Investigation of Effects of Wind Turbine Noise on General Health and Sleep Disturbance

by

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AUTHOR'S DECLARATION

This thesis consists of material all of which I authored or co-authored: see "Statement of Contributions" included in the thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

STATEMENT OF CONTRIBUTIONS

This dissertation is an original intellectual product of the author, L.Jalali and contains six chapters including an introduction, literature review, three manuscripts, and a concluding chapter. L.Jalali is the sole author of Chapters 1, 2 and 6 (introduction, literature review and conclusion), and the first author and main contributor to the manuscripts that comprise Chapters 3-5. Chapters 3, 4, and 5 have been published in the Journals of *Environmental Pollution*, *Environmental Research*, and *Noise and Health*, respectively. L.Jalali was responsible for all major areas of concept formation, sleep data collection and analysis, as well as manuscript composition. The author's supervisors Professor P. Bigelow and Professor S. McColl were involved throughout the project in concept formation and manuscript composition. M. Gohari supported and advised on statistical analysis of the data. M.R. Nezhad-Ahmadi conducted noise data collection and supported the analysis. Mapping and calculation of the population size in study area were done by R. Waterhouse, a GIS Analyst in the Niagara Region Public Health. Other co-authors to these three manuscripts provided insights and review.

The fieldwork reported in Chapters 3 to 5 was covered under University of Waterloo Ethics Certificate, number 19445, and supported by Ontario Research Chair in Renewable Energy Technologies and Health and the Niagara Region Public Health.

Main tools that were developed and used in the course of this research were the "Wind Turbine and Health-Related Quality of Life (HRQoL)" questionnaire, sleep questionnaire, sleep diary, and portable sleep and noise measurement system. The "Wind Turbine and HRQoL" questionnaire was an outcome of collaboration with the "Renewable Energy Technologies and Health team" at the University of Waterloo. The sleep questionnaire consisted of pre-developed and standardized measures, and the sleep diary comprised of the main questions from *the NSF*

Sleep Diary (National Sleep Foundation, 2007). A key tool that was developed and used for the objective study portion of this research was a field measurement system for synchronous sleep and noise assessment. The author formed the main concept for this specific tool through discussion of the research problem and collaboration with the engineering team. In the design of this tool, researchers in engineering disciplines supported the project for noise measurement and synchronization of noise and sleep data. They were involved in the early stages of concept formation and contributed to noise data collection and noise analysis.

The author also worked with Dr. R. Ramakrishan, a Professor in the Faculty of Engineering and Architectural Science at Ryerson University, who brought to the team his expertise and experience in measurement and assessment of audible and low frequency sound from wind turbines. The author also had collaboration with Dr. S. Adibi, Vice Chancellor Research Fellow at the Royal Melbourne Institute of Technology, who added to the team through his leading edge research and innovation in areas of mobile health, the optimisation of wireless-based technologies and the integration of biomedical sensors into mHealth systems. The result of this collaboration was a book chapter published by Springer and some parts of this chapter are reported in Chapter 6.

ACCQ Sleep Labs supported this project by training L.Jalali on sleep measurement techniques and technologies, data collection systems, and scoring of measured sleep data. Sleep data in the study were scored blindly by two professional sleep technologists. L.Jalali also received advice from Professor M. Basner, Associate Professor of Sleep and Chronobiology in University of Pennsylvania, in study design and review of the manuscript.

I testify that I am the primary author of the manuscripts in my dissertation, and that the work was dominated by my intellectual efforts.

ABSTRACT

Background: Although wind energy is now one of the fastest growing sources of power in Canada and many other countries, the growth in both number and size of wind turbines (WTs) has raised questions regarding potential health impacts on individuals who live close to such turbines. Suspected health-related effects of exposure to WT noise have attracted much public attention, with symptoms such as sleep disturbance reported by residents living close to wind energy developments.

Objective: The overall objective of this study was to better understand and investigate the association between WT noise exposure and self-reported and objective measures of sleep and general health in nearby residents.

Methods: This thesis consists of four studies: 1) a narrative review of the literature pertaining to general health and sleep effects related to WT noise, 2) a health and quality of life (QoL) field study exploring changes in QoL by using standard scales, 3) a sleep survey study evaluating self-reported sleep quality of residents by standard and validated sleep questionnaires, and 4) an objective sleep and noise study that included polysomnography and inside noise measurements during two consecutive nights. Participants also completed sleep diaries over a one week period. The field studies employed a prospective cohort design, with two data-collection times: before and after WT operation.

Results: The literature review was intended to examine the peer-reviewed literature regarding evaluations of potential health effects such as degraded QoL, annoyance, and sleep disturbance among people living near WTs. Of 200 relevant articles, 30 articles (reporting on 11 cross-sectional studies) investigated a relationship between WTs and health, and fulfilled the inclusion

criteria. The evidence, found in the review, was judged to be not sufficient to establish a cause-and-effect relationship. To address the limitations in existing research, it was recommended that a prospective study, with objective sleep and noise measurements before and after operation of WTs, be conducted.

In the health and QoL study, the mean values for the Mental Component Score of SF12 ($p<0.001$), Satisfaction with Life Scale ($p=0.002$), Wind Turbine Syndrome Index ($p<0.001$), and Canadian Community Health Survey- Satisfaction with Life ($p=0.048$) significantly worsened after WT operation. These results were strongly associated with concerns about property values, attitude to WTs, noise sensitivity and visual and noise annoyance.

In the subjective sleep study, the mean scores of the Pittsburgh Sleep Quality Index (PSQI), Epworth Sleepiness Scale (ESS) and Insomnia Severity Index (ISI) significantly increased. Changes in PSQI scores over time were strongly associated with negative attitudes to WTs, turbine visibility, and concerns about property values. Changes of ISI scores were also strongly related to property devaluation concerns and negative attitudes to WTs.

No major differences were found in the objective sleep data of participants in terms of the effects on whole-night sleep parameters, sleep discontinuity, sleep quantity, and sleep efficiency. The reported effects on sleep, obtained by sleep diaries, support the findings from polysomnography in regards to sleep quantity.

The average A-weighted noises measured in Time1 (T1) and Time2 (T2) observations were not significantly different, with means of 36.55 dB(A) (SD=4.18) in T1 and 36.50 dB(A) (SD=4.20) in T2 for Total Time in Bed (TIB) ($p=0.959$). The average Z-weighted sound pressure levels measured in T1 and T2 observations were also not significantly different, with means of 63.78 dB (Z) (SD= 5.07) in T1 and 61.93 dB (Z) (SD=6.00) in T2 for TIB ($p=0.218$).

Conclusions: The results of this study based on advanced sleep recording methodology together with extensive noise measurements, in an ecologically valid setting, cautiously suggest that there are no major changes in the sleep of participants newly exposed to WTN. Results of the subjective data provide evidence for the role of individual differences and psychological factors in reports of sleep disturbance and degraded QoL by people living near WTs.

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I am very grateful to all members of my dissertation committee: Dr. Diane Williams from the School of Public Health and Health Systems, Professor John Vanderkooy from the Department of Physics and Astronomy and Professor Colleen Carney from the Department of Psychology at Ryerson University. Their expertise and constructive criticism were instrumental in the development of this thesis project. I value having such an array of insightful minds concerned about and interested in my research.

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My sincere thanks to the University of Waterloo, School of Public Health and Health Systems, in particular, I would like to thank Tracy Taves, Carol West-Seebeck, Tracie Wilkinson, Krista Nicol, and all the others in the department who helped me navigate the whole Ph.D. process.

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I wish to express my most sincere appreciation and love to my beloved family: my parents and my sibling, who I am forever indebted to them for what they have done for me to succeed, my cute sons, for their encouragements with their childish words, and my friends who have supported me throughout this process.

I wish to express my special gratitude and love to my husband for his ongoing motivation and encouragement. I owe thanks to him not only for his care, support and loving inspiration but also for his help in the long nights data collections. This thesis is as much a product of his support, and patience as it is of my efforts.

DEDICATION

To my wonderful mother and deeply missed brother who left us very early in the journey of life, and are not here to celebrate this accomplishment with me.

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List of Abbreviations

Acronym	Definition	Acronym	Definition
AASM	American Academy of Sleep Medicine	QoL	Quality of Life
AHI	Apnea-Hypopnea Index	REM	Rapid Eye Movement
EEG	Electroencephalogram	SWS	Slow Wave Sleep
EOG	Electrooculogram	S1 and S2	Stages one and two of sleep
EMG	Electromyogram	SSC	Sleep Stage Changes
ECG	Electrocardiogram	SP	Sleep Period
ESS	Epworth Sleepiness Scale	SPL	Sound Pressure Level
ISI	Insomnia Severity Scale	SWL	Satisfaction with Life
LAeq/DBA	A-weighted equivalent sound pressure level/ A-weighted decibels	T1 and T2	Time1 and Time2
Lzeq/DBZ	Z-weighted equivalent sound pressure level/ Z-weighted decibels	TIB	Total in Bed
MCS	Mental Component Score	TST	Total Sleep Time
PSG	Polysomnography	WASO	Wake time After Sleep Onset
PSQI	Pittsburgh Sleep Quality Index	WTSI	Wind Turbine Syndrome Index
PLM	Periodic Limb Movement	WTN	Wind Turbine Noise
PCS	Physical Component Score	WT	Wind Turbine

Chapter 1: Introduction

Background

Many countries around the world are moving away from fossil fuel and nuclear energy and instead embracing renewable energy sources such as solar, wind, hydro, and bio-fuel. The increasing growth of renewable energy technologies (RETs) such as wind is intended to have positive impacts on human health and well-being. These positive impacts are expected through reductions in air pollution, generation of spent nuclear fuel, greenhouse gas emissions, and a shift away from consuming energy from carbon-based resources, which are in limited supply. Clearly, there are tremendous health advantages in implementing RETs for the population at large. However, there are also potential local-level risks in increasing use of RETs, and they differ from those generally positive impacts likely to be experienced by the larger population.

In Canada, industrial wind operations are an important part of the country's long-term energy strategy. The oldest wind turbine (WT) in Ontario was built in 1994 in Tiverton, on the shore of Lake Huron (Canadian Geographic, 2016). This WT was installed to test performance in winter conditions. Ontario's first commercial wind farm was established in November 2002, also in Tiverton. It is comprised of five 1.8 megawatt WTs (Huron Wind, 2016). Currently, there are 2302 WTs in Ontario, with the majority having been built after 2006 (Canwea, 2015). In 2003, the capacity for WT energy in Ontario was 15MW, and in 2015, this rose to over 4361 MW of energy, which supplies over five percent of the province’s electricity demand. The goal is to increase it to 15% by 2025 (Canwea, 2015, Ontario’s Long-Term Energy Plan).

WTs consist of a base, tower, blades, and a generator to convert mechanical energy from the blades to electrical energy. During operation, WTs produce sound, which contains several components that can be broadly categorized as mechanical noise emitted by the rotating machinery in the hub and aero-dynamical sounds generated by the blades interacting with the air (Bolin et al. 2011). Mechanical noises are of less importance in modern WTs due to improved sound insulation, and even as the size of WTs increases, mechanical noise does not increase with the size of turbine as rapidly as aerodynamic noise (Wagner et al. 1996). Aerodynamic sources are dominant in modern WTs and are the main source of low frequency noise (Bolin et al. 2011). The noises from WTs are described as swishing, whistling, whooshing, resounding, and pulsating/throbbing, in an audible repeatable tone (Pedersen and Waye 2008), or reported as loud, sharp, rough, fluctuating, and modulating in more quantifiable measures (Waye and Öhrstrom 2002). Pedersen et al. (2009) stated that the sound of WTs is more annoying than equally loud sounds from other sources. Findings of other studies showed that people pay attention to more-annoying noises for a longer period of time (Waye and Öhrstrom 2002).

Consistent reports of health-related symptoms from residents who live near wind farms have been a concern since the beginning of the modern wind power history in the 1970s (Pederson et al. 2009). Health concerns reported in WT communities include dizziness, nausea, ear pressure, tinnitus, sleep disturbance, headache and other symptoms (Schmidt and Klokker 2014; Seltenrich 2014; Ambrose et al. 2012; Jeffery et al. 2013; Enbom-Lakartidningen 2013; Phillips 2011, McMurtry 2011). The term ‘‘Wind Turbine Syndrome’’ was coined in 2009 as the title of a self-published book to describe the association of these symptoms with WTN exposure (Pierpont 2009). In the popular literature, sleep disturbance has been among the most common symptoms and complaints reported by residents living close to wind farms (Krogh et al. 2011; Pierpont 2009).

Even without WTs, sleep disturbance is relatively common in the general population. A general agreement has developed from population-based studies that approximately a third of the population report one or more of the symptoms of insomnia: difficulty initiating sleep, difficulty maintaining sleep, waking up too early, and in some cases, nonrestorative or poor-quality sleep (Ancoli-Israel and Roth 1999). Sleep disturbance has multiple causes, including medical conditions, stress, and external stimuli such as noise.

It is well established that noise can disturb sleep. In fact, sleep disturbance is considered the most serious non-auditory effect of environmental noise exposure (Basner et al. 2014; Muzet 2007; Fritschi et al. 2011). Human beings perceive, evaluate, and react to environmental noises during sleep (Dang-Vu et al. 2010). WHO's publications ‘‘Night Noise Guidelines for Europe’’ and ‘‘Burden of Disease from Environmental Noise’’ indicate the importance of limiting nocturnal noise exposure for health and well-being. With respect to WTN, the key issue is whether the noise is loud enough to disrupt sleep (McCunney et al. 2014). For some environmental noises, such as traffic noise, a number of laboratory and field studies have provided sufficient evidence to conclude that they are significant causes of sleep disturbance, and depending on the related noise levels, may impair well-being during the subsequent waking period (Basner et al. 2006; Basner et al. 2008; Hume et al. 2003; Ohrstrom et al. 2006). For WTN, such evidence is limited, and published results from previous cross-sectional studies have been inconsistent in terms of possible effects of WTN on sleep. On one hand, those studies that measure or calculate noise as an exposure assessment found no or only weak associations between noise and sleep disorders. As an example, a large Canadian study that provided the most-comprehensive assessment of the association between exposure to WTN and sleep found no sleep-noise association for noise levels under 46 dB(A) (Michaud et al. 2015). A few other cross-sectional studies with reasonable sample sizes found only weak dose-response relationships between noise and self-reported sleep (at levels between 40- 45 dB (A)) or found that annoyance ratings were more strongly associated with self-reported sleep disturbance than was noise (Bakker et al. 2012; Mccunney et al. 2014; Pawlaczyk-Łuszczyńska et al. 2014; Pedersen and Waye 2004a).

On the other hand, those studies that used “distance to nearest WT” as an exposure measure almost all agreed that self-reported sleep disturbances were more frequent in subjects living closer to WTs than in subjects living further away (Krogh et al. 2011; Kuwano et al. 2013; Nissenbaum et al. 2012; Paller 2014; Shepherd et al. 2011). Based on the current published literature, it is not possible to conclude that sleep disturbances reported by residents close to WTs are attributable to WTN, or whether other factors also play a role. Most critically, due to the cross-sectional design of previous studies, and a paucity of WTN and health research that used prospective longitudinal designs, the temporal sequence of exposure–outcome relationships cannot be demonstrated.

Study Rationale

In spite of the fact that health concerns surrounding the use of industrial wind operations are increasing in Canada and around the world, few epidemiological studies have focused on WT effects on sleep. Given the complexity of the relationships between WTN and sleep, a mixed-methods approach should be used to better understand and investigate the effect of turbines on the general health and sleep of nearby residents. The importance of the program of research for this dissertation lies in determining the sleep impact of current industrial wind operations by providing physiologic measures and describing the events that may occur during sleep. Moreover, there have been only limited numbers of studies that report measures taken inside the bedroom. This dissertation research recorded sound pressure levels within study bedrooms, characterizing the noise to which individuals are truly exposed.

The findings that emerge from this research further the understanding of WT noise as a possible environmental health hazard and have the ability to serve as a model for further investigations of WTs and sleep disturbance. As this is the first epidemiological study using a gold standard of sleep measurement in an Ontario population, this study will contribute to the body of knowledge used to aid the review of legislation surrounding noise exposure limits with respect to WTs, as well as the review of setback limits for the construction of industrial wind operations.

The results of this study fit within the broader Renewable Energy Technologies and Health research program, which is exploring areas for improvement in renewable energies and determining possible health impacts related to the use of these technologies.

Ontario WT Health-Related Regulation

Current Ontario regulations related to WT placement are in the form of specific setbacks and noise thresholds. In 2008, Ontario published the document titled “Noise Guidelines for Wind Farms” and provided regulatory guidance based on wind speeds with sound exposure limits. The noise limit ranges from the lowest level of 40 dB (A) (which are allowed at wind speeds of 4 m/s) up to a maximum value of 51.0 dB (A) (which are allowed with wind speeds 10 m/s and above) (Noise Guidelines for Wind Farms, 2008). In 2009, the Ontario government took the second step in regulating WTs and issued the setback regulation of at least 550 metres from all noise receptors (Ministry of Energy, Guide to Provincial Approvals for Renewable Energy Projects, 2015). Most of these standards apply to turbines over 50 kW. The Chief Medical Officer of Health of Ontario issued a report in 2010 and confirmed the ability of these regulations to protect Ontario residents from adverse health effects. On February 11, 2011, the government of Ontario decided that it would not allow development of off-shore WTs until more research about this technology was available (Government of Ontario, 2011). This decision does not affect the development of on-shore WTs, which continue to be regulated with the above setback regulation and noise policy, guidelines and regulations.

Organization of Thesis and Research Hypothesis

The research reported here explores the possibility of sleep disturbance and degraded QoL in people living within close proximity of WTs. The hypothesis is that individuals living near newly operational wind-energy technology experience poorer sleep and lower QoL score than before the turbines were operational. This research involves a prospective cohort study, with multiple data-collection methods, and is grouped into three field studies, presented in Chapters 3-5 (Figure 1.1).

Chapter 3 presents the result of the first field study and refers to data collected using the "Wind Turbine and Health-Related QoL" questionnaire. This questionnaire consists of five sections: renewable energy in Ontario, housing and community, environmental stressors, overall QoL and general health perceptions, and demographic questions. General health and QoL were measured by standard scales such as SF12, the Satisfaction with Life Scales (SWLS) developed by Diener et al (1985) and the Canadian Community Health Survey, and a new-developed scale called "Wind Turbine Syndrome Index" (WTSI).

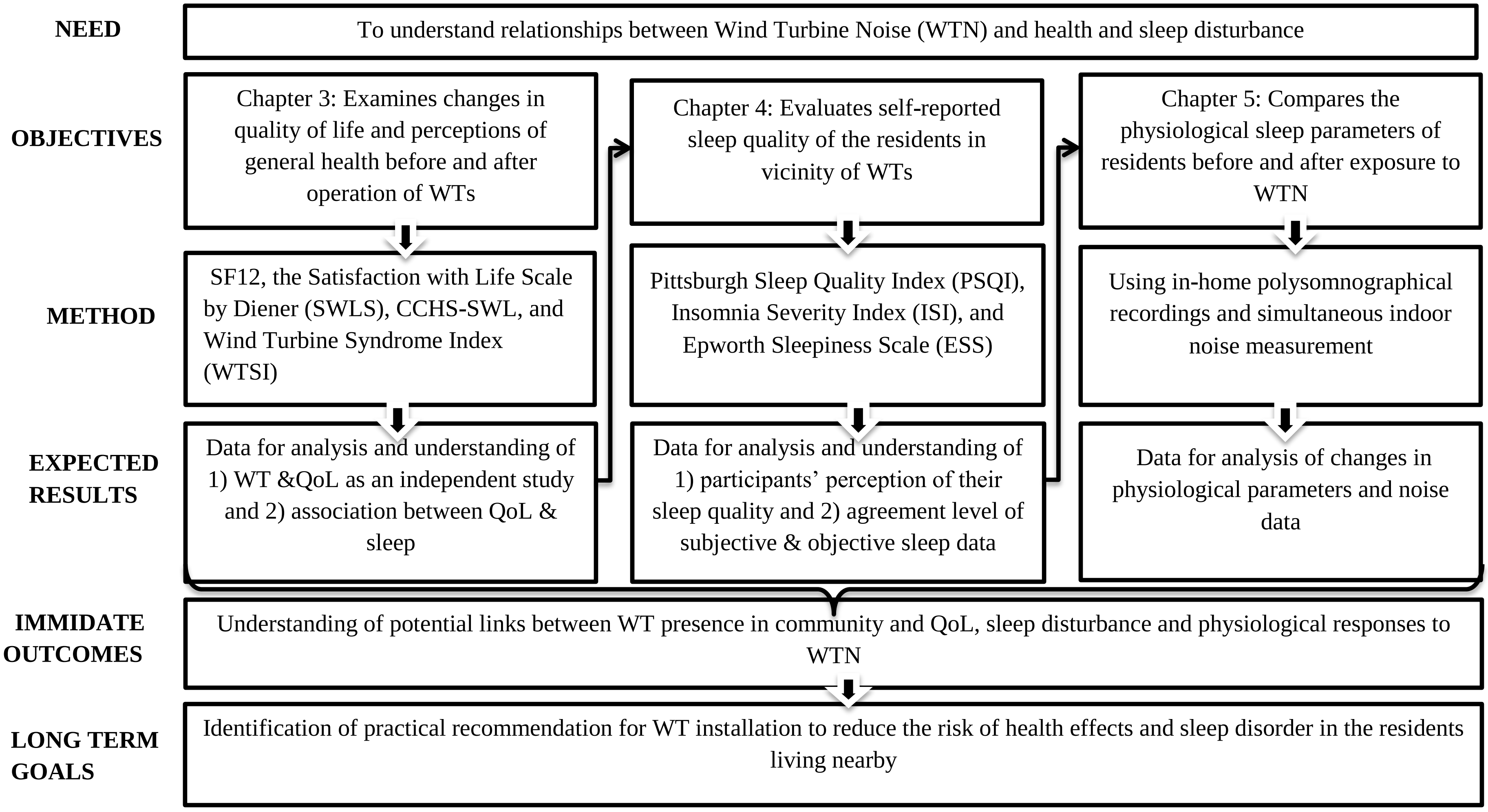
Chapter 4 presents the results of a self-reported sleep study that investigated the effect of WT exposure on subjective sleep outcome measures. This sleep questionnaire is comprised of validated instruments relating to sleep disturbance, daytime sleepiness and insomnia. Standard sleep scales such as the Pittsburgh Sleep Quality Index (PSQI), Insomnia Severity Index (ISI), and Epworth daytime Sleepiness Scale (ESS) were included in the questionnaire.

Chapter 5 presents results of the third study, which consisted of polysomnography sleep assessment with simultaneous noise measurement, and collection of information using a sleep diary. Noise measurements were conducted concurrently inside the bedroom of each participant. Different noise exposure parameters were calculated (LAeq, LZeq) and analyzed in relation to whole-night sleep parameters. Figure 1.2 shows the conceptual diagram of the study, with different wireless sensors placed on the body for the collection of physiological signals and in the indoor and outdoor environment for the collection of environment data such as noise level, wind speed, and temperature.

Two rounds of data were collected from individuals in all three studies, one pre- and one post-WT operation. Chapters 3-5 are structured with an introduction, methods, results, discussion, and conclusions sections.

The remainder of the thesis is divided into two chapters, consisting of a review of literature on health effects related to WTNs (Chapter 2), and an overview of the thesis findings (Chapter 6). The methodological limitations and future directions are also briefly described in Chapter 6.

Figure 1.1: A Mixed- Method Study for Assessment of Sleep and Wind Turbine Noise



NEED	To understand relationships between Wind Turbine Noise (WTN) and health and sleep disturbance		
OBJECTIVES	Chapter 3: Examines changes in quality of life and perceptions of general health before and after operation of WTs	Chapter 4: Evaluates self-reported sleep quality of the residents in vicinity of WTs	Chapter 5: Compares the physiological sleep parameters of residents before and after exposure to WTN
METHOD	SF12, the Satisfaction with Life Scale by Diener (SWLS), CCHS-SWL, and Wind Turbine Syndrome Index (WTSI)	Pittsburgh Sleep Quality Index (PSQI), Insomnia Severity Index (ISI), and Epworth Sleepiness Scale (ESS)	Using in-home polysomnographical recordings and simultaneous indoor noise measurement
EXPECTED RESULTS	Data for analysis and understanding of 1) WT &QoL as an independent study and 2) association between QoL & sleep	Data for analysis and understanding of 1) participants' perception of their sleep quality and 2) agreement level of subjective & objective sleep data	Data for analysis of changes in physiological parameters and noise data
IMMIDATE OUTCOMES	Understanding of potential links between WT presence in community and QoL, sleep disturbance and physiological responses to WTN		
LONG TERM GOALS	Identification of practical recommendation for WT installation to reduce the risk of health effects and sleep disorder in the residents living nearby		

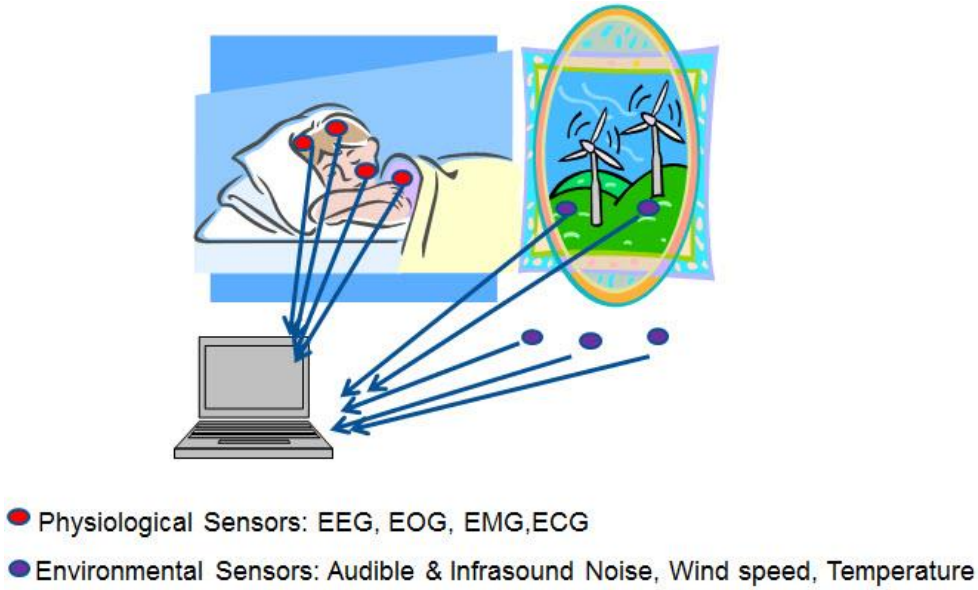


Figure 1-2: Conceptual Diagram of Placement Sensors on the Body for Physiological Data Collection and Indoor and Outdoor for Noise and Environment Data Collection

Chapter 2 : Literature Review

This section first describes the exposure, outcome of the study and possible pathways by which exposure may affect the outcome. The first section of this chapter provides a detailed description of the noise definition, method of measurements and existing metrics for quantifying the noise, followed by WHO recommendations for protection of public from night noise.

In the next section, sleep process, different sleep measurement techniques, and advantages and disadvantages of each method are discussed. In addition, we describe how noise interferes with sleep as well as the factors that influence the relationship of noise and sleep.

Literature reviews of relevant studies are also included in this chapter. We discuss the findings of the previous studies to provide an overview of existing studies with the intention of proposing an optimal field study for investigating the effects of WTN on sleep.

Exposure Measurement: Noise

Sound is a physical phenomenon resulting from the compression and expansion of air. Caused by vibration or turbulence, it propagates from a source in all directions (Suter 1991). It has several important properties, including level or intensity that is measured directly in decibels (dB); duration that is continuous, intermittent or impulsive, and frequency that is the rate of repetition of the sound pressure oscillations as they reach the ear. Several classes of noise metrics exist for quantifying noise exposure. Maximum A-weighted Sound Level, (LAmax), Sound Exposure Level (SEL) and Equivalent Sound Level (Leq) are commonly used noise metrics. The LAmax and SEL quantify the noise associated with individual events, and provide no information on the cumulative noise exposure. By contrast, Leq is a cumulative noise metric, calculated based on the variation of sound pressure over time and the duration of the noise, and can be represented in a 24-hour period or divided into daytime, evening, and night (Noise Metric and Acoustic Terminology, 2004).

Specific health complaints are associated with different types of noise sources (e.g., traffic, aircraft, industrial, wind turbines) and a variety of different noise metrics may be relevant. In sleep research, measures of instantaneous effects such as awakenings and onset of motility are better assessed with the LAmax and SEL, and long-term effects such as mean motility and after-effects are more correlated with Leq and other indicators that average the noise over a long period of time (Night Noise Guideline, 2009). Both the WHO and the European council (EC) recommend using Lnight as the primary indicator for sleep disturbance. The Night Noise Guidelines (NNG) for Europe and the Environmental Noise Directive (END) allow the possible use of both LAmax and SEL in addition to Lnight to predict sleep quality (Fritschi et al. 2011).

Noise exposure can be measured directly outside and inside homes or can be modelled for a given geographical area. Some studies estimate the exposure based on distance between the source and the receiver. Noise measurement has advantages over noise mapping and prediction in terms of accounting for any unexpected exposures and variables such as neighbors' contributions and attenuation of noise due to environmental conditions. In noise prediction method, there is also potential for exposure misclassification (Swift 2010).

Choosing the method of noise assessment depends on the location of the study, sample size and study design. With the rapid advancement of measurement technologies and portable devices, the cost of measurement is decreasing and noise measurement in field is becoming increasingly more feasible.

The U.S. Environmental Protection Agency (EPA) has chosen A-weighted level as the basic measure of environmental noise, due to correlation with hearing. Focusing on the mid- and high-range frequencies we hear, it approximates the response of the human ear to typical sounds and filters low and high frequencies. Although dB (A) measurement is often reported in noise studies, there may be a significant low frequency noise energy that is not effectively captured by this metric and this is especially problematic in WT studies. A-weighting measurement techniques used in the existing research studies does not fully describe the WTN characteristics. Figure 2.1 shows low-frequency components of WT sound spectrum before and after A-weighting. The original spectrum has been taken from Van den Berg's study (2006). The shaded area represents the degree of alteration of the spectrum by A-weighting. Representing this sound as 42 dB (A) ignores the components in low-frequency.

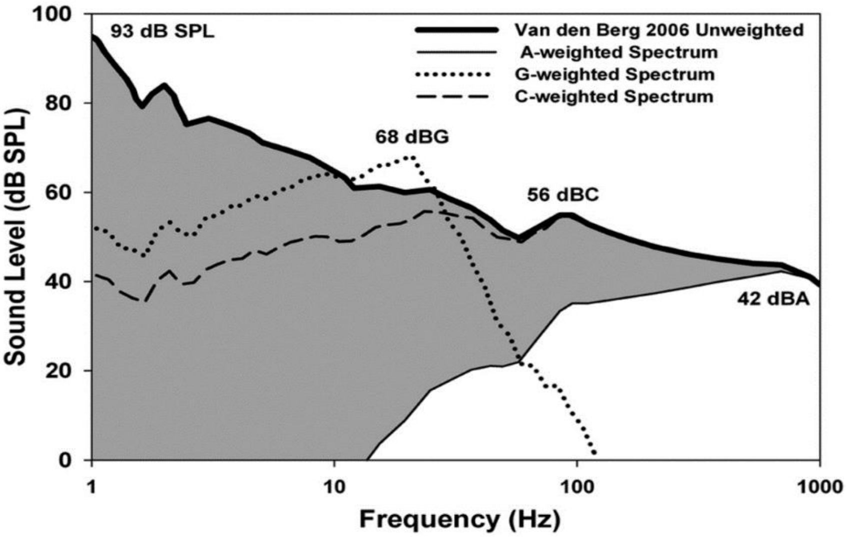


Figure 2.1: Unweighted and Weighted WTN Spectrum (taken from Van Den berg 2006)

WHO guidelines (WHO, 1999) recommended for the protection of public from night noise (11pm-7am) are that sound pressure levels should not exceed from LAmax=45 dB and LAeq=30 dB inside the bedroom and LAmax=60 dB and LAeq=40 dB outside the bedroom. According to the Night Noise Guidelines (2009), different continuous sound levels during the night (Lnight, outside) are associated with the following effects: < 30 dB - no significant biological effects; 30–40 dB - some effects on sleep such as body movements, awakening, self-reported sleep disturbance, and arousals (dependend on the source and the number of events); 40–55 dB - adverse health effects among the exposed population with more severe effects on vulnerable groups; and > 55 dB - annoyance and sleep disturbance in high percentage of the population (Night Noise Guideline, 2009, Basner et al. 2014).

Outcome Measurement: Sleep

Sleep, an active process that involves distinct characteristics and many vital physiological changes in the body organs, is fundamental for physical and mental health. Physiological processes involve protein biosynthesis, excretion of specific hormones, and memory consolidation, which prepare the organism for the next wake period (Münzel and Gori 2014). Sleep is divided into two different behavioral states: REM (rapid eye movement) sleep in which dreaming occurs and non-REM sleep. Non-REM sleep subdivided into three sub-stages, distinguished by levels of EEG during polysomnographic recordings. Each sequential stage of non-REM sleep is indicative of a deeper sleep, with stage 1 (S1) as the lightest and stage 3 (S3) as the deepest. Stage 3 also called slow wave sleep (SWS). There are usually about five cycles of sleep during a night and each cycle lasts about 90 minutes. A typical night's sleep includes about two hours of SWS, three quarters of which accumulate in the first half of the night. In contrast, REM sleep, which also lasts for about two hours, occurs predominantly during the second half of the night (Peplow 2013). SWS and REM sleep are considered very important for restoration and memory consolidation during sleep (Stickgold 2005; Basner et al. 2012). Wake and stage 1 phases, although physiological parts of the sleep process, are typical indicators of disturbed or fragmented sleep, and they do not contribute significantly to the recuperative value of sleep (Wesensten 1999).

The most common sleep indicators, measured in sleep research, are number of awakenings (AWR), number of awakenings plus changes to stage one (AS1), number of changes of sleep stages (CSS), and number of arousals (ARS).

Effects of noise on sleep are measured using any of the following methods: polysomnography (PSG), actigraphy, Seismo-Somnography (SSG), ECG and sympathetic tone measurement, behaviorally signal awakening, and self-reported study.

Polysomnography (PSG): PSG, the most valid method and the gold standard for sleep assessment, involves measuring brain activity (EEG), eye movement (EOG), muscle tone (EMG), heart activity (ECG), airflow through the mouth and nose, respiratory efforts, and blood oxygen level. Through analysis of PSG data, various sleep related factors and information can be extracted. These include total sleep time, sleep efficiency, portion of each sleep stage, and sleep stage latency. Moreover, PSG can also detect sleep arousals, which are shorter activations in the EEG and do not qualify to be scored as an awakening, and respiratory function including the presence of snoring and apnea, oxygen saturation, and periodic limb movement (AASM, 2007). The polysomnogram is the only measure that reliably indicates whether a person is awake or asleep and that provides information on sleep depth (Basner et al. 2012). It also detects subtle physiological changes and gives detailed structural information about sleep. One important consideration with PSG is that, the electrodes and data collection system may interfere with the sleep itself and cause sleep disturbance. To overcome this disadvantage, at least one night needs to be considered as adaptation.

Actigraphy: Actigraphy, a non-invasive method of monitoring human rest and activity cycles, measures acceleration of body movements using a compact body- worn device that is as small as a watch. Some devices may sample other physiological signals such as ECG. Actigraphs are inexpensive and less disturbing than the sensors applied for PSG. Actigraphy may lack subtle physiologically detailed information on sleep stage architecture, but still provides an accurate idea of some types of awakening. The limitations of actigraphy include limited comparability among studies because each device vendor has implemented its own algorithm to differentiate wake from sleep periods (Basner et al. 2012).

Seismo-Somnography (SSG): The SSG is a non-contact method for ambulant measurement of sleep physiology parameters by detecting heart and breathing rate as well as subject’s movement. The human body generates vibration energy by movements of the body itself, by the activity of the heart, and by the lifting and lowering of the thorax and abdomen while breathing. SSG delivers these activities through the four sensors, and physiological parameters and the subject’s movement activity can be calculated from the sensor signals. The main advantages of SSG are that no parts are in direct contact with the body of the subjects, and it is developed for unattended sleep-data collection over a long period of time (Lercher and Brink 2010; Brink et al. 2006).

Measures of sympathetic tone and ECG: The amount of action in the sympathetic nervous system can be measured directly by using micro-neurography, where nervous system electrical activity is monitored and recorded for analysis, or indirectly via signal processing of the electrocardiogram waveform (Swift 2010).

An ECG-based algorithm, developed by Basner et al. (2007), is a technique for measuring vegetative arousal, which is activated by subcortical brain structure, and they may or may not evolve into cortical arousals. This method is less disruptive, invasive, and expensive than polysomnography. The analysis of the ECG data is automatic and objective; therefore, it is more reliable, faster, and cheaper than PSG analysis. Despite the advantages, the ECG algorithm is not able to differentiate between wake and sleep unless polysomnography is performed simultaneously (Basner et al. 2007).

Signal awakening: Behavioral awakenings are defined as awakening by the subject enough to initiate a physical acknowledgment such as pushing a button. This method is very easy to use and inexpensive; however, it is very specific with a low sensitivity (Basner et al. 2012).

Self-reported sleep disturbance: Self-reported sleep disturbance is the lowest complexity approach for measuring sleep disturbance. However, considering many other conditions and factors, the reliability of method is not high as a standalone assessment tool. In this approach, assessment is subjective rather than objective and it is based on the awake period since the subject is unaware of himself and of sleep disturbance during the night (Silva et al. 2007).

How Noise Influences Normal Sleep

The human body adapts to decrease sympathetic activity and increase parasympathetic activity during the sleep period, which is characterized by decreased sensory and motor functioning relative to the wake state. During sleep, the auditory response is reduced but not stopped completely. This system is permanently open, and humans react to sound and respond to incoming sensory stimuli from the external world while sleeping. Noise may exert its effects either directly, through non-conscious physiological stress (from synaptic interactions between the acoustic nerve and different structures of the central nervous system) or indirectly, through psychological stress reactions and cognitive perception of sound (Münzel and Gori 2014). The direct pathway might be the main mechanism in sleeping individuals (Basner et al. 2014). Figure 2.2 shows different noise pathways.

In direct pathway, noise stimulates the brain’s reticular activating system. This system is part of the body’s arousal system. It receives input from auditory system and relays this information to cardio-respiratory brainstem networks and through the thalamus to the cortex (Suter 1991). The thalamus has a gating function; based on the sensory information and the current central nervous system state information may be relayed to or withheld from the cortex. If the information coming from the peripheral receptors is passed on to the cortex, it may lead to a cortical arousal, and if filtered at thalamus gate, it prevents further processing and permits the sleep process to evolve (Halász and Terzano 2004).

Both physiological and psychological routes activate the autonomic nervous system and the endocrine system and determine the impact of noise on neuroendocrine homeostasis. A long-term over-activation of these systems may have adverse health effects such as changes in blood pressure, cardiac output, blood lipids, carbohydrates, electrolytes, and thrombosis/fibrinolysis. Such changes do not require the involvement of cortical structures and the cognitive perception of noise (Munzel et al. 2014).

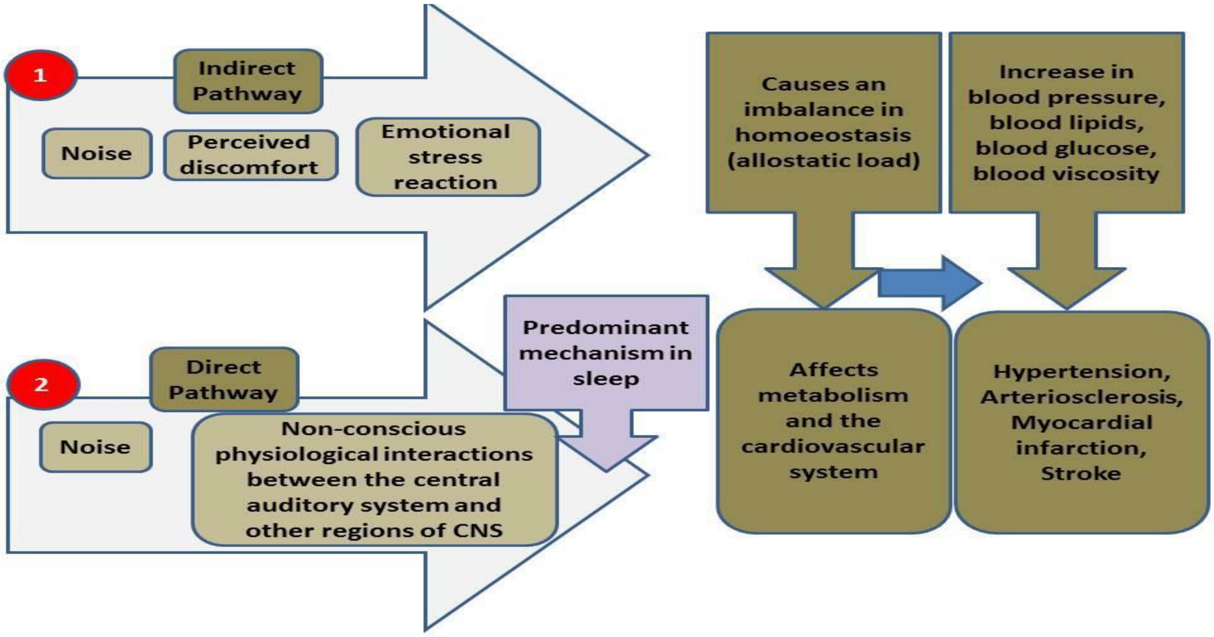


Figure 2.2: Noise Pathways

Noise has ability to affect sleep in several ways. The immediate effects include sleep onset delay, difficulty returning to sleep after awakening, increased arousals and awakenings, increased body movements, waking too early, alterations in sleep stages and depth, reducing the total amount of sleep and autonomic responses. The secondary effects are daytime sleepiness, decrease in daytime performance, cognitive function impairment, and mood changes. Long-term effects include self-reported chronic sleep disturbance, cardiovascular disease, hypertension, and changes in hormonal and immune function (WHO 2011).

There are two ways to investigate noise-induced sleep disturbances. An event-related analysis concentrates on the reactions such as awakenings or body movements of the sleeper to a single noise event, whereas collecting cumulative data concentrates on structural changes in sleep based on the whole sleep period. Both event-related and whole night outcomes are interrelated. Some studies only consider event-related for intermittent noises. An event-related analysis establishes a direct temporal association between the occurrence of a noise event and the reaction to the noise. This technique is only possible with synchronous sampling of electrophysiological and acoustical signals (Basner et al. 2010). Most sleep-related studies collect data from subjects concerning cumulative sleep effects. However, in this method, there are potential influences of non-noise sources (Miller and Eagan 1998).

Factors Influencing the Relationship of Noise and Sleep

Response to noise and the extent of sleep disturbances depend on acoustical features, personal characteristics, situational moderators, and environmental conditions. They range from a none or minimal physiological reaction to an autonomic reaction, to a cortical arousal of different degrees, and to a full cortical arousal with regaining of waking consciousness and body movements (Basner et al. 2012). Guski et al. (1999) pointed out that at best, about one third of the variances in reaction to community noise can be attributed to noise indicators, another third to non-acoustical factors such as personal or social variables; however the last third cannot be explained.

Acoustical features: Sleep disturbances are clearly related to noise levels, the number or the peak level of noise events, frequency spectra, complexity of sound, duration (continuous or intermittent), rise time (the time a noise event needs to reach its maximum level), and the meaning of the noise. People are less disturbed by continuous than by intermittent noises (Eberhardt and Akselsson, 1987; Ohrstrom and Rylander 1982). Continuous noise most likely causes REM sleep interruption, whereas SWS interruption is more sensitive to intermittent noise intrusions (Eberhardt and Akselsson 1987). Low frequency sound is more disturbing, and sound energy at very high frequency domains is also associated with higher arousal probabilities

(Basner et al. 2011). Noise from WTs has a major low frequency component and has considerable amplitude modulation that makes it unique and challenging in terms of measurement as well as in the interpretation of its potential impacts on sleep. The inaudible portion of the WTN lies in the infrasound spectrum (< 20Hz) where the noise cannot be heard by the hearing system. Some investigators speculate that although the infrasound cannot be heard but it will be perceived by hearing system and can have physiological effect on hearing cells (Salt and Hullar 2010).

Personal characteristics: Each person's experience with the particular noise varies significantly. The susceptibility to noise depends on personal characteristics such as personality traits, diurnal type, age, gender, individual noise sensitivity, sensitization and habituation, health status, psychological stress, socioeconomic status, salience of intruding noises for individuals, and fear of harm connected with the source. As an example, individual degrees of noise sensitivity are a major determinant for result outcomes in noise and sleep research and cause an underestimation of the true effect if not considered in the analysis (Marks and Griefahn 2007). Arousals occur naturally during sleep and increase with age (Boselli et al. 1998) which may make the elderly more vulnerable to WTN.

Situational moderators: Situational factors that affect sleep and noise research are sleep stages, elapsed sleep time, and repeated exposure (Basner et al. 2011). The momentary sleep stage is a strong moderator for the effects of noise on arousal probability. Arousal probabilities are highest for S1, S2, followed by REM and SWS. The first two hours of sleep are often less likely to be affected by noise as SWS occurs predominantly during this period. Noise influences sleep differently throughout the night, with a higher vulnerability of sleep to noise towards the end of the night. Marks et al. (2008) findings also confirm an increased probability of awakenings and heart rate increase during the second half of the night due to the decreased sleep pressure in the early morning. Toward the morning, subjects are not only more easily aroused from sleep, but also it is harder to re-initiate sleep after spontaneous or noise-induced awakenings (Basner et al. 2011). During nights with a higher number of noise events, arousal probabilities decrease as habituation happens by a decrease in the importance of noise events due to repeated stimulation (Basner et al. 2011).

Environmental conditions: It has been shown that noise in the field has less of an effect on sleep than noise in the lab (Pearsons and Barber 1995). The reasons are mainly noise and environment habituation and the simultaneous influence of other acoustic and non-acoustic stimuli that modify or even mask the responses to noise (Fidell and Pearsons 1995; Pearsons and Barber 1995; Porter et al. 2000). Other factors that influence night-time noise and sleep include following: occurrence in residential areas with low background noise levels, vibration produced by the noise source, position of the bedroom relative to the noise source, coping methods such as closing windows and a home equipped with double-glass windows, house orientation, duration of time in a residence, and noise exposure before sleep. Fruhstorfer et al. (1984) pointed out that exposure to noise in the daytime makes subsequent sleep worse. Important differences are also seen in types and levels of exposures that annoy rural residents as compared to city dwellers (Pedersen and Waye 2008).

With regard to WTN, environmental conditions such as wind speed, wind shear, temperature, day/night, wind direction, and humidity can influence the WTN measurements and noise exposure to residents. For instance, stable atmospheric conditions at night can increase emission levels of WTN, which occur in combination with a decrease of the background noise levels (Bolin et al. 2011).

Study Location

One important factor in the design of sleep disturbance and noise studies is the location of test subjects (Miller and Eagan 1998). In a laboratory, study exposures can be manipulated, subjects can be randomized to different groups, variables can be controlled for, and so dose-response relationships between exposure and outcome can be assessed more accurately. By comparison, in field studies, the level of ecological validity is high and sleep disturbance is measured in an everyday-life setting with the opportunity of adaptation to the noise (Swift 2010). Long-term studies are difficult to conduct in laboratory because ethical issues related to exposure in subjects to potentially harmful noise levels for long periods; it is also difficult to generate some types of noise sources such as WTN that have a significant low frequency component in the laboratory setting (Vanderkooy 2013).

Wind Turbine Noise and Health Effects

This review is intended to examine the peer-reviewed literature regarding evaluations of potential health effects such as degraded QoL, annoyance, general health and sleep disturbance among people living near WTs. The purpose of this review is (1) to explore the association between WTN and general health, QoL and sleep disturbance, (2) to identify key variables that may mediate the relation between them, and (3) to suggest hypotheses for the present field study.

A comprehensive search of the peer-reviewed literature conducted in the PubMed and Scopus databases identified over 200 potentially relevant references. However, only 30 articles, reporting on 11 cross-sectional studies, investigated a relationship between WTs and health and fulfilled the inclusion criteria. A profile of each study is given in Tables 2.1 to 2.4. There are multitudes of reported health effects from WTs, and the results of studies that investigated WTN with respect to potential human health effects are summarized below. To be included in the review, studies had to study annoyance, stress, general health, sleep or quality of life as outcomes in subjects living in proximity with WTs.

All of the reviewed studies have a cross-sectional design. In regards to sleep disruption, a dose-response relationship was found between self-reported sleep disturbance and A-weighted noise exposure in three large epidemiological studies from Sweden, the Netherlands and Poland, with 351, 725 and 156 participants, respectively (Pedersen and Waye 2004; Bakker et al. 2012; Pawlaczyk-Luszczynska et al. 2014). However, sleep disturbance was only weakly associated with A-weighted sound pressure levels in the Swedish study, and in the Dutch study, sleep disturbance was only seen at high exposure levels of above 45 dB(A), and was significantly related to annoyance. In the Polish study, the proportion of subjects suffering from insomnia was only higher in the noise category of 40–45 dB(A), not 35–40 dB(A), and they reported a significant relationship between the frequency of annoyance and sleep disturbance.

Comparison studies were also done in Japan (754 exposed, 332 unexposed), the U.S.A. (38 exposed, 41 unexposed) and New Zealand (39 exposed, 158 unexposed), and found a higher level of disturbed sleep among exposed groups (Kageyama et al. 2016; Nissenbaum et. al. 2012; Shepherd et al. 2011). The Japanese study estimated WTN from the results of actual measurement at some locations, and concluded that the odds ratio of insomnia was significantly higher when the noise exposure level exceeded 40 dB(A), and noise sensitivity and visual annoyance were also associated with insomnia.

Scores on the Pittsburgh Sleep Quality Index (PSQI) and Epworth Sleepiness Scale (ESS) were used as outcome measures in the American study and in a study from Canada (only PSQI used)

(Nissenbaum et. al. 2012; Michuad et al. 2015). Nissenbaum et al.'s study demonstrated a significant relationship between PSQI results and distance to WTs. The Canadian study conducted by Health Canada is a large-scale epidemiology study with the most-comprehensive assessment of the association between exposure to WTN and sleep to date. The Health Canada study did not find any sleep-noise association for noise levels under 46 dB(A). This study collected sleep using actigraphy and calculated outdoor WTN levels near the participants' home. The findings also did not support any association between self- reported sleep quality and WTN levels (Michaud et al. 2015). Another study from Canada collected self-reported sleep disturbance and health data from an Internet survey and found a borderline significant relationship between the distance to WTs and disturbed sleep (P=0.08) (Krogh et al. 2011). This study lacked a systematic recruitment method, encouraged people with health issues to participate, and would have been remarkably prone to bias.

Regarding other health effects, Shepherd et al. (2011) and Feder et al. (2015) used the WHO-QoL questionnaire to measure life satisfaction of people living in the vicinity of WTs. Shepherd's study found lower scores in physical health, environmental scores and general satisfaction with health among WT-exposed subjects compared to those of unexposed controls. In contrast, Feder et al.'s findings, with 1238 subjects, did not support an association between exposure to WTN up to 46 dB(A) and any of the WHO-QoL domains.

Nissenbaun et al. (2012) and Mroczek et al. (2012) used the SF 12/36 general health questionnaire to measure mental and physical component scores of health. In the Nissenbaum el al. study (with 38 exposed and 41 non-exposed participants), the mental component scores dropped significantly as distances between dwellings and WTs decreased. This contrasts with the Mroczek et al. (2012) study, which reported significantly improved QoL on all eight scales of the SF-36s among a Polish population of 220 individuals living within 700m of a wind farm, compared to the 424 individuals living beyond 1500m.

Pawlaczyk-Luszczynska et al. (2014) from Poland also assessed the mental health of 156 participants by using the Goldenberg GHQ-12, and obtained a mean score close to the normative result for the reference Polish population. A-weighted sound pressure levels were calculated as the sum of the contributions from the wind power plants in the area.

Six cross-sectional studies conducted in Sweden (754+351 subjects), the Netherlands (725 subjects), Poland (156 subjects), Canada (1238 subjects) and Japan (747 subjects) demonstrated a significant relationship between A-weighted sound exposure and annoyance (Bakker et al. 2012; Michaud et al. 2015; Pawlaczyk-Luszczynska et al. 2014; Pedersen et al. 2004; Pedersen and Waye 2007; Yano et al. 2013). A recent meta-analysis included eight cross sectional studies with an overall moderate quality, and 2433 participants revealed that the odds of being annoyed (OR: 4.08; 95% CI: 2.37 to 7.04; $p < 0.001$) and reporting sleep disturbance (OR: 2.94; 95% CI: 1.98 to 4.37; $p < 0.001$) were significantly increased with greater exposure to WTN.

Magari et al. (2015) in the USA collected un-weighted sound pressure levels (from 6.3Hz through 3150 Hz) at individual residences between 0.4 and 4.0 km from WTs and found no apparent exposure-response relationship between an individual's level of annoyance and the short-duration sound level measurements. The sound was collected inside and outside the survey respondents' homes; however, the authors did not mention whether they obtained measurements inside the bedrooms. They only found a correlation between an individual's concern regarding health effects and the prevalence of sleep disturbance and stress among the study population. The authors also did not report how sleep was measured.

Present evidence on the association of exposure to WT and adverse health effects supports that WTN is associated with annoyance, and provide reasonably consistent evidence that exposure is associated with sleep disturbance at noise level over 40 dB(A). Studies of QoL including physical and mental health scales and residential proximity to WTs reported conflicting findings, and the existing evidence does not support a direct link between WTN and QoL.

In terms of outcome measurement, all the studies (except one) used subjective technique and assessed sleep and health based on self-reported symptoms. Self-reported sleep disturbance can be affected by indirect effects of individual differences such as visual and attitudinal factors as confirmed in the most previous peer-reviewed studies, and an objective outcome measurement method is crucial (Feder et al. 2015; Magari et al. 2014; Mroczek et al. 2015; Pawlaczyk-Luszczynska et al. 2014; Pedersen and Persson Waye 2004, 2007, 2008; Pedersen et al. 2011). Health Canada's study is the first objective research conducted in this area and is the most-comprehensive assessment of the association between exposure to WT noise and sleep to date. This study used both subjective and objective methods to measure sleep. However, Actigrahy, used in this study, estimates sleep-wake schedules by measurement of activity, and is not ideal for measuring the sleep disturbance related to WTN. WTs have relatively slow to moderate sounds. Basner et al. (2008) stated that, for low maximum sound pressure levels, the strongest association between noise and effects on sleep could be observed in measured arousals by PSG.

Common features among most of the reviewed studies include modeled WTN levels and use of proximity to WTs as the exposure variables. Noise measurement has advantages over noise mapping and prediction in terms of accounting for any unexpected exposures and variables such as neighbors' contributions and attenuation of noise due to environmental conditions. In noise prediction method, there is also potential for exposure misclassification. A-weighting measurement technique used in the reviewed studies does not fully describe the WTN characteristics. This technique is used in almost all the WT and health related studies, and a significant low frequency noise energy emitted by WTs is not effectively captured by this metric, which is a significant limitation.

No study has attempted to measure inside noise and synchronize noise's data with sleep physiological signals. In the existing published research, an event-related analysis, which concentrates on the reactions of the sleeper to a single noise event, is lacking. The strength of this technique is that it establishes a direct temporal association between the occurrence of a noise event and the reaction to the noise. This technique is only possible with synchronous sampling of electrophysiological and acoustical signals (Basner et al. 2010). Collecting cumulative data, concentrates on structural changes in sleep based on the whole sleep period, can be strongly influenced by non-noise sources (Miller and Eagan 1998).

Existing evidence is not sufficient to establish a cause-and-effect relationship, as all the studies have employed cross sectional designs. Prospective cohort studies that document prior baseline health and noise status are lacking, and because studies rarely involve simultaneous measurement of both exposure and health outcomes, the temporal sequence of exposure–outcome relationships cannot be demonstrated.

Table 2.1: Summary of Health and Wind Turbine Noise Studies

Studies/Country	N/ Response Rate/Age condition	Exposure Assessment	Outcome Measurement	Number of WTs& Power	Study location / Site topography	SPLs & distance from WTs	Confounders considered
Pedersen & Waye 2004 Sweden	351/68.4% 18-75	Modelled sound pressure levels in dB(A) outside residences	Author-formulated questionnaire: unipolar annoyance scale presence or absence of sleep disturbance	N:16 power: 150–650 kW Tower height: 47-50m	5 Rural areas/ flat terrain	<30 to >40 dB(A) 0.15–1.2 km	Age, gender, noise sensitivity, visual impact and attitude to WTs in some analyses
Pedersen & Waye 2007 Sweden	754/57.6% 18-75	Modelled sound pressure levels in dB(A) outside residences	Author-formulated Questionnaire: unipolar annoyance scale. presence or absence of sleep disturbance	N:478 power : 500 kW	Seven suburban and rural area/ flat (3 areas) and complex (4 areas)	31.4–38.2 dB(A) 0.6–1 km	Age, gender, housing, employment, terrain residence, attitude to WTs, duration, urbanisation, visual impact, background noise, noise sensitivity
Bakker et al. 2012 The Netherland	725/ 37% 18-75	Modelled sound pressure levels in dB(A) outside residences	Author-formulated questionnaire: 5-point ordinal scale & 2 Likert scales for annoyance. Sleep disturbance : Frequency	N:1846 power : ≥500 kW	Rural area (with and without major road) and densely populated built up area/ Flat terrain	21–54 dB(A) 0–2.5 km	Age, gender, employment, terrain, urbanisation, economic benefit from turbines, background noise, noise sensitivity, attitude to turbines and turbine visibility
Shepherd et al. 2011 New Zealand	39 exp.& 158 non-exp. 33% ≥ 18	Distance to WTs; noise levels estimated 24–54 dB(A)	Annoyance: 7-item scale Sleep: 7-item scale QoL: WHO-HRQoL	N:66 power :2300 kW	semi-rural /coastal & hilly terrain	20–50 dB (A) exp.<2km non-exp. > 8km	Length of residence, geographic and socio-economic matched areas

Table 2.2: Summary of Health and Wind turbine Noise Studies-Continued

Studies/Country	N/ RR/ Age condition	Exposure assessment	Outcome measurement	number of WTGs& Power	Study location & site topography	SPLs & distance from WTGs	Confounders considered
Krogh et al. 2011 Canada	109/88.9% ≥ 18	Exposure to WTs (noise levels not reported)	Used sleep survey designed by Harry (2007)	N: 5 WTs farms power : 1.65 MW	Rural/flat terrain	Not Reported/ 0.35–2.4 Km	Gender in some analyses
Nissenbaum et al. 2012 USA	38 exp. & 41 non-exp. /40% ≥ 18	Estimated sound levels derived from a study conducted previously	Sleep disturbance: PSQI & ESS QoL: SF-36v2	N:31 power : 1.5 MW	2 rural areas/not reported	32–57 dB exp < 1.5 km Non-exp: 3–6.6 km	Age, gender, site, and household clustering
Pawlaczyk-Luszczynska et al. 2014 Poland	156/71% Age:15-82	A-weighted sound pressure levels were calculated	Annoyance: 5-point ordinal scale Mental Health: Goldberg questionnaire GHQ-12 sleep & general health:7-point ordinal scale	N:108 power:0.15, 1.5 & 2 MW	Rural area (railroads & roads also present) / flat terrain	30–48 dB (A) 0.24–2.5 km	Age, gender, attitude to WTs in general or to visual impact, sensitivity to landscape littering, sensitivity to noise, mental health status, self-assessment of physical health
Magari et al. 2014 USA	62/92.9% Not reported	Outdoor and indoor sound level measured	Used questionnaire developed by Pedersen and Waye	N:84 power : 1.5 MW hub height:80 m rotor diameter: 77m	Rural area/ not reported	0.4-4km	Gender, age, benefiting economically from WTs, number of turbines visible from, general attitude to WTs or landscapes, noise sensitivity

Table 2.3: Summary of Health and Wind turbine Noise Studies-Continued

Studies/Country	N/ Response Rate/Age	Exposure Assessment	Outcome Measurement	Number of WTs& Power	Study location / Site topography	SPLs & distance from WTs	Confounder considered
Michaud et al. 2015 Feder et al. 2015 Canada	1238/78.9% 18-79	Calculated outdoor WTN levels at the dwelling	Sleep:PSQI, actiwatch QoL: WHO-QoL perceived stress scale (PSS) scores, hair cortisol concentrations, resting blood pressure, and heart rate	N:315 and 84 power: 660 kW to 3 MW	Rural and semi-rural / Flat land	0.25 and 11.22 km <46dB (A)	Sex, BMI group, age group, marital status, employment, smoking status, caffeine consumption education, bedroom location and windows position, other noise sources, personal benefit, annoyance, chronic diseases
Mroczek et al. 2015 Poland	1277/85% >18	Distance	SF-36v2, Visual Analogue Scale	Not reported	Rural area/not reported	< 2km	Age, gender, education, somatic symptom of stress, wind farm status, employment, distance, chronic disease, smoking, alcohol
Kageyama et al.2016 Japan	Exp.747& non-exp.332/ 49% &45% >18	Outside measured noise	Total Health Index (THI) developed by Suzuki et al. Insomnia questions developed by authors on the basis of the literature	N:50 farms Power: 400 to 3000 kW	Rural areas/ not reported	Not reported	Visual annoyance, noise sensitivity, attitude to WTs, benefit from WTs, Interest in environmental issues

Table 2.4: Summary of the Results of Health and Wind turbine Noise Studies

Studies/Country	Summary of Results
Pedersen and Waye 2004 Sweden	Proportion of people perceiving and being annoyed by the WTN increased along with increasing A-weighted SPLs. 13% of annoyance was explained by noise and this percentage increased to 46% with considering the attitude to visual impact. Some of the respondents also stated sleep disturbance by WTN, and the proportions seemed to increase with higher SPL.
Pedersen and Waye 2007 Sweden	Annoyance was significantly associated with SPLs from WTs as well as having a negative attitude toward turbines, living in a rural area, WT visibility, and living in an area with rocky or hilly terrain.
Shepherd et al. 2011 New Zealand	Lower sleep quality and self-reported energy levels and lower scores for being less satisfied with the conditions of their living space were reported in exposed group.
Krogh et al. 2011 Canada	A borderline significance for relationship between sleep disturbance and distance from the WTs was found. Excessive tiredness also significantly increased in exposed group.
Nissenbaum et al. 2012 USA	Participants living within 1.4 km of a WTs reported worse sleep, were sleepier during the day, and had worse SF-36 Mental Component Scores compared with those living farther than 3.3 km from turbines.
Bakker et al. 2012 The Netherlands	Proportion of people perceiving and being annoyed by the WTN increased along with increasing A-weighted SPLs. Annoyance was also correlated with a negative attitude toward the visual effect of WTs on the landscape and benefited economically from turbines. Sleep disturbance increased with increasing SPL only at pressures of 45 dB (A) and higher, and was related to annoyance.
Magari et al. 2014 USA	There was no apparent exposure response relationship between an individual's level of annoyance, an individual's assessment of their satisfaction with their living environment and sound measurements collected at the time of the survey. There was a correlation between an individual's concern regarding health effects and the prevalence of sleep disturbance and stress among the study population.

Table 2.5: Summary of the Results of Health and Wind turbine Noise Studies-Continued

Studies/Country	Summary of Results
Pawlaczyk-Luszczynska et al. 2014 Poland	Odds ratio of outdoors annoyance by the WTN increased along with increasing A-weighted sound noise category. Only 7% of variance in annoyance explained by the noise and this number increase to 62.8% for the model containing noise category, general attitude to WTs and sensitivity to landscape littering. Respondents who reported outdoors annoyance were more likely to report difficulties with falling asleep, dizziness and heart-aches. The proportion of subjects often suffering from insomnia was higher in the noise category of 40–45 dB than 35–40 dB and WTN was reported as being more annoying than other environmental noises.
Michaud et al 2015 Feder et al. 2015 Canada	Beyond annoyance, results do not support an association between exposure to WTN up to 46 dB(A) and the evaluated health-related outcomes. Self-reported health effects, sleep disturbance, sleep disorders, quality of life, and perceived stress were not related to WTN levels. Concern for physical safety and closing bedroom windows to reduce WTN during sleep also increased with increasing WTN levels.
Mroczek et al. 2015 Poland	Living in close proximity of wind farms does not result in the worsening of, and might improve, the QoL in this region. Within all subscales of SF-36, those living closest to wind farms reported the best QoL, and those living farther than 1500 m scored the worst.
Kageyama et al.2016	The odds ratio of insomnia was significantly higher when the noise exposure level exceeded 40 dB, whereas the self-reported sensitivity to noise and visual annoyance with WTs were also independently associated with insomnia.

Chapter 3 : General Health Study before and after Turbine Operation

Introduction

In this chapter, the methods and results of first field study are presented. The main objectives of this study were first to examine the mental and physical health and life satisfaction of people before and after a new WT operation as an independent study, and second to investigate the association of sleep quality with Health-Related QoL (HRQoL).

On one hand, sleep disruption can affect various physical and mental conditions and ultimately influence HRQoL. On the other hand, physical health is an important determinant of sleep quality, and health problems such as increased bodily pain related to chronic conditions can be a major factor affecting sleep quality.

The measurement of HRQoL can serve as an alternative way to monitor the relationship between the presence of WTs and health problems experienced by people living in their vicinity. The available literature has few studies related to QoL and residential proximity to WTs, and the few that exist report conflicting findings, which prevents from definitive conclusions. This chapter presents the results of the HRQoL study independent of the sleep study. The association of the sleep quality and HRQoL will be subjects of another investigation (the results are not included in this dissertation).

Methods

Study areas and population: This study was carried out in a rural area of flat agricultural fields in the Township of West Lincoln, in southern Ontario, Canada. Operation of five Vestas V100-1.8 MW turbines, with hub heights of 90m and rotor diameters of 100m, began in June 2014.

To estimate the population and number of residential dwellings within a 2000m radius of the wind farm, residential address centroids were generated from Municipal Property Assessment Corporation (MPAC) parcel data (each centroid represents the centre location of the property) and converted into a projected coordinate system (NAD83 UTM 17N) for use in Geographic Information System (GIS) software. For the parcel centroids within 2000m of the five turbines, 221 civic addresses were identified and selected for the study. WT coordinates were extracted from publicly available engineering documents that were listed on the Renewable Energy Approval section of the company website (Vineland Power Inc.2015). The euclidean distance between a participant's address centroid within 2000m of the nearest WT was calculated using standard proximity geoprocessing tools found within ArcGIS desktop. All geospatial data manipulations and analysis were carried out using ArcGIS desktop version 10.3.1 (Environmental Systems Research Institute, Redlands, CA, US). Figure 3.1 shows dwellings for areas that intersect the 2000m buffer from WTs.

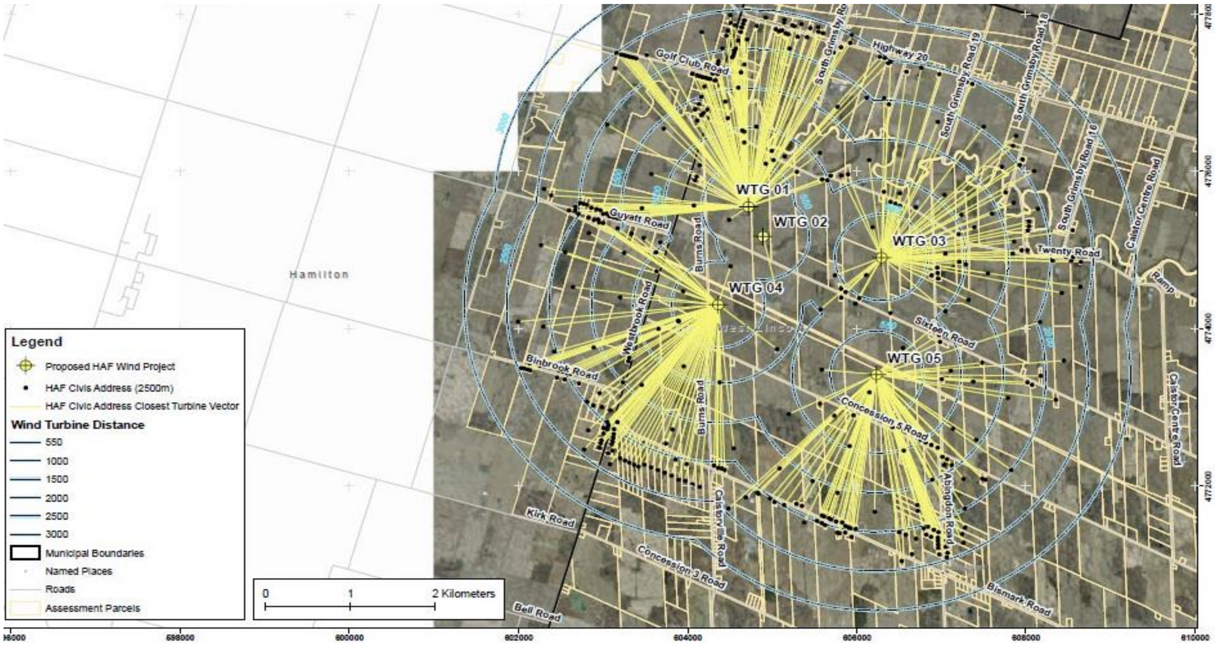


Figure 3.1: HAF Project- Participant Selection

Questionnaire development: The "Wind Turbine and Health-Related QoL" Questionnaire consisted of five sections: RETs in Ontario, housing and community factors, environmental stressors, overall QoL and general health perceptions, and demographic questions.

This questionnaire incorporated a series of validated scales, including the Satisfaction with Life Scale (SWLS; Diener et al. 1985), and the SF-12 physical and mental health assessment scale (Ware et al. 1996) plus several questions adapted from the "Wind Farm Perception Study" (van den Berg et al. 2008) and the Canadian Community Health Survey (CCHS 2015). "Wind Farm Perception Study" investigated the perception of Dutch wind farms by its surrounding residents and focused on noise annoyance and visual impact of WTs.

The SWLS is a global measure of life satisfaction and consists of five items, each scored on a Likert scale of 1 to 7 depending on the participant's level of agreement or disagreement. The scores of the five questions are summed to obtain the overall SWLS score, which is interpreted as follows: extremely satisfied (31-35), satisfied (26-30), slightly satisfied (21-25), neutral (20), slightly dissatisfied (15-19), dissatisfied (10-14) and extremely dissatisfied (5-9).

The SF-12 scale is a validated assessment of both physical and mental health and a shortened version of the SF-36 scale (Ware et al. 1996) which both have been used frequently to assess the impact of environmental stressors on health in previous studies (Nissenbaum et al. 2012; Schreckenberg et al. 2010; Villeneuve and Ali 2009). The SF-12 uses 12 questions, rated on a 5-point Likert scale and eight subscale scores can be derived: physical functioning, role physical, bodily pain, general health, vitality, social functioning, role emotional and mental health. Results are expressed in terms of two meta-scores: Physical Component Scale (PCS) and Mental Component Scale (MCS). The PCS and MCS scores range from 0 to 100, and are designed to have a mean score of 50 and a standard deviation of 10 in a representative sample of the United States population. PCS scores ≤50 were considered 'below average physical health status' and PCS scores >50 were considered 'above average physical health status'. Regarding to MCS, there are no universally accepted cut-points to identify probable diagnoses of a common mental disorder. As a screening tool for depressive disorders, Vilagut et al. (2013) and Kiely and Butterworth (2015) recommended a cut-point score of MCS ≤45.6 and MCS ≤ 40, respectively. They recommended that cut-points ranging between 40 and 45 are also acceptable. Based on this recommendation and cut- point of MCS-SF36 of ≤42 (Ware et al. 1994), in this study , MCS scores ≤42 were considered 'at-risk for depression. SF-12 scores were also calculated using Quality Metric's Health Outcomes Scoring Software 4.5 (Qualitymetric 2015).

Participants also rated their general health, mental health and QoL in response to several stand-alone questions and by using a 5-point verbal rating system (VRS) ranging from Excellent=1 to

Poor=5. In T2 observation, participants also rated their QoL based on the condition of “No Turbine”. They were asked to rate their expected QoL, if no turbines existed in their community, and their actual QoL at the time of questioning.

Pierpont (2009) has proposed the existence of “Wind Turbine Syndrome” (WTS) related to living near WTs, comprised of a collection of subjective symptoms including sleep disturbance, headache, tinnitus, ear pressure, dizziness, vertigo, nausea, visual blurring, tachycardia, irritability, problems with concentration and memory, and panic episodes. To assess Pierpont’s proposed WTS, eight questions from the ‘General Health Questionnaire (headache, irritability, concentration problems, nausea, vertigo, undue tiredness, tinnitus, and overall sleep quality) were combined to create a WTS index. Each of the eight variables was scored on a scale of 1-4 (with 4 being the extreme negative) and a score out of a maximum 32 points was determined.

To measure annoyance, participants were asked to rate different stressors in the community on how much they annoy, similar to the ‘Project Wind Farm Perception’ survey, which measured environmental exposure, annoyance and stress (Pedersen and Waye 2004). For example, participants were asked: “please indicate whether you have noticed and whether you are annoyed when you are indoors in your home by WTN.” The participants rated their level of annoyance on a 5-point scale from 1 (do not notice/not annoyed=1) to 5 (very annoyed=5), or ‘not applicable’. Participants were assigned to the following categories based on their noise perception and annoyance scores: “do not notice” (1) and “notice” (2–5), “not annoyed” (1–3) and “annoyed” (4–5). Noise sensitivity was measured on a 5-point scale, from “not at all sensitive” (1) to “very sensitive” (5). Attitudes to WTs in general were assessed with a 5-point scale from ‘‘very positive’’=1, to ‘‘very negative’’=5. Noise sensitivity and attitude were also dichotomised into ‘‘not sensitive’’ (1-3) and ‘‘sensitive’’ (4–5), and attitude into ‘‘not negative’’ (1-3) and ‘‘negative’’ (4–5).

Subjective general background sound was derived from three questionnaire items. Participants were asked to agree or not agree on a 5-point VRS with the following statements: (1) ‘‘when outside on a calm summer morning, I can hear only birds’ song and other nature sounds’’; (2) ‘‘traffic noise is almost always present outdoors’’; and (3) ‘‘it is never really quiet in the area’’. Self-reported distances from residents’ home to the nearest WT were compared to calculated distances to investigate survey participants’ perceptions of distance.

General study design: This study employed a prospective cohort design, with two data collection times: before and after WT operation. The first data collection (T1) was conducted post turbine erection but pre operation to avoid construction noise effects on perceived annoyance and general health. The second collection (T2) occurred in 2015, after the turbines became operational and was chosen to be at the same time of year as T1’s to minimize seasonal and temperature effects. Residents would also be expected to spend considerable time outdoors at this time of the year, and we hypothesized residents would be most sensitive to annoyance and stress due to WTN.

Participant recruitment: For all 195 eligible households within 2000m of the WTs (businesses, one church and several unoccupied houses were excluded (n=26)), letters of “advance notice” including study details and the researchers’ contact information were placed in mailboxes two weeks prior to survey distribution. For homes without mailboxes, advance notices were delivered to the door. Residents were informed that more than one person in each household could participate but all must be over 18. Within two weeks of “advance notice” letter delivery, two researchers visited each eligible household. During door-to-door recruitment, researchers provided information about the study, including potential risks and participant responsibilities. For those who agreed to participate, a study package, containing the survey instruments, information letters, and prepaid return mail envelopes, was provided. A study package was left in mailbox if researchers visited a house three times and were not able to meet the residents. Reminder postcards or phone calls (participants' choice) were made three to four weeks after the surveys were distributed. Those who were not interested in participating were invited to fill out a short questionnaire asking only a few questions about their age, their support of community-owned renewable energy, and any anticipated effects of WTs on their health. Figure 3.2 shows the participation recruitment flow chart.

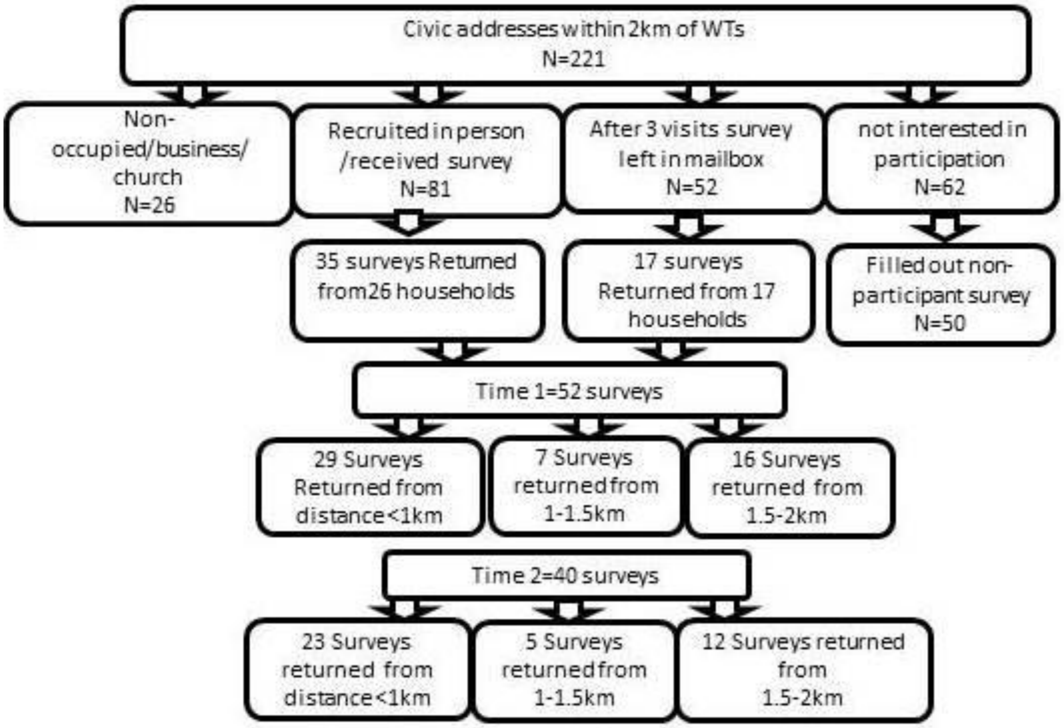


Figure 3.2: Flow Diagram of Participants Recruitment at T1 and T2

Statistical Analysis

Questionnaire results were coded and entered into a spreadsheet (Microsoft Excel 2010). All analyses were performed using SPSS, Version 22, for the Windows 8 operating system (IBM 2013). Independent variables assessed in this study included the following: distance to WT (<1000m, >1000m), age (continuous and categorical: middle age: 30-55 and older adult >55), gender (male, female), attitudes to WT (negative, not negative), concerns about property values (concerned, not concerned), visual annoyance (annoyed, not annoyed), noise annoyance (annoyed, not annoyed) and turbine visibility (visible, not visible). Dependent variables included the following: PCS, MCS, CCHS_SWLS and SWLS (continuous and dichotomous variables). Data were analysed for normality using Shapiro-Wilk tests. Non-parametric analyses were performed for those variables that were not normally distributed. Wilcoxon signed rank test used for comparing mean distribution of two continuous and related samples, and Mann-Whitney test was used to compare mean differences of measures in two independent groups. Nominal data were compared using the McNemar and Chi-Square test.

Independent sample t-test and chi square tests were used to compare the mean distribution of continues and categorical variables for two non-related samples (participants and non-participants), respectively. Spearman's rank correlation coefficients were calculated to determine the strength of the relationship between annoyance, attitude, noise sensitivity and distance from WTs.

The SWLS ("satisfied": > 20; "dissatisfied": ≤ 20), WTSI (score $\geqslant 16$ considered 'symptomatic'), MCS (score ≤ 42 considered "risk for depression"), and PCS (score ≤ 50 considered "below-average physical health") were analyzed both as continuous and dichotomous variables. The intra-scale reliability of WTSI was determined by computing Cronbach's alpha coefficient. A value of 0.70 or more was taken as indicating satisfactory reliability of the scale. A p-value of <0.05 was considered statistically significant.

Results

The demographics of survey participants are outlined in Table 3.1. Of 195 identified residential households within 2000m of five 1.8 MW turbine farms, 52 questionnaires in T1 and 40 questionnaires in T2 were returned. All analysis was performed on data of 40 participants who filled both round of the questionnaires.

The average age of participants was 54.3 years, with no statistically significant difference among men and women (p=0.926). Over half of the participants (55%) were female (p=0.635). All participants lived on a farm or in single detached houses, and the majority (92.5%) could see at least one WT from their dwelling. Of the participants, 46.2% had a negative attitude towards WTs, and 28.2% were 'rather or very' sensitive to noise. The proportions of participants that rated themselves 'rather or very' sensitive to noise (p=0.887) and those who rated their attitude as negative to WTs (p=0.595) were the same in both distance groups.

The majority (78.4%) of participants either did not notice, or noticed but were not annoyed by WTN when inside; 45% were "rather or very" visually annoyed, and 16.2% were "rather or very" annoyed aurally. Sixty-five percent of participants did not notice WT vibration, and only 10% (4 people) reported feeling "annoyed or very annoyed" because of vibration. Noise annoyance and noise perception were not associated with the time people spent at home (over or less than 6 hours away from home in weekdays and weekends). Of participants, 45% believed that WTs could cause negative health effects in nearby residents; 17.5% (7 people) reported changes in their physical and mental health due to WTs' presence; and 12.5% (5 people) claimed their use of over-the-counter drugs had increased after turbines became operational. A majority of participants (70%) were concerned about their property values as a result of living close to WTs, and 42.5% were feeling worried and anxious after the operation of turbines. Reported background noise levels in general significantly increased after WT operation in the community (p=0.002). The difference between the calculated and perceived distances from the nearest WT was not statistically significant (p=0.742); participants reported living an average of 1.22km from a WT (averaged measured distance: 1.17km) and would have preferred a setback of 4.46 km on average.

Fifty residents who were not interested in study filled out the short questionnaire. Analysis of these questionnaires showed that non-participants and participants did not significantly differ in terms of age (p=0.130), sex (p=0.440), and support for community-owned renewable energy (p=0.361). More participants (57.5%) lived less than 1000m from the nearest WT than did non-participants (31.7%; p=0.020).

Table 3.1: Demographic Characteristics of Respondents to a Wind Turbine and Health Study

Variables		N	%
Gender	Male	18	45
	Female	22	55
Marital status	Married/ common-law	36	92.3
	Separated / widow/single	3	7.7
Occupation	Full time/part time employment	23	57.5
	Retired	13	32.5
	Others	4	10
Education	Post-graduate /college/university	32	84.2
	High school diploma/ Less than secondary	6	15.8
Own their home	Owner	37	95
	Renter or others	2	5
Distance to nearest wind turbine	<1000m	23	57.5
	>1000m	17	42.5
Turbine visibility	Yes	37	92.5
	No	3	7.5
Noise sensitivity	Not noise sensitive or hardly sensitive	28	71.8
	Rather or very sensitive	11	28.2
General attitude to wind turbines	Negative	18	46.2
	Neither negative or positive	7	17.9
	Positive	14	35.9
Owned the land that wind turbine is located		2	5
Age (mean, range)		54.26 (30-78)	

Table 3.2 shows the self-reported health scale values of residents before and after WT operation. There were significant differences in the mean scores for MCS, SWLS, WTSI, and CCHS-SWL before and after operation, whereas the mean score for the PCS did not change significantly. After exposure, 23.7% were at risk for depression (i.e., MCS≤42) compared to 0% at the first observation (p=0.004). For the SWLS scale, 33.3% of participants were not satisfied with their life after exposure (i.e., SWLS score≤20) compared to 10.3% before exposure (p=0.012). The percentage of participants reported below-average physical health status (i.e., PCS≤50) did not changed significantly (27.5% compared to 25.6%) after exposure (p=1.000).

Table 3.2: Mean Values of Health Outcomes before and after Exposure to Wind Turbine

Variables/ Number of subjects	Time1 N=40 Mean ±SD	Time 2 N=40 Mean ±SD	P*
Physical Component Score (PCS)	54.28±6.61	53.31±6.44	0.283
Mental Component Score (MCS)	56.08±4.34	49.10±11.53	**<0.002**
Satisfaction with Life Scale (SWLS)	28.95±5.81	23.85±8.46	**<0.001**
Canadian Community Health Scale-Satisfaction with Life (CCHS-SWL)	38.92±5.38	37.29±5.91	**0.039**
Wind Turbine Syndrome Index (WTSI)	11.20±2.86	15.00±4.94	**<0.001**

*Wilcoxon signed rank test was performed for analysis.

Tables 3.3 and 3.4 show the changes of different health scales versus age, sex, distance, noise sensitivity, attitude to WTs, concern about property values, visual and noise annoyance, and turbine visibility. Participants who reported negative attitudes to WTs, who were concerned about property values, or who were visually annoyed had significantly lower MCS scores. The SWLS was significantly related to noise sensitivity and visual and noise annoyance, just as WTSI was related to concerns and attitudinal cues, aural and visual annoyance and noise sensitivity.

Mental health, satisfaction with life, and symptoms related to WTs stayed constant or changed only slightly for participants who had a positive or neutral attitude to WTs, and for those who were not visually annoyed by the turbines. WT-related symptoms as well as degraded life satisfaction were more frequent in participants who were noise sensitive and annoyed by WTN. Anxiety about properties values was associated with increased reporting of mental health and WT-related symptoms (Figures 3.3-3.5).

Table 3.3: Health Outcomes Changes over Time versus Age, Gender, Distance, Noise Sensitivity, Attitude to WTs, Concern about Property Values

Variables N=40 **Mean** ± SD	**Physical Component Scale (PCS)**			**Mental Component Scale (MCS)**		
	Time 1	**Time 2**	**P***	**Time 1**	**Time 2**	**P[*]**
Male	56.18±4.06	52.21±7.53	0.197	56.14±3.29	50.60±10.71	0.392
Female	52.82±7.83	52.67±7.54		56.04±5.08	47.87±12.28	
Middle age	55.94±6.05	53.78±5.34	0.573	56.31±4.07	50.96±10.06	0.321
Older adult (>55)	52.35±6.87	51.01±9.17		55.83±4.74	47.04±12.94	
Distance < 1000m	53.72±7.63	53.10±6.62	0.376	55.88±5.16	46.55±13.44	0.301
Distance >1000m	55.10±4.89	51.61±5.57		56.38±2.92	52.55±7.35	
WT [a] is visible from property	54.06±6.84	52.07±7.57	0.648	56.09±4.51	48.60±11.81	0.403
Not visible	56.93±0.16	57.34±3.20		55.97±1.58	55.20±4.94	
Have concern about property-value	54.36±6.37	52.17±7.93	0.762	56.07±4.48	45.76±12.17	**0.003**
No concern	54.12±7.41	53.15±6.42		56.12±4.20	56.87±3.78	
Negative attitude to WT	54.66±6.30	51.94±8.03	0.487	56.75±4.84	44.60±13.38	**0.018**
Positive/neutral	53.65±6.94	53.25±7.06		55.78±3.93	53.27±8.29	
Not noise/slightly Sensitive	54.27±6.69	52.96±6.96	0.267	55.63±4.37	50.51±11.48	0.140
Very sensitive	55.22±6.22	51.34±9.10		56.79±4.32	44.78±11.46	
Not visually annoyed	54.26±7.52	53.93±6.79	0.104	55.27±4.45	51.44±11.18	**0.030**
Visually annoyed	54.31±5.57	50.67±7.99		57.04±4.13	46.23±11.62	
Not noise-annoyed	54.44±6.22	52.69±7.50	0.806	55.83±4.08	49.86±11.47	0.227
Noise-annoyed	53.43±9.14	51.19±7.67		57.46±5.80	44.77±11.99	

[*] p value compares the mean difference between T2 and T1 for each two categories and Mann Whitney U test was used to obtain each p-value.

Table 3.4: Health Outcomes Changes over Time versus Age, Gender, Distance, Noise Sensitivity, Attitude to WTs, Concern about Property Values

[*] p value compares the mean difference between T2 and T1 for each two categories and Mann Whitney U test was used to obtain each p-value.

Variables N=40 **Mean** ± SD	**Satisfaction with Life Scale (SWLS)**			**Wind Turbine Syndrome Index (WTSI)**		
	Time 1	**Time 2**	**p**	**Time 1**	**Time 2**	**P[*]**
Male	30.83±3.38	25.00±7.51	0.141	10.05±2.04	14.72±5.47	0.512
Female	26.43±8.03	22.86±9.27		12.14±3.14	15.23±4.56	
Middle age	28.62±7.00	23.65±9.34	0.828	10.38±1.88	14.45±5.02	0.923
Older adult (>55)	28.28±6.38	24.05±7.68		12.10±3.49	15.58±4.92	
Distance < 1000m	26.61±7.70	21.59±8.87	0.569	11.70±3.29	15.68±5.72	0.944
Distance >1000m	31.12±3.44	26.76±7.13		10.53±2.06	14.12±3.69	
WT is visible from property	28.25±6.82	23.75±8.37	0.879	11.19±2.94	15.33±4.98	0.100
Not visible	31.00±3.46	25.00±11.53		11.33±2.08	11.00±1.73	
Have concern about property-value	28.70±6.74	23.63±7.78	0.312	11.21±3.22	16.81±4.59	**<0.001**
No concern	27.92±6.64	24.33±10.21		11.17±1.90	10.92±2.87	
Negative attitude to WT	28.61±8.01	22.67±8.64	**0.022**	11.44±3.84	17.78±5.05	**0.001**
Positive/neutral	28.25±5.52	25.40±8.22		11.09±1.79	12.25±3.07	
Not noise/slightly Sensitive	27.48±7.58	23.96±8.87	**0.041**	11.64±3.10	13.79±4.75	**0.001**
Very sensitive	30.73±3.10	23.54±7.74		9.91±1.81	18.09±4.16	
Not visually annoyed	27.41±6.91	24.64±8.57	**0.031**	11.90±3.32	13.45±4.61	**<0.001**
Visually annoyed	29.82±6.20	22.82±8.47		10.33±1.94	17.00±4.74	
Not noise-annoyed	28.03±7.10	24.50±8.36	**0.016**	11.29±2.93	14.41±4.86	**0.021**
Noise-annoyed	30.83±1.60	19.40±8.71		10.67±2.66	19.00±3.74	

The results of expected QoL if no turbines existed in participant community (conditional QoL) and their actual QoL at the time of questioning showed significant difference between the two (p=0.001). Participants believed their QoL would have remained constant if no turbines had been built in their community (Table 3.5).

Table 3.5: Comparison of Health and Quality of Life before and after Exposure to Wind Turbine

Variables	**Time1 N=40**			**Time2 N=40**			**p**
	Excellent/ very good	**Good**	**Fair/poor**	**Excellent/ very good**	**Good**	**Fair/poor**	
General health	82.5%	17.5%	0%	67.5%	20%	12.5%	**0.002**
Mental health	92.5%	7.5%	0%	75%	15	10%	**<0.001**
Quality of Life (QOL)	92.5%	7.5%	0%	67.5%	22.5	10%	**<0.001**
Conditional QOL	-	-	-	87.5%	12.5%	0%	**0.001***

*This p value resulted from comparison of conditional QoL and the actual QoL in T2.

Correlations between distance, noise annoyance, and subjective factors are shown in Table 3.6. Noise annoyance was not correlated with the distance to WTs, but rather to the individual's noise sensitivity. Visual annoyance was strongly correlated with attitude to turbines, noise sensitivity and noise annoyance. General attitude was not correlated with distance to WTs; participants closer to WTs were neither more negative nor more positive than those farther away.

The number of participants who benefited economically from the turbines was too small (n=2) for meaningful statistical analysis.

Table 3.6: Correlation between Annoyance, Attitude, Noise Sensitivity and Distance from Wind Turbines

Variables	Visual annoyance	Noise annoyance	Attitude to wind turbines	Sensitivity to noise
Distance	-0.098	-0.288	0.007	-0.164
Visual annoyance	-	0.405**	-0.683 **	0.631**
Noise annoyance	-	-	0.342*	-0.232
Attitude to wind turbines	-	-	-	0.443**
Sensitivity to noise	-	-	-	-

*p<0.05 **p<0.001

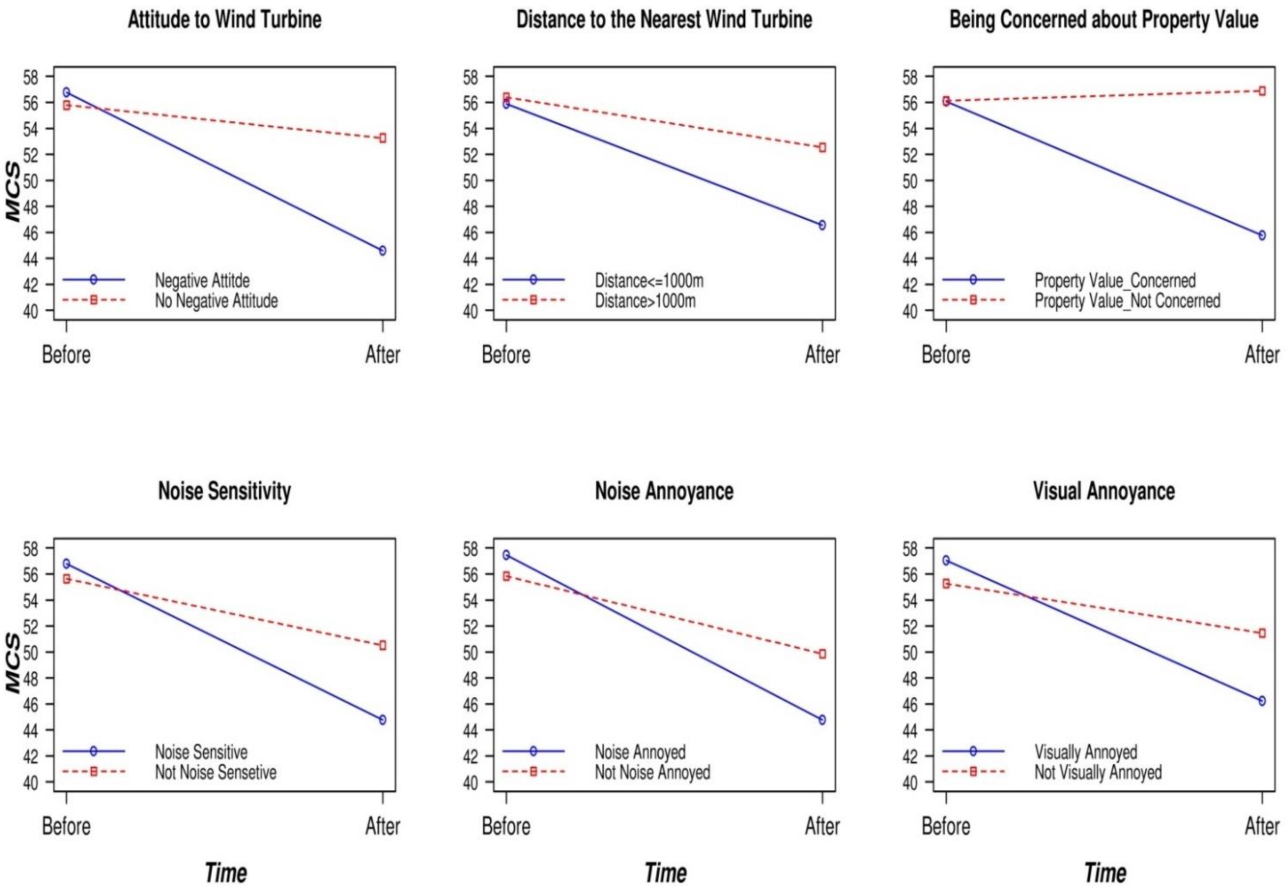


Figure 3.3: Variation of Mental Component Score over Time versus Distance, Attitude, Concern about Property Value, Noise Sensitivity and Noise and Sight Annoyance

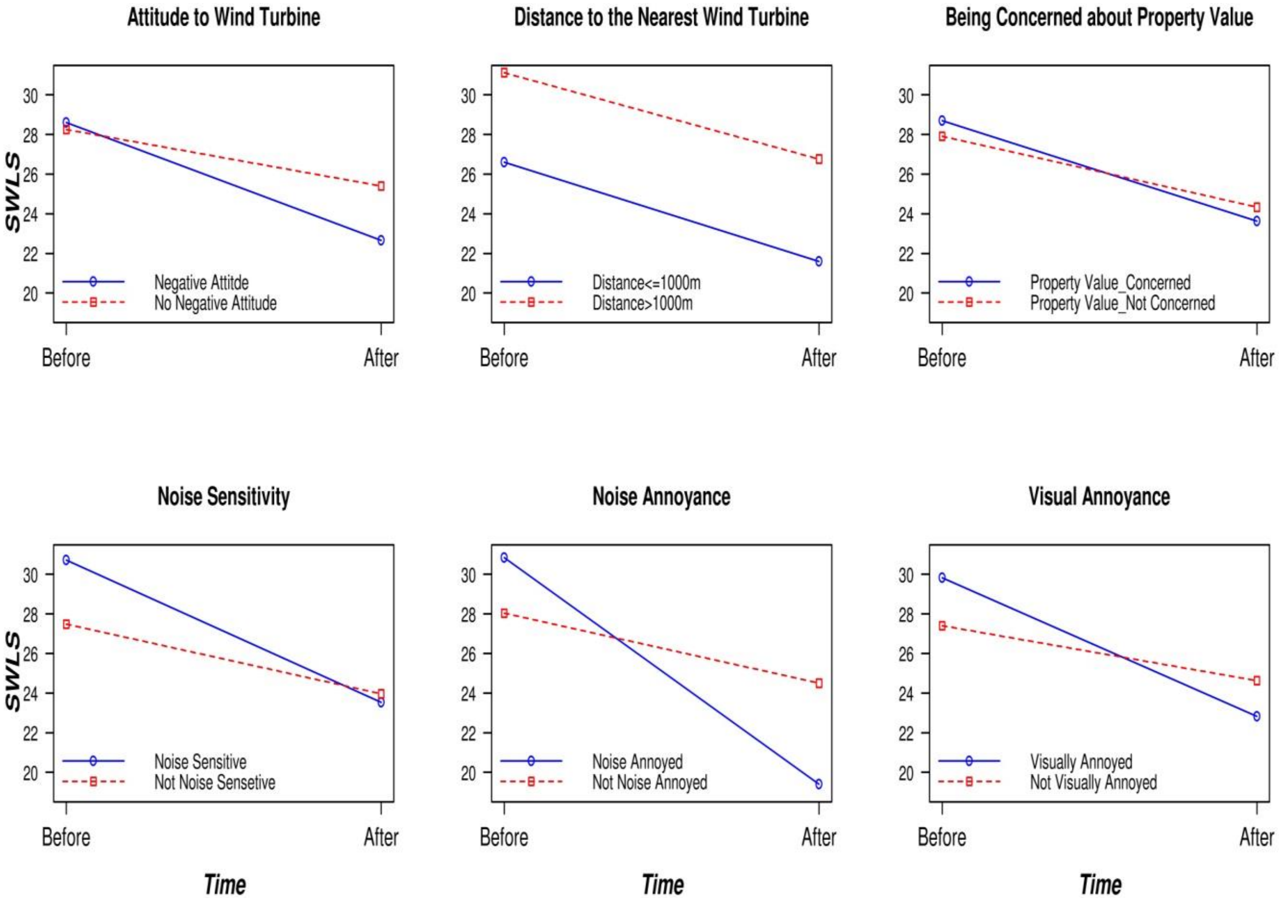


Figure 3.4: Variation of Satisfaction with Life Scale over Time versus Distance, Attitude, Concern about Property Values, Noise Sensitivity and Noise and Sight Annoyance

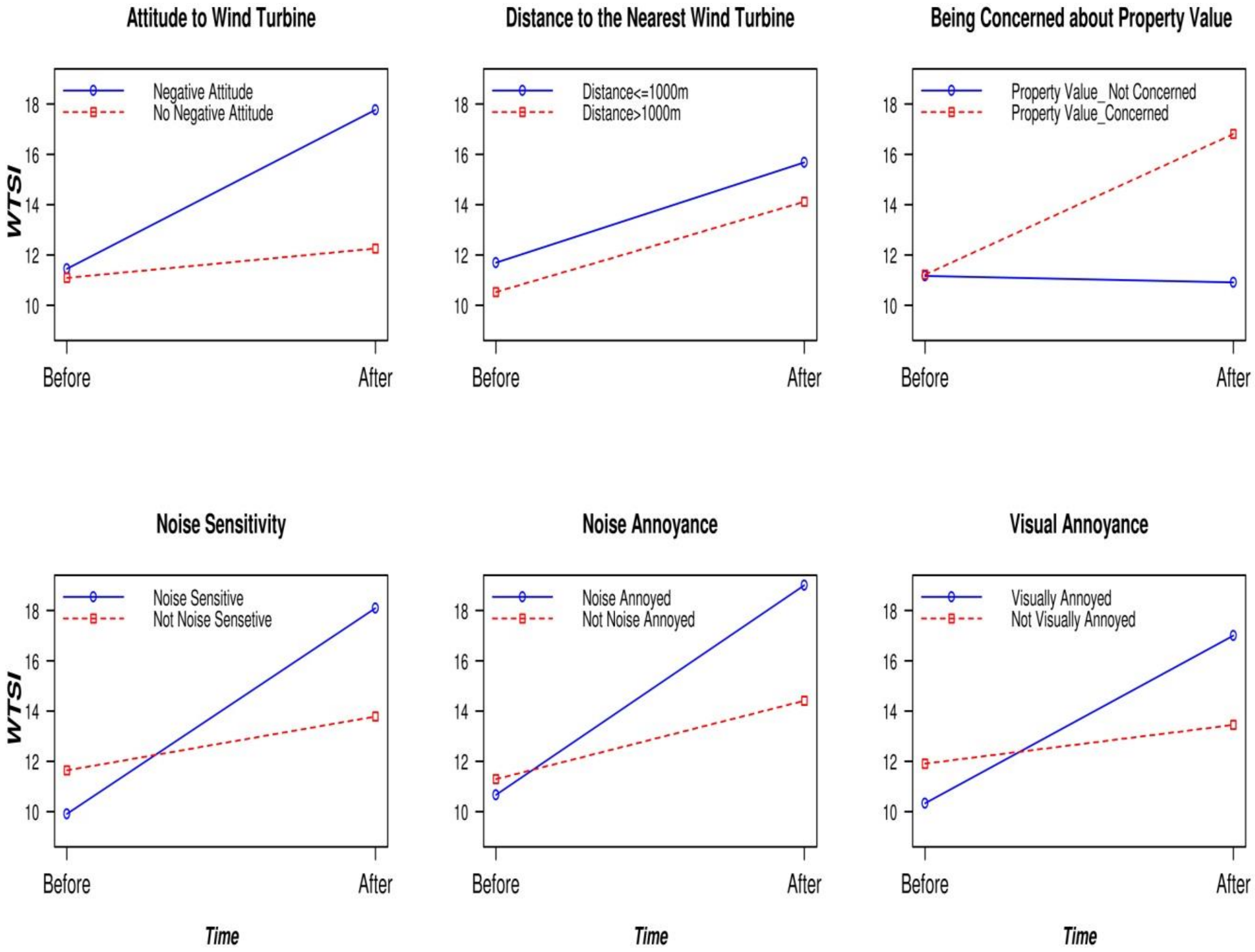


Figure 3.5: Variation of Wind Turbine Syndrome Index over Time versus Distance, Attitude, Concern about Property Values, Noise Sensitivity and Noise and Sight Annoyance

Discussion

This study provides baseline community health and QoL survey measures as well as post-operation follow-up health assessment measures by using multiple standard and validated questionnaires. It is the first prospective cohort study in this field to address a knowledge gap in the science base related to WTN exposure and health. The results of this study support important role of individual differences and annoyance in reporting of lower mental health and degraded life satisfaction, by people who live close to WTs. Mental health and satisfaction with life stayed constant or changed only slightly for participants who had a positive or neutral attitude to WTs and for those who were not visually annoyed by the turbines. Degraded life satisfaction was more frequent in participants who were noise sensitive and annoyed by WTN. Anxiety about properties values was also associated with reporting of lower mental health. A worsened WTS index, with a number of symptoms, including headache, irritability, concentration problems, nausea, vertigo, undue tiredness, tinnitus, and reduced overall sleep quality, were also observed in those participants who had negative attitudes to WTs, had concerns for property devaluation, and were aurally or visually annoyed by WTs (figures 3.3-3.5). Although work by Dr. Pierpont does not meet the basic criteria for a scientific research, it seems to be one of the primary popular literature studies referenced by most of the related websites. General public does not always have access to scientific publications and often get their information from sources that are less reliable such as popular literature and internet. They may psychologically get affected by collection of these symptoms and become convinced that they have those symptoms, described in the book, and attribute their symptom to WTs.

Comparing the results from the current study to previous findings may be difficult due to different health and QoL instruments and different study designs. However, in general, the current findings are consistent with the results of previous studies. Association between health effects and annoyance or subjective factors like general attitude to WTs, attitude to visual impacts, and sensitivity to noise has been confirmed in previous peer-reviewed studies (Feder et al. 2015; Magari et al. 2014; Mroczek et al. 2015; Pawlaczyk-Luszczynska et al. 2014; Pedersen and Waye 2004; 2007; 2008; Pedersen et al. 2011). Mroczek et al. (2015) in their WT and health study measured QoL by using SF-36 scale among a Polish population of individuals living within 700m and beyond 1500m of a wind farm. They reported significant differences in physical and mental component scores between residents who reacted calmly and those who responded with apprehension. Feder et al. (2015) also used the WHO-QoL scale in their study measuring life satisfaction in 1238 Canadians living close to WTs, and reported lower physical and environmental health scores among participants experiencing high visual annoyance. In the same study, noise sensitivity was found to be significantly associated with three out of four sub-scales of the WHO-QoL questionnaire. Pawlaczyk-Luszczynska et al. (2014) also found that subjects' general attitude to WTs influenced their reported frequencies of feeling nervous or tense. Several studies have also indicated that annoyance may lead to sleep disturbance and psychological distress (Klaeboe 2011; Stansfeld and Matheson 2003).

A possible mechanism for the health effects observed after WT exposure is an effect on general health mediated through secondary variables such as annoyance. Previous studies have provided evidence that adverse health effects may not be directly related to the physical effects of WTs, but instead emerge from annoyance (Bakker et al. 2012; Pedersen and Waye 2007). The primary outcome assessed in five peer-reviewed studies related to the health effects of WTs was annoyance (Bakker et al. 2012; Pawlaczyk-Luszczynska et al. 2014; Pedersen and Waye 2004, 2007; Yano et al. 2013), and several studies have indicated that annoyance may lead to sleep disturbance and psychological distress (Klaeboe 2011; Stansfeld and Matheson 2003). In the current study, 45% of participants were visually annoyed by WTs, and this annoyance was strongly correlated with their reported mental health, WT symptoms, and life satisfaction.

Modern WTs generate sound power levels (SPLs) ranging from 98–104 dB(A) at source for a wind speed of 8 m/s, which typically results in an SPL of 33–40 dB(A) reaching a dwelling 500m away (Pedersen and Waye 2007). However, the easily perceived modulation of the sound increases the risk of it being negatively perceived, and leading to elevated annoyance reports (Schmidt and Klokker 2014). This risk is more pronounced in rural areas than urban ones due to a combination of higher expectations of ambient quiet and lower levels of background noise (Schmidt and Klokker 2014).

Another possible cause for reporting health effects can be a range of social and psychological factors that may increase worry about wind farms and consequently the likelihood of individuals reporting symptoms in connection them. Psychological mechanisms that can increase symptom reporting in host communities include ‘nocebo effects’, misattribution of symptoms to a novel technology, increased symptom monitoring triggered by worry or annoyance, and psychosocial factors from negative media reporting (Rubin et al. 2014). As an example, Deignan et al. (2013) stated that emotionally-charged words and phrases in some Ontarian newspapers or anti-WT websites may invoke perceptual characteristics and cause fear, concern and anxiety in certain individuals.

Almost half of the participants in this study had negative attitudes to WTs and were anxious about their installation. This number is much higher than in studies of other communities such as a Swedish study (13%) (Pedersen and Waye 2004), a New York study (Magari et al. 2014) (34%) and a polish study (Pawlaczyk-Łuszczyńska et al. 2014) (20%). Public resistance is becoming the main obstacle to the deployment of wind energy technologies (van den Berg et al. 2008). In Ontario, opponent groups have been very active in the last few years publicising the alleged health impacts of turbines. In the West Lincoln community, anti-WT organization was established in the Township to oppose industrial WT installations. Despite three years of protest, turbines went up in 2014, and residents had a long list of health, safety, economic and environmental concerns. The Ontario Government needs to develop new policies to support more communities that host wind facilities, and create an educational program to disseminate correct knowledge to local communities. It should be possible to provide information and opportunities for discussion in communities with potential for commercial wind farm development. Many residents in West Lincoln felt their situation was unfair as some landowners were paid hosting fees while neighbours received none. Bidwell (2011) claimed in his studies that attending an information session about wind farm development can change both attitudes towards wind farms and the strength of those attitudes.

This study has several important limitations. The study design suffers from the lack of a time-matched control group to ensure that confounding variables and extraneous factors have not influenced the results. To address this limitation, we considered people living far from the turbines (>1000m) as unexposed/low-exposed group and compared them to high exposed subjects (<1000m), and found that reporting symptoms were not related to the distance and it was strongly related to individual differences. Moreover, the result of the current study showed that participants believed their QoL would have remained constant if no turbines had been built in their community. This finding shows that other factors may not be significantly involved in the outcome.

Information on general health and QoL was acquired through self-reported questionnaires, which increased the risk of reporting bias. However, we utilized standard scales that are in themselves well validated as measures of physical and mental health and wellbeing. Recall bias for symptoms might have resulted in people who were worried about possible adverse health effects remembering more symptoms from the recent past than people who were not worried, even if the actual level of symptoms was the same in the two groups.

Voluntary response bias might occur as we allowed more than one person in each household to participate in the study. To address this limitation, a separate analysis, taking only one respondent from each household (the first one who received survey and completed the questionnaire) (n=31), was done and the results were compared to the results of full sample of all respondents' analysis (n=40). Comparison showed no significant differences in the results of both analysis and thus all 40 participants were kept in study analysis.

Although non-participants and participants did not significantly differ in terms of age (p=0.130), sex (p=0.440), and support for community-owned renewable energy (p=0.361), residents closer to turbines were more interested in participating in the study than those further away (p=0.02) and this may have affected results of the study. The presence of this bias may have led to overestimation of the association between exposure and outcome in this research. Because residents who lived further away from turbines and expected to have fewer health effects had less interest in participation.

The study had a relatively small sample size and low response rate. We also had instability of estimates of prevalence of some behaviour such as OTC drug use because of the small sample size. Although we used various methods to increase participation, including phone call/postcard reminders, offering an incentive for taking the survey, door-to-door recruitment instead of mail, and pre-notifying residents about the study, we think that other factors were the primary reasons for the low response rate. One key factor was likely related to the socio-political context. WTs are a divisive issue in Ontario and the local community actively and strongly opposed the installation of wind farms; this likely affected participation. Due to this reason, it was also impossible to mask the purpose of the study from participants. There also were various groups and blogs that were unsupportive of the research as they felt it was associated with the provincial government who they feel are responsible for the proliferation of wind farms across Ontario.

Conclusion

This study has shown visual and noise annoyance, general attitude to WTs, noise sensitivity, and concern about property value are associated with the reporting of negative health states. Here, residents who were annoyed by the sound or sight of turbines, or who had a negative attitude towards them or concerned about property devaluation, experienced lower mental health and life quality, and reported more symptoms than residents who were not annoyed and had positive attitudes toward turbines. We concluded that these factors may have an important role in reports of health complains by people living in the vicinity of WTs. Due to the discussed limitations we cannot make strong conclusions from this study; further studies that include a larger number of participants would allow firm conclusions to be drawn.

Chapter 4 : Evaluation of Subjective Sleep Disturbance before and after Turbine Operations

Introduction

In Chapter 4, general descriptive and comparison analyses are performed related to the second study to investigate the effect of WT exposure on subjective sleep outcome measures. The main objectives of this study were first to examine sleep quality perception of residents before and after a new WT operation as an independent study.

Published results from previous cross-sectional studies have been inconsistent in terms of possible effects of WT noise on sleep. On one hand, those studies that used modeled or measured noise to assess exposure found no, or only weak association between noise and sleep disorders. As an example, a large Canadian study that provided the most-comprehensive assessment of the association between exposure to WT noise and sleep to date, found no sleep-noise association for a noise level under 46 dB(A) (Michaud et al. 2015). On the other hand, those studies that used "distance to nearest WT" as an exposure measure, almost all agreed that self-reported sleep disturbances were more frequent in subjects living closer to WTs than in subjects living further away (Krogh et al. 2011; Kuwano et al. 2013; Nissenbaum et al. 2012; Paller 2014; Shepherd et al. 2011a).

Based on the existing findings, it is not possible to conclude that self-reported sleep disturbance is caused directly by WT noise or whether other factors have played a role as well. Most critically, due to the cross-sectional design of previous studies, there is a complete lack of prospective longitudinal designs, and a temporal sequence of exposure–outcome relationships cannot be demonstrated.

As a second objective of this study, we investigate discrepancies between subjective and objective sleep measures. A number of studies have found disagreement between subjective and objective sleep assessments. Jackowska et al. (2011) found that people's judgments of sleep efficiency are associated with psychosocial stress and affective responses. One study of patients with sleep disorders found that participants underestimated and overestimated sleep duration, with subjective estimations being influenced by psychological factors (Vanable et al. 2000).

This chapter presents the results of the subjective sleep data as an independent study, and disagreement levels for the subjective and objective sleep data will be the focus of future investigation (not presented in this dissertation).

Methods

General study design and questionnaire development: This research employed a prospective cohort design and included a sleep questionnaire, comprised of validated instruments relating to sleep disturbance, daytime sleepiness and insomnia. In order to measure participants' sleep quality, the Pittsburgh Sleep Quality Index (PSQI) was used. The PSQI is a 19-item self-rated sleep questionnaire evaluating sleep quality and disturbances over a previous month; these items are grouped into seven domains: subjective sleep quality, sleep latency, sleep duration, habitual sleep efficiency, sleep disturbances, use of sleep medication, and daytime dysfunction. Each component of the PSQI obtains scores ranging from 0 (no impairment) to 3 (maximum impairment). A total score, ranging from 0 to 21, is obtained by adding up the 7 component scores; higher scores indicate worse sleep quality, and a score > 5 suggests poor sleep quality (Buysse et al. 1989).

Subjective daytime sleepiness was evaluated by means of the Epworth Sleepiness Scale (ESS). The ESS is a questionnaire consisting of eight self-rated items, each scored from 0–3, asking participants to rate their chance of dozing off during eight different common situations of daily living. It provides a score between 0 (least sleepy) and 24 (most sleepy) (Johns 1991).No specific time frame is specified. According to the University of Maryland Medical Centre, an ESS score > 10 is considered to indicate significant daytime sleepiness.

The nature, severity, and impact of insomnia were assessed by the Insomnia Severity Index (ISI) (Bastien et al. 2001). ISI is a 7-item self-report questionnaire assessing the severity of sleep onset, sleep maintenance, early morning awakening problems, sleep dissatisfaction, interference with sleep, difficulties with daytime functioning, noticeability of sleep problems by others, and distress caused by sleep difficulties in the previous month. A 5-point Likert scale is used to rate each item (0 = no problem; 4 = very severe problem), yielding a total score ranging from 0 to 28. The total score is interpreted as follows: absence of insomnia (0–7); sub-threshold insomnia (8–14); moderate insomnia (15–21); and severe insomnia (22–28).

PSQI, ESS and ISI are all retrospective measures referring to the previous month (for PSQI and ISI) or recent time's periods (For ESS), and all are measured at the same time.

Participant Selection: A detailed description of the participant selection has been reported previously in Chapter 3.The sample size for this study was 37. A certified sleep technologist/ sleep researcher supervised the distribution and encouraged participation. This study received ethics clearance from University of Waterloo Human Research Ethics Committee.

Statistical Analysis

PSQI scores were calculated using the scoring instructions available from the University of Pittsburgh Sleep Medicine Institute (Buysse et al. 1989). Independent variables assessed in this study included the following: distance to WT (<1000m, >1000m), age (continuous and categorical: middle age: 30-55 and older adult >55), gender (male, female), attitudes to WT (negative, not negative), concerns about property values (concerned, not concerned) and turbine visibility (visible, not visible). The dependent variables that were assessed included the following: ESS, PSQI and ISI (continuous variables). Due to the small sample size, distances to WTs were dichotomised only to above and below 1000m, (categorizing to higher number of groups would have resulted in only a small number of participants in each category). Normality assumptions for sleep measures were examined using Shapiro-Wilks tests. Non-parametric analyses were performed for those variables (PSQI-T2, ESS-T1, ESS-T2, ISI-T1, and ISI-T2) that were not normally distributed. Wilcoxon signed rank test used to compare mean distribution of two continuous and related samples, and Mann-Whitney test was used to compare mean differences of measures in two independent groups. Independent sample t-test and chi-square tests were used to compare the mean distribution of continues and categorical variables for two non-related samples (participants and non-participants/ participants and “lost to follow up” groups), respectively.

The distributions of continuous variables are presented as mean (SD) and frequency and percentage of categorical variables are also reported.

Results

Table 4.1 shows the demographic characteristics of the participants. 50 questionnaires in T1 and 37 questionnaires in T2 were returned. The mean age of participants was 54.2 years, and 43.2% were male. The majority (91.9%) lived in privately owned detached houses in the countryside and the landscape was rather flat and mainly agricultural. Of the participants, 45.9% had a negative attitude to WTs, 51.3% had positive or neutral attitude to turbines, and 67.6% were concerned about the value of their properties.

Table 4.1: Demographic Characteristics of Participants of Wind Turbine and Sleep Study

Variable		**N**	**%**
Gender	Male	16	43.2
	Female	21	56.8
Marital status	Married/ common-law	34	91.9
	Separated or widow	3	8.1
Occupation	Full time employment	18	48.6
	Retired	12	32.4
	Part-time/self-employment	7	18.9
Education	Post-Graduate college/university	31	83.7
	High school diploma/Less than secondary	4	10.81
	Not answered	2	5.49
Own their home	Yes	34	91.9
	Rented or others	3	8.1
Distance to nearest turbine	<1000m	22	59.5
	>1000m	15	40.5
Turbine visibility	Yes	34	91.9
	No	3	8.1
Bedroom facing turbine	Yes	22	59.5
	No	15	40.5
Bedroom location	First floor	23	62.2
	Second floor	14	37.8
Double glass window	Yes	34	91.9
	Not answered	3	8.1
Noise sensitivity	Not or hardly sensitive	20	54
	Slightly sensitive	7	18.9
	Rather or very sensitive	10	27
Concerns for property	Yes	25	67.6
devaluation	No	12	32.4
General attitude toward	Very negative	9	24.3
wind turbines	Negative	8	21.6
	Neither negative or positive	7	18.9
	Positive	8	21.6
	Very positive	4	10.8
	Not answered	1	2.7
Window status at bedtime	Usually open	18	48.6
	Closed	18	48.6
	Not answered	1	2.7
Age (mean, range)		54.25	(33,78)

There also was no significant difference between the participants and “lost to follow up” group by age (p=0.251, sex (p=0.948), distance (p=0.676), ESS means (p=0.376), PSQI means (p=0.636) and ISI means (p=0.758).

The mean values for each of the dependent variables in T1 and T2 and the p values are shown in Table 4.2. The mean of the PSQI, ESS and ISS scores significantly increased by 2.11(SD=4.34), 2.45(SD=4.71) and 3.32 (SD=6.24) units after exposure, respectively.

Table 4.2: Mean Scores of Sleep Outcomes before and after Exposure, in Wind Turbine Sleep Study

Variable	**Time1 N=37 Mean (SD)**	**Time2 N=37 Mean (SD)**	**P* (T1, T3)**
Pittsburgh Sleep Quality Index	4.08 (2.13)	6.19 (3.89)	**0.006**
Epworth Sleepiness Scale	4.68(3.22)	7.13(5.25)	**0.002**
Insomnia Severity Index	3.11(3.58)	6.43(6.66)	**0.005**

*Wilcoxon signed rank test was performed for analysis.

To uncover the reason for decreasing sleep quality, participants were questioned about ten different factors that generally interrupt sleep. Only 13.9% (5 people) identified WTs as the sound source of sleep disturbance (from1-2 times a week to less than once a week), and other factors such as aircraft, wind, and thunderstorms were more often identified as causing sleep disturbance than WTs.

The mean differences of dependent variables (T2-T1) compared between two groups of independent variables such as distance from the nearest WT, sex, age, concern about property values, attitude to WTs, noise sensitivity, and window and bedroom situation. The results are shown in Table 4.3. Changes in PSQI scores over time were strongly associated with negative attitudes to WTs, turbine visibility, and being concerned about property values. Changes of ISI scores also strongly related to property devaluation concerns and negative attitude to WTs. As demonstrated in Figure 4.1, PSQI and ISI values stayed constant over the time for people who did not have anxiety about the value of their properties, and also for those with positive or neutral attitudes to WTs.

The number of participants, who benefited economically from the turbines, was too small for meaningful statistical analysis.

Table 4.3: Sleep Outcomes Changes over Time versus Gender, Age, Distance, Turbine Visibility, Bedroom and Windows Status, Concern about Property Values, Attitude to Wind Turbines and Noise Sensitivity

* p value compares the mean difference between T2 and T1 for each two categories and Mann Whitney U test was used to obtain each p-value.

Variables N=37	**Pittsburgh Sleep Quality Index**			**Epworth Sleepiness Scale**			**Insomnia Severity Index**		
	Time1 Mean(SD)	**Time2 Mean(SD)**	**P***	**Time1 Mean(SD)**	**Time2 Mean(SD)**	**P***	**Time1 Mean(SD)**	**Time2 Mean(SD)**	**P***
Male	3.44(2.19)	5.69(3.70)	0.453	4.81(3.25)	5.80(3.53)	0.186	1.81(2.68)	5.33(4.70)	0.256
Female	4.57(1.99)	5.95(2.99)		4.57(3.28)	6.90(5.05)		4.10(3.92)	5.50(5.77)	
Middle age (30-55)	4.15(2.18)	5.60(3.41)	0.602	4.45(2.95)	5.47(3.42)	0.164	1.90(1.91)	4.42(4.36)	0.845
Older adult (>55)	3.87(2.12)	6.07(3.30)		5.06(3.68)	7.67(5.46)		4.69(4.64)	6.66(6.36)	
Distance < 1000m	4.09(2.33)	6.52(3.52)	0.212	5.09(3.04)	7.15(3.99)	0.744	3.64(4.10)	6.42(5.72)	0.511
>1000m	4.07(1.87)	4.87(2.75)		4.07(3.49)	5.47(4.94)		2.33(2.61)	4.07(4.40)	
Turbine visible	4.03(2.10)	6.18(3.20)	**0.030**	4.88(3.26)	6.62(4.48)	0.817	3.18(3.70)	5.90(5.26)	0.105
Turbine not-visible	4.64(2.89)	2.00(1.00)		2.33(1.53)	4.33(4.04)		2.33(2.08)	0.3(0.57)	
Bedroom toward turbine: Yes	4.05(1.98)	5.81(3.35)	0.988	4.50(2.87)	6.95(4.66)	0.083	2.91(3.66)	5.57(5.99)	0.479
No	4.13(2.39)	5.87(3.29)		4.93(3.77)	5.64(4.10)		3.40(3.58)	5.21(4.13)	
Bedroom's floor: First	4.13(2.20)	5.77(2.67)	0.794	5.61(3.62)	7.14(4.81)	0.561	3.30(3.28)	5.27(4.25)	0.716
Second	4.00(2.07)	5.92(4.18)		3.14(1.56)	5.23(3.56)		2.79(4.15)	5.69(6.83)	
Windows: Close at bedtime	3.83(2.41)	6.06(3.70)	0.515	5.06(3.24)	6.56(3.03)	0.302	2.78(3.56)	5.44(4.76)	0.685
Open at bedtime	4.44(1.82)	5.78(2.96)		4.39(3.33)	6.61(5.42)		3.50(3.77)	5.61(5.89)	
Double glass window: Yes	4.15(2.18)	5.91(3.34)	0.781	4.59(3.06)	6.24(3.97)	0.853	2.97(3.66)	5.60(5.37)	0.321
No	3.33(1.53)	4.50(2.12)		5.67(5.50)	9.50(12.02)		4.67(2.51)	2.50(0.71)	
Concern for property value: Yes	3.96(1.94)	7.12(3.15)	**0.001**	4.00(2.50)	6.48(4.00)	0.059	3.40(3.76)	7.39(5.48)	**0.003**
No	4.33(2.53)	3.25(1.60)		6.08(4.14)	6.33(5.35)		2.50(3.26)	1.66(1.43)	
Negative Attitude to turbine: Yes	3.71(1.99)	7.31(3.52)	**0.002**	3.41(2.15)	5.80(3.61)	0.241	3.47(4.47)	8.67(5.98)	**0.003**
No	4.53(2.22)	4.42(2.45)		5.95(3.61)	6.89(5.14)		2.95(2.69)	2.84(2.94)	
Not-noise sensitive	4.44(2.11)	5.48(3.40)	0.053	5.48(3.31)	7.00(4.75)	0.778	3.11(3.74)	5.03(5.64)	
Rather or very sensitive	3.10(1.91)	6.89(2.80)		2.5(1.65)	4.50(2.44)		3.10(3.31)	6.75(3.73)	0.323

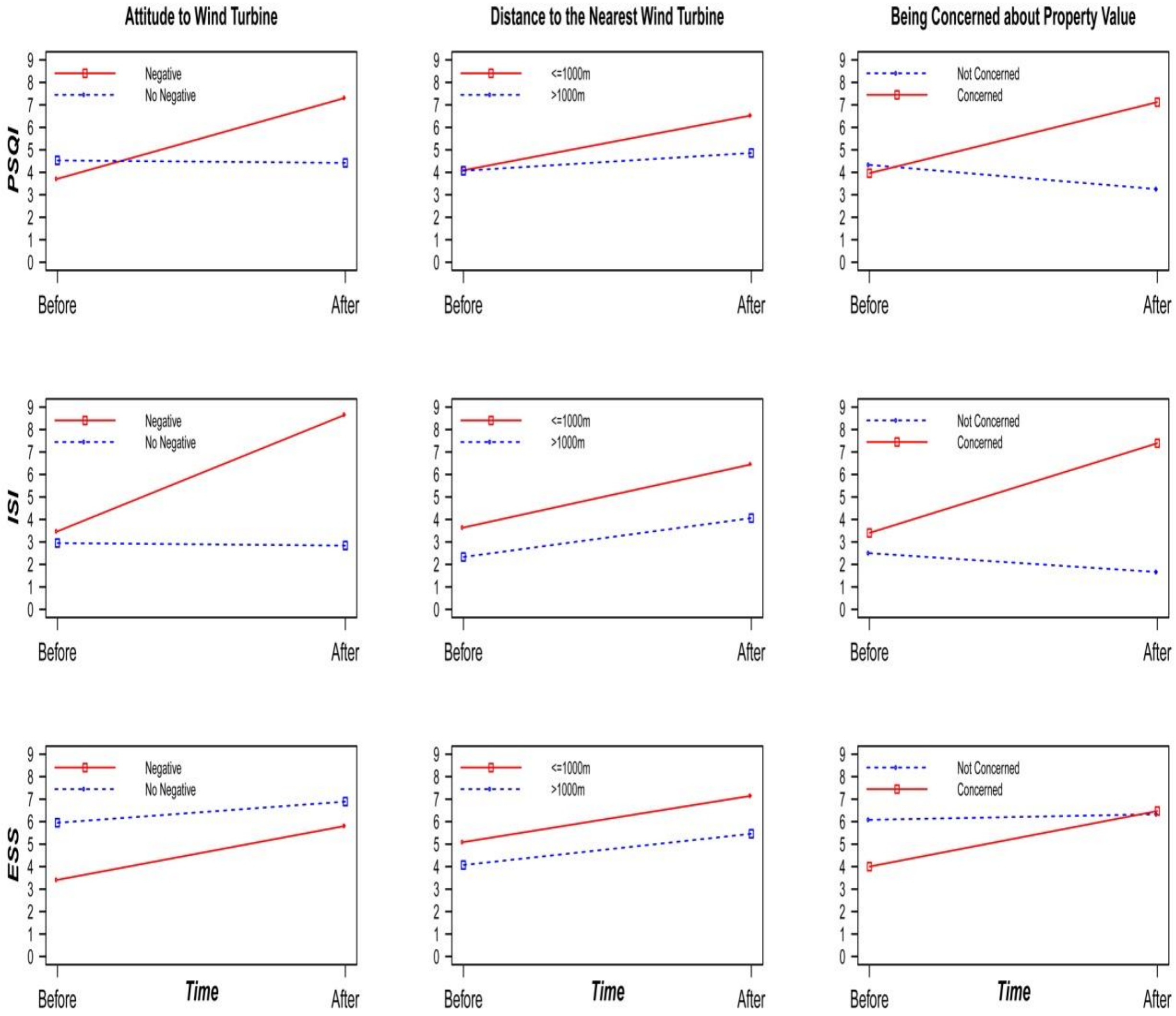


Figure 4.1: Variation of Pittsburgh Sleep Quality Index (PSQI), Insomnia Severity Index (ISI) and Epworth Sleepiness Scale (ESS) over Time versus Distance, Attitude to Turbines, and Concern about Property Value

Discussion

This study is the first to use a repeated sleep measurement before and after WT operation to investigate the impacts of WT presence on self-reported sleep quality along with considering psychological factors such as visibility of and attitude toward WTs and concern related to property devaluation. Hosting a new wind farm in the community was found to be associated with increased reports of poor sleep quality, daytime sleepiness, and rates of insomnia as evidenced by significantly greater means for PSQI, ESS and ISI scores. Changes of PSQI and ISI values were strongly associated with negative attitudes to WTs and concerns about property values. Changes of PSQI scores were also associated with WT visibility, with those able to see turbines from their residence experienced worse sleep than others.

Results of this study are consistent with the majority of previous epidemiological studies showing that people’s sleep is disturbed by exposure to WTs (Bakker et al. 2012; Kuwano et al. 2013; Nissenbaum et al. 2012; Onakpoya et al. 2015; Pawlaczyk-Łuszczyńska et al. 2014; Pedersen and Persson Waye 2004b; Shepherd et al. 2011). However, contrary to expectation, changes in the mean values of sleep variables were not associated with distance to WTs but instead strongly associated with subjective factors such as attitude to WTs, visual impact, and concern about property values.

Findings from previous research in the field of WTN and health effects support a relationship between subjective factors and health-related symptoms from annoyance to sleep disorders, stress and psychological disorders (Bakker et al. 2012; Pawlaczyk-Łuszczyńska et al. 2014; Pedersen and Waye 2007, 2004a; Wolsink and Sprengers 1993). Pedersen and Waye (2004a,

2007) indicated that attitude toward the visual effect of WTs is an important contributor to any annoyance associated with WTN and it increases the chance of perceiving noise and reporting symptoms such as poor sleep quality, negative emotions and self-reported stress. Taylor et al. (2013) also confirmed such results and stated that individual differences play a key role in the link between perceived noise and WT-related symptom-reporting. They claimed that those who had a more-negative attitude to WTs perceived more noise from turbines and reported more symptoms.

A possible mechanism for the sleep effects observed in this study may be attributed to the indirect effects of concerns and attitudinal cues. Most participants (77.8% in T2 + 8.4% also chose the "Not Applicable" or "Don't Know" options) believed that WTs did not interrupt their sleep in previous month, thus confirming the low level of noise in the community. In addition, general outdoor noise levels in the area, obtained from a conference paper by Ramakrishnan and Seharwat (2015), were reported to range from 40 – 45dB(A) before and 38 – 42 dB(A) after turbine operation. Increases in perceptions of poor sleep at a time when the average noise level had not changed significantly demonstrate that other factors may be at play in an individual's perceived of sleep quality. Concerns about new environmental changes, especially those associated with non-perceptible exposures such as low frequency noise, appear to act as a trigger for such reports of ill health (Petrie et al. 2001; Taylor et al. 2013). Several studies have observed that people who are concerned about an environmental risk are more likely to report health symptoms (Claeson et al. 2013; Mcmahan and Meyer 1995; Moffatt et al. 2000; Petrie and Broadbent 2005). Magari et al. (2014) on their health impacts of WTN study stated a correlation between participant concerns regarding health effects from WTs and their having experienced sleep disturbances and stress.

Ruminating about daily events is one of the common sources of sleep disturbance. Operation of any new WT development is likely to be a source of concern, leading local people to ruminate about it at night. Rumination, like worry, functions as a source of pre-sleep cognitive arousal and interferes with sleep quality, perhaps causing sleep-related difficulties (Guastella and Moulds 2007).

Concern about property values is commonly cited as an issue in communities close to WTs. In the current study, 67.6% of participants were concerned about the value of their property, and PSQI and ISI values stayed constant over the time for people who did not have anxiety about the value of their properties.

WT as a new element of the landscape can be potential source of stress and fear (Pedersen 2011). Stress is frequently seen as a significant contributor to disease, and clinical evidence supports the effects of stress on immune and cardiovascular systems (Brotman et al. 2007; Segerstrom and Miller 2004). The Ontario Government needs to develop new policies to support communities that host wind facilities and address their concerns and fears. Ellenbogen and Grace (2012) suggested strategies engaging the public in wind energy projects, including public education related to renewable energy, incentives for community-owned wind developments, compensation to those experiencing documented loss of property values, and comprehensive setback guidelines.

To the best of authors' knowledge, this is the first study of WT-related sleep disturbances that measured sleep repeatedly, by using multiple standard sleep questionnaires before and after exposure. Beaudreau et al. (2012) stated that the PSQI and ESS questionnaires are internally consistent, and they are valid measures of self-reported sleep problems. Considering these strengths, this study has also several important limitations that mostly discussed in chapter 3. Future studies should involve representative samples of the population including vulnerable groups such as children, chronically ill subjects, elderly, and habitually short sleepers, and also evaluate sleep quality in residents living adjacent to older WTs.

Conclusion

This novel work has highlighted the role of psychological factors and how they may lead to development of health complaints in residents near the WTs. It appears that self-reported sleep reported of participants may be associated to the indirect effects of visual and attitudinal cue and concern about property devaluation rather than distance to the nearest WTs or noise as itself. However, firm conclusions are not possible due to the discussed limitations.

Chapter 5 : Before-after Field Study of Effects of WTN on Polysomnographic Sleep Parameters

Introduction

Chapter 5 presents findings based on the analysis of polysomnography and sleep diary data on 16 healthy subjects. Noise measurements and recordings were conducted concurrently inside the bedrooms of each participant.

In the previous literature, a number of different methods have been used to assess noise effects on sleep quality, such as questionnaires, signalled awakenings, actigraphy, and various physiological recordings obtained by PSG. PSG is the most comprehensive method of evaluating sleep and is deemed the gold standard for measuring sleep. It is most often used in laboratory settings; however, with the recent emergence of portable wireless PSG systems and sleep monitoring devices, high quality home sleep assessment has become a reality. Presently, portable computerized PSG in unattended home-settings is a viable alternative to laboratory-based systems for obtaining adequate sleep recordings (Mykytyn and Sajkov 1999). Sleep recordings obtained at home using portable PSG also has advantages because sleep patterns in the laboratory may not be representative of typical sleep as subjects must adapt to the unfamiliar environment (Agnew et al. 1966). Testing location is also important when studying the effects of environmental noise on sleep, as people may adapt to noise in their home setting (Aasvang et al. 2011, Pearsons 1995). Moreover, in a laboratory, it is difficult to generate some types of environmental noises, and noise from WTs is especially problematic because of its significant low frequency component (Vanderkooy 2013).

The present study aims at comparing the sleep of residents before and after exposure to WTN, using in-home polysomnographical recordings and simultaneous indoor noise measurement.

Methods

Participants and study design: This research employed a mixed methods approach and prospective cohort design with subjective sleep diaries, and synchronous measurement of physiological sleep signals and indoor noise. Residents in the vicinity of a planned WT installation were invited to participate in the study. Turbine characteristics were discussed in detail in Chapter 3. Turbines had an estimated power of about 26 million kW per year. Residents who lived within a 2000m radius from the under-construction turbines and met further criteria required for valid and reliable home sleep assessment were eligible for participation. Required criteria include followings: over 18 years of age, general good health, no known sleep disorder, no children under five years of age living in the same household, no regular nightshift work, not being regularly disturbed during the night by other noise sources such as traffic or trains, no regular use of sleeping pills, and no hearing loss (one or both ears, self-reported, not confirmed by audiometry). Sixteen subjects have completed the objective noise and sleep study. The study was conducted in two periods: The first time of data collection (T1) was conducted post turbine erection but pre operation to avoid construction noise effects on sleep quality. The second time of data collection (T2) occurred after the turbines became operational from September to October to minimize seasonal and temperature effects. Participants were also asked to fill out a rescreening form before T2 to point out any changes to their sleep environment as well as health conditions that might affect their sleep as compared to T1.

Subjects slept for two consecutive nights in their own bedroom with the recording equipment, and were encouraged to follow their normal sleeping habits. A trained sleep technician, along with a researcher with expertise in acoustical assessment, installed the noise measurement instrumentation, performed all PSG sensor applications, checked for signal impedances, and performed calibrations and instrument diagnostic tests. These visits were scheduled so as not to interfere with participants' habitual bedtime routine. The subjects were free to have the bedroom window in their usual position (open or closed during the night). In each case, the researcher noted the position of the bedroom window. Polysomnographic recordings were obtained from a Somte PSG (Compumedics, Melbourne, Australia) sleep system. As the first nights served for adaptation of participants, only results from the second nights were analysed. The start and stop of sleep recordings were pre-set by the technician according to each subject's reporting of expected bedtime and final awakening. Sleep data were stored on a computer using a PSG digital system.

Participants were also provided with sleep diaries and were asked to enter information over a period of one week. Sleep diary has been regarded as the "gold standard" for subjective sleep assessment (Carney et al. 2012). The current sleep diary was designed based on National Sleep Foundation Diary with the same format, completed at the end of day and in the morning. The sleep diary and PSG are both prospective measures and were conducted at the same time.

The sleep diaries enabled participants to record their times of going to bed, attempting to fall asleep, waking up and getting out of bed, nocturnal awakenings, and daytime napping periods. In addition, subjective ratings of sleep quality, depth of sleep, mood and stress level, and how rested participants felt were recorded. Participants also answered a series of behavioral questions, such as whether they slept with the windows open, and if they used earplugs or other sleep aids. The designed diary had two sections: one filled out at bedtime and one in the morning. Sleep-related physiologic signals were obtained by six electroencephalograms (EEGs) (C3/A2-C4/A1, O3/A2-O4/A1, F3/A2-F4/A1), positioned according to the 10–20 international electrode placement system, right and left electrooculograms (EOGs), five electromyograms (submental, anterior tibialis) (EMGs), and left and right electrocardiograms (ECGs). Physiological data recorded during polysomnography are listed in Table 5.1.

Table 5.1: Physiological Data Recorded in Polysomnography

Sensor Type	Number of Channels	Monitored Parameter	Purpose
EEG(Electroencephalogram)	6	Brain waves	Sleep Staging
EOG(Electrooculogram)	2	Eye movement	Identification of REM
Chin EMG(Electromyogram)	3	Muscle tone	Identification of REM
ECG(Electrocardiogram)	2	Electrical conduction in heart	Heart rate and rhythm
Limb	4	Leg movement and muscle tone	Identification of restless leg syndrome and periodic leg movement
Oximeter	1	Blood SaO2	Oxygen Saturation
Nasal pressure	1	Airflow	Respirations
Snore and Position	1	Detect snores/Body position	Respirations/Movement
Thoracic RIP band	1	Respiratory Effort	Respirations
Abdominal RIP band	1	Respiratory Effort	Respirations

In order to screen for breathing-related sleep disorders such as central or obstructive sleep apnea as well as periodic leg movements, the following data were also collected: finger pulse rate, oxygen saturation (finger pulse oximeter), nasal airflow (nasal cannula), respiratory movements (two piezoelectric belts), body position, and leg movements. Figure 5.1 shows a test subject under sleep and noise study.

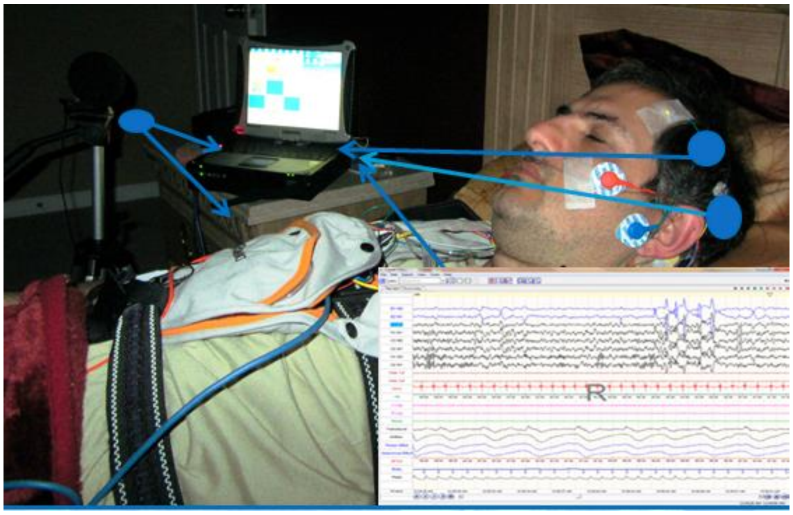


Figure 5.1: Test Subject under Sleep and Noise Study

Each PSG recording was scored manually (using Profusion 3 software from Compumedics) and blindly (regarding noise exposure and distance) by an experienced sleep technician in 30 second epochs according to the standard developed by American Academy of Sleep Medicine (AASM) (Medicine and Iber 2007).

From these data, the following sleep parameters were derived: (1) sleep period (SLP), defined as the time elapsed from sleep onset to final awakening, (2) sleep onset latency (SOL), defined as the period of time between reported lights out and 2 minutes of unbroken sleep, (3) time spent in stages one and two (S1, S2), (4) rapid eye movement (REM), (5) slow wave sleep (SWS), (6) wake time after sleep onset (WASO), defined as total amount of time awake excluding SOL, (7) total sleep time (TST), which is SLP minus WASO (8) sleep stage changes to a lighter stage (SSC), i.e., S1 to wake, S2 to S1 or wake, SWS to S2, S1 or wake, REM to S2, S1 or wake, (9) Apnea-Hypopnea Index (AHI), (10) periodic limb movement index (PLM), and (11) arousal index. An arousal is defined as an abrupt and transient shift of EEG frequencies consisting of alpha, theta and/or frequencies greater than 16 Hz. In this study, arousals were classified according to the criteria published in AASM (2007) and were divided into spontaneous arousals (SP arousals), respiratory-event (RE)-related arousals (arousals following apnea or hypopnea), and arousals associated with periodic limb movements (LM arousals). Only the spontaneous arousals were hypothesized to be related to noise; hence, the other types of arousals were scored but were not analyzed directly with regards to noise exposure. In Figure 5.2, structure of sleep is shown by plotting the different stages of sleep against the sleep time. Figure 5.3 shows frequency of arousal in sleep of one of the participants, and Figure 5.4 shows the physiological reaction of test-subjects to a slammed door noise.

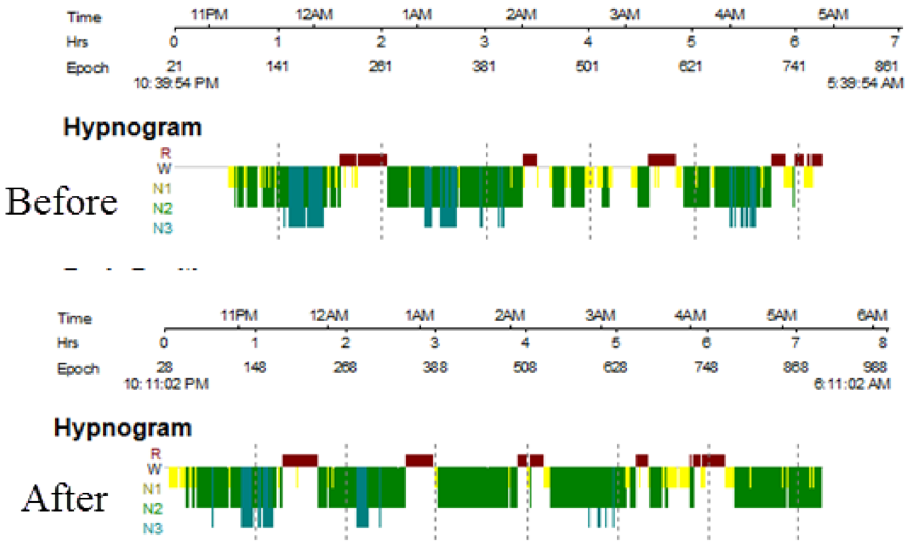


Figure 5.2: Hypnogram of the Participant in Field Study

(Yellow=stage1 of sleep, Green=stage2, Blue=deep sleep and red=REM sleep)

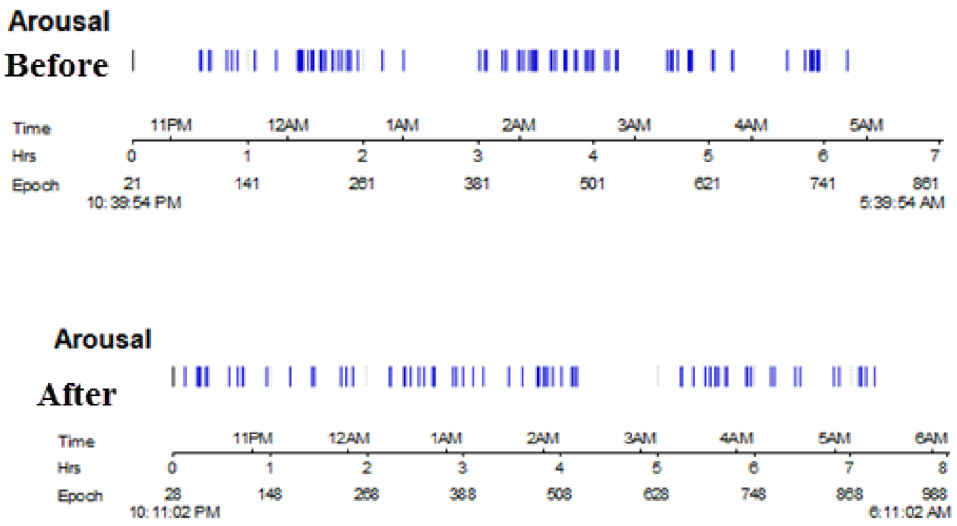


Figure 5.3: Arousal Scoring Over the Night

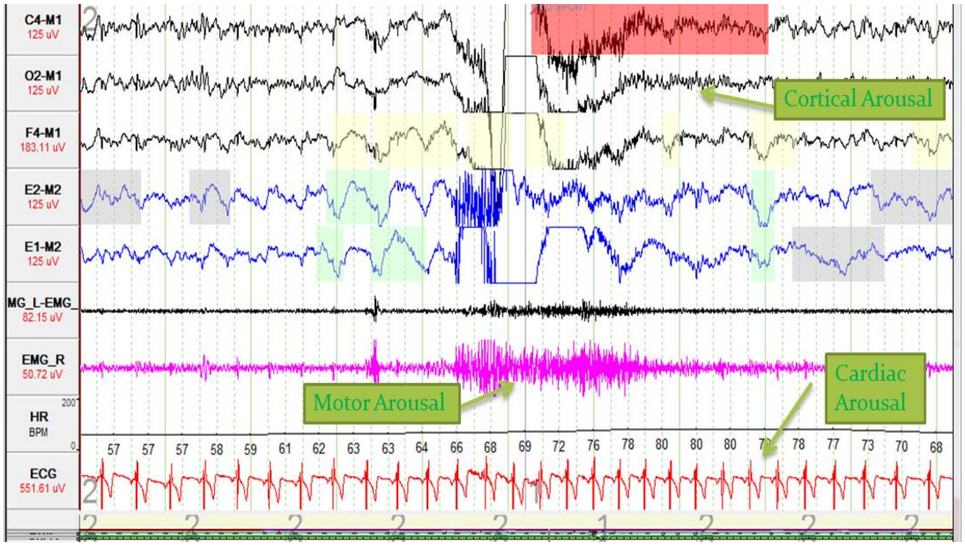


Figure 5.4: Physiological Reactions to Noise in Subject under Study

Noise exposure assessment: A noise-measurement system was placed in participants' bedroom to record both audible and low frequency noise for duration of their sleep. The system was programmed to turn on and off automatically at the start and end of each period. The indoor microphone was fitted with a windscreen and mounted on a microphone stand in the bedroom at a location close to participants' head, at the same height as the sleeping person and one meter horizontally from the participants' head. A Soundbook analyzer (MK1) (Sinus/Messtechik, Leipzig, Germany) was used with a G.R.A.S 40AZ low frequency microphone. The whole system is capable of measuring noise in the 0.5 Hz to 20,000 Hz frequency range. The system was calibrated before and after each recording using a known frequency (250Hz) and Sound pressure level (SPL) (114 dB) source. The results of the sound measurements and recordings were transferred from the Soundbooks to a personal computer. Further processing and calculations were performed using the software package Samurai 2.6.

At two participants' residences, varying each night, indoor noise was measured, for total of 16 nights before and 16 nights after operation of the turbines. In total 64 sets of data were collected. For each night and each residence, noise data were recorded for 10 hours. For each subject, two cuts of full data were analyzed. The first cut was noise measurement for the period that the subject was in bed (TIB, from lights off to lights on). The second cut was noise measurement for one-hour (1H) during the night at a point where inside spikes (eg. coughing, dog barking, snoring) were minimal. Z-weighted and A-weighted parameters for TIB and 1H noise (L_{Aeq} -TIB, L_{Zeq} -TIB, and L_{Aeq} -1H, L_{Zeq} -1H) were measured for each night. Frequency band for Z-weighted noise parameters was from 5Hz to 20KHz. The sound analyzer was time-synchronized to the sleep recording instrumentation.

In addition to noise measurements, weather, temperature, and wind speed data were collected from the companies that had weather stations close to the location of the study. Wind speed data, taken at 10m height, was used for before and after analysis of noise versus wind speed, from the closest weather station to the WTs. Additionally, wind speed and temperature data, taken at 95m height at the location of WTs, were used for after turbine operation analysis. The wind speed data at the height of 95m is average of wind speed at the location of five turbines.

Participants’ noise sensitivity and attitude to WTs were measured on a 5-point scale ranging from “not at all sensitive” to “very sensitive.” and ‘‘very positive’’ to ‘‘very negative,’’ respectively. Noise sensitivity and attitude were dichotomised into ‘‘not sensitive’’ and ‘‘sensitive’’ (1–3 vs 4–5), and attitude into ‘‘not negative’’ and ‘‘negative’’ (1–3 vs 4–5).

This study was reviewed and received ethics clearance through the University of Waterloo Research Ethics Committee, and written consent was obtained from all participants prior to the study. A certified sleep technician performed, monitored, and scored all PSG recordings.

Statistical Analysis

All analyses were performed using SPSS, Version 22 for the Windows 8 operating system (IBM Corp). Normality assumption were examined using Shapiro-Wilks tests and descriptive statistics, including means and standard deviations, were performed on a number of dependent and independent variables for sleep parameters. Comparisons before and after exposure for objective sleep variables that could be treated as continuous variables (sleep duration, number of awakenings) were performed by paired t-tests or the Wilcoxon signed rank test, as appropriate. For subjective sleep ratings, McNemar tests were used. For normal data, an independent samples t-test was used to compare the means of variables for two independent groups. Non-parametric tests such as Mann-Whitney test was used to compare mean differences of measures in two independent groups. Spearman’s rank correlation coefficients were calculated to determine the strength of the relationship between the noise exposure parameters and the sleep parameters.

In addition, an event-related analysis was performed on a few subjects at different distances from the WTs and with different levels of wind speed. A time period of 60 seconds (two sleep epochs) after a high level of noise was screened for sleeper reactions.

Results

Table 5.2 shows the demographic characteristics of the participants. Ten women and six men with a mean age of 55.9 years participated in the study. All participants lived on farms or in single detached houses; 87.5% could see at least one WT from their dwelling, and 62.5% lived at a distance of under 1000m from the nearest turbine. Regarding the participants noise sensitivity, 12.5% (2 people) of survey respondents were “rather or very sensitive” to noise.

Table 5.2: Demographic Characteristics of Participants in Wind Turbine and Sleep Study

Variable		N	%
Gender	Male	6	37.5
	Female	10	62.5
Marital status	Married/ common-law	14	87.4
	Separated or widow	2	12.6
Occupation	Full time employment	8	50
	Retired	5	31.3
	Part-time/self-employment	3	18.7
Education	Post-Graduate college/university	13	81.2
	High school diploma/Less than secondary	3	18.8
Own their home	Yes	16	100
	Rented or others	0	
Distance to nearest turbine	<1000m	10	62.5
	>1000m	6	37.5
Turbine visibility	Yes	14	87.5
	No	2	12.5
Bedroom facing wind turbine	Yes	14	87.5
	No	2	12.6
Bedroom location	First floor	9	56.3
	Second floor	7	43.8
Double glass window	Yes	13	81.3
	Not answered	3	18.7
Noise sensitivity	Not or slightly sensitive	12	75
	Rather or very sensitive	2	12.5
	Not answered	2	12.5
Attitude to turbines	Negative	8	50
	Neither negative or positive	2	12.5
	Positive	6	37.5
Owned The land that wind turbine is located		3	18.8
Age (mean, range)		55.94 (39,78)	

Table 5.3 compares different sleep factors from T1 and T2 observation. All scorings were judged to be of sufficient quality to provide reliable sleep staging and EEG arousal data. Calculation of SOL relied on the participant's reporting of lights out. There were no significant differences between measured sleep factors in T1 and T2 observations. Neither sleep discontinuity factors (WASO, duration of S1 sleep, SSC and the number of awakenings), nor sleep quantity factors (TST and duration of S2 sleep) showed any significant changes after the new exposure. The difference between mean number of arousal indices in T1 and T2 of observation was not significant (p=0.079), with the mean of 15.92 (SD=7.15) in T1 and 13.23(SD=5.29) in T2. The mean of REM sleep and sleep efficiency remained unchanged after exposure. The percentage of SWS decreased after exposure; however, this change was not significant (p=0.145). The mean of sleep latency remained unchanged and in general all the participants in T2 except two had SOL less than 20 minutes. Those two participants with long sleep latency also had long SOL in T1.

Regardless of exposure presence, sleep efficiency, arousal index, SSC and WASO in both T1 and T2 of observation were strongly related to age; older adults (>55) had lower sleep efficiency (P<0.001), higher number of arousals (p=0.041), higher number of SSC (p=0.016) and longer awakening (P<0.001) than middle age group (30-55 years old). The distribution of all sleep factors did not significantly differ between men and women.

Table 5.3: Comparison of Mean Sleep Factors at Time1 and Time2 of Observations, Wind Turbine and Sleep Study

Sleep factors N=16	**Time 1 (Mean ±SD)**	**Time 2 (Mean ±SD)**	**p-Value**
Wake after Sleep Onset (WASO, min)	34.81±25.95	34.37±26.92	0.950
Stage 1 of sleep (%)	16.25±7.54	16.16±6.96	0.953
Sleep Stage Changes (SSC) /hour	9.25±2.78	8.66±2.80	0.444
Number of awakening	20.50±10.37	17.63±9.19	0.145
Sleep Efficiency (SE)%	88.5±7.06	89.40±6.87	0.634
Sleep Period (SLP, min)	415.12±71.64	437.07±53.44	0.281
Total Sleep Time (TST, min)	380.31±68.80	402.13±36.44	0.226
Stage 2 of Sleep%	56.94±9.45	58.17±6.70	0.526
Slow Wave Sleep (SWS)%	7.33±7.14	5.72±5.58	0.145
REM Sleep%	19.47±3.70	19.94±5.02	0.728
Spontaneous arousal/hour	10.48±5.25	8.91±3.65	0.179
Respiratory arousal	3.39±4.42	2.72±3.53	0.298
Limb movement arousal	0.53±1.81	0.1±0.25	0.284
REM sleep latency	90.37±42.60	88.84±36.62	0.871
Sleep latency (min)	14.91±17.73	11.06±16.88	0.371

Paired t-test or Wilcoxon signed rank test used for comparing mean distribution of two continuous and related samples

Tables 5.4-5.6 compare changes of sleep factors over time based on age, sex, distance, and bedroom and window situation. REM sleep latency is decreased in middle age but increases in older adults after exposure (p=0.042); SSC also changed in different ways for men and women, with men having more SSC after exposure and women less (p=0.042).

Table 5.4: Changes of Sleep Discontinuity Factors over Time by Age, Sex, Distance, Bedrooms and Windows Situation, Wind Turbine and Sleep Study

Variables N=16	**Wake after Sleep Onset**			**Sleep Stage Changes**			**Spontaneous Arousal**			**Number of Awakenings**		
Mean ± SD	**Time 1**	**Time 2**	**p-Value**	**Time 1**	**Time 2**	**p-Value**	**Time 1**	**Time 2**	**p-Value**	**Time 1**	**Time 2**	**p-Value**
Men	34.67±30.16	32.25±20.69	0.958	8.58±2.43	9.65±2.43	**0.042**	7.93±3.96	7.51±1.86	0.428	20.83±10.24	17±11.47	0.706
Women	34.90±24.85	35.65(31.07		9.66±3.02	8.06±2.96		12.01±5.50	9.75±4.27		2.3010.98	18±8.21	
Middle age[*]	20.17±11.03	20.33±15.82	0.758	8.21±1.68	7.68±2.12	0.837	8.93±3.16	7.61±1.33	1.00	16.67±9.27	16.22±9.31	0.146
Older adult	53.64±28.05	52.43±28.33		10.60±3.43	9.91±3.22		12.47±6.87	10.58±5.02		25.43±10.17	19.43±9.43	
Distance												
<1000m	32±25.32	29.65±18.92	0.635	8.54±1.88	8.64±3.49	0.428	9.68±3.59	8.90±3.14	0.635	19±8.98	18.10±10.53	0.181
>1000m	39.50±28.73	42.25±37.57		10.44±3.75	8.70±1.27		11.82±7.48	8.93±4.72		23±12.85	16.83±7.25	
Bedroom's												
Floor: First	22.72±13.50	30.50±34.08	0.252	8.12±1.62	7.67±2.11	1.000	8.78±3.22	7.62±1.34	0.918	14.67±8.15	14.67±8.41	0.080
Second	50.35±30.66	39.36±14.57		10.71±3.38	9.92±3.21		12.67±6.71	10.57±5.02		28±7.96	21.43±9.32	
Window at bedtime												
Close	25.17±9.74	25.50±17.42	0.324	8.83±1.77	8.45±2.03	0.260	9.25±3.81	7.82±1.57	0.252	19.67±9.81	19.33±10.17	0.105
Open	42.94±32.10	38.83±32.66		9.58±3.50	8.21±2.89		11.39±6.35	8.72±3.74		20.78±11.83	14.67±6.95	

*: Middle age considered from 30-55 and older adult considered >55.

* p value compares the mean difference between T2 and T1 for each two categories and Mann Whitney U test was used to obtain each p-value.

Table 5.5: Changes in Sleep Quality Parameters over Time by Age, Sex, Distance, Bedrooms and Windows Situation, Wind Turbine and Sleep Study

Variables **N=16, Mean** ± SD	**Sleep Latency**			**Total Sleep Time**			**Sleep Efficiency**		
	Time 1	**Time 2**	**P-V**	**Time 1**	**Time 2**	**P-V**	**Time 1**	**Time 2**	**P-V**
Men	9.92±9.93	9.0±12.61	0.604	380.33±49.13	384.20±29.28	0.328	89.97±4.52	87.91±6.95	0.230
Women	17.90±21.05	12.30±19.54		380.30±80.92	411.10±37.63		87.62±8.34	90.29±7.04	
Middle age *	9.06±8.16	6.67±10.71	0.470	376.05±49.15	389.17±34.39	0.623	92.73±3.50	93.59±4.37	0.918
Older adult	22.43±24.09	16.71±22.21		385.79±92.47	421.58±32.70		83.05±6.86	84.01±5.70	
Distance	15.10±19.30	9.85±19.72	0.678	387.65±77.57	406.11±34.97	0.647	89.30±7.09	89.99±7.21	0.890
<1000m	14.58±16.53	13.08±12.13		368.08±55.54	396.16±41.12		87.17±7.48	88.42±6.81	
>1000m									
Bedroom: First	13.05±13.36	7.50±10.46		359.61±51.11	391.56±36.91		90.82(6.16)	91.71±6.57	0.995
Floor: Second	17.29±23.17	15.64±22.87	0.657	406.93±82.96	418.0±32.18	0.351	85.51(7.47)	86.43±6.50	
Window: Close	10.83±9.60	7.66±13.25	0.197	368.66±49.84	390.66±27.69	0.774	91.05(2.81)	92.27±4.88	0.881
at bedtime: Open	14.33±20.25	7.27±5.43		369.39±59.60	403.06±38.17		86.68(8.94)	88.49±7.51	

*: Middle age considered from 30-55 and older adult considered >55

* p value compares the mean difference between T2 and T1 for each two categories and Mann Whitney U test was used to obtain each p-value

Table 5.6: Changes in Deep and REM Sleep Parameters over Time by Age, Sex, Distance, Bedrooms and Windows Situation

Variables **N=16, Mean** ± SD	**Slow Wave Sleep**			**REM Sleep**			**REM Sleep Latency**		
	Time 1	**Time 2**	**P-V**	**Time 1**	**Time 2**	**P-V**	**Time 1**	**Time 2**	**P-V**
Men	5.98±6.43	4.37±5.10	0.713	19.88±4.42	20.20±7.28	0.933	87.33±44.62	83.67±41.06	0.635
Women	8.14±7.75	6.53±5.96		19.23±3.43	19.79±3.52		92.20±43.68	91.95±35.65	
Middle age[*]	8.60±8.37	6.94±6.62	0.918	19.88±4.74	20.32±5.05	0.984	94.00±32.07	92.73±3.50	**0.042**
Older adult	5.70±5.35	4.14±3.77		18.96±1.91	19.46±5.32		82.21±43.49	83.05±6.86	
Distance									
<1000m	8.25±8.18	6.91±5.82	0.958	19.09±3.07	19.95±5.45	0.716	88.70±36.56	78.75±32.83	0.428
>1000m	5.80±5.31	3.73±4.99		20.12±4.81	19.93±4.68		93.17±54.98	105.67±88.84	
Bedroom: First	9.16±8.39	6.16±6.84	0.174	19.47±4.53	20.80±4.95	0.478	78.0±25.59	90.17±30.25	0.071
Floor: Second	4.98±4.73	5.16±3.84		19.49±2.60	18.84±5.27		106.28±56.02	87.14±46.12	
Window: Close	8.28±9.13	5.60±6.46	0.426	20.05±5.52	20.10±4.59	0.718	76.92±19.50	95.25±36.19	0.169
at bedtime: Open	7.47±5.90	6.14±5.55		18.96±2.41	20.08±5.77		96.44±53.87	83.50±40.27	

*: Middle age considered from 30-55 and older adult considered >55.

* p value compares the mean difference between T2 and T1 for each two categories and Mann Whitney U test was used to obtain each p-value.

Sleep quantity and sleep quality were compared using sleep diary data from before and after exposure. Total sleep time (p=0.472), number (p=0.126) and length (p=0.062) of awakenings and sleep latency (p=0.942) did not change significantly after exposure. However, reported quality of sleep significantly declined after exposure (p=0.008). Participants also reported higher levels of stress before bedtime (p=0.039) and in the morning (p=0.064), and also reported feeling sleepy (p=0.013) in the morning and throughout the day (p=0.014) after exposure. The results of the sleep diaries over 7 days are reported in Table 5.7.

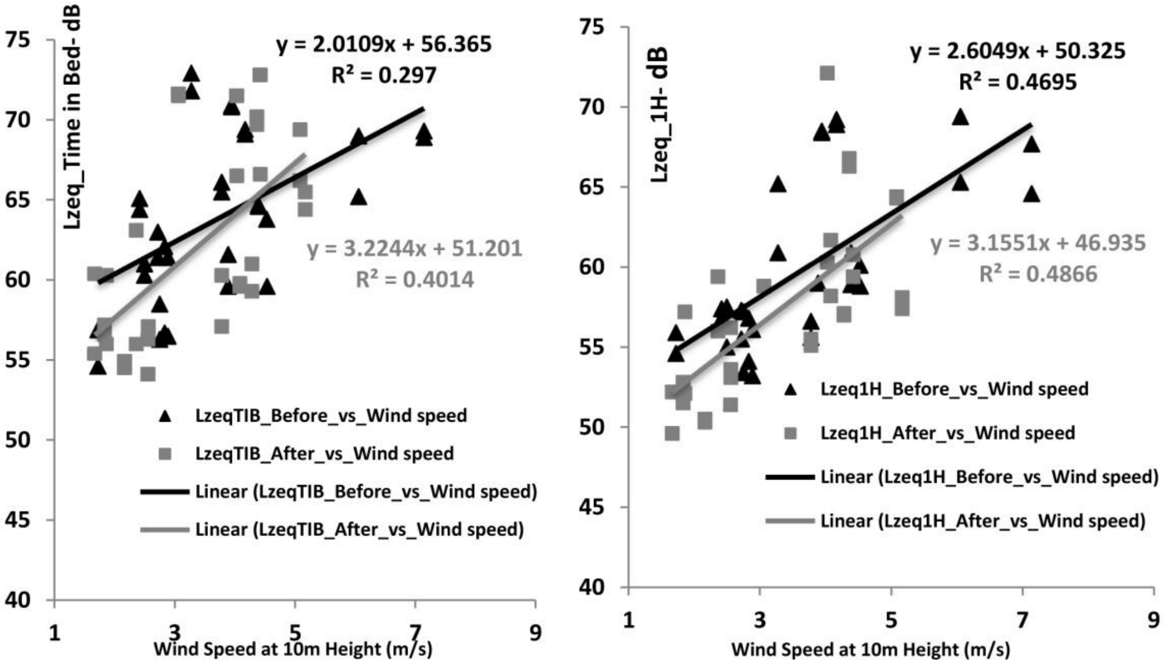
Of participants, 90.1% in T1 and 96.1% in T2 believed that outside noise did not wake them up and no one reported waking up to close their windows due to outside noise (33.7% of participants in T1 and 44.8% of them in T2 slept with open windows).

Table 5.7: Changes in Sleep-Related Factors Measured by Sleep Diaries

Variables	Time1: N=16 (7 days data)			Time2: N=16 (7 days data)		
Feeling throughout the Day	Fairy/ Fully awake		Tired/Sleepy	Fairy/ fully awake		Tired/Sleepy
	80.4%		19.6%	67.3%		32.7%
Feeling in the Morning	Rested	Moderately Rested	Tired/Sleepy	Rested	Moderately Rested	Tired/Sleepy
	61.9%	23.7%	14.4%	49%	31.6%	19.4%
Mood throughout the Day	Pleasant	Moderately	Unpleasant	Pleasant	Moderately	Unpleasant
	74.2%	18.6%	7.2%	69.4%	21.4%	9.2%
Stress Level before Bedtime	Relaxed	Moderately Tense	Tense and Stressful	Relaxed	Moderately Tense	Tense and Stressful
	75%	16.7%	7.3%	67.3%	20.4%	12.2%
Stress in the Morning	Relaxed	Moderately Tense	Tense and Stressful	Relaxed	Moderately Tense	Tense
	82.3%	11.5%	6.2%	65.3%	26.5%	8.2%
Likely to Doze off	No Chance		Moderate/ High Chance	No Chance		Moderate/ High Chance
	86.5%		13.5%	73.2%		26.8%
Sleep Quality	Good/Fairly Good		Bad/ Fairly Bad	Good/Fairly Good		Bad/ Fairly Bad
	82.7%		17.3%	74.5%		25.5%
Total Sleep Time	Mean (SD) 7.63(1.15)			Mean (SD) 7.54(0.98)		
Sleep Onset Latency	14.65(17.95)			14.53(17.86)		

Noise and wind data analysis: The means of wind and temperature data from 10:00 pm to 8:00 am for each night were used in the analysis. The means of wind speed, at height of 10 m, were not significantly different (p=0.559) between T1 and T2 periods of observation: 3.64 m/s (SD=1.19) in T1 and 3.33 m/s (SD=1.39) in T2. The mean of wind speed at hub height for exposure nights was 6.48 (SD=1.84) m/s, with a range of 3.70 m/s to 9.40 m/s. The cut-in wind speed for the turbines was 4 m/s. The average A-weighted noises measured in T1 and T2 observation were not significantly different with means of 36.55 dB(A) (SD=4.18) in T1 and 36.50 dB(A) (SD=4.20) in T2 for TIB (p=0.959) and mean of 31.52 dB(A) (SD=5.16) in T1 and 31.23 dB(A) (SD=4.91) in T2 for 1H (p=0.740). The average Z-weighted noises measured in T1 and T2 observation were also not significantly different with means of 63.78 dB(Z) (SD=5.07) in T1 and 61.93 dB(Z) (SD=6.00) in T2 for TIB (p=0.218) and mean of 59.93 dB(Z) (SD=5.22) in T1 and 57.44 dB(Z) (SD=5.33) in T2 for 1H (p=0.090).

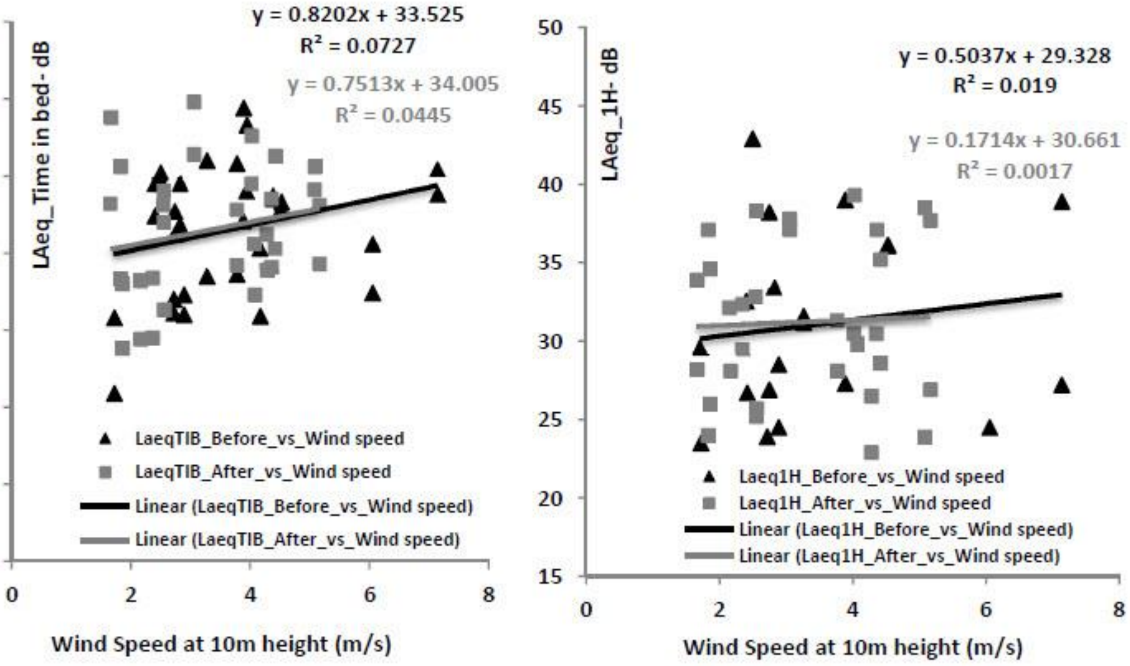
Figures 5.5 a and b show the Z-weighted noise exposure for TIB and 1H for T1 and T2 of observation versus wind speed at the height of 10m. Increasing trends in the noise level are observed by increasing wind speed, and slope of noise at T2 is higher than T1 for both TIB and 1H noise equivalent. The slope of noise for TIB is 3.22 (p<0.001) for T2 versus 2.01 for T1(p=0.001) and noise the slope of noise for 1H is 3.15 (p<0.001) at T2 versus 2.60 at T1 (p<0.001).



(a) (b)

Figure 5.5 a, b: Time 1 and Time2, Z-Weighted Equivalent Noise for "Time in Bed "and "1H" versus Wind Speed at the Height of 10m

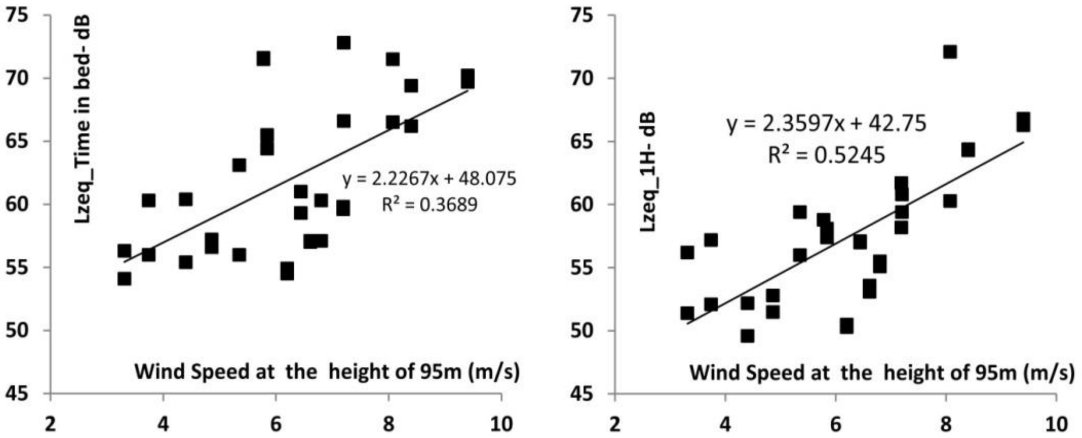
Figures 5.6 a and b show the A-weighted noise exposure for TIB and 1H for T1 and T2 of observation versus wind speed at the height of 10m. Increasing trends in the noise level are observed by increasing wind speed however none of the findings were significant. For TIB, the slope of noise is 0.75 for T2 (p=0.247) versus 0.82 for T1 (p=0.136), and for 1H noise the slope of noise is 0.17 (p=0.823) at T2 versus 0.50 (p=0.638) at T1.



(a) (b)

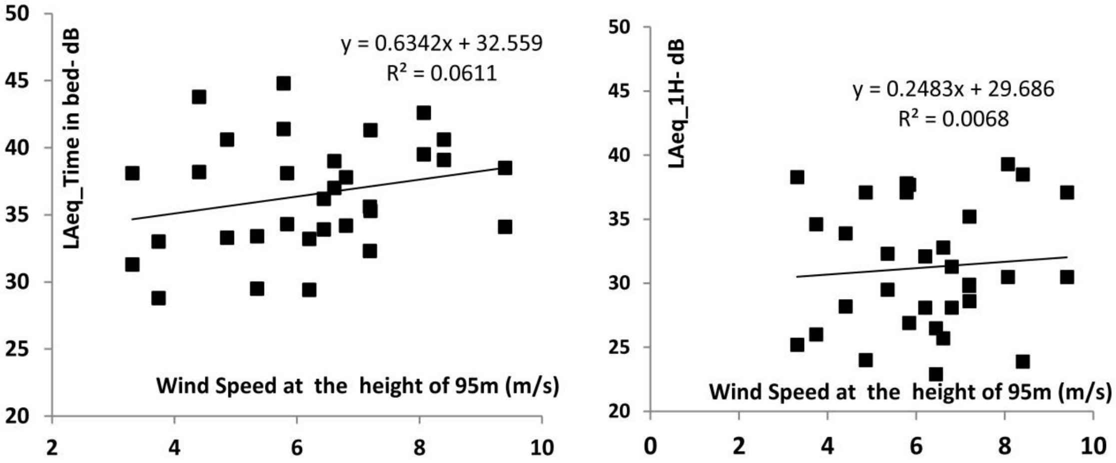
Figure 5.6 a,b: Time 1 and Time2, A- Weighted Equivalent Noise for “Time in Bed “and “1H” versus Wind Speed at the Height of 10m

Figures 5.7(a and b) and 5.8 (a and b) demonstrated the Z-weighted and A-weighted at T2 for TIB and 1H versus wind speed at the height of 95m. The slopes of Z-weighted noise versus wind speed are 2.23 for TIB ($p<0.001$) and 2.36 for 1H ($p<0.001$). The slopes of A-weighted noise versus wind speed noise are 0.63 for TIB ($p=0.171$) and 0.24 for 1H ($p=0.650$).



(a) (b)

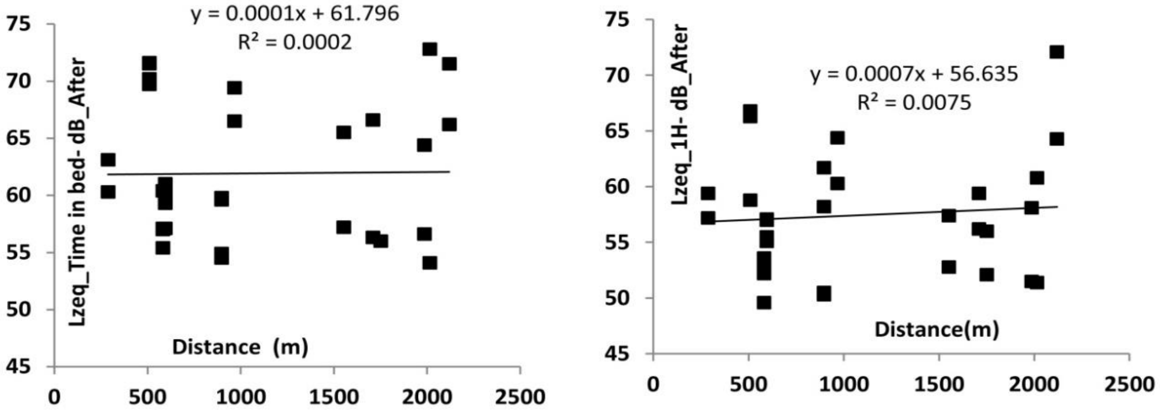
Figure 5.7a,b: Time2 Z- Weighted Equivalent Noise for "Time in Bed "and "1H" versus Wind Speed at the Height of 95m



(a) (b)

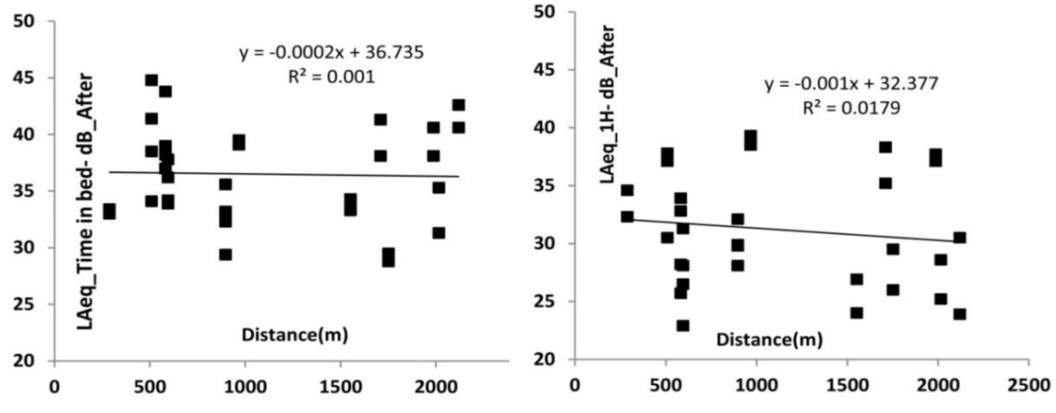
Figure 5.8 a,b: Time2 A- Weighted Equivalent Noise for "Time in Bed "and "1H" versus Wind Speed at the Height of 95m

Figures 5.9 and 5.10 identify the relationship between distance from the closest WT and noise levels (L_{Aeq}, L_{Zeq}) for TIB and 1H. Results of Spearman's correlation indicate that there is no significant correlation between distance and inside noise after exposure (L_{Aeq}-TIB: r = -0.047, p=0.862, L_{Aeq}-1H: r = -0.353, p=0.180, L_{Zeq}-TIB: r = -0.230, p=0.392 L_{Zeq}-1H: r = -0.080, p=0.769).



(a) (b)

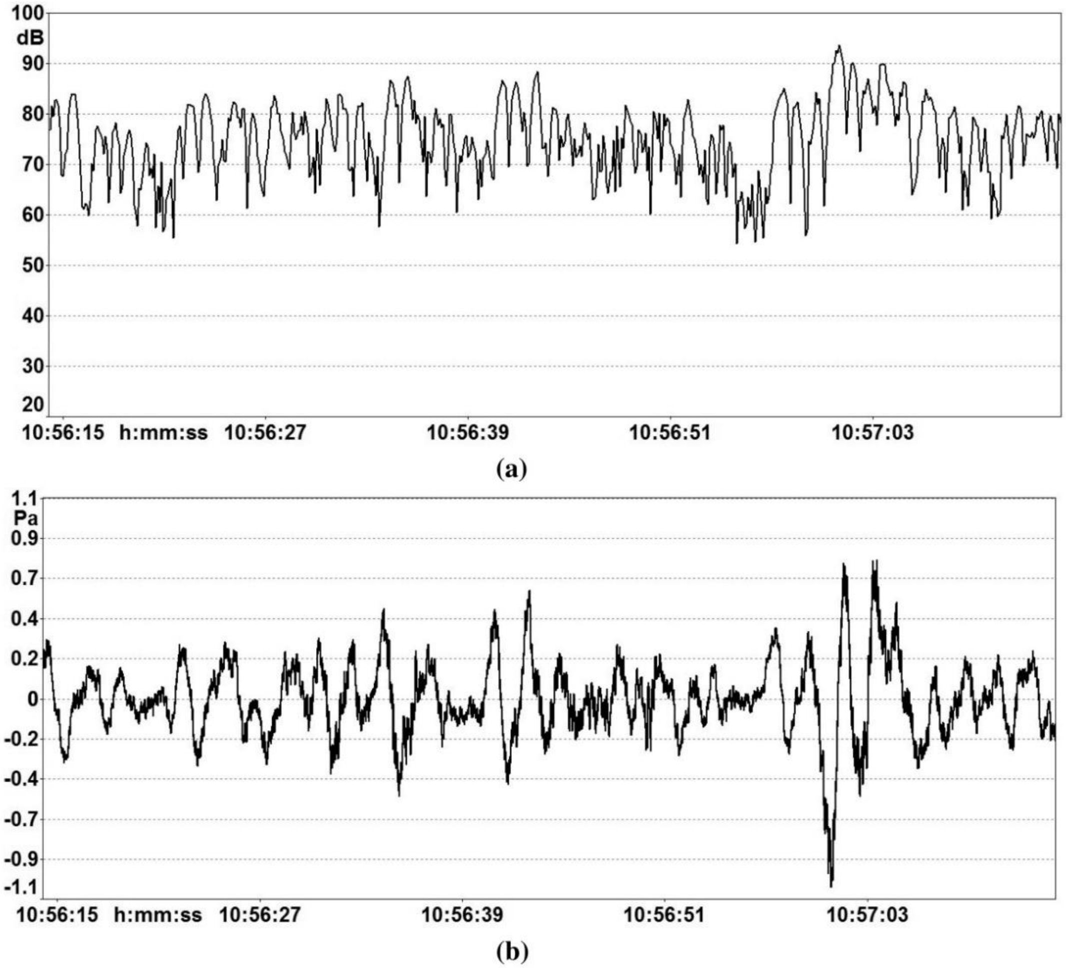
Figure 5.9 a, b: Time 2 Z- Weighted Equivalent Noise versus Distance from the Closest Wind Turbine for "Time in Bed" and "1 H"



(a) (b)

Figure 5.10 a, b: Time 2, A-Weighted Equivalent Noise versus Distance from the Closest Wind Turbine for "Time in Bed" and "1 H"

Figure 5.11 a and b provide an example of typical low frequency waveform swing measured inside the bedroom at distance of 550m from the turbines at T2. All the noise recordings were observed to identify non-relevant peak noise levels. For this particular example, the measured peak of noise is 0.7Pa, which is approximately equivalent to sound pressure level (SPL) of 91dB. The peak of noise signal varies from 57dB to about 91dB, which is about 34dB variation on the amplitude of the noise signal.



(a)

(b)

Figure 5.11a, b: Time variation of Turbine Noise (raw data) in Pascal and Peak of Z-Weighted Data in dB, Indoor, 550m Distant

Associations between noise exposure and sleep parameters: The Spearman's rank correlation coefficients were used for the associations between average noise difference (LAeq 2- LAeq 1) and sleep factors difference in T1 and T2 of study. Noise difference correlated with number of awakening's difference (r=0.605, p=0.001), SSC difference (r=0.600, p=0.001), arousal difference (r=0.551, p=0.004) and percentage of S2 difference (r=-0.499, p=0.009).

Discussion

A detailed analysis of the individual sleep epochs measured by polysomnography in the present study showed no major changes in the sleep of participants residing near new industrial WTs in their community. The analysis considered the possible effects on whole-night sleep parameters, sleep discontinuity (increased number and length of awakenings, number of sleep stage changes and length of shallow sleep), sleep quantity and quality (reduced total sleep time, reduced stage 2, and REM and SWS sleep), and sleep efficiency. Previous noise-effect studies have regarded SSC as the primary indicator for disturbed sleep (Basner and Samel 2005). The number of SSCs per hour, measured in this present study, remained unchanged after exposure. The results obtained by sleep diary support findings from polysomnography about sleep quantity; whereas, perceived sleep quality measured by sleep diary decreased after exposure to WTs.

A total of 640 night-hours of indoor noise measurement on 32 nights were performed, at different distances and locations, before and after turbine operation. Results of the noise measurement showed that average noise levels during the exposure period were low to moderate, with an average of 31.29 dB(A) in 1H with minimal indoor spikes. The mean of inside noise levels did not significantly change after turbines operation. Outside sound monitoring also was performed at four residential houses before and after exposure. The outside sound levels ranged between 40 – 45 dB(A) before and 38 – 42 dB(A) after the turbines became operational

(Ramakrishnan and Seharwat 2015). These results also indicate that the wind farm project resulted in no significant changes in the ambient sound pressure levels in the surrounding area based on monitoring that was conducted during this study.

Previous studies, investigating the relationship between sleep and WTN, mostly had cross sectional designs and were based on self-reported symptoms. Only two studies measured objective sleep parameters in relation to WT sound exposure. In general, the current findings are consistent with the results of those two objective studies; however, their study designs were different with the current study and both used actigraphy for measuring sleep and did not compare the sleep data before and after exposure (Lane et al. 2016; Michaud et al. 2015). Lane studied 11 subjects exposed to WTs and 10 unexposed subjects and found no significant changes for the worse in sleep parameters in the exposed group. Results of a very recent large study, conducted by Health Canada, provided the most-comprehensive assessment of the association between exposure to WTN and sleep, and showed that outdoor WTN levels near participants' homes were not associated with sleep factors measured by actigraphy (Michaud et al. 2015).

Sleep disturbances are often indicated by body movements, which are easier to record and much easier to evaluate than polysomnograms. The current study relied on polysomnograms, which recorded and evaluated according to internationally accepted criteria, and it provides information about sleep depth, and reliably detected EEG arousals. Basner et al.(2008) showed in their study that, for low maximum sound pressure levels and chronic exposure situations with partial adaptation, the strongest association between noise and effects on sleep was observed for EEG arousals. In the present study, the mean of spontaneous arousal indices did not change significantly after exposure.

Failing to find an association between noise exposure and any of the sleep parameters might be due to the relatively low level of indoor noise. Adaptation to moderate levels of noise is possible due to the more continuous character of the noise; Aasvang et al. (2011) also found that people were more easily habituated to continuous traffic noise compared to intermittent rail road sounds. Some adaptation processes might have happened in order to compensate for sleep disruption throughout the night and produce no or minimal global effect on sleep. Basner et al. (2011) suggested that traffic noise events may cause awakenings in study participants, but these awakenings replaced the majority of awakenings that would otherwise have spontaneously occurred.

An event-related analysis was performed on a three subjects at different distances from the WTs and with different levels of wind speed. The results vary; in some observations, arousals were captured immediately after WTN events (high peak level of noise), as shown in Figure 5.12 and in some, no changes were observed in participants' physiological signals (Figure 5.13). The reactions of subjects to noise was non-specific, as is the case in most studies, and it was unclear whether these reactions were induced by noise or spontaneous. Basner (2008) used a formula in his study to calculate sleep reactions induced by noise. However, in the current study the numbers of noise events were limited and mostly moderate and drawing a conclusion would have needed more rigorous and detailed analyses with larger sample size.

Discrepancies between subjective and objective evaluations of sleep, such as were found in this study, are not surprising and have been explained previously in other studies. Jackowska et al. (2011) pointed out that people's judgments of sleep efficiency are associated with psychosocial stress and affective responses. Concern about environmental changes, especially those associated with new but non perceptible exposures, such as low frequency noise appear to act as a trigger for such reports of ill health (Petrie et al. 2005; Taylor et al.2013). Self-reported sleep disturbance may also be associated to the indirect effects of individual differences such as visual and attitudinal factors. Further research into the effects of WTs on sleep quality, emotions such as pre- and post-construction anxiety, and fear for health is warranted.

Several points need to be considered; due to the field study design, there was a lack of control, both with regards to the exposure levels and wind speed, and with other possible sources of variation that might affect results.

Some operational characteristics of WTs may have also influenced the study. Exposure to WT sound occurs irregularly, and people living in the vicinity of turbines are not exposed every night and examination of sleep quality in one night may be affected by WTN and sleep quality in the nights preceding data collection. Moreover, several other factors impact measurement and exposure to WTN, including characteristics of the participants' home, weather conditions, local flora and topography, and the number of and layout of the turbines. Larger wind farms tend to generate more noise than smaller ones, as several WTs in the same vicinity can lead to increased pulse sounds, with increased sound pressure levels of 5 dB (van den Berg 2004). It is also common for old turbines to operate at a fixed speed, or perhaps at one or two fixed speeds, depending on the wind speed. However, new turbines are fully variable in blade rotational speed and so are able to operate at the most efficient rotational speed across a wide range of wind speeds. The result of this technological improvement is that at low speeds of rotation in light winds, noise emissions are lower. Further research is needed to evaluate sleep quality in residents living adjacent to older WTs.

A potential source of bias for repeated measure studies is "order effects" in which repeated uses of a diagnostic test such as PSG influence dependent variables. In the current study, Contrary to expectation, the mean arousal index in T1 was higher than the same index in T2 of observation (p=0.079). This result might be related to “order effect”, and participants might get used to the system after frequent uses and there is no way to control for it.

The strength of this study is that it involved baseline noise and infrasound monitoring and objective and subjective sleep assessments during turbine construction and follow-up during the operation period. This study is the first published study of WT-related sleep disturbances assessed using polysomnographic techniques while simultaneously collecting inside sound pressure levels. Further studies should be performed involving the simultaneous field collection of PSG and noise signals but with a large sample size and including comprehensive single-event analyses.

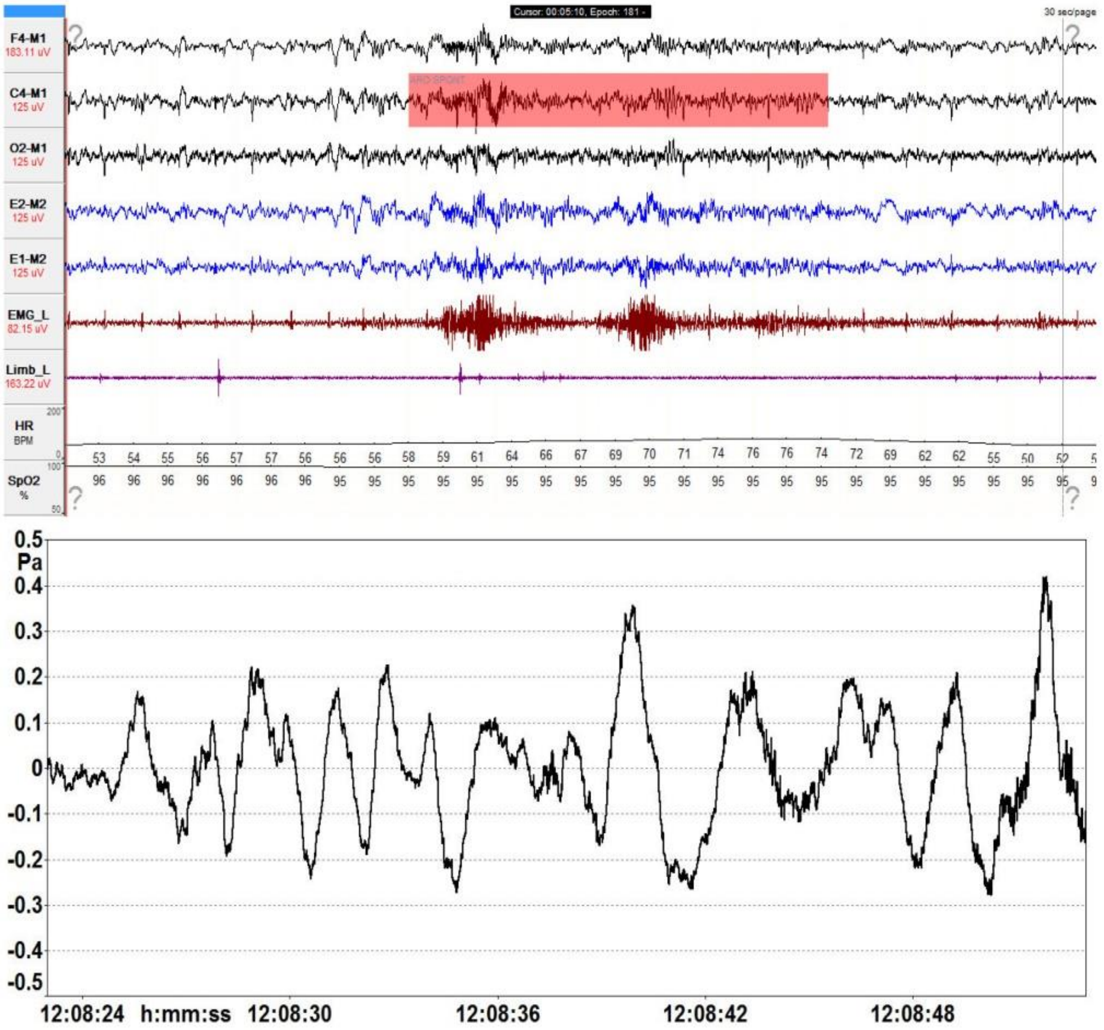


Figure 5.12: Sleeper's Reactions to a Single Noise Event at Distance of 1986 m from the Turbine

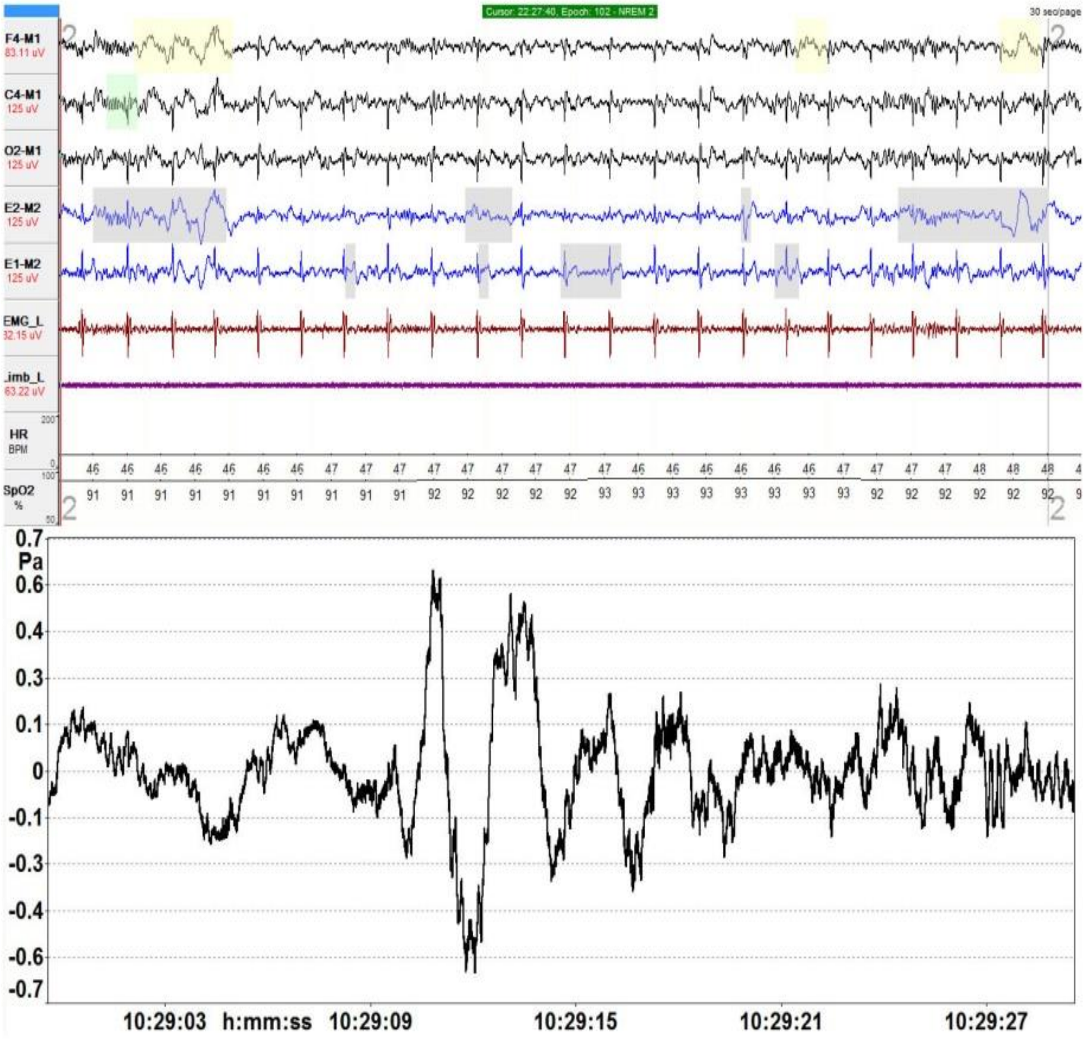


Figure 5.13: Sleeper's Reactions to a Single Noise Event at Distance of 967m from the Turbine

Chapter 6 : Conclusion and Future Direction

Summary of the Work

The main objective of this thesis research was to understand and investigate the effect of turbines on the general health and sleep of nearby residents. As mentioned in Chapter 2, a literature review was conducted to analyze and summarize the results of studies related to WTN and general health and sleep effects. The findings indicated that the existing evidence is not sufficient to establish a cause-and-effect relationship, as all the studies have used cross sectional designs. Prospective cohort studies with objective sleep and noise measurement that document prior baseline health and noise status are lacking, and because studies rarely involved simultaneous measurement of both exposure and health outcomes, the temporal sequence of exposure–outcome relationship cannot be demonstrated.

Based on the findings in the literature, we designed and organized a prospective cohort study in the field to address a knowledge gap in the science related to WTN exposure and health. The conducted research is the first to use a prospective cohort and mixed-methods design, with noise and health measurements obtained before and after operation of WTs. This study is one of the first to use highly rigorous, repeated measurements to investigate sleep disturbance due to WTN. It has addressed some of the limitations of previous studies, such as cross sectional designs, self-reported symptoms, subjective measurement of sleep and limited ability to control for confounding factors. All measurements in this study were performed in an ecologically valid setting and taking into account several modifying variables such as noise sensitivity, bedroom location and window positioning. This study is the first epidemiological research on this topic that uses a gold standard of sleep measurement to capture the full physiological data for sleep assessment based on the AASM standard in an Ontario population. This study also provides baseline community health and QoL survey measures, as well as post-operation follow-up health measures by using multiple standard and validated questionnaires.

Moreover, this is one of only a limited number of studies that has recorded sound pressure levels within study bedrooms, and captured objectively the noise to which individuals are truly exposed. The noise-measurement system is a universal portable measuring system for acoustic, vibration, and engineering measurement, and can support up to eight input channels for measurement of environmental signals, including audible and inaudible (low frequency) noises. With this combined sleep and noise system, it is possible to capture 22 physiological and 8 environmental values simultaneously and synchronously.

In short, we conducted three studies: a health and QoL field study exploring changes in QoL and perceptions of general health before and after operation of WTs, a sleep survey study evaluating self-reported sleep quality of residents, and an objective sleep study conducted through PSG. The results of the subjective data (the first and second studies) support the important role of individual differences and annoyance in reporting lower mental health, degraded life satisfaction and sleep quality by people who live close to WTs. A detailed analysis of the individual sleep epochs measured by PSG in the third study showed no major changes in the sleep of participants residing near new industrial WTs in their community. The analysis considered the possible effects on whole-night sleep parameters, sleep discontinuity, sleep quantity and quality, and sleep efficiency. Concerning noise measurement, 640 night-hours of indoor noise measurement on 32 nights were performed, at different distances and locations, before and after turbine operation. Results of the noise measurement showed that average noise levels during the exposure period were low to moderate, with an average of 31.29 dB(A) in 1H with minimal indoor spikes. The mean of inside noise levels did not significantly change after turbine operation.

As a summary, the results of this study conclude that the WTN level itself is not sufficient to explain the impact of WT presence on general health and sleep in this study population. Reporting health effects in a WT's vicinity is mediated by other factors such as attitude, noise sensitivity and WT visibility. Therefore, it is possible that a segment of the population will remain annoyed or report other health impacts even if noise regulation or setback policies are changed.

Recommendation for Future Research

As detailed in the previous chapters, a simultaneous and synchronous portable PSG and noise measurement system has been used for the assessment of WTN effects on sleep (Figure 6.1). As shown in Figure 6.2, in the current PSG systems, the information from sensors attached by wires to the different parts of the body goes into a central processing unit. This central unit collects all information and sends it to a remote computer where the associated software stores the real-time data for post processing and analysis. This method requires many wires going from different sensors to the central unit. It also needs a setup, which may not be very convenient or comfortable for participants and may influence sleep itself. Moreover, with the existing PSG technology, using polysomnography in the field has been very costly, and it is not practical for studies with large sample sizes. It might be more prone to selection bias by attracting only people who are concerned about environmental stressors, and it also reduces participation rates and therefore the generalizability of the findings (Basner et al. 2012).

A highly desirable approach for future study would involve a cost-effective objective method that is self-administered by subjects, analyses the data automatically, and has high validity. Moreover, nonintrusive data collection techniques, without the need to connect each individual to sensors and these then to a central processing system, are highly preferable.

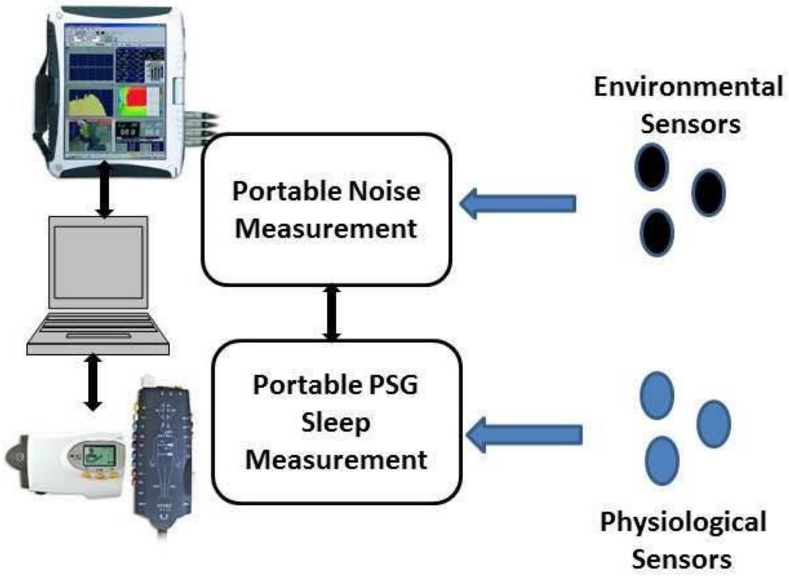


Figure 6.1: Synchronous Measurement of Sleep and Noise

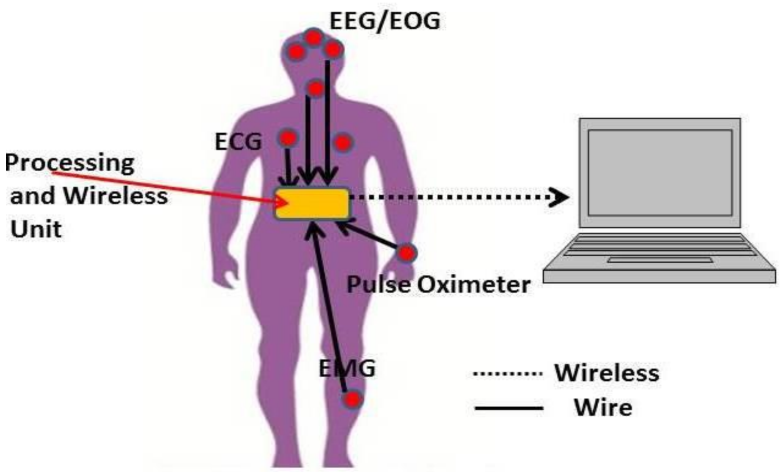


Figure 6.2: Existing Wireless PSG System Technology for Sleep Monitoring

With rapid development of technologies in the mobile health area as well as advanced sensor technologies, the cost of proposed measurement systems is decreasing. With the use of smartphones as part of the measurement system proposed for the near future, the complete measurement system will become more compact and more convenient for subjects and researchers. Figure 6.3 shows one visual example of sleep monitoring using this proposed mobile health technology.

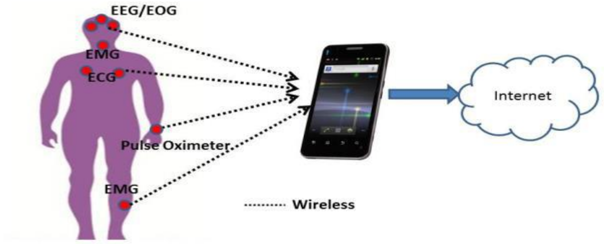


Figure 6.3: Mobile Health Vision of PSG sleep monitoring Technology (Taken from Jalali and Bigelow, 2014)

Sleep and noise measurement using smartphones will certainly become reality. However, the use of smartphone technology for this purpose requires a number of new features in both physiological sensor systems and mobile phones. Less expensive, more compact, and more energy-efficient sensor technologies need to be developed to make the adoption of such a solution more widespread. From the perspective of patient comfort, the ideal scenario would be a technology where each individual sensor could communicate directly to the mobile phone. In this approach, the wiring from each individual sensor to a central processing and transceiver unit would be removed. Only minimal processing would be done on each sensor node, and further advanced processing could be transferred to the mobile phone processor or other servers available in the cloud. This technology needs to evolve further at both the sensor and smartphone levels in order to support the collection of high-quality data from physiological sensors and transfer it directly and seamlessly to smartphones.

In addition to methods limitation, WT sound has a unique nature that is variable over time and is highly dependent on wind speed and directions, as well as locale. Sleep is also a dynamic brain process that can be affected by a large diversity of factors, including medical conditions, stress, and external stimuli. Due to the multi-disciplinary nature of the problem, collaboration between physicians, public health professionals, psychologists, acoustics scientists, and wireless sensing experts is required to address different aspects of this research through a comprehensive and systematic approach.

It is also clear that more longitudinal work with prospective designs is crucial to demonstrate the relationships between chronic noise exposure and long-term effects. Such designs afford stronger internal validity given the impossibility of randomly assigning subjects to varying community noise levels for a long period. While less economical, large-scale prospective studies may provide a much higher degree of control over the type and quality of the data collected, and with that, better statistical control over potential confounders. The future study should involve representative samples of the population, including vulnerable groups such as chronically ill subjects, those with insomnia or mood disorders, and the elderly and habitually short and light sleepers.

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