
	WTN-Continuous	90.1 [70.6 to 95.2]	20.0 [11.3 to 56.3]	425.0 [360.0 to 480.0]	30.0 [11.3 to 103.8]	517.5 [490.0 to 543.8]	2.0 [1.0 to 4.0]
	WTN-Sleep	88.0 [76.4 to 93.3]	20.0 [15.0 to 30.0]	440.0 [397.5 to 475.0]	30.0 [15.0 to 90.0]	495.0 [465.0 to 540.0]	3.0 [2.0 to 3.0]
	WTN-Wake	89.6 [83.9 to 94.7]	15.0 [10.0 to 30.0]	425.0 [411.3 to 480.0]	22.5 [15.0 to 57.5]	517.5 [476.3 to 547.5]	2.0 [0.3 to 4.0]
Rural Control	Control	89.7 [83.5 to 93.0]	20.0 [10.0 to 30.0]	450.0 [425.0 to 475.0]	15.0 [10.0 to 63.8]	500.0 [483.3 to 573.8]	2.5 [1.3 to 4.0]
	WTN-Continuous	86.5 [76.4 to 93.4]	22.5 [15.0 to 30.0]	440.0 [375.0 to 483.8]	45.0 [10.0 to 115.0]	532.5 [490.0 to 550.0]	2.0 [1.0 to 4.8]
	WTN-Sleep	89.8 [76.1 to 92.7]	20.0 [15.0 to 32.5]	465.0 [417.5 to 500.0]	30.0 [17.5 to 67.5]	520.0 [506.3 to 545.0]	2.0 [1.8 to 3.3]
	WTN-Wake	82.9 [73.9 to 90.9]	25.0 [16.3 to 37.5]	462.5 [420.0 to 480.0]	50.0 [22.5 to 92.5]	532.5 [506.3 to 592.5]	3.0 [1.3 to 3.8]
RTN-Sleep Disturbed	Control	83.6 [79.7 to 91.9]	30.0 [15.0 to 30.0]	410.0 [378.8 to 450.0]	40.0 [28.8 to 60.0]	477.5 [450.0 to 519.0]	2.0 [1.0 to 2.3]
	WTN-Continuous	81.4 [72.9 to 89.7]	25.0 [18.8 to 60.0]	420.0 [356.3 to 482.5]	50.0 [8.8 to 63.8]	513.0 [477.5 to 545.5]	2.0 [1.0 to 3.3]
	WTN-Sleep	86.9 [83.5 to 92.1]	20.0 [18.0 to 30.0]	420.0 [412.5 to 457.7]	35.0 [27.5 to 60.0]	500.0 [454.3 to 562.5]	3.0 [2/0 to 4.0]
	WTN-Wake	80.5 [49.6 to 90.0]	30.0 [18.8 to 32.5]	427.5 [345.0 to 451.3]	60.0 [0.0 to 90.0]	477.5 [420.0 to 555.0]	1.5 [0.8 to 2.3]

Note. Values represent Median [IQR] for each participant group (WTN-sleep disturbed, n=14; WTN-non sleep disturbed, n=18; rural control, n=18 and RTN-sleep disturbed, n=18) under each noise condition. WTN=Wind Turbine Noise. RTN=Road Traffic Noise. mins=minutes. n=number.

Table 4.4 Median [IQR] PSG sleep stage outcomes for each group and noise condition.

Group	Noise condition	N1 (mins)	N2 (mins)	N3 (mins)	REM (mins)	N1 %	N2 %	N3 %	REM %	N2 Latency (mins)	N3 Latency (mins)	REM Latency (mins)	Total Wake Time (mins)
WTN-Sleep Disturbed	Control	32.3 [26.6 to 63.3]	195.3 [171.0 to 208.5]	94.8 [56.1 to 118.3]	86.0 [59.5 to 109.9]	9.9 [6.0 to 14.6]	45.6 [42.1 to 52.3]	23.1 [12.9 to 28.3]	21.0 [18.2 to 26.4]	7.0 [4.3 to 15.5]	25.3 [20.0 to 38.8]	68.8 [58.8 to 118.4]	106.3 [73.8 to 130.3]
	WTN-Continuous	29.0 [21.6 to 35.9]	192.8 [157.4 to 214.5]	101.5 [64.1 to 112.6]	84.8 [42.4 to 109.1]	8.6 [5.9 to 10.9]	45.5 [43.3 to 49.8]	24.8 [20.9 to 29.1]	22.7 [17.3 to 24.9]	11.5 [8.8 to 19.9]	26.5 [21.4 to 36.5]	81.3 [66.1 to 97.8]	95.5 [56.0 to 134.0]
	WTN-Sleep	37.8 [24.4 to 43.9]	199.8 [179.9 to 212.1]	107.3 [59.5 to 119.4]	101.3 [71.1 to 113.1]	8.2 [5.5 to 11.1]	45.8 [41.8 to 50.9]	24.2 [14.1 to 28.6]	23.8 [16.7 to 25.9]	11.0 [5.4 to 13.5]	19.5 [12.4 to 28.3]	77.3 [67.8 to 175.5]	75.8 [55.9 to 98.5]
	WTN-Wake	30.5 [28.0 to 47.5]	186.5 [158.5 to 212.5]	65.5 [39.5 to 122.0]	91.5 [73.0 to 99.0]	7.7 [7.1 to 12.1]	44.4 [40.3 to 52.5]	20.8 [11.4 to 28.8]	23.0 [20.3 to 25.8]	11.5 [9.5 to 17.5]	29.5 [19.5 to 51.5]	110.5 [74.0 to 126.0]	101.0 [85.5 to 155.0]
WTN-Non Sleep Disturbed	Control	41.8 [28.8 to 64.9]	199.5 [169.9 to 220.4]	83.0 [44.6 to 116.4]	96.8 [76.0 to 105.9]	9.5 [7.5 to 16.9]	44.9 [42.2 to 51.3]	20.1 [10.8 to 26.7]	20.2 [18.4 to 25.4]	17.3 [13.6 to 23.5]	40.0 [30.8 to 59.5]	92.8 [79.1 to 124.3]	66.8 [42.6 to 91.4]
	WTN-Continuous	42.8 [23.0 to 67.5]	199.3 [178.8 to 216.5]	73.3 [45.3 to 118.6]	92.0 [82.6 to 105.6]	10.9 [5.0 to 17.3]	45.3 [40.3 to 52.7]	15.8 [12.5 to 26.3]	21.6 [19.8 to 26.3]	16.0 [9.6 to 21.4]	33.0 [26.4 to 46.8]	109.3 [72.0 to 145.3]	75.3 [41.0 to 107.9]
	WTN-Sleep	41.0 [21.5 to 52.3]	197.5 [160.8 to 215.0]	80.0 [65.3 to 113.8]	106.0 [76.5 to 117.0]	8.7 [5.9 to 14.6]	45.6 [39.3 to 49.1]	19.5 [15.9 to 23.9]	23.5 [19.8 to 26.4]	14.0 [10.8 to 21.5]	30.0 [22.0 to 43.8]	91.5 [59.5 to 109.0]	64.5 [41.0 to 99.3]
	WTN-Wake	51.3 [26.4 to 59.3]	197.5 [174.3 to 230.3]	71.8 [45.8 to 110.0]	103.8 [81.0 to 120.5]	11.4 [5.8 to 16.1]	44.4 [38.7 to 52.1]	14.5 [11.9 to 26.4]	22.9 [19.1 to 28.8]	16.5 [11.3 to 20.3]	32.3 [25.5 to 39.6]	85.8 [76.6 to 99.3]	55.3 [40.6 to 85.0]
Rural Control	Control	31.3 [26.6 to 53.6]	219.8 [184.1 to 242.4]	80.0 [49.0 to 113.6]	108.3 [84.4 to 120.4]	7.3 [5.4 to 12.3]	46.3 [43.0 to 51.3]	18.3 [11.5 to 25.1]	24.4 [19.4 to 27.2]	18.8 [11.5 to 35.8]	31.8 [22.0 to 50.9]	90.0 [79.5 to 113.4]	50.5 [37.5 to 101.5]
	WTN-Continuous	33.0 [27.3 to 47.9]	202.3 [190.8 to 236.3]	83.3 [53.6 to 116.0]	97.5 [88.4 to 121.0]	7.7 [5.5 to 14.6]	48.0 [41.3 to 51.8]	18.9 [15.2 to 27.2]	22.7 [19.3 to 24.9]	21.3 [10.5 to 29.5]	38.3 [28.5 to 47.0]	97.3 [86.4 to 117.4]	60.8 [34.9 to 84.8]
	WTN-Sleep	36.8 [26.0 to 55.6]	186.5 [163.3 to 218.1]	88.0 [74.0 to 112.3]	96.5 [75.6 to 137.6]	8.5 [5.3 to 14.5]	45.5 [41.5 to 49.8]	21.0 [15.8 to 24.0]	24.0 [19.0 to 28.4]	19.3 [14.1 to 33.1]	33.5 [23.5 to 47.6]	100.8 [80.4 to 114.3]	62.0 [43.1 to 135.9]
	WTN-Wake	31.3 [23.8 to 51.6]	215.5 [179.6 to 230.3]	88.5 [63.3 to 122.6]	91.8 [79.8 to 107.9]	7.0 [5.2 to 12.1]	46.5 [42.2 to 52.6]	21.0 [14.7 to 26.4]	21.6 [18.7 to 24.8]	20.3 [10.4 to 24.8]	33.5 [28.5 to 48.3]	93.5 [77.4 to 103.1]	69.5 [52.0 to 98.9]
RTN-Sleep Disturbed	Control	27.3 [22.3 to 35.6]	196.3 [182.9 to 207.3]	90.8 [79.9 to 120.8]	97.8 [80.5 to 121.0]	7.0 [5.3 to 8.7]	47.9 [41.1 to 51.6]	23.1 [17.9 to 26.6]	23.6 [20.7 to 29.5]	20.5 [13.5 to 44.3]	31.5 [24.4 to 54.8]	100.5 [84.5 to 160.6]	46.8 [25.9 to 60.3]

Group	Noise condition	N1 (mins)	N2 (mins)	N3 (mins)	REM (mins)	N1 %	N2 %	N3 %	REM %	N2 Latency (mins)	N3 Latency (mins)	REM Latency (mins)	Total Wake Time (mins)
	WTN-Continuous	36.8 [25.5 to 50.1]	209.8 [195.5 to 230.8]	95.3 [67.3 to 119.4]	108.3 [97.8 to 120.4]	7.7 [6.1 to 11.9]	47.3 [42.9 to 49.9]	21.8 [18.1 to 24.5]	24.4 [21.9 to 25.5]	20.5 [14.4 to 26.3]	30.8 [25.6 to 60.1]	111.5 [81.1 to 136.3]	65.3 [35.8 to 101.8]
	WTN-Sleep	37.8 [21.9 to 48.4]	210.3 [184.0 to 230.6]	92.3 [72.9 to 110.4]	114.3 [91.3 to 134.4]	8.5 [5.6 to 10.5]	46.4 [41.0 to 49.5]	20.9 [16.1 to 24.9]	24.8 [22.9 to 26.3]	23.8 [14.4 to 28.1]	35.3 [21.3 to 52.9]	104.5 [82.1 to 152.1]	52.8 [34.5 to 74.3]
	WTN-Wake	33.0 [24.0 to 42.0]	172.5 [146.5 to 199.5]	94.5 [90.0 to 125.5]	107.5 [95.5 to 112.0]	7.3 [5.7 to 8.2]	43.7 [35.8 to 47.4]	25.6 [20.6 to 28.7]	25.7 [20.2 to 27.8]	28.0 [12.5 to 55.0]	39.5 [23.5 to 67.0]	120.5 [88.0 to 144.0]	70.0 [28.5 to 86.0]

Note. Values are Median [IQR] for each participant group (WTN-sleep disturbed, n=14; WTN-non sleep disturbed, n=18; rural control, n=18 and RTN-sleep disturbed, n=18) under each noise condition. WTN=Wind Turbine Noise. RTN=Road Traffic Noise. mins=minutes.

There were also no significant differences in the proportions of participants with PSG or sleep diary sleep efficiencies <85% across the four participant groups during the WTN-Continuous condition (PSG: WTN-sleep disturbed 9/14, WTN-non sleep disturbed 9/18, rural control 6/18, RTN-sleep disturbed 7/16, p=0.367; Sleep diary: WTN-sleep disturbed 8/12, WTN-non sleep disturbed 7/18, rural control 8/18, RTN-sleep disturbed 10/16, p=0.336), control condition (PSG: WTN-sleep disturbed 9/14, WTN-non sleep disturbed 8/18, rural control 7/18, RTN-sleep disturbed 3/16, p=0.088, Sleep diary: WTN-sleep disturbed 8/14, WTN-non sleep disturbed 8/17, rural control 7/18, RTN-sleep disturbed 10/16, p=0.528). There were also no significant differences in the proportion of participants with sleep latencies >30 or >20 minutes between groups or conditions.

4.3.4 Prior nights noise condition main effects

There were no statistically significant main effects of prior night's noise condition, apart from PSG time in bed (p<0.01). However, no further PSG time in bed effects were apparent following adjustment for prior night condition effects.

4.3.5 Noise condition main effects

There were no statistically significant main effects of noise condition for Box-Cox transformed PSG or sleep diary determined sleep efficiency. The untransformed mean [95% CI] PSG determined sleep efficiency for the control, WTN-Sleep, WTN-Continuous and WTN-Wake condition was 86.4 [83.1 to 89.7], 85.5 [82.7 to 88.4], 85.3 [82.1 to 88.5] and 84.7 [81.9 to 87.6] % respectively. For the sleep diary determined sleep efficiency, the untransformed mean [95% CI] for the control, WTN-Sleep, WTN-Continuous and WTN-Wake condition was 79.9 [73.5 to 86.3], 83.2 [77.7 to 88.6], 75.1 [68.9 to 81.2] and 75.3 [69.9 to 80.6] % respectively. There were no other statistically significant main effects of noise condition for PSG or sleep diary determined sleep latency, wake after sleep onset,

total sleep time, number of awakenings, time spent in bed or any of the PSG sleep stage outcomes.

4.3.6 Group main effects

There were no statistically significant group main effects on Box-Cox transformed PSG or sleep diary determined sleep efficiency. The untransformed mean [95% CI] PSG determined sleep efficiency for the WTN-sleep disturbed group, WTN-non sleep disturbed group, the rural group and RTN-sleep disturbed group was 79.3 [73.6 to 85.0], 85.7 [81.4 to 90.1], 87.7 [83.8 to 91.5] and 88.7 [85.1 to 92.3] % respectively. For sleep diary determined sleep efficiency, the untransformed mean [95% CI] for the WTN-sleep disturbed group, WTN-non sleep disturbed group, the rural group and RTN-sleep disturbed group was 73.2 [64.8 to 81.5], 81.2 [73.7 to 88.7], 81.4 [73.8 to 89.0] and 78.5 [70.8 to 86.1] % respectively.

There was a significant main effect of group on PSG determined wake after sleep onset (p=0.004), which was higher in the WTN-sleep disturbed group (Mean [95%CI] 98.3 [65.4 to 131.2] min) than the rural group (38.1 [18.3 to 57.9] minutes, p=0.016) and the RTN-sleep disturbed group (32.0 [15.5 to 48.6] minutes, p=0.004), but there were no further main effects of group in sleep diary determined wake after sleep onset (See Appendix 8 for more details)

Although there was a statistically significant main effect of group (p=0.040) on total time spent in REM sleep (WTN-sleep disturbed group 82.4 [63.5 to 101.3] minutes, WTN-non sleep disturbed group 98.3 [85.8 to 110.9] minutes, rural group 105.7 [93.1 to 118.3] minutes and RTN-sleep disturbed group 111.8 [100.5 to 123.1] minutes) there were no significant post-hoc pairwise differences between groups (See Appendix 8). Furthermore, there were no other statistically significant main effects of group for PSG or sleep diary

determined sleep latency, total sleep time, number of awakenings, time spent in bed or any other PSG sleep stage outcomes.

4.3.7 PSG versus sleep diary parameters

Across all participants (all groups combined), all PSG sleep parameters were significantly positively correlated with their sleep diary determined counterparts under each of the noise exposure conditions (Appendix 9). Furthermore, Bland-Altman analysis showed no evidence to support systematic bias between PSG versus sleep diary sleep efficiency, sleep latency, total sleep time, wake after sleep onset or number of awakenings (all *p*'s >0.05).

4.3.8 At home monitoring versus in laboratory self-reported sleep outcomes

Self-reported wake after sleep onset in the WTN-Continuous condition was greater in the laboratory compared to at home in the WTN-sleep disturbed group (mean difference [95% CI] 122.6 [32.2 to 213.0] minutes, *p*=0.013), the rural control group (90.3 [12.6 to 167.9] minutes, *p*=0.025) and the RTN-sleep disturbed group (31.8 [8.1 to 55.5] minutes, *p*=0.012). Self-reported wake after sleep onset was also higher in the laboratory compared to home during the control condition in the WTN-non sleep disturbed group (83.4 [10.3 to 156.5] minutes, *p*=0.028) and the RTN-sleep disturbed group (33.9 [10.7 to 48.2] minutes, *p*=0.005); who also self-reported reduced total sleep time in the laboratory compared to at home (-1.6 [-3.1 to 0.09] hours, *p*=0.040) (See Appendix 10 for further details).

4.3.9 Perceived noise sensitivity

Twelve participants (17.6%) in total were classified as highly noise sensitive (>78 in top quartile of the Weinstein Noise Sensitivity Scale). However, there were no significant differences in the proportion of noise sensitive individuals between groups (*p*=0.070; 3/14 (21.4%) in the WTN-sleep disturbed group, 3/18 (16.7%) in the WTN-non sleep disturbed

group, 6/18 (33.3%) in the RTN-sleep disturbed group and none in the rural control group). After adjusting for age and noise sensitivity there remained no significant group, noise exposure condition or interaction effects on PSG or sleep diary determined sleep efficiency.

There was a significant negative correlation between noise sensitivity and PSG sleep efficiency in the control condition ($r_s(63) = -0.400$, $p<0.001$), but not for sleep diary determined sleep efficiency. However, there were no significant correlations between perceived noise sensitivity and the control minus WTN-Continuous condition sleep efficiency difference with either PSG sleep efficiency ($r_s(63) = -0.012$, $p=0.923$) or sleep diary determined sleep efficiency ($r_s(61) = 0.140$, $p=0.276$), or any other objective or subjective sleep parameters.

4.4 DISCUSSION

This is the largest laboratory study reported to date that has investigated the impact of WTN on PSG and sleep diary parameters. It was hypothesised that both objective PSG and sleep diary derived sleep parameters would be more disrupted, with more wake and less sleep, on the three WTN nights (WTN-Continuous, WTN-Sleep, WTN-Wake) compared to the quiet control night, with a greater difference in residents reporting WTN-related sleep disruption versus undisturbed residents. After adjusting for age and hearing thresholds, the WTN-sleep disturbed group showed significantly greater PSG wake after sleep onset than the rural and RTN-sleep disturbed group, but with no differences between noise conditions suggestive of poorer sleep overall. Wake after sleep onset increases with age, and in the oldest group, was perhaps greater than expected age-related normal values for healthy adults (WTN-sleep disturbed: mean [95% CI] 98.3 [65.4 to 131.2] minutes compared to ~70 minutes for healthy individuals between 66-83 years (Dikj, Groeger, Stanley & Deacon, 2010)). Furthermore, ISI scores were higher in the WTN-

sleep disturbed group compared to the rural control and RTN exposure groups and more suggestive of subthreshold insomnia (ISI 8-14) rather than clinical insomnia (ISI ≥15; Morin et al., 2011). ESS scores also tended to be higher but remained below the standard clinical cut off >10 for defining significant sleepiness (Johns, 1992). Furthermore, all groups showed PSQI global scores >5 suggestive of relatively poor self-reported sleep quality (Buysse et al., 2008), particularly in the WTN-sleep disturbed group. Therefore, despite no consistent in-laboratory WTN effects on sleep, the WTN-sleep disturbed group showed consistent evidence of poorer sleep overall compared to the remaining groups.

Failure to demonstrate significant effects of WTN exposure on the primary sleep efficiency outcome could potentially reflect Type II error. Based on previously reported data we estimated that this sample size had 80% power to detect an absolute difference in sleep efficiency in the order of 4.5% for group-by-noise condition comparisons and 1.8% between noise conditions. Based on average total sleep time of around 7 hours and 8.4 hours of time in bed (sleep efficiency 83%), this would equate to around a 19- and 7.5-minute difference in sleep time between groups and conditions respectively. However, the overall findings do not support significant group or condition effects on conventional PSG or sleep diary outcomes, or that residents living near a wind farm and reporting WTN related sleep disruption exhibit a conditioned response to WTN exposure at levels approximating typical levels in the field. Several first night effects were detected, supporting that WTN-specific exposure effects of a similar magnitude would likely also have been detected with this sample size.

These results are consistent with the previous laboratory study reported in Chapter 3, which found no significant differences in PSG or sleep diary sleep latency in the presence versus absence of WTN during the sleep onset period in healthy good sleepers not habitually exposed to WTN (Liebich et al., 2022). The current results are also consistent with the WiTNES study, which found no differences in PSG measured sleep

outcomes on WTN nights versus control nights in participants both with and without habitual WTN-exposure (Smith et al., 2020). However, in the WiTNES study, REM latency increased, and REM sleep time was reduced in WTN versus control nights (Smith et al., 2020), while in the current study there were no significant main effects of noise condition for REM sleep time. Subjective sleep outcomes were more difficult to compare with the WiTNES study, given the current study used the more widely used and psychometrically validated Consensus Sleep Diary (Carney et al., 2012), while the WiTNES study used a morning Likert rating scale to assess self-reported sleep disruption (Smith et al., 2020). In addition, the WiTNES study used a different noise delivery protocol to the current study, which involved varying synthesised WTN samples that had different noise levels and frequency content, whereas the current study used a real-world recorded WTN sample to approximate median WTN levels measured in the field (25 dB(A)).

The present results were also somewhat different from those reported by Ageborg Morsing et al. (2018) who found more awakenings and reduced N3 sleep during WTN exposure compared to quiet control nights, but no further significant effects on other objective or self-reported sleep outcomes. However, only six healthy participants without prior WTN exposure were studied and WTN exposures were more representative of outdoor WTN levels and thus worst-case exposure conditions compared to the current study (Ageborg Morsing et al., 2018; Haugen, 2011). In the current study 25 dB(A) is very similar to median yearly indoor WTN levels of 26 dB(A) recorded from another study (Nguyen et al., 2021). Effects of WTN on sleep are likely to be greatest during worst-case conditions, but the results from this study support that at median noise exposure levels, effects on sleep are relatively minimal.

Despite the WTN-sleep disturbed group self-reporting habitual WTN related sleep disruption, the proportion of insomnia-like symptoms, such as sleep latency >30 minutes and <85% sleep efficiency, were not significantly different from other groups, or impacted

by continuous WTN exposure compared to control conditions. There were also no differences in the proportion of participants with sleep latencies >20 minutes in the WTN-Continuous versus control condition. This finding is similar to a previous field study by Jalali et al. (2016a), which found that 12.5% of participants (n=2/16) showed sleep latencies >20 minutes post operational WTN exposure, with no difference compared to pre-operational WTN exposure, but also with no detectable change in environmental noise levels pre- versus post-operation suggesting WTN levels were below measurable limits.

ISI scores were higher in the WTN-sleep disturbed group compared to rural control and RTN exposure groups and more suggestive of subthreshold insomnia (ISI 8-14) rather than clinical insomnia (ISI ≥15 (Morin et al., 2011)). ESS scores also tended to be higher, but below the standard clinical cut off >10 for defining excessive daytime sleepiness (Johns, 1992). Furthermore, all groups showed mean PSQI global scores >5 suggestive of relatively poor self-reported sleep quality (Buysse et al., 2008), particularly in the WTN-sleep disturbed group who also showed higher PSG wake after sleep onset than in the rural control and RTN-sleep disturbed groups. Therefore, despite no consistent in-laboratory WTN effects on sleep, the WTN-sleep disturbed group showed consistent evidence of poorer sleep overall compared to the remaining groups.

Previous studies have also suggested that perceived noise sensitivity likely influences noise effects on sleep, such that individuals with higher noise sensitivity are more likely to report negative noise, including WTN, effects on sleep than those with lower noise sensitivity (Weinstein, 1978). Although there was a significant negative correlation between noise sensitivity and PSG sleep efficiency on the control night, this was not the case for sleep diary sleep efficiency, differences in PSG or sleep diary sleep efficiency, or any other sleep outcomes on control versus WTN-Continuous condition nights. Given no group, noise exposure condition or interaction effects on PSG or sleep diary sleep efficiency after controlling for age and noise sensitivity, these results do not support the

position that noise sensitivity influences 25 dB(A) WTN effects on sleep. These results are perhaps not surprising given the absence of WTN effects on sleep outcomes and similar previous findings in a sample of healthy individuals without habitual WTN exposure reported in Chapter 3 (Liebich et al., 2022).

4.4.1 Study limitations

The main limitation of this study is that SPL and other WTN characteristics are likely to become measurably sleep disruptive at higher exposure levels not examined in this study. The WTN sample used in this study was comparable to long-term median levels recorded in the field and contained prominent amplitude modulation that was anticipated to impair sleep. However, levels remained below recommended maximum indoor night-time noise limits, so the absence of detectable sleep disruption at the levels used in this study does not preclude the possibility of sleep disruption at higher levels closer to current noise guideline limits.

In this repeated measures laboratory study with multiple conditions the testing of more than one WTN level was logistically and financially infeasible. In retrospect, if a higher WTN level had been used and shown either negative or positive results, it would have been more informative. However, 25 dB(A) was chosen to test for possible disruption to sleep as measured by extended sleep latencies and night-time wakeful periods with WTN that was clearly audible while awake, especially in participants reporting WTN related sleep disruption. The negative results regarding sleep latency and wake after sleep onset measures, even in the WTN sensitive group, is thus informative.

Results from separate night experiments in the same study sample, including groups with different prior exposures and self-reported noise-related sleep difficulties, will be particularly useful to evaluate the sleep disruption characteristics of different levels of WTN compared to RTN exposure during established sleep.

Sleep itself is highly variable with marked changes in sensory acuity which depends on sleep depth. Consequently, the selected WTN sample was played on a 3-minute loop to facilitate tighter control over noise levels than is possible with longer and more variable noise samples. However, there is also the potential for variable annoyance levels during wake and habituation effects over time during wake and sleep to influence sleep propensity. WTN offset/onset could also have an alerting effect on participants due to the temporal profile of the WTN. Previous work supports that noise onset effects on sleep are relatively modest (Lechat et al., 2021a; Lechat et al., 2021c; Liebich et al., 2022; Dunbar et al., 2021), particularly at low but audible SPLs. Rapid onset/offset of WTN was considered important for evaluating potential sleep- versus wake-dependent WTN effects utilised in this study, whereas more tapered onsets have the potential to more variably influence attention towards WTN prior to sleep onset and the return to sleep from overnight wake periods.

Age was significantly different between groups and statistical adjustment using age as a covariate may not adequately control for age as a potential confounder for comparisons between groups. Furthermore, the overall degree of WTN related sleep disruption in the home environment was reported to be moderate in the WTN-sleep disturbed group. By study design, the intention was to capture residents living near wind turbines with the greatest degree of disturbance attributed to WTN most likely to exhibit sleep difficulties due to noise. This group showed some signs of more chronically disturbed sleep compared to the other groups, but at relatively modest levels below those typically used to classify chronic insomnia. However, it also remains unclear how representative the recruited sample might be of highly disturbed individuals. Several factors made this group particularly challenging to recruit including travel-distance to the sleep laboratory, COVID-19 travel restrictions, the time commitment necessary to accommodate the multi-night study protocol and reluctance of some individuals to engage

in research. In addition, the inclusion criterion of WTN-sleep disturbed and non-sleep disturbed participants residing <10 kilometres from the nearest wind turbine meant that participants could live some distance away from wind turbines where habitual WTN exposure are likely to be more variable and lower than closer distances. Study inclusion inevitably relied on somewhat arbitrary cut-offs from self-reports where more direct assessments of habitual noise exposure would clearly be preferable. Thus, several potential recruitment biases may have influenced study participation and between group comparisons. However, consistent WTN exposure effects would still be expected to be apparent from within-subjects comparisons between nights, for which this study also had substantially greater statistical power. Nevertheless, further research using higher noise exposure levels in noise-sensitive individuals remain warranted to establish WTN levels that objectively impact on the ability of nearby residents to sleep.

A further limitation was that the morning sleep diary did not capture the participant's perception of overnight WTN exposures compared to their usual experiences at home. The WTN-sleep disturbed group reported moderate WTN related sleep disruption at their residence but showed no significant differences in self-reported sleep disruption between control and WTN exposure conditions, potentially reflective of lower level WTN exposure in the laboratory compared to home environment. Alternatively, hyperawareness or hypervigilance towards the presence versus absence of WTN during the sleep period could have impacted responses on all study nights. Two-week at home sleep diary measures were largely not different from in-laboratory sleep diary outcomes, apart from greater self-reported wake after sleep onset in the laboratory compared to home. This could reflect factors beyond WTN effects, such as participant discomfort in the laboratory due to sleep equipment and/or sleeping in a foreign environment (Lee et al., 2016), in addition to noise impacts. However, we attempted to control these effects via an

acclimatisation night, randomisation of study nights, participant blinding of noise exposure conditions and comparisons between noise exposure versus a quiet control night.

4.4.2 Further research

Although effects of higher WTN levels remain unclear, the current study found no evidence to support that average WTN levels experienced around three kilometres from a wind farm have measurable impacts on objective or self-reported sleep outcomes in a carefully controlled laboratory setting. Although more representative of real-world WTN exposures, field studies lack sufficient control over extraneous variables such as, weather, wind speed, study blinding, nocebo effects amongst many other variables likely to confound underlying cause-and-effect relationships. Thus, a key next step for further research is to identify specific WTN features and SPLs that are more likely to be problematic for sleep and how these relate to real-world WTN exposure in the field. This will require appropriately controlled daytime listening tests and overnight exposure studies to understand dose-response relationships with annoyance and sleep disturbance compared to other noise types. Ultimately, noise policies and guidelines require appropriate evidence to protect public amenity around industries that generate noise, particularly at night.

In addition to further studies using higher WTN SPLs, more subtle microstructural effects of WTN on sleep warrant further examination given they are more sensitive to sleep disturbance than traditional measures of sleep macrostructure (Basner, Glatz, Griefahn, Penzel & Samel, 2008; Carter, Hunyor, Crawford, Kelly & Smith, 1994; Guilleminault, Stoohs, Clerk, Cetel & Maistros, 1993). For example, using power spectral analysis, subtle yet significant SPL and sleep stage effects of WTN compared to RTN have been demonstrated in healthy sleepers (Dunbar et al., 2021). Odds ratio product, a sensitive objective marker of sleep depth has also been shown to identify subtle sleep

changes to sleep with nocturnal traffic noise (Smith et al., 2021). Other spectral features (Lechat et al., 2021b) and K-complex responses to WTN versus RTN (Lechat et al., 2021a) may also be more sensitive and useful markers of sleep disruption than traditional metrics and warrant further examination in WTN exposed residents who do and do not self-report WTN related sleep disruption at home and in the laboratory when exposed to much higher WTN SPLs.

The potential for WTN exposure to effect daytime outcomes such as mood, anxiety and daytime performance also remains to be determined and warrants further investigation. Anecdotal data suggest that some residents living near wind farms report daytime impacts that they attribute to nocturnal WTN exposure (Harry, 2007; Krogh et al., 2011). Given the potential for both psychological factors and/or microstructural effects on sleep quality (Göder et al., 2006; Wichniak et al., 2003), mood and daytime performance could be impacted without necessarily objective changes in markers of sleep time or quality.

4.4.3 Conclusions

WTN impacts on PSG and sleep diary determined sleep macrostructure parameters were assessed in a carefully controlled sleep laboratory setting in a sample including four sub-groups: WTN exposed residents with and without self-reported prior WTN related sleep disruption, rural participants with no prior WTN exposure and RTN residents reporting RTN related sleep disruption. Despite an overall group main effect on PSG wake after sleep onset, there were no further significant noise condition or group main effects or group-by-noise interaction effects on other conventional objective and subjective markers of sleep time or quality. Overall, these results do not support that acute WTN exposures approximating median WTN exposure levels around three kilometres from a windfarm, measurably impact sleep assessed using conventional sleep scoring metrics,

including in individuals with self-reported sleep difficulties attributed to WTN living at a similar distance. However, further studies remain warranted to test for effects of higher WTN exposure levels on traditional sleep macrostructure outcomes, subtle microstructural sleep parameters and impacts on next-day mood, anxiety, and performance.

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Data availability statement

The data underlying this article will be shared on reasonable request to the corresponding author.

CHAPTER 5. AN EXPERIMENTAL INVESTIGATION OF THE EFFECT OF NOCTURNAL WIND TURBINE NOISE ON NEXT-DAY MOOD, ANXIETY AND COGNITIVE PERFORMANCE OUTCOMES

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TL contributed to study design, data collection, analysis and interpretation and manuscript preparation. LL, KH, BZ, GM, & PC contributed to conception and study design, interpretation of the data and drafting of the manuscript. BL, CD, DPN & HS contributed to data collection, data-analysis, data interpretation and drafting of the manuscript.

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ABSTRACT

Introduction: Daytime functioning impairments as a result of nocturnal wind turbine noise (WTN) exposure has been anecdotally reported by some residents living near wind turbines. However, experimental studies are lacking, and thus causal conclusions are unable to be determined. Wind turbine noise related daytime functioning impairments have the potential to occur via more subtle sleep disruption effects not captured by key sleep macrostructure outcomes or via psychological effects without necessarily any detectable sleep disruption. Thus, this controlled laboratory study sought to assess prior night WTN exposure effects on next-day sustained attention, memory, mood disturbance and state anxiety.

Methods: Sixty-eight participants aged (mean±SD) 49.2±19.5 (38 females, 30 males) from four different prior exposure condition groups were recruited; including residents living within 10 kilometres of a wind farm with and without self-reported WTN related sleep disruption; urban residents reporting RTN related sleep disruption; and control participants from quiet rural areas. Following an acclimatisation night, all participants were exposed to four different full-night conditions in random order; quiet control (background noise 19 dB(A)); continuous WTN (25 dB(A)) throughout the night; WTN (25 dB(A)) only during established sleep; and WTN (25 dB(A)) only during wake and N1 sleep. Group and noise condition effects on next-day mood, anxiety, and cognitive performance were examined via linear mixed effects model analyses.

Results: There was a small but statistically significant noise condition effect in digit span forwards recall, with greater recall following the WTN-Continuous night versus the WTN-Sleep night (p=0.048). However, there were no further significant noise condition or group-by-noise condition effects on any other mood, anxiety, or cognitive performance indicators (all p's >0.05).

Conclusion: Given no evidence of poorer outcomes in the presence of WTN compared to control conditions, this study does not support that nocturnal WTN exposure at 25 dB(A) in a carefully controlled environment negatively impacts next-day mood, anxiety, or cognitive performance.

Keywords: mood, anxiety, cognitive performance, wind farm, wind turbine, environmental noise.

An experimental investigation of the effect of nocturnal wind turbine noise on next-day mood, anxiety, and cognitive performance outcomes.

5.1 INTRODUCTION

Sleep disruption is anecdotally reported from residents living near wind turbines (Basner et al., 2014; Crichton et al., 2014; Janssen et al., 2011a; Krogh et al., 2011; Michaud et al., 2016). Unique acoustic features of WTN, including time-varying components such as amplitude modulation and the predominance of low frequencies that travel longer distances and penetrate building structures more readily than higher frequencies, could be more disruptive to sleep than other noise types. The awareness of any noise, including WTN prior to sleep onset and during awake periods across the night could contribute to annoyance and hyper-arousal, delay the initiation of sleep and promote more and longer wake periods across the night (Micic et al., 2018; Perlis et al., 1997; Riemann et al., 2010). Furthermore, sensory processing of WTN could also cause direct physiological disruption of sleep which could lead to subsequent daytime consequences. For example, a previous literature review has described that sleep disruption (i.e., sleep fragmentation) has the potential to lead to deficits in attention, working memory and cognitive processing speed, particularly when slow wave sleep (i.e., deep sleep) is disrupted (Reynolds & Banks, 2010). Furthermore, subtle sleep disruption (i.e., sleep fragmentation) effects associated with heart-rate acceleration (Griefahn, Bröde, Marks, & Basner, 2008) and peripheral vasoconstriction responses (Catcheside et al., 2002) could also still occur in the presence of WTN without necessarily eliciting more frequent cortical arousals or awakenings across the night and thus impact daytime functioning. For example, Martin, Wraith, Deary and Douglas (1997) showed that one overnight exposure to frequent brief pure-tone noise events (tones ranging between 38-101 dB) after reaching

N2 sleep, to elicit frequent autonomic activation responses but without more frequent arousals or awakenings or any change in total sleep time, caused increased next-day sleepiness (p=0.001) and mood disturbance (p<0.001) in 16 healthy participants. Furthermore, in healthy individuals not habitually exposed to WTN, Dunbar et al. (2021) also found subtle sleep stage and SPL dependent effects of WTN on quantitative power spectral analysis of EEG responses to noise, with some differences compared to RTN. Although not directly comparable to WTN exposure, previous research has also shown that nocturnal exposure to airplane, road, rail noise can lead to sleep disruption and subsequent daytime attention and memory deficits (Basner, Samel, & Isermann, 2006; Elmenhorst et al., 2010). Despite these other environmental stimuli being much greater in SPL than WTN, if WTN does disrupt sleep it could also produce next-day deficits in mood, anxiety, and cognitive performance outcomes such as impaired levels of alertness, sustained attention, processing speed and working memory in a similar way to these other environmental noise studies.

Previous environmental noise studies of aircraft, rail and traffic noise exposure during sleep have shown inconsistent effects on cognitive performance. Some studies have shown deficits in reaction time (Marks & Griefahn, 2007), mood disturbance (Martin et al.,, 1997) sustained attention, visual attention, and memory (Haines, Stansfeld, Job, Berglund, & Head, 2001; Meis et al., 2000; Sanz, Garcia, & Garcia, 1993). However, other studies have found no significant daytime impairments (Griefahn, Schuemer-Kohrs, Schuemer, Moehler, & Mehnert, 2000; Marks & Griefahn, 2005; Schapkin et al., 2006). Negative effects on mood, nervousness and irritability in response to WTN have been reported by some residents living near wind turbines in two self-reported survey-based studies (Pohl et al., 2018; Wolsink, 2000). However, methodological limitations associated with cross-sectional field studies with self-report outcomes preclude causal inference,

which ultimately requires controlled interventional study designs. In a controlled laboratory study of 50 participants, including 24 residents with and 26 residents without habitual WTN exposure, Smith et al. (2020) compared the effect of a WTN night (32 dB L_{AEq}) from 10:00pm to 7:00am versus a control background noise night (13 dB) on two mood dimensions including pleasantness and social orientation after the previous night via a self-report morning questionnaire. Results showed significantly lower feelings of pleasantness following the WTN night versus the control night, but with no difference between habitual WTN exposure and unexposed groups. Similar results occurred for self-reported irritation, with significantly increased irritation following the WTN night versus the control night and no differences between those with versus without prior WTN exposure. However, these subjects were not blinded to the study objectives nor WTN exposures and thus their psychological awareness and presenting WTN related annoyance could have confounded the results. Further impacts on next-day cognitive performance were also not assessed. However, given the study design involved varying WTN characteristics (e.g., amplitude modulation beats and frequencies) across the 8-hour sleep period, conclusions surrounding next-day cognitive performance would have been confounded by the varying WTN exposures used. As a result, carefully controlled experimental studies to further investigate the impact of WTN during the sleep period on next-day cognitive performance, mood and anxiety using psychometrically validated assessments remain warranted.

While the study reported in Chapter 4 found no evidence to support that WTN exposure significantly disrupts sleep as assessed with standard PSG sleep macrostructure variables, next-day impacts could still remain via more subtle microstructural changes in sleep quality and/or through indirect psychological effects associated with awareness and attitudinal factors. Thus, the purpose of this study was to examine the impact of realistic WTN exposure levels, equivalent to year-long median indoor levels recorded in the field

(25 dB(A)) and containing full-spectrum WTN characteristics including infrasound, low frequency noise and amplitude modulation during the sleep period (Nguyen et al., 2021) on next-day cognitive performance, mood, and anxiety in a controlled laboratory environment. Cognitive performance outcomes in the current study included measures of alertness, sustained attention, processing speed and working memory. To test for potential prior noise exposure, attitudinal or perceptual difference effects, the study sought to recruit two groups of residents who live within 10 kilometres of a wind farm, one with and one without reports of WTN related sleep disruption, a quiet rural control group and a further control group of urban residents reporting RTN related sleep disruption.

In addition, psychological factors such as knowledge, attitudes, and beliefs around WTN could promote both sleep disruption and problematic daytime impacts. Therefore, to further test for potential wake-dependent attitudinal or perceptual effects, the study also tested for wake versus sleep dependent WTN exposure effects across four different noise exposure nights including; a control background noise night (19 dB(A)); a full-night of 25 dB(A) WTN exposure; 25 dB(A) WTN exposure targeted to periods of EEG defined wake and light N1 sleep; and 25 dB(A) WTN exposure targeted during established sleep periods (N2, N3 and REM sleep). It was hypothesised that next-day mood, anxiety, and cognitive performance indicators would be more disrupted under the three WTN exposure conditions (WTN-Continuous, WTN-Wake and WTN-Sleep) versus quiet control background noise, and that differences would be greater for residents with prior WTN exposure and self-reported WTN related sleep disruption.

5.2 METHODS

5.2.1 Study setting and design

Participants spent seven consecutive nights in a sound attenuated bedroom (with average night-time background noise levels of 19 dB(A)) at the Adelaide Institute for Sleep Health, Nick Antic Sleep Laboratory.

A four group (WTN-sleep disturbed, WTN-non sleep disturbed, rural control, RTN-sleep disturbed) by four noise condition (WTN-Continuous, WTN-Sleep, WTN-Wake, Control) single-blinded design was used to investigate the effect of nocturnal WTN exposure on next-day mood, anxiety, and cognitive performance. Further details regarding participant recruitment and group allocation methodology are reported in Chapter 4. The first night was an acclimatisation night, after which participants were exposed to six experimental conditions in random order. However, only four experimental conditions are relevant to and reported in this thesis.

5.2.2 Participants

Participants were recruited via rural and wind farm community advertising, word of mouth and social media platforms including Facebook and Gumtree. Data collection occurred between June 2019 and February 2021. The study was approved by the Southern Adelaide Clinical Human Research Ethics Committee (SAC HREC protocol number 343.18) and was prospectively registered on the Australian and New Zealand Clinical Trial Registry (ACTRN12619000501145, UTN U1111-1229-6126). For further details regarding participant recruitment please see Chapter 4.

5.2.2.1 Inclusion and exclusion criteria

Study inclusion was based on location and the presence versus absence of self-reported WTN and/or RTN related sleep disturbance. Participants were excluded from the study based on factors known to impact sleep (<18 years of age, heavy sleep medication

use, history of substance abuse, recent night shift work, recent international travel across >2 time zones). Eligible participants were classed into one of the four study groups based on their residential location and questionnaire responses indicating either the presence or absence of self-reported WTN or RTN related sleep disruption (for further details see Chapter 4).

5.2.3 Intervention

5.2.3.1 Noise stimulus and protocol

The WTN stimulus was recorded indoors at a South Australian residence located 3.3 kilometres from the nearest wind turbine (Hansen et al., 2014b) reproduced in each of the laboratory bedrooms using an RME BabyFace Pro sound card, a Lab Gruppen amplifier and Krix loudspeakers (KX-4010s and custom-built non-vented subwoofer). Sound calibration was carried out to ensure that the signal was faithfully reproduced at the participant's head. The WTN stimulus included an amplitude modulated tone at multiple frequencies in 1/3-octave bands centred at 31.5 and 63 Hz and infrasound at the blade-pass frequency of 0.8 Hz and harmonics (Figure 4.1a). The selection of 25 dB(A) was based on a previous field study that showed that the median indoor SPL at night was between 25 and 30 dB(A) for distances from 1-3 kilometres from a wind turbine (Nguyen et al., 2021). Further details regarding the WTN stimulus can be found in Chapter 4 – Section 4.2.3.2.

Overnight technicians supervising the sleep studies commenced and stopped noise replay according to EEG observations and pre-defined study protocols. Thus, it was not possible to fully blind overnight technical staff although the replay system masked noise filenames and levels. On the control night no WTN was played, so participants were exposed only to background noise (19 dB(A), which was approximately six dB(A) below

the reproduced noise level to ensure that normal hearing subjects were able to perceive the WTN above background noise level (Song & Yorke, 2009; Zwicker & Fastl, 2013). On the remaining nights, 25 dB(A) WTN was only played between lights out and lights on time; continuously in the WTN-Continuous condition; only during established sleep periods (N2, N3 or REM) in the WTN-Sleep condition; and only during wake or transitional N1 sleep in the WTN-Wake condition.

5.2.4 Measures

5.2.4.1 Psychomotor Vigilance Task (PVT)

The 10-minute PVT was selected as the primary outcome as it is one of the most widely used assessments for alertness and sustained attention, a basic cognitive process affecting all higher level or downstream cognitive processes. The PVT demonstrates high sensitivity in identifying sleep deprivation and has high test-retest reliability (r = >0.80) (Basner & Dinges, 2011). Participants were asked to sit comfortably and respond to a visual LED-digital counter stimulus, presented at randomly-timed intervals from 2-10 seconds following the previous response by pressing a button with the thumb of the dominant hand (Loh et al., 2004). The primary outcome of interest was median reaction time (milliseconds), with further outcomes of mean reaction time (milliseconds), number of errors made, and number of lapses made (number of reaction times greater than 500 milliseconds).

5.2.4.2 Digit Symbol Substitution Test (DSST)

Participants completed a 2-minute computerised version of the DSST via Inquisit (Millisecond Software, version 1) to assess sustained attention, associative learning, visual spatial skills, response speed and scanning ability (Borchert, 2012; McLeod, Griffiths, Bigelow, & Yingling, 1982). The DSST is based on the Coding subtest of the WISC-V

(Wechsler, 2014) and the WAIS-IV (Wechsler, 2008). In the computerised version, the digit symbol code was displayed at the top of the screen and participants were asked to enter in the correct digit corresponding to each symbol as fast and accurately as possible. Participants completed the DSST each day throughout the study, using five alternate versions of the DSST of equivalent difficulty, administered in randomised order across days to minimise learning effects. The DSST is one of the most commonly used neuropsychological tests due to its high discriminant validity and high sensitivity in identifying cognitive impairment (r = >0.80) (Jaeger & Domingo, 2016). DSST outcomes analysed included total correct responses and total errors made.

5.2.4.3 Digit Span task

The visual Digit Span task is also based on the Digit Span subtest of the WISC-V (Wechsler, 2014) and the WAIS-IV (Wechsler, 2008) and assesses individual's short term and working memory. The visual Digit Span task was also administered via Inquisit software. This involved two tasks (forward and reverse) that required participants to watch the screen when a series of digits were presented at a rate of one per second and to then recall the digits in correct order (Borchert, 2020; Woods et al., 2011) in either forward or reverse order (Beaumont, 1985; Conklin, Curtis, Katsanis, & Lacono, 2000). The number of digits presented increased by one until two consecutive failed attempts of the same digit length occurred. Five different versions of the Digit Span task were used and presented in a randomised order across days to reduce potential learning effects. The Digit Span forward and backwards tests have demonstrated high (Cronbach's $\alpha = 0.89$) and moderate (Cronbach's $\alpha = 0.60$) internal consistency respectively (de Paula et al., 2016). Digit Span outcomes of interest involved the backward and forward two error maximal length, which is the traditional measure of digit span, and refers to the last digit span an individual gets correct prior to making two consecutive errors of the same length (Woods et al., 2011).

5.2.4.4 Profile of Mood States (POMS)

The POMS is a 65-item questionnaire that assesses how individuals are feeling on six subscales of mood disturbance including anger, confusion, depression, fatigue, tension, and vigour (McNair, Lorr, & Droppleman, 1981). Participants were asked to rate each item on a 5-point Likert scale, with scores ranging from 0 (not at all) to 4 (extremely). A total mood disturbance score was calculated by adding all subscale items together and then subtracting the vigour subscale, where higher scores indicate greater mood disturbance with a maximum score of 200 (Mackenzie, 2001). The POMS shows moderate internal consistency across subscales (Cronbach's α = 0.67 to 0.95) and is considered to be a reliable measure of mood disturbance (Curran et al., 1995).

5.2.4.5 The State-Trait Anxiety Inventory (STAI)

The STAI is a 40-item questionnaire that assesses both state and trait anxiety (Spielberger, 2010; Spielberger et al., 1971). Participants were asked to complete the STAI upon arrival to the sleep laboratory, and subsequently completed the 20-item state anxiety scale each morning following experimental nights. Participants were asked to rate how well they align with each item on a 4-point Likert scale, from 1 (almost never) to 4 (almost always). Items were added to reflect total scores, and scores were reversed for 19 anxiety-absent items. Total scores can range from 20-80, where higher scores indicate greater 'State' or 'Trait' anxiety. Scores of 39-40 indicate clinically significant symptoms of state anxiety for adults (Knight, Waal-Manning, & Spears, 1983) and scores of >54 for older adults (Kvaal, Ulstein, Nordhus, & Engedal, 2005). The STAI has high internal consistency (Cronbach's α = 0.86 to 0.95) and high content validity with strong correlations with the Taylor Manifest Anxiety Scale (r = - 0.73) and the Cattel and Scheier's Anxiety Scale Questionnaire (r = 0.85) (Julian, 2011).

5.2.5 Procedure

Each morning, following completion of an online sleep diary, participants completed a battery of questionnaires and daytime performance tests including the POMS, STAI-State form, PVT, DSST and Digit Span tasks within two hours of the final morning awakening. Participants were then able to shower, have breakfast and were free to leave the laboratory until 5:30pm for the next study night. Chapter 4 has further details regarding experimental procedures including overnight set-up and noise exposure methods.

5.2.6 Data and statistical analysis

IBM Statistical Package for Social Sciences (SPSS; Version 25) was used for statistical analyses. Variables that failed normality tests were $\log_{10}$ transformed prior to further statistical analyses and *p*-values indicated with an * indicate results based on transformed data. All data are presented as median (IQR), unless otherwise specified. Similar to Chapter 4, for all linear mixed model analyses, the acclimatisation night (night 1) was initially included in the analysis to test for potential 'first-night effects' and then excluded to control for such effects in follow-up analyses.

Linear mixed effects model analyses were used to assess fixed and interaction effects of noise condition, group, and the prior night's noise condition to test for potential carry-over effects between conditions across sequential nights. Given a significant age and hearing threshold difference between groups identified in Chapter 4, age and hearing threshold were included as covariates and specified as random factors in all analyses. As in Chapter 4, if a significant order effect was identified, models were re-run to adjust for both condition and age as random effects. In a secondary analysis, night number was also included to test for potential cumulative effects of noise exposure nights spent in the

laboratory in regard to the primary outcomes (PVT median reaction time and number of PVT lapses).

Models used a first-order autoregressive covariance structure, with noise condition and the prior night's condition specified as repeated measures within-subjects and subject ID as a random effect, each with their own intercept. Statistically significant interactions and/or main effects were examined using Sidak adjusted pairwise comparisons within each linear model. *p* values <0.05 were considered statistically significant.

5.3 RESULTS

5.3.1 Participant demographics

A CONSORT diagram and more detailed demographic outcomes from the 68 study participants (mean±SD: age 49.2±19.5; range: 18-80 years, 38 females) are presented in Chapter 4. There was a statistically significant difference in age between groups, where the WTN-sleep disturbed group was significantly older (66.3±6.9 years) than the rural control group (46.7±20.7 years, p=0.006) and the RTN-sleep disturbed group (33.5±15.1 years, p<0.001); and the WTN-non sleep disturbed group was significantly older than the RTN-sleep disturbed group (54.2±16.3 versus 33.5±15.1 years, p=0.001). After adjusting for age, significant differences in sleepiness, insomnia severity, sleep quality, perceived noise sensitivity and hearing thresholds (<1000 Hertz) remained between groups; where the WTN-sleep disturbed group showed greater ESS, ISI, PSQI and perceived noise sensitivity scores compared to the rural control group and greater ISI and PSQI scores than the RTN-sleep disturbed group. The WTN-non sleep disturbed group had a higher BMI and lower PSQI-sleep efficiency scores compared to the RTN-

sleep disturbed group. The WTN-sleep disturbed group also had higher hearing thresholds (dB HL) for frequencies 125-1000 Hertz compared to the RTN-sleep disturbed group.

As shown in Chapter 4, and as a confirmation of the intended selection procedure for the four groups, the WTN-sleep disturbed group showed a greater degree of WTN related sleep disruption in their home environment compared to the three other groups and the RTN-sleep disturbed group showed a significantly greater degree of RTN related sleep disruption in their home environment compared to the three other groups. At baseline, Trait Anxiety was not different between groups $F(3,62.1) = 1.41$, $p=0.248$.

5.3.2 First night effects

There were significant differences in night for the digit span forwards task ($p=0.001$), digit span backwards task ($p=0.012$) and number of correct DSST values ($p<0.001$). Pairwise comparisons revealed significantly lower forwards digit span after the acclimatisation night compared to the WTN-Continuous night ($p<0.001$) and the WTN-Wake night ($p<0.001$). Furthermore, there was significantly lower backwards digit span after the acclimatisation night compared to the control night ($p=0.015$), the WTN-Sleep night ($p<0.001$) and the WTN-Continuous night ($p<0.001$). Lastly, there was significantly lower correct values on the DSST after the acclimatisation night compared to the control night ($p<0.001$), the WTN-Sleep night ($p<0.001$), the WTN-Continuous night ($p<0.001$) and the WTN-Wake night ($p<0.001$). There were no other significant differences in night for PVT median reaction time, PVT mean reaction time, number of PVT errors, number of PVT lapses, mood disturbance, state anxiety or number of DSST errors (all p's >0.05). Given the impact of some 'first-night effects' the acclimatisation night (night 1) was excluded in further analyses to control for such effects.

5.3.3 Group-by-noise condition interaction effects

Table 5.1 summarises next-day mood, anxiety, and cognitive performance outcomes for each group and noise condition. Figure 5.1(A) shows PVT median reaction time and number of PVT lapses during the background noise (control), WTN-Continuous, WTN-Sleep and WTN-Wake exposure conditions within each group as well as the overall group effect irrespective of noise condition (combined) and plots that indicate the overall noise condition effect irrespective of group. Figure 5.1(B) shows change in PVT median reaction time and number of PVT lapses from the control condition for each WTN condition including a combined noise condition effect within each group and the overall noise condition effect irrespective of group.

There were no significant group-by-noise condition interaction effects on PVT median reaction time, number of PVT lapses (Figure 5.1) or any other secondary mood, anxiety, and cognitive performance outcomes (See Appendix 11 for further details).

Table 5.1 Median [IQR] next-day mood, anxiety, and cognitive performance outcomes across groups and noise conditions.

Group	Noise condition	PVT Mean RT (ms)	Total PVT Errors (n)	Total PVT Lapses (n)	Digit Span Backwards	Digit Span Forwards	DSST Correct (n)	DSST Errors (n)	Mood Disturbance	State Anxiety
WTN-Sleep Disturbed	Control	297.8 [253.0 to 337.6]	1.0 [0.0 to 1.8]	2.0 [1.0 to 3.8]	5.0 [4.0 to 6.0]	6.0 [6.0 to 7.0]	28.0 [18.5 to 45.5]	3.0 [1.5 to 5.0]	16.0 [-6.0 to 23.8]	30.0 [21.5 to 42.5]
	WTN-Continuous	282.8 [266.3 to 333.1]	0.0 [0.0 to 1.0]	3.0 [0.0 to 3.0]	4.5 [4.0 to 6.0]	7.0 [5.0 to 7.0]	40.0 [26.0 to 46.0]	3.0 [2.0 to 4.0]	7.5 [4.0 to 32.8]	41.5 [30.0 to 44.8]
	WTN-Sleep	287.4 [263.5 to 341.2]	1.0 [0.0 to 1.5]	2.5 [0.0 to 4.8]	5.0 [4.0 to 6.3]	6.0 [5.0 to 6.3]	35.5 [28.0 to 41.3]	2.0 [1.0 to 5.0]	9.0 [-3.3 to 23.5]	30.0 [23.5 to 40.3]
	WTN-Wake	275.7 [261.4 to 357.6]	0.0 [0.0 to 3.0]	2.0 [1.0 to 4.0]	5.0 [4.0 to 6.0]	7.0 [6.0 to 7.0]	37.5 [19.3 to 44.3]	3.0 [2.0 to 4.3]	12.0 [-6.0 to 40.0]	38.0 [29.0 to 41]
WTN-Non Sleep Disturbed	Control	272.1 [261.9 to 287.4]	1.0 [0.0 to 2.0]	1.0 [0.0 to 3.0]	6.0 [5.0 to 7.8]	6.0 [5.0 to 8.0]	42.0 [35.0 to 50.0]	2.0 [1.0 to 3.0]	-6.5 [-10.5 to -0.5]	30.0 [23.3 to 31.8]
	WTN-Continuous	277.7 [260.4 to 289.9]	1.0 [0.3 to 2.0]	1.5 [1.0 to 2.0]	7.0 [5.0 to 9.0]	7.0 [5.3 to 8.8]	44.0 [34.0 to 58.0]	2.0 [1.0 to 3.0]	-7.0 [-15.5 to -3.0]	27.0 [22.3 to 32.5]
	WTN-Sleep	267.0 [256.9 to 282.4]	1.0 [0.5 to 2.0]	1.0 [0.0 to 3.0]	6.0 [5.0 to 8.0]	8.0 [6.0 to 8.0]	42.0 [37.0 to 63.0]	2.0 [1.0 to 4.0]	-11.0 [-14.5 to 7.5]	29.0 [24.0 to 35.0]
	WTN-Wake	267.3 [248.6 to 280.8]	1.0 [0.0 to 2.0]	1.0 [0.0 to 2.0]	6.0 [5.0 to 7.8]	7.0 [6.0 to 8.0]	44.5 [35.3 to 56.8]	2.5 [1.0 to 3.0]	-8.0 [-12.8 to 4.5]	29.0 [23.5 to 34.0]
Rural Control	Control	266.0 [254.2 to 291.7]	1.0 [0.0 to 2.0]	1.0 [0.0 to 2.0]	6.0 [6.0 to 7.8]	7.0 [6.0 to 8.0]	50.5 [46.5 to 60.8]	2.0 [1.0 to 3.0]	-2.0 [-10.5 to 16.8]	26.5 [24.0 to 32.8]
	WTN-Continuous	260.8 [253.0 to 274.7]	1.0 [1.0 to 3.0]	0.0 [0.0 to 1.0]	6.0 [6.0 to 7.0]	7.0 [6.0 to 8.0]	48.5 [44.5 to 61.5]	1.0 [1.0 to 3.0]	-2.5 [-6.5 to 17.0]	30.0 [22.0 to 31.0]
	WTN-Sleep	270.7 [257.9 to 284.0]	1.0 [0.0 to 2.0]	1.0 [0.0 to 2.0]	6.0 [5.0 to 7.0]	7.0 [6.0 to 7.3]	48.5 [43.3 to 55.8]	2.0 [1.0 to 2.0]	8.0 [-11.5 to 18.8]	25.0 [21.5 to 35.3]
	WTN-Wake	256.3 [250.9 to 293.1]	0.0 [0.0 to 2.0]	1.0 [0.0 to 2.0]	6.0 [5.0 to 7.0]	7.0 [6.0 to 8.0]	53.0 [43.3 to 57.5]	2.0 [1.0 to 3.0]	2.0 [-7.8 to 19.3]	27.0 [23.5 to 28.8]
RTN-Sleep Disturbed	Control	267.3 [243.6 to 297.9]	1.0 [0.0 to 2.0]	0.5 [0.0 to 2.5]	7.0 [5.8 to 8.3]	7.0 [6.0 to 8.0]	54.5 [45.0 to 69.5]	1.5 [1.0 to 3.8]	5.0 [-1.3 to 9.5]	31.5 [25.8 to 36.0]
	WTN-Continuous	267.4 [247.0 to 286.1]	1.0 [0.0 to 1.8]	1.0 [0.0 to 1.3]	6.5 [5.0 to 8.0]	7.0 [6.0 to 8.3]	57.0 [47.8 to 73.8]	2.0 [1.0 to 3.0]	3.0 [-0.3 to 8.0]	30.5 [26.3 to 36.8]
	WTN-Sleep	272.3 [244.4 to 299.5]	1.0 [0.0 to 2.0]	1.5 [0.0 to 3.3]	7.5 [6.0 to 8.3]	7.0 [6.0 to 7.3]	52.5 [38.8 to 67.0]	2.0 [1.0 to 3.3]	-1.0 [-5.0 to 3.3]	31.5 [26.8 to 36.5]
	WTN-Wake	288.6 [246.7 to 313.8]	1.0 [0.0 to 2.0]	1.0 [0.0 to 3.0]	6.0 [5.0 to 7.0]	8.0 [6.0 to 9.0]	56.0 [48.0 to 70.0]	3.0 [1.0 to 3.0]	2.0 [-5.0 to 4.0]	30.0 [25.0 to 35.0]

Note. Values represent Median [IQR] for each participant group (WTN-sleep disturbed, n=14; WTN-non sleep disturbed, n=18; Rural control, n=18; RTN-sleep disturbed, n=18) under each noise condition. RT=Reaction Time. PVT=Psychomotor Vigilance Task. DSST=Digit Symbol Substitution Test. ms=milliseconds. WTN=Wind Turbine Noise. RTN=Road Traffic Noise. n=number.

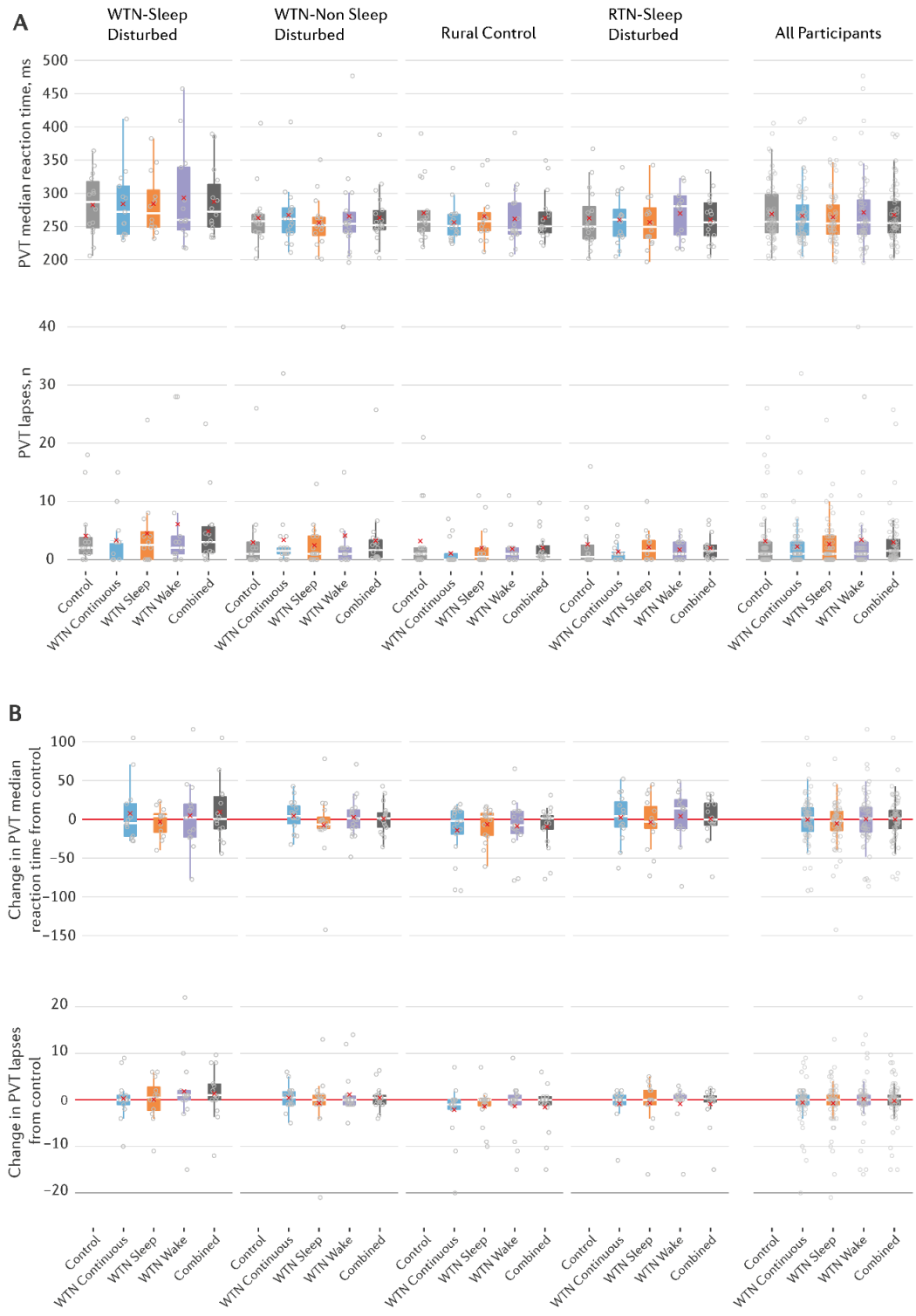

*Figure 5.1 Box and whisker plots showing **(A)** PVT median reaction time in milliseconds (upper panel) and number of PVT lapses (lower panel) across groups and noise conditions and **(B)** difference scores from control (for each WTN condition) for PVT median reaction time in milliseconds and number of PVT lapses for each group.*

Note. Plots depict group mean (X) and median (gaps) for each group (WTN-sleep disturbed, n=14; WTN-non sleep disturbed, n=18; rural control, n=18; RTN-sleep disturbed, n=18; and across all participants, n=68) and under each noise condition (control background noise, WTN-continuously across the night, WTN-only during sleep periods, WTN-only during wake period exposures and combined across all noise conditions). The box bounds the IQR divided by the median. Whiskers are Tukey-style (extend to a maximum 1.5 x IQR beyond the box as described in Krzywinski and Altman (2014). Circles indicate individual data points. PVT=Psychomotor Vigilance Task. WTN=Wind Turbine Noise. RTN=Road Traffic Noise. ms=milliseconds.

5.3.4 Noise condition main effects

There were no statistically significant main effects of noise condition on PVT median reaction time, number of PVT lapses or any other secondary mood, anxiety, and cognitive performance outcomes (See Appendix 11 for further details).

5.3.5 Group main effects

There were no statistically significant group main effects on PVT median or mean reaction time or number of PVT lapses. There was a significant main effect of group on the digit span maximum number of backwards trials successfully recalled prior to missing two consecutive lists of the same length ($F(3, 179) = 3.856$, $p=0.010$), with reduced backwards recall in the WTN-sleep disturbed group than in the WTN-non sleep disturbed group (mean [95%CI] difference -1.63 [-3.10 to -0.15], $p=0.023$) and the RTN-sleep disturbed group (mean [95%CI] difference -1.92 [-3.47 to -0.37], $p=0.008$).

There was also a significant main effect of group on the number of correctly identified symbols on the DSST ($F(3, 55) = 5.037$, $p=0.004$), where the WTN-sleep disturbed group correctly identified fewer symbols on the DSST compared to the rural control group (mean [95%CI] difference -18.62 [-36.48 to -0.75], $p=0.037$) and the RTN-sleep disturbed group (mean [95%CI] difference -25.40 [-43.49 to -7.31], $p=0.002$). There was also a significant main effect of group on next-day state anxiety ($F(3,182) = 2.839$, $p=0.039$, where the WTN-sleep disturbed group had greater next-day state anxiety compared to the rural group (mean [95%CI] difference 0.146 [0.02 to 0.27], $p=0.012$). However, there were no other significant group effects in any other outcomes.

5.3.6 Cumulative noise exposure effects over time

There were no statistically significant group-by-night number interactions for PVT median reaction time ($F(16,147) = 0.573$, $p=0.900$; or main effects of night number ($F(6, 161) = 1.436$, $p=0.204$ or group ($F(3,65) = 0.714$, $p=0.547$. Similarly, there were no statistically significant group-by-night number interactions for number of PVT lapses ($F(16, 155) = 0.747$, $p=0.742$; or main effects of night number ($F(6, 167) = 1.172$, $p=0.324$ or group ($F(3, 85) = 0.949$, $p=0.421$.

5.4 DISCUSSION

To our knowledge, this was the first experimental study to investigate the impact of WTN exposure during the sleep period on next-day mood, anxiety, and cognitive performance including alertness, sustained attention, processing speed and working memory. There were no noise condition or group-by-noise condition interaction effects to support any noise condition or group-dependent impairments in any next-day mood, anxiety, and cognitive performance outcomes. Given no evidence of poorer outcomes in the presence of WTN compared to control conditions across the full sample, or any significant group-by-noise condition interactions, WTN exposure at 25 dB(A) in a carefully controlled environment does not appear to impact next-day mood, anxiety, or cognitive performance outcomes. These results indicate that the null hypothesis was in fact supported and the alternative hypothesis (i.e., that these outcomes would be more disrupted following the three WTN exposure nights compared to the control night, particularly in residents with prior WTN exposure and self-reported WTN related sleep disruption in the home environment) was rejected.

Even the WTN-sleep disturbed group who were most likely to exhibit negative responses in the presence of WTN, showed no evidence to support impairments in the

WTN-Continuous or WTN-Wake conditions compared to the quiet control night. Although this could potentially reflect a Type II error, particularly given the relatively small individual group size (n=14), there was also no evidence to support WTN effects in the full sample (n=68). Thus, Type II error appears unlikely. Based on PVT measures as the primary outcome and data from acclimatisation and control nights in the current study, we estimated the pooled within-subject standard deviation in median reaction time and lapses to be around 28.6 milliseconds and 3.9 lapses respectively. Thus, around 17 participants per group should provide 80% power to detect a 43 millisecond and a 6-lapse difference for group-by-noise condition interactions and a 17 millisecond and a 2-lapse difference between noise conditions with a two-tailed significant level of 0.05. In comparison to a 9- and 8-hour sleep opportunity, a 2-point difference in PVT lapses corresponds to approximately one night with a 3-hour sleep opportunity (Belenky et al. 2003) or three nights with 6-hour sleep opportunities respectively (Van Dongen, Maislin, Mullington and Dinges, 2003).

Together with the current findings, these previous studies (Belenky et al., 2003; Van Dongen et al., 2003) appear to suggest that daytime impairments are more likely to occur through cumulative sleep disruption effects over multiple nights, which also corresponds to the criteria for insomnia disorder (e.g., sleep disruption for at least three nights a week for three months) (American Psychiatric Association, 2013, 2020). In the current study, there were no significant differences in number of nights spent in the laboratory (i.e., the cumulative effect of noise exposure over six nights) for PVT median reaction time or PVT lapses. In addition, the current study findings support that single night studies are likely not sufficient to test for cumulative effects on daytime functioning of potentially very subtle WTN related sleep disruption over extended periods of time. Therefore, failure to demonstrate significant effects of WTN exposure on macrostructure sleep outcomes is perhaps more likely a key factor in non-significant daytime functioning

outcomes found in the current study. Whilst this does not rule out the possibility of microstructural effects on sleep, it is possible that if there are such effects, they do not appear to carry over into next-day functioning, at least in the measures that were used as part of this thesis. This does not rule out the impact of more microstructural impacts of daytime functioning which is also an important consideration for future research. Overall, the findings do not support significant noise condition effects on next-day mood, anxiety, and cognitive performance outcomes. Furthermore, individuals with prior WTN exposure do not appear to exhibit conditioned responses to acute WTN exposure, which might be expected for WTN-sleep disturbed individuals with potentially heightened arousal, noise sensitivity or maladaptive coping strategies (e.g., rumination of unhelpful cognitions such as WTN is damaging to health) and/or anxiety (worry, panic, nervousness) regarding potential WTN effects.

However, there were some significant group main effects in the current study in tasks involving working memory, associative learning, processing speed and sustained attention indicative of lower DSST scores in the WTN-sleep disturbed group compared to the rural control and RTN-sleep disturbed group, and lower digit span backwards recall task performance in the WTN-sleep disturbed group compared to the WTN-non sleep disturbed group and the RTN-sleep disturbed group. In addition, the WTN-sleep disturbed group also showed greater next-day state anxiety compared to the rural group. However, as described in Chapter 4, the WTN-sleep disturbed group was significantly older than the rural control group and the RTN-sleep disturbed group. As a result, there was also some evidence to support a trend moving towards the WTN-sleep disturbed group having more disrupted mood, anxiety and cognitive performance scores compared to the three other groups. This could reflect a broad range of factors including age as well as other demographic differences impacting mood, anxiety, and cognitive performance. The WTN-sleep disturbed group was recruited with the intention of capturing a population with

established WTN related sleep disturbance. However, this group was the most challenging to recruit and the overall degree of WTN sleep disruption was rated as moderate so it remains possible that a larger group of more severely impacted individuals may exhibit different outcomes. Thus, further work in a larger sample of most impacted individuals remains warranted to better understand the potential impact of nocturnal WTN exposure on sleep and next-day outcomes on individuals more likely to exhibit conditioned responses to WTN than the current sample. However, recruitment of larger samples of WTN-sleep disturbed individuals may be challenging as those potentially most impacted may not be prepared to engage in research, biasing towards the null hypothesis.

It is worth noting that this study was the first experimental study to use psychometrically validated tools of mood, anxiety, and cognitive performance outcomes. Prior studies have found that participants reported significantly increased irritation and lower pleasantness within 15 minutes of waking on a mood questionnaire (measured via a Likert scale) after a 32 dB L_{AEq} WTN exposure night compared to a control background noise night (Smith et al., 2020). These are somewhat different measures of mood disturbance compared to those used in this study. WTN exposure SPLs were also higher and more likely to reflect worst-case rather than median WTN exposure conditions of the current study. Responses immediately after waking may also be more prone to attentional biases compared to responses within two hours of waking. The selection of 25 dB(A) WTN in the current study was based on a previous study that involved a year-long measurement of WTN and showed that the median indoor SPL was between 25 and 30 dB(A) for distances approximately 1-3 kilometres from the nearest wind turbine (Nguyen et al., 2021), and is thus likely to be more representative of typical exposure levels. However, this does not preclude significant daytime impacts from higher and worst-case WTN exposure conditions, particularly in individuals more prone to noise-disturbed sleep. For example, the World Health Organization (1999) states that continuous indoor noise >30

dB(A) is likely to impact sleep and therefore, future studies investigating WTN SPLs >30 dB(A) remain warranted.

Subtle sleep disruption effects associated with heart-rate acceleration (Griefahn et al., 2008) and peripheral vasoconstriction responses (Catcheside et al., 2002) could also still occur in the presence of WTN without necessarily eliciting more frequent cortical arousals or awakenings across the night and thus impact daytime functioning. For example, Martin et al. (1997) showed that overnight exposure to frequent brief pure-tone noise events to elicit frequent autonomic activation responses but without more frequent arousals or awakenings or any change in total sleep time caused increased next-day sleepiness and mood disturbance. Furthermore, in healthy individuals not habitually exposed to WTN, Dunbar et al. (2021) found subtle sleep stage and SPL dependent effects of WTN on quantitative power spectral analysis of EEG responses to noise, with some differences compared to RTN. Thus, noise exposure-dependent effects on daytime impairments could potentially occur because of more subtle disruption of sleep from WTN exposure without necessarily any measurable changes in overall sleep macrostructure and daytime performance assessments used in this thesis. Thus, the measures used in this study may not have been sensitive enough at picking up more subtle daytime impairments after one night of WTN exposure and that perhaps these impairments may be more likely to occur following more chronic WTN exposures (i.e., over cumulative nights of WTN exposure). As a result, using more sensitive tools including quantitative EEG power spectral analysis could be beneficial in examining microstructural sleep and daytime functional impairments (e.g., daytime alpha, delta or beta power) that might occur after prolonged WTN exposure (Åkerstedt & Gillberg, 1990). Therefore, a key remaining question is whether nocturnal WTN exposure impacts sleep disruption and next-day outcomes using more sensitive techniques than the conventional measures used in the current study.

5.4.1 Conclusions

This study does not support that WTN exposure at 25 dB(A) in a carefully controlled environment negatively impacts next-day mood, anxiety, or cognitive performance outcomes, or that prior WTN exposure and self-reported sleep impacts attributed to WTN detectably influence these outcomes. However, these results from WTN levels that approximate median noise levels in a real-world exposure setting does not preclude effects at higher and less frequent but worst-case WTN exposure levels, or effects in sub-groups of individuals most sensitive to noise impacts who may have been under-represented in this and potentially other studies.

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unrelated to the submitted work. TL, BZ, GM, CD, BL, DPN and HS have no conflicts of interest to declare.

Data availability statement

The data underlying this article will be shared on request to the corresponding author.

CHAPTER 6. GENERAL DISCUSSION AND CONCLUSIONS

6.1 Overview of thesis aims

The broad aim of this thesis was to investigate the effect of nocturnal WTN on sleep and next-day mood, anxiety, and cognitive performance outcomes under carefully controlled experimental conditions in a laboratory environment. Furthermore, this thesis examined the potential role of wake-dependent psychological effects of WTN exposure during the sleep period on sleep and daytime functioning outcomes. The purpose was to gain a deeper understanding of potential mechanisms underpinning reports of WTN related sleep disturbance from some residents living near wind turbines and to determine if WTN related sleep disturbance could be due to direct WTN effects on sleep, indirect psychological effects of WTN exposure, or potentially a combination of both. This was to help identify what strategies could potentially help to reduce sleep disruption and distress by affected individuals. This Chapter summarises the main findings presented in Chapters 2 – 5 and discusses the theoretical and clinical implications of the findings in relation to WTN guidelines, methodological considerations, limitations, and directions for future research for this field.

6.2 Summary of findings and original contribution to knowledge

In **Chapter 1**, an overview of WTN and its potential effects on sleep was introduced. It was posited that WTN could impact sleep due to its prominent low frequency noise components that may promote annoyance and be more difficult to habituate to compared to higher frequency noises, and through psychological mechanisms that may precipitate and perpetuate sleep disruption. More specifically, WTN could act as a precipitating stress ‘trigger’ towards the development of insomnia over time. Insomnia could then potentially be perpetuated by maladaptive coping strategies such as spending excessive time in bed or

staying in bed awake, reinforcing a conditioned response when attempting sleep. Therefore, WTN could potentially impact sleep through physiological and/or psychological mechanisms.

Chapter 2 systematically reviewed studies that investigated the presence versus absence of WTN on sleep using validated objective and subjective sleep assessment methods. Previous reviews have focused on associations between WTN and annoyance but not on sleep specifically (Basner & McGuire, 2018; Schmidt & Klokker, 2014). Additionally, prior systematic reviews have assessed the effect of WTN on sleep collected only via self-report assessments, mostly from questionnaires that had not been psychometrically validated (Onakpoya et al., 2015). Accordingly, the aim of the review presented in Chapter 2 was to systematically review the effect of WTN on quantitatively assessed objective and subjective sleep outcomes collected using psychometrically validated assessment methods. Meta-analytic results of five studies showed no significant differences in objective sleep onset latency, total sleep time, sleep efficiency or wake after sleep onset in the presence versus absence of WTN. A similar quantitative assessment of subjective sleep estimates could not be meaningfully undertaken due to inconsistent measurement methods. Regardless, the review recommended that these results be interpreted with caution given the inconsistent measurement methodologies and WTN interventions across studies, as well as limited sample sizes. This review illustrated the need for further carefully controlled experimental studies using ecologically valid WTN to test for potential effects on objective and psychometrically validated subjective sleep assessment outcomes. This chapter informed the study designs and experimental methodologies employed in **Chapters 4 and 5.**

In **Chapter 3** a pilot study was conducted to examine the effect of WTN on objective and subjective sleep latency in 23 healthy, suburban-dwelling good sleepers not habitually exposed to WTN; to help avoid potential confounding effects from subjective biases towards WTN from prior exposure. All participants underwent counterbalanced nightly conditions of

background noise alone as the control condition (23 dB(A)) and WTN at 33 dB(A) during the sleep onset period. There were no significant differences in objective or subjective sleep latency between noise conditions. Whilst the presence of undetected small effects could not be ruled out, these results illustrate that WTN at 33 dB(A) does not extend sleep latency in healthy sleepers without prior WTN exposure. This was the first experimental study to assess the presence versus absence of WTN during the sleep onset period on PSG derived and sleep diary determined sleep latency. However, these findings may not extend to residents in wind farm areas who have been habitually exposed to WTN and potentially sensitised to sleep disruption effects. The study design also precluded an examination of effects on other important objective and subjective sleep macrostructure parameters, such as total sleep time and sleep efficiency. Thus, further investigation remained warranted to evaluate the impact of full-night WTN exposure conditions on sleep macrostructure parameters in residents living in close proximity to wind farms with and without self-reported WTN related sleep disturbance.

In a separate and larger laboratory study presented in **Chapter 4**, the impact of ecologically relevant nocturnal WTN exposure on objective and subjective sleep outcomes, and potential prior WTN exposure effects, were examined in two groups of residents who lived close to wind farms, one with and one without self-report WTN related sleep disruption, a group of rural residents without prior WTN exposure and urban residents who report RTN related sleep disruption. The study also aimed to elucidate possible effects of prior WTN exposure and wake-dependent psychological effects of WTN on sleep. All participants were exposed in random order to four separate nights, including; a quiet control night with background noise only (19 dB(A)); a full-night of WTN exposure at 25 dB(A); 25 dB(A) WTN exposure only during established sleep periods; and 25 dB(A) WTN exposure only during wake periods. This was the largest study to date to have tested for WTN effects on sleep and the only study to date to have tested for potential sleep- versus wake-dependent WTN effects

on overnight sleep. Contrary to predictions, there were no significant group-dependent or main effects of WTN exposure condition on any traditional PSG sleep and sleep diary reported outcomes. Thus, there was no evidence to support that WTN exposure at 25 dB(A), negatively impacts sleep, even in participants reporting WTN related sleep disturbance prior to participating in the study. This does not rule out WTN effects at higher SPLs, nor the possibility for smaller and more subtle effects to sleep that may have been missed.

Lastly, **Chapter 5** analysed next-day mood, anxiety and cognitive performance outcomes from the same study discussed in **Chapter 4.** Whilst the findings in Chapter 4 did not support that WTN negatively impacts objective or subjective sleep parameters measured via traditional sleep scoring methods, next-day outcomes could have nevertheless still potentially been impacted via more subtle microstructural sleep changes that traditional sleep scoring methods may not be sufficiently sensitive to detect. Furthermore, psychological effects potentially contributing to noise-related sleep difficulties via insomnia, could have also influenced subsequent mood, anxiety, and daytime performance outcomes without necessarily any objective evidence of sleep disruption. Daytime impairments are a key diagnostic criterion of insomnia, so are an important consideration in the context of overnight noise exposure. Furthermore, the interest in impacts on sleep presumes that if sleep is negatively impacted by WTN it may have negative daytime functional consequences. Thus, one could argue that daytime functioning and mood are the next outcome effect of most importance. Therefore, **Chapter 5** examined the impact of nocturnal WTN exposure on next-day mood, anxiety, and cognitive performance outcomes across the four different study groups following each of the WTN exposure conditions. Similarly to **Chapter 4,** this was the first experimental study to investigate the impact of nocturnal WTN on next-day mood, anxiety and cognitive performance outcomes using psychometrically validated assessments of mood and anxiety and direct, objective measures of cognitive performance. There was no

consistent evidence of poorer daytime outcomes following WTN exposure compared to a quiet control night, and no evidence of any sleep- or wake-dependent WTN exposure effects overall or in any sub-group, including the WTN-sleep disturbed group. However, this study was powered to detect a 2-point difference in PVT lapses between noise conditions, which corresponded to roughly three nights with 6-hour sleep opportunities (compared to 8-hour sleep opportunities) or one night receiving a 3-hour sleep opportunity in comparison to receiving one night with an 8-hour sleep opportunity. Therefore, it is possible that daytime impairments might occur through cumulative sleep disruption effects. Irrespectively, this study did not show any evidence of cumulative sleep disruption effects over six consecutive nights in the laboratory. Thus, consistent with the overall findings of no significant impacts on sleep in Chapter 4, the overall conclusions from the work presented in Chapter 5 were that nocturnal WTN at 25 dB(A) does not significantly impact next-day mood, anxiety, or cognitive performance.

6.3 Theoretical Implications: Does wind turbine noise impact sleep and next-day outcomes?

Together, the results of this thesis suggest that full-spectrum WTN at 25 dB(A) does not negatively impact the objective or subjective sleep macrostructure or next-day mood, anxiety or cognitive performance of residents living near wind farms, in quiet rural areas or in RTN-sleep disturbed individuals. Despite somewhat different methodologies and WTN exposure levels, these results are consistent with three previous studies on the impact of WTN on PSG sleep outcomes (Ageborg Morsing et al., 2018; Jalali et al., 2016a; Smith et al., 2020). These results are also consistent with the study discussed in Chapter 3 (Liebich et al., 2022), which found no significant differences in objective or subjective sleep latencies in the presence of a slightly higher WTN SPL (33 dB(A) compared to the background noise in a

different sleep laboratory (also with a higher background noise level - 23 dB(A)). Taken together, the findings of this thesis do not support the position that WTN at realistic exposure levels in the field negatively impact objectively measured sleep macrostructure including sleep latency, wake after sleep onset, total sleep time, sleep efficiency, number of awakenings and the times and proportions of sleep spent in NREM and REM sleep. These results were consistent across a range of different populations including healthy unexposed urban individuals, individuals living in close proximities to wind turbines who do versus do not report WTN related sleep disruption, rural unexposed individuals or individuals reporting RTN related sleep disruption.

Perhaps more importantly and also contrary to the hypotheses, 25 dB(A) full-spectrum WTN did not appear to impact the self-reported sleep, nor next-day mood, anxiety or cognitive performance outcomes of any of the four studied population groups in Chapter's 4 and 5. Thus, acute overnight WTN exposure at 25 dB(A) does not appear to be sufficient to elicit significant difficulty initiating or maintaining sleep as would be expected if insomnia were to explain WTN related sleep disruption in individuals living near wind farms. This was particularly unexpected in the group of residents that reported WTN related sleep disruption. One possible explanation is that the WTN intervention used in the study reported in Chapters 4 and 5 was not sufficiently loud or intrusive to cause sleep disturbance and daytime impairments reported by some residents living near wind farms. The WTN level administered in the study described in Chapter's 4 and 5 approximated year-long median WTN exposure levels from another study conducted in the field (Nguyen et al., 2021) and was considered high enough above background noise to be easily detected (Song & Yorke, 2009; Zwicker & Fastl, 2013). This study showed that the median indoor SPL at night was between 25 and 30 dB(A) for distances from 1-3 kilometres from the nearest wind turbine in a South Australian wind farm (Nguyen et al., 2021). However, given that WTN has time-varying acoustic features

highly dependent on external factors such as wind speed and direction, location, number of turbines, surrounding topography and a range of further meteorological factors such as temperature and wind shear, there are times when WTN is likely to be substantially different in character than the median (greater SPLs, increased amplitude modulation) (Micic et al., 2018; Öhlund & Larsson, 2013). Thus, higher, and worst-case WTN levels could cause detectable sleep disturbance, conditioned responses to WTN exposure whilst individuals try to sleep and subsequent day time impacts, as discussed in **Chapter 1.** It is also possible that a single night of noise exposure was not sufficient and that multiple nights of exposure may be needed to elicit detectable effects on next-day mood and functioning. Thus, although there was no consistent evidence from the work described in this thesis to suggest that 25 dB(A) WTN disturbs sleep or impacts next-day mood or functioning, further work to test for effects of higher WTN exposure levels across multiple nights may be warranted.

Whilst no significant WTN effects on sleep or next-day mood or function were found in this thesis work, Chapter's 4 and 5 illustrate that the WTN-sleep disturbed group did appear to show poorer sleep and daytime mood and function in general, with significantly greater insomnia severity, sleepiness, wake after sleep onset, and poorer sleep quality, backwards recall and associative learning compared to the three other groups. The WTN-sleep disturbed group was also the only group that overall showed sleep efficiency scores less than 85% (a commonly used cut-off for discriminating good sleep from poor sleep; American Academy of Sleep Medicine (2014)), which occurred in all four noise exposure conditions, including the no noise control condition. Furthermore, although not statistically significantly different from the other groups, the next-day mood, anxiety and cognitive performance outcomes in the WTN-sleep disturbed group tended to be worse than the three other groups.

6.4 Clinical implications

Despite no significant effect of 25 dB(A) full-spectrum WTN on sleep and daytime functioning in the work presented in this thesis, it is still important to consider the potential clinical implications for the treatment of residents who report WTN related sleep disruption. Irrespective of whether the WTN sample used in the current thesis objectively or subjectively impacted the studied individuals, the sleep disturbed sample group and other residents living near wind farms nevertheless report sleep disturbance, daytime functional impacts, and reduced quality of life, which they attribute to WTN.

Whilst the results of the current thesis do not support the position that acute WTN exposure at median levels cause detectable impairments, sleep-disturbed residents may nevertheless benefit from either the use of foam earplugs and/or noise masking devices to improve sleep quality (if its specifically the noise emitted by the wind turbine). Otherwise, cognitive behavioural therapy for insomnia (i.e., the first-line treatment for insomnia) targeted at changing sleep behaviours and psychological disturbance to WTN or using cognitive behavioural techniques targeted at noise disturbance more generally may be advantageous. For example, even just the unequal distribution of benefits from the planning to operational stages of wind turbines can influence a resident living near a wind turbine's perception and lead to increased worry and rumination at night and evidently lead to sleep disruption, and perhaps even a community divide due to having a particular meaning to the sleeper. Thus, a more specific focus on thoughts, beliefs and attitudes towards WTN could potentially be useful to alleviate symptoms such as worry and rumination via cognitive behavioural approaches.

In support of this idea, Leventhall, Benton, and Robertson (2008) previously conducted a small intervention study on nine individuals with unresolved low frequency noise complaints.

The intervention involved psychotherapy, with elements of reassurance, relaxation therapy, stress management and imaginal exposure. Whilst statistical analyses were not reported, all participants reported benefits in quality of life and coping skills, supporting the potential value of this approach. Cognitive behaviour therapy has also been used as an effective treatment for tinnitus-related distress and has involved elements of psychoeducation surrounding tinnitus, relaxation, cognitive restructuring of negative beliefs about tinnitus, exposure, behavioural activation and mindfulness (Hesser, Weise, Westin, & Andersson, 2011). Therefore, cognitive behaviour therapy directed towards WTN disturbance is a promising avenue for future research regarding the effective treatment for individuals attributing sleep and daytime impairments to WTN.

The work in this thesis investigated the impact of one specific WTN stimulus reproduced at an ecologically relevant SPL below the current WTN guidelines specified by the World Health Organization. The World Health Organization (1999) states that for continuous indoor noise, >30 dB(A) is likely to impair sleep. However, the World Health Organization (1999, p. xiii) also states that “when noise is continuous, the equivalent sound pressure level should not exceed 30 dB(A) indoors if negative effects on sleep are to be avoided” and that “for noise with a large proportion of low frequency sound, a lower guideline value is recommended”. This is because these guidelines are based on positive associations between dB(A) and annoyance levels to RTN, which has more prominent mid-to-high frequencies within the 200-2000 Hertz range compared to WTN.

Given no evidence to support that 25 dB(A) WTN negatively impacts sleep or next-day functioning in a range of individuals, single night exposures of 25 dB(A) do not appear to be problematic. Whilst this importantly contributes to the body of knowledge surrounding WTN effects on individuals, future research targeting higher WTN exposure levels remain warranted to test if indoor WTN guidelines are appropriate to minimise potential sleep

impacts. Therefore, further work to test for potential sleep disruption effects above 25 dB(A) and longer exposure times remain warranted.

6.5 Methodological considerations and limitations

The experimental studies in this thesis are amongst the largest and most comprehensive to date that have investigated the impact of WTN on sleep in a carefully controlled laboratory environment and the first study to test for potential wake-dependent psychological effects of WTN on individual's ability to achieve and maintain sleep overnight and their next-day functioning.

A major strength of the study was the comprehensive assessment of sleep and daytime functioning using objective EEG assessments of sleep and psychometrically validated instruments to assess subjective measures of sleep quality and next-day cognitive performance, mood and anxiety (Liebich et al., 2021; Van de Water et al., 2011). A further strength was the in-laboratory design allowing for highly reproducible and carefully controlled whole-night noise exposures in a noise-attenuated laboratory setting. This was important to ensure that the WTN exposure, including its low frequency and infrasonic components, could be faithfully reproduced and manipulated, and potential external confounder variables, such as extraneous noise (including varying frequencies, amplitude modulation and SPLS) and other variables impossible to control in a real-world exposure environment could be controlled as much as possible, which overcomes previous laboratory based studies (Ageborg Morsing et al., 2018; Smith et al., 2020). Whilst laboratory-based studies cannot fully replicate the home environment (Campbell & Neill, 2011; Ghegan, Angelos, Stonebraker, & Gillespie, 2006), careful control of external factors remains fundamentally important to establish if noise exposure causes detectable sleep disturbance and daytime impacts.

Despite the work in Chapter's 4 and 5 involving amongst the largest samples of individuals studied to date in the context of WTN exposure in a laboratory environment, failure to demonstrate WTN impacts on sleep could still reflect Type II error. Thus, small differences could potentially have been missed and would require a larger sample of WTN-sleep disturbed participants to detect. In addition, the overall degree of WTN related sleep disruption in the home environment reported by the WTN-sleep disturbed group was in the moderate range. By study design, the intention was to capture residents living near wind turbines with the greatest degree of sleep disturbance attributed to WTN. This group appeared to demonstrate some signs of more chronically disturbed sleep compared to the other groups, but at relatively modest levels below those typically used to classify chronic insomnia. However, it also remains unclear how representative the recruited sample might be of highly disturbed individuals given several factors that made this group particularly challenging to recruit; including travel-distance to the sleep laboratory, COVID-19 travel restrictions, the time commitment necessary to accommodate the multi-night study protocol and reluctance to engage in research. We also did not have prevalence data to support the anecdotal reports of WTN related sleep disturbance in the field. Thus, multiple potential biases may have influenced study participation within each sample group. Whilst potential recruitment bias could influence between group comparisons, any consistent WTN exposure effects would still have been expected from within-subjects comparisons between nights, for which there was also substantially greater study power across the full study sample. Age was also significantly different between groups so was treated as a covariate in all statistical models. Further research with larger sample sizes, higher WTN levels and ideally in age-matched groups remain warranted to test for potential conditioned responses to WTN during wakefulness, particularly in residents reporting WTN related sleep disruption and daytime impacts.

6.6 Future directions

Given the largely negative findings of this study, one of the key next steps for research in this area is to examine the effects of worst-case WTN exposure on objectively measured sleep and next-day functioning. This effort will require a deeper understanding of what specific noise features and SPLs constitute worst-case WTN exposure in the field and should be guided by long-term field measurements, daytime listening test data and established noise limits for the selection of noise samples before undertaking more challenging overnight exposure studies of sleep disruption effects. Similar to the experiments described in this thesis, future studies should also consider that WTN exposure could cause difficulty initiating and maintaining sleep through psychological and behavioural effects of insomnia and direct sleep disruption effects that may reduce sleep time and quality. It is possible that WTN-sleep disturbed individuals are frequently exposed to, and experience sleep disturbance related to more disruptive WTN than was used in the current study. Consequently, future experimental studies should administer WTN interventions more representative of worst-case levels in real-world environments and at currently accepted night-time noise limits, which could potentially be somewhat different. One of the major challenges with investigating noise effects on sleep is that conclusions are potentially limited to the characteristics of the specific noise sample used in the study, for which generalisation beyond the particular noise sample is inevitably somewhat problematic. Although future studies should consider the use of multiple WTN exposure samples from a range of wind farm environments particularly those associated with noise complaints, multi-night studies are more logistically challenging and expensive to conduct. Thus, more strategic selection of noise samples based on noise complaints and daytime listening test data may be particularly useful to identify the most annoying and intrusive noise samples potentially most problematic for sleep.

Another potentially important avenue for future research to consider is to also go beyond traditional measures of sleep and next-day functioning to test for microstructural changes in brain activity and other markers of physiological disturbances during sleep and more sensitive measures of daytime functioning. For example, high density electroencephalography (EEG) and quantitative EEG (qEEG) enable much finer-grained analysis of sleep than conventional sleep staging. These techniques are able to detect more subtle changes in the brain in the presence versus absence of a stimulus (D'Rozario et al., 2017). For instance, increased slow wave activity during slow wave sleep is associated with improved declarative memory and faster reaction times, whereas reduced theta activity in non-REM sleep is a predictor of daytime sleepiness in healthy participants (Göder et al., 2006; Wichniak et al., 2003). EEG K-complex detection (Lechat, Hansen, Catcheside, & Zajamšek, 2020; Lechat et al., 2021a), markers of sleep disruption more strongly associated with mortality than traditional sleep metrics (Lechat et al., 2021b) and markers of cardiovascular activation responses (Betta et al., 2020; Catcheside et al., 2002) are also likely to be of high value for identifying WTN features and noise levels most disruptive to sleep. Thus, more sensitive indicators of sleep and daytime impairment could enable the detection of WTN related disturbance and should be employed in future research. Ongoing research within a larger trial associated with this thesis work is specifically testing for SPLs dependent effects of WTN compared to RTN on sleep using both conventional and more sensitive EEG and cardiovascular response markers of sleep disruption. Results from those experiments are very likely to help inform the selection of WTN exposure levels most relevant to future work.

Lastly, the effects of cognitive behaviour therapy for insomnia, or cognitive behaviour therapy in general on WTN-sleep disturbed individuals living in wind farm areas should also be studied. Irrespective of the largely negative findings from this thesis work, there are some residents who report sleep problems and decreased quality of life that they causally attribute

to living near a wind farm. Even though causal relationships remain unclear, insomnia symptomatology and noise disruption still warrant strategic intervention through noise abatement, noise masking and cognitive behavioural therapies. Future research could involve debriefing individuals who were deemed “WTN sleep disturbed” and also testing the efficacy of strategies shown to be effective in the management of distress related to noise disturbance amongst clinical populations of interest, such as WTN-sleep disturbed individuals (Aazh, Landgrebe, Danesh, & Moore, 2019).

6.7 Conclusions

Based on the findings of this thesis, 25 dB(A) WTN, equivalent to year-long median WTN levels around 1-3km from an established wind farm in South Australia does not impact conventional objective or subjective markers of sleep time and quality or next-day mood, anxiety or cognitive performance. Results did not significantly differ between groups of residents recruited from areas close to a wind farm who do or do not report habitual WTN related sleep disruption, individuals from quiet rural areas, or urban residents reporting RTN related sleep disruption. Furthermore, there was no evidence to support that WTN exposure at 25 dB(A) elicited a conditioned response to impair the initiation and maintenance of sleep during the overnight sleep opportunity. Further research is required to more comprehensively understand the relationship between nocturnal WTN, sleep and daytime functioning. Future research should investigate sleep microstructure during nocturnal WTN exposure and assess for effects on next-day performance tasks using more sensitive measures. Additionally, WTN interventions of varying acoustic characteristics should be tested, including samples collected under worst-case conditions. Cumulative effects over multiple consecutive nights of noise exposure should also be considered. This will allow for a greater understanding of how nocturnal WTN exposure during sleep may impact individuals and help to guide the need for

and design of strategic interventions to assist residents who report WTN related sleep disruption. This thesis illustrates the importance of using carefully controlled experimental designs and supports that future experimental research to further investigate the impact of WTN with more disruptive noise levels is warranted.

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APPENDICES

Appendix 1 Systematic Review and Meta-Analysis Database Searches.

PubMed Search:

((((("wind farm noise"[Title/Abstract]) OR "wind turbine noise"[Title/Abstract]) OR "wind turbine sound"[Title/Abstract]) OR "wind turbine noise exposure"[Title/Abstract]) AND sleep[Title/Abstract]

Returned – 28 results

Restricted to English articles – 27 results

Restricted to articles published from 2000 onwards – 27 results

Restricted to human species – 21 results

Scopus Search:

(TITLE-ABS-KEY (*"wind farm noise"*) OR TITLE-ABS-KEY (*"wind turbine noise"*) OR TITLE-ABS-KEY (*"wind turbine sound"*) OR TITLE-ABS-KEY (*"wind turbine noise exposure"*) AND TITLE-ABS-KEY (*"sleep"*))

Returned – 61 results

Restricted to English articles – 60 results

Restricted to article or conference paper only – 48 results

Science Direct Search:

"wind farm noise" OR "wind turbine noise" OR "wind turbine sound" OR "wind turbine noise exposure" AND "sleep"

Returned – 89 results

Restricted to Research Articles only – 80 results

Web of Science Search:

(TS=("wind farm noise" OR "wind turbine noise" OR "wind turbine sound" OR "wind turbine noise exposure" AND sleep))

Returned – 323 results

Restricted to article or proceedings papers only – 274 results

Medline Search:

(("wind farm noise" or "wind turbine noise" or "wind turbine sound" or "wind turbine noise exposure") and "sleep").mp. [mp=title, abstract, original title, name of substance word, subject heading word, floating sub-heading word, keyword heading word, organism supplementary

concept word, protocol supplementary concept word, rare disease supplementary concept word, unique identifier, synonyms]

Returned – 33 results

Restricted to humans and articles published from 2000 onwards – 26 results

CINIHAL Search:

AB "wind farm noise" OR AB "wind turbine noise" OR AB "wind turbine sound" OR AB "wind turbine noise exposure" AND AB "sleep"

Restricted to articles published from 2000 onwards, English language and human species – 2 results

Appendix 2 Recruitment poster used to recruit participants in the study reported on in Chapter's 4 and 5.

Appendix 3 Online laboratory sleep diary used in Chapter 4.

Laboratory Sleep Diary

Researchers, please complete the next 3 questions.

Please enter Participant ID:

Participant ID: _____

What morning is this?

☐ Morning 1 ☐ Morning 2 ☐ Morning 3 ☐ Morning 4 ☐ Morning 5 ☐ Morning 6 ☐ Morning 7

What condition is this?

☐ CA ☐ CB ☐ CC ☐ CD ☐ CE ☐ CF ☐ CG

Sleep Items

Participants, please complete the rest of this questionnaire.

Q1 How long did it take you to fall asleep last night, after the lights were turned out for the final time?

_____ Hours _____ Minutes

Q2 How much time do you think you SPENT IN BED last night, from the time the lights were turned out until lights were turned on this morning?

_____ Hours _____ Minutes

Q3 How much time do you think you SPENT AWAKE last night, *not including the initial time you took to get to sleep*?

_____ Hours _____ Minutes

Q4 What awakened you this morning?

- ☐ Noise
- ☐ Discomfort
- ☐ Technician
- ☐ Spontaneous
- ☐ Other

Q4.1 If other, please specify:

_____

Q5 After your final awakening this morning, how long did you stay in bed trying to sleep?

_____ Hours _____ Minutes

Q6 If you were awake across the night, how many times do you think you woke up?

_____ Awakenings

Q7 If you were awake across the night, how much time do you think you SPENT ASLEEP last night, from the time the lights were turned out until lights were turned on this morning?

_____ Hours _____ Minutes

Q8 Did you wake up earlier than you planned?

☐ Yes ☐ No

Q8.1 If yes, how much earlier?

_____ Hours _____ Minutes

Q9 How frequent were your awakenings compared to a normal night?
0=Never woke; 10=Woke a lot.

0	1	2	3	4	5	6	7	8	9	10
☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

Q10 How much time did you spend awake compared to a normal night?
0=Much less than usual; 10=Much more than usual.

0	1	2	3	4	5	6	7	8	9	10
☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

Q11 How would you rate the quality of your sleep?

☐Very poor ☐Poor ☐Fair ☐Good ☐Very good

Q12 How did you sleep compared to a normal night?

☐Much worse than usual ☐A little worse than usual ☐About usual ☐A little better than usual ☐Much better than usual

Q13 If your night was different from a normal night, why was this? (i.e., wires uncomfortable, different environment, noise etc.)

_____

Q14 How easy was it to fall back to sleep after awakening?
0=Easy; 10=Difficult

0	1	2	3	4	5	6	7	8	9	10
☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

Q15 Compared to a normal night, was it easier to fall asleep following awakenings?
0=Easier; 10= More difficult

0	1	2	3	4	5	6	7	8	9	10
☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

Q16 Please rate the depth of your sleep:
0=Light; 10= Deep

0	1	2	3	4	5	6	7	8	9	10
☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

Q17 Compared to a normal night, was your sleep deeper or lighter than usual?
0=Lighter; 10= Deeper

0	1	2	3	4	5	6	7	8	9	10
☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

Noise Items

Q18 Did you hear any noise throughout the night?

☐ Yes ☐ No

Q18.1 If yes, when did you hear the noise (select all applicable)

☐ When I was falling asleep ☐ When I woke throughout the night

Q18.2 If yes, how frequent was the noise?
0=Not at all; 10=Extremely

0	1	2	3	4	5	6	7	8	9	10
☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

Q18.3 If yes, how disturbing was the noise?
0=Not at all; 10=Extremely

0	1	2	3	4	5	6	7	8	9	10
☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

Q18.4 In total, how many times throughout the night did you hear noise(s)?

_____

Q18.5 Please describe the types of noises you heard during the night:

_____

_____

Q19 Did any noise impair your sleep quality?
0=Not at all; 10=Extremely

0	1	2	3	4	5	6	7	8	9	10
☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

Q20 Did any noise interfere with you getting to sleep initially?
0=Not at all; 10=Extremely

0	1	2	3	4	5	6	7	8	9	10
☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

Q21 Did any noise interfere with you getting back to sleep if you woke during the night?
0=Not at all; 10=Extremely

0	1	2	3	4	5	6	7	8	9	10
☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

Q22 How do you feel this morning?

	0	1	2	3	4	5	6	7	8	9	10
0=Fatigued; 10=Rested	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
0=Sleepy; 10=Awake	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
0=Tense; 10=Relaxed	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
0=Irritated; 10=Happy	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

Q23 Did anything happen last night that you think is important or that you would like to tell us about?

_____

_____

Thank you very much for logging your sleep.

Appendix 4 Linear mixed model analyses (df, F and p statistics) for noise condition and group main and interaction effects for PSG and sleep diary outcomes adjusted for age and hearing thresholds.

	Noise Condition			Group			Group by Noise Condition		
	df	*F*	*p*	*df*	*F*	*p*	*df*	*F*	*p*
PSG sleep efficiency (%)**	3,113	0.653	0.582	3,47	2.459	0.074	9,114	0.655	0.748
Sleep diary sleep efficiency (%)**	3,110	2.050	0.111	3,39	1.408	0.255	9,110	1.471	0.168
PSG sleep latency (min)*	3,121	2.474	0.065	3,61	1.595	0.200	9,121	0.890	0.537
Sleep diary sleep latency (min)*	3,105	1.479	0.224	3,44	1.063	0.374	9,111	1.290	0.250
PSG total sleep time (min)	3,113	1.177	0.322	3,49	1.463	0.236	9,112	1.039	0.414
Sleep diary total sleep time (min)	3,116	2.208	0.091	3,55	1.369	0.262	9,112	1.811	0.074
PSG time spent in bed (min)	3,131	0.273	0.845	3,174	1.189	0.315	9,132	1.785	0.077
Sleep diary time spent in bed (min)	3,120	0.777	0.509	3,58	0.130	0.942	9,125	0.755	0.658
PSG wake after sleep onset (min)	3,113	0.346	0.792	3,66	4.864	0.004†	9,115	0.582	0.809
Sleep diary wake after sleep onset (min)	3,117	1.757	0.159	3,60	0.784	0.508	9,122	1.341	0.223
PSG number of awakenings (N)*	3,113	0.367	0.777	3,45	0.278	0.841	9,106	0.901	0.527
Sleep diary number of awakenings (N)*	3,114	0.479	0.698	3,45	0.337	0.798	9,115	0.600	0.794

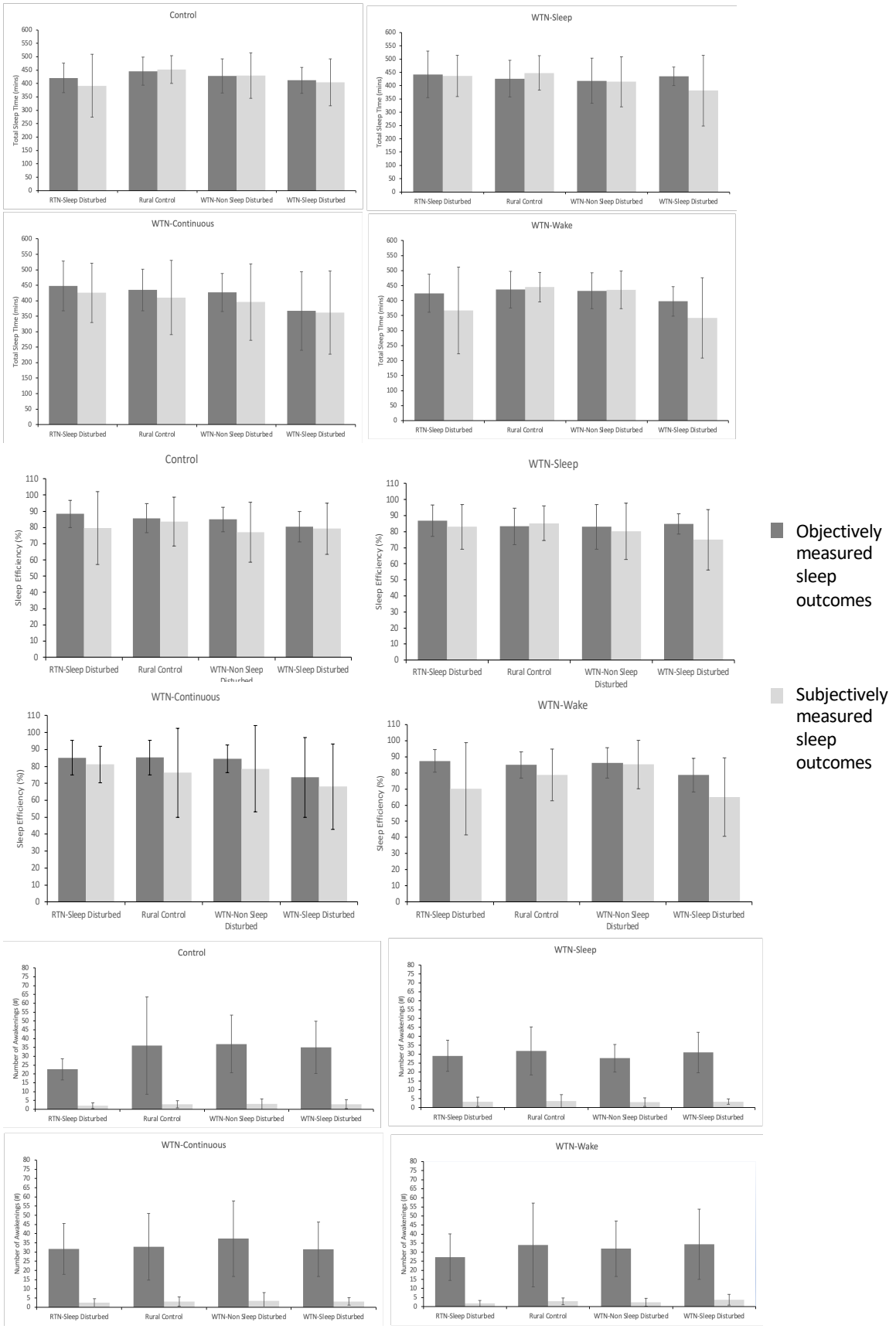
Note. Shaded area shows primary outcomes. *indicates Box-Cox normalised outcomes. **indicates $\log^{10}$ transformed outcomes. All other outcomes reflect normally distributed outcomes. †The WTN-sleep disturbed group had significantly more PSG-wake after sleep onset compared to the rural group (p=0.016) and the RTN-sleep disturbed group (p=0.004). PSG=Polysomnography. df=degrees of freedom.

Appendix 5 Linear mixed model analyses (df, F and p statistics) for noise condition and group main and interaction effects for PSG sleep stage outcomes adjusted for age and hearing thresholds.

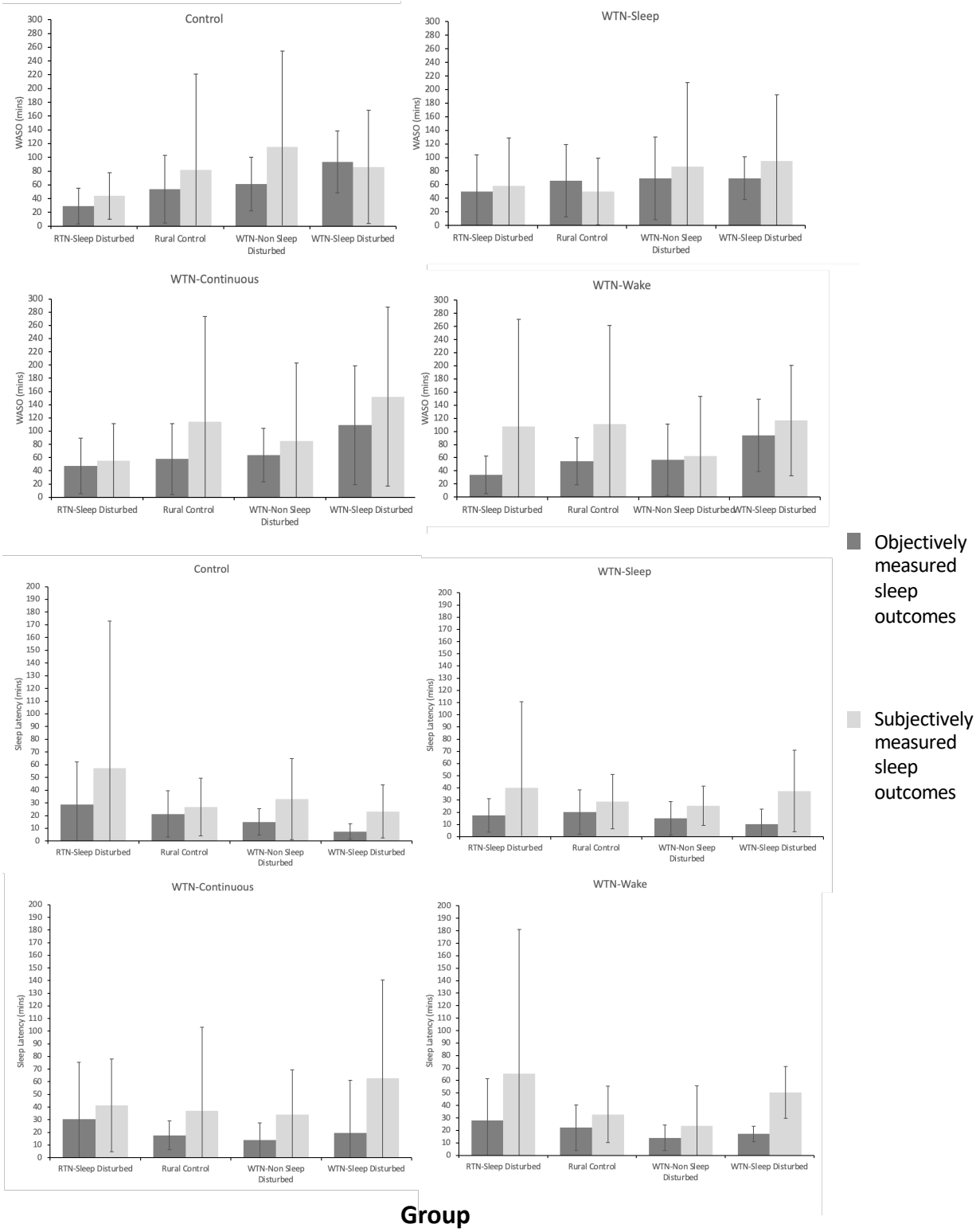
	Noise Condition			Group			Group by Noise Condition		
	df	*F*	*p*	*df*	*F*	*p*	*df*	*F*	*p*
N1 (min)	3,112	0.356	0.785	3,60	0.490	0.691	9,104	0.924	0.507
N2 (min)	3,109	2.044	0.112	3,43	1.003	0.401	9,112	1.803	0.075
N3 (min)	3,109	0.853	0.468	3,55	0.176	0.912	9,108	0.907	0.522
REM (min)	3,114	0.974	0.408	3,45	3.008	0.040*	9,112	0.702	0.706
N1 %**	3,111	0.229	0.876	3,34	0.847	0.478	9,109	0.638	0.762
N2 %	3,107	1.618	0.190	3,45	0.616	0.608	9,106	1.193	0.307
N3 %	3,105	0.338	0.798	3,46	0.265	0.850	9,108	1.477	0.165
REM %	3,114	0.944	0.422	3,45	2.628	0.062	9,114	0.747	0.665
N2 latency (min)**	3,118	2.110	0.103	3,60	1.530	0.216	9,116	1.067	0.392
N3 latency (min)**	3,115	1.068	0.365	3,61	0.220	0.882	9,121	0.614	0.783
REM latency (min)**	3,146	0.093	0.964	3,119	2.043	0.112	9,126	1.723	0.090
Total wake time (min)**	3,111	0.567	0.638	3,58	2.587	0.062	9,113	1.040	0.413

Note. *No significant post-hoc pairwise comparisons between groups. N1=Stage 1, N2=Stage 2, N3=Stage 3, REM=Rapid Eye Movement Sleep. *df*=degrees of freedom. **indicates $\log^{10}$ transformed outcomes. All other outcomes reflect normally distributed outcomes.

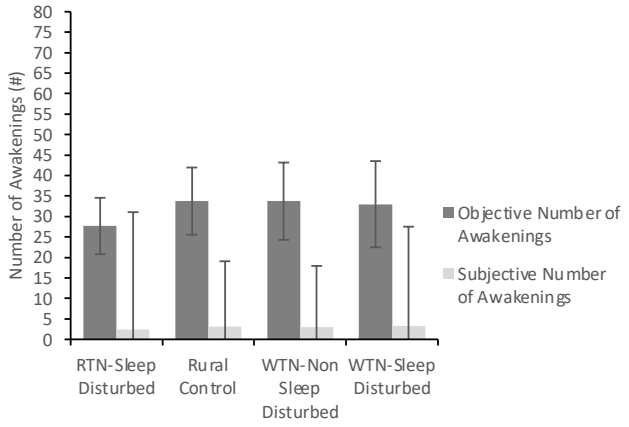
Appendix 6 Mean group comparisons for objective and subjective total sleep time, sleep efficiency and number of awakenings under each noise condition. Note. Error bars reflect standard deviations.

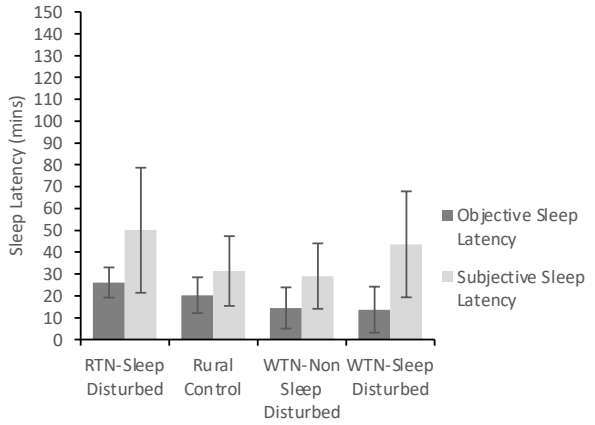


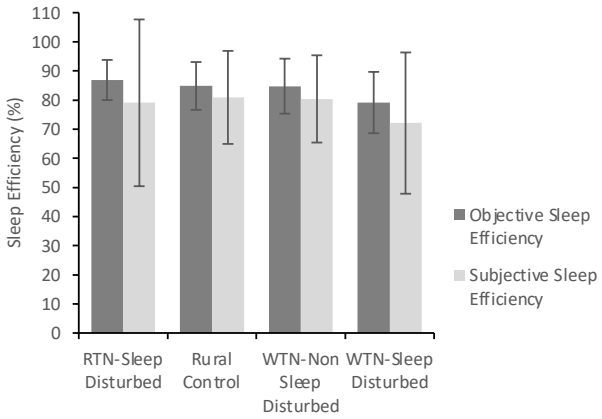
Appendix 7 Mean group comparisons for objective and subjective wake after sleep onset and sleep latency under each noise condition. Note. Error bars reflect standard deviations.

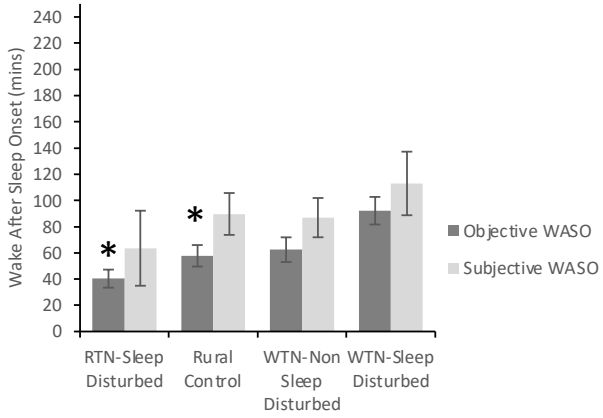


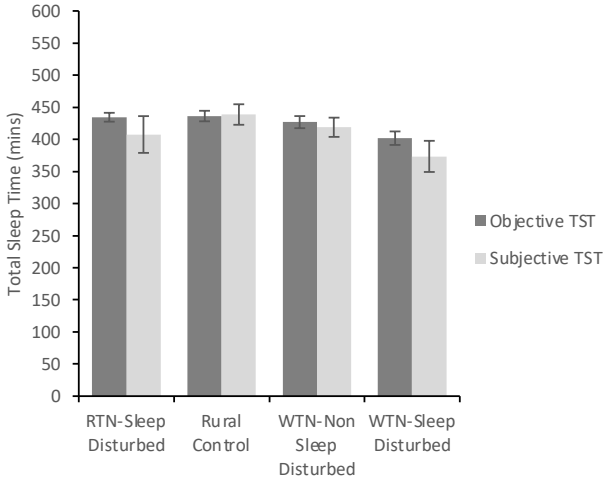
*Appendix 8 Group main effects for each objective and subjective sleep parameter irrespective of noise condition. Note. * Indicates p<0.05 from WTN-Sleep disturbed group.*

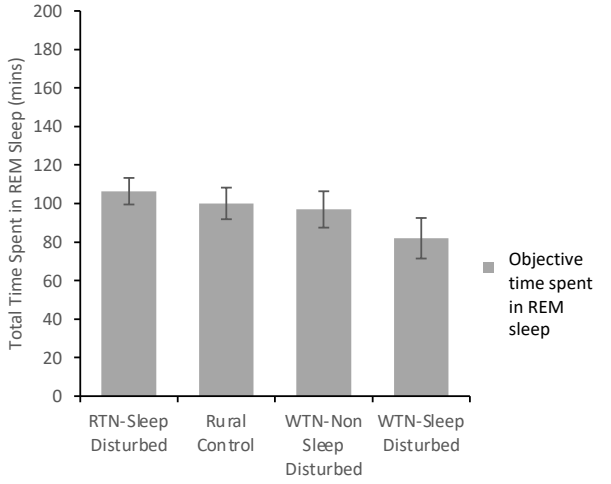












Appendix 9 PSG versus sleep diary parameters correlational analyses.

	Control	WTN-Continuous	WTN-Sleep	WTN-Wake
Sleep Efficiency	r_s = 0.494, p<0.001	r_s = 0.523, p<0.001	r_s = 0.621, p<0.001	r_s = 0.482, p<0.001
Sleep Latency	r_s = 0.456, p<0.001	r_s = 0.338, p=0.005	r_s = 0.414, p=0.009	r_s = 0.291, p=0.023
Wake After Sleep Onset	r_s = 0.467, p<0.001	r_s = 0.562, p<0.001	r_s = 0.600, p<0.001	r_s = 0.510, p<0.001
Total Sleep Time	r_s = 0.671, p<0.001	r_s = 0.595, p<0.001	r_s = 0.710, p<0.001	r_s = 0.566, p<0.001
Number of Awakenings	r_s = 0.271, p=0.029	r_s = 0.260, p=0.035	r_s = 0.413, p=0.001	r_s = 0.532, p<0.001

Note. WTN=Wind Turbine Noise. r_s =Spearman's rank correlation coefficient.

Appendix 10 Means and standard deviations of at-home self reported sleep parameters versus in-laboratory self-reported sleep parameters.

	Control								**WTN-Continuous**							
	WASO		TST		Sleep latency		Sleep efficiency		WASO		TST		Sleep latency		Sleep efficiency	
	Home	Lab	Home	Lab	Home	Lab	Home	Lab	Home	Lab	Home	Lab	Home	Lab	Home	Lab
WTN-sleep disturbed	38.3± 25.4	85.0± 87.0	7.1± 1.0	7.0± 1.5	18.1± 13.9	23.6± 23.5	70.0± 20.1	79.8± 17.1	38.3± 25.4	160.9 ± 150.4	7.1± 1.0	5.1± 3.4	18.1± 13.9	70.9± 85.9	68.3± 22.0	68.3± 28.7
WTN-non sleep disturbed	31.6± 20.2	115.0 ± 139.2	7.1± 0.8	6.8± 2.2	25.9± 22.3	33.0± 32.0	79.7± 11.2	77.2± 18.5	30.1± 20.6	85.0± 117.8	7.1± 0.8	6.6± 2.1	25.3± 21.8	33.9± 35.5	80.3± 11.1	78.6± 25.5
Rural control	23.9± 20.4	81.8± 138.9	7.5± 0.8	7.5± 0.9	20.2± 16.0	26.8± 22.7	79.8± 8.5	83.6± 15.1	23.9± 20.4	114.2 ± 159.5	7.5± 0.8	6.8± 2.0	20.2± 16.0	36.9± 66.1	79.8± 8.5	76.3± 26.3
RTN-sleep disturbed	17.6± 22.7	47.1± 32.8	7.6± 1.1	6.0± 2.6	22.1± 10.7	53.0± 118.5	77.5± 23.1	79.6± 23.2	18.3± 23.4	50.1± 47.2	7.6± 1.1	6.4± 2.3	21.2± 10.5	38.8± 38.7	83.0± 9.0	81.7± 10.1

Note. WTN=Wind Turbine Noise. RTN=Road Traffic Noise. WASO=Wake After Sleep Onset. TST=Total Sleep Time.

Appendix 11 Linear mixed model analyses (df, F and p statistics) for noise condition and group main and interaction effects for mood, anxiety, and cognitive performance outcomes.

	Noise Condition			Group			Group by Noise Condition		
	df	*F*	*p*	*df*	*F*	*p*	*df*	*F*	*p*
PVT Median Reaction Time (milliseconds)*	3,99	1.026	0.384	3,46	0.752	0.527	9,114	0.054	0.983
PVT Mean Reaction Time (milliseconds)*	3,102	1.452	0.232	3,45	0.884	0.457	9,103	0.530	0.850
PVT Errors (n)*	3,144	1.340	0.264	3,169	1.058	0.368	9,141	0.514	0.862
PVT Lapses (n)	3,110	0.532	0.661	3,60	1.162	0.332	9,114	0.526	0.853
Digit Span Forwards Recall (n)	3,108	2.202	0.092	3,59	2.364	0.080	9,113	1.154	0.332
Digit Span Backwards Recall (n)	3,163	0.375	0.771	3,179	3.856	0.010^	9,159	0.879	0.546
DSST Correct (n)	3,102	0.481	0.696	3,55	5.037	0.004ǂ	9,101	0.320	0.967
DSST Errors (n)*	3,114	0.519	0.670	3,52	2.367	0.081	9,120	0.854	0.568
Total Mood Disturbance*	3,130	2.243	0.086	3,178	1.792	0.150	9,131	0.837	0.583
State Anxiety*	3,138	1.018	0.387	3,182	2.839	0.039ǂǂ	9,135	3.248	0.074

Note. Shaded area shows primary outcome. *Log transformed data. ^Lower digit span backwards recall in the WTN-sleep disturbed group compared to the WTN-non sleep disturbed group (p=0.023) and the RTN-sleep disturbed group (p=0.008). ǂLower symbols correctly identified in the WTN-sleep disturbed group compared to the rural control group (p=0.037) and the RTN-sleep disturbed group (p=0.002). ǂǂGreater next-day state anxiety in the WTN-sleep disturbed group compared to the rural group (p=0.012). PVT=Psychomotor Vigilance Task. DSST=Digit Symbol Substitution Test. df=degrees of freedom. n=number.