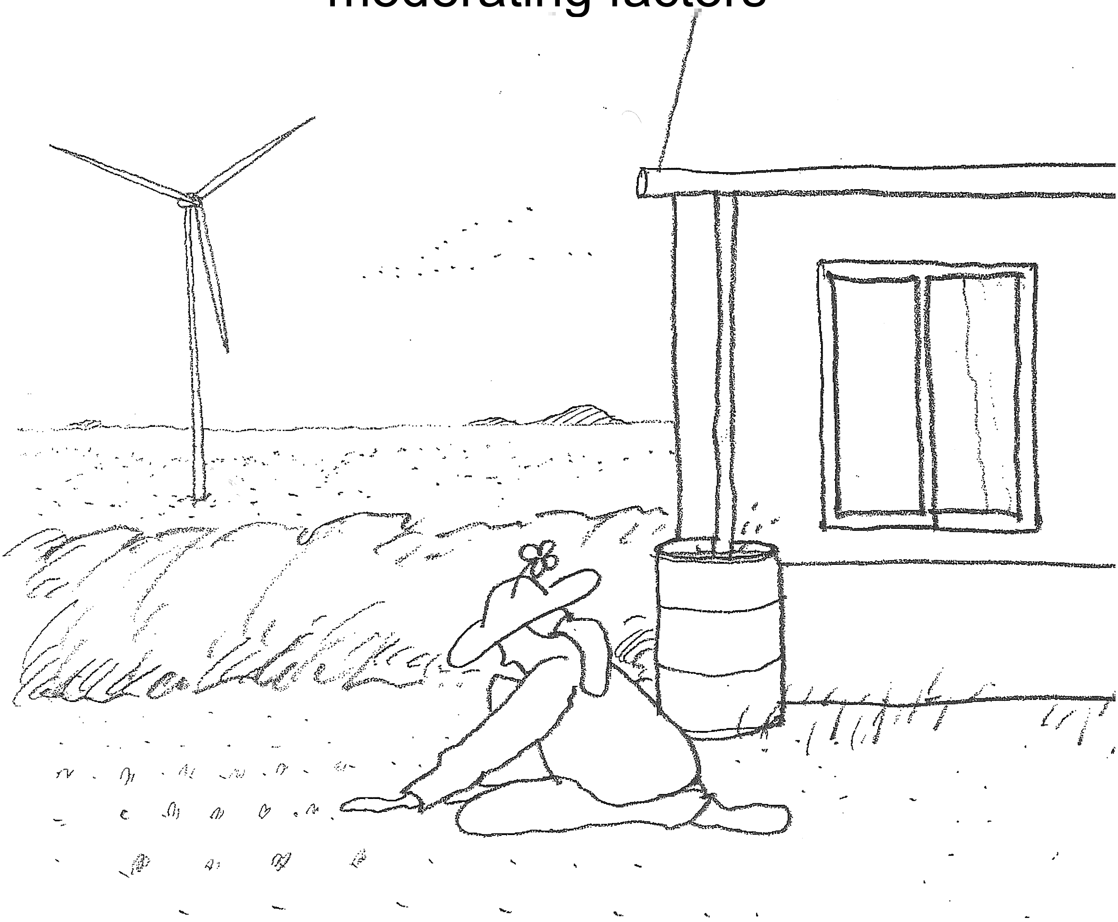
Human response to wind turbine noise

Perception, annoyance and moderating factors



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Till Thorvald som lärde mig att fånga vinden, och till Britt som visade mig vägen in i den akademiska världen.

Abstract

Aims The aims of this thesis were to describe and gain an understanding of how people who live in the vicinity of wind turbines are affected by wind turbine noise, and how individual, situational and visual factors, as well as sound properties, moderate the response.

Methods A cross-sectional study was carried out in a flat, mainly rural area in Sweden, with the objective to estimate the prevalence of noise annoyance and to examine the dose-response relationship between A-weighted sound pressure levels (SPLs) and perception of and annoyance with wind turbine noise. Subjective responses were obtained through a questionnaire (n = 513; response rate: 68%) and outdoor, A-weighted SPLs were calculated for each respondent. To gain a deeper understanding of the observed noise annoyance, 15 people living in an area were interviewed using open-ended questions. The interviews were analysed using the comparative method of Grounded Theory (GT). An additional cross-sectional study, mainly exploring the influence of individual and situational factors, was carried out in seven areas in Sweden that differed with regard to terrain (flat or complex) and degree of urbanization (n = 765; response rate: 58%). To further explore the impact of visual factors, data from the two cross-sectional studies were tested with structural equation modelling. A proposed model of the influence of visual attitude on noise annoyance, also comprising the influence of noise level and general attitude, was tested among respondents who could see wind turbines versus respondents who could not see wind turbines from their dwelling, and respondents living in flat versus complex terrain.

Results Dose-response relationships were found both for perception of noise and for noise annoyance in relation to A-weighted SPLs. The risk of annoyance was enhanced among respondents who could see at least one turbine from their dwelling and among those living in a rural in comparison with a suburban area. Noise from wind turbines was appraised as an intrusion of privacy among people who expected quiet and peace in their living environment. Negative experiences that led to feelings of inferiority added to the distress. Sound characteristics describing the amplitude-modulated aerodynamic sound were appraised as the most annoying (swishing, whistling and pulsating/throbbing). Wind turbines were judged as environmentally friendly, efficient and necessary, but also as ugly and unnatural. Being negative towards the visual impact of the wind turbines on the landscape scenery, rather than towards wind turbines as such, was strongly associated with annoyance. Self-reported health impairment was not correlated to SPL, while decreased well-being was associated with noise annoyance. Indications of possible hindrance to psycho-physiological restoration were observed.

Conclusions Wind turbine noise is easily perceived and is annoying even at low A-weighted SPLs. This could be due to perceived incongruence between the characteristics of wind turbine noise and the background sound. Wind turbines are furthermore prominent objects whose rotational movement attracts the eye. Multimodal sensory effects or negative aesthetic response could enhance the risk of noise annoyance. Adverse reactions could possibly lead to stress-related symptoms due to prolonged physiological arousal and hindrance to psychophysiological restoration. The observed differences in prevalence of noise annoyance between living environments make it necessary to assess separate dose-response relationships for different types of landscapes.

Sammanfattning på svenska

Vindkraftverk generar elektricitet utan utsläpp av växthusgaser. I Sverige och andra länder planeras därför för mer vindkraft. Det är inte känt hur vindkraftverken påverkar närboende och det finns en oro bland allmänheten för att ljudet ska vara störande. Avhandlingens syfte var därför att ta reda på hur vanligt det är att störas av vindkraftljud vid olika ljudtrycksnivåer, att undersöka hur andra faktorer än ljudet påverkar störning av ljud samt att beskriva eventuella hälsorisker.

En tvärsnittsstudie utfördes i ett flackt jordbrukslandskap i södra Sverige. Ett slummässigt urval människor boende i närheten av vindkraftverk fick svara på frågor om miljöpåverkan i sin boendemiljö, inklusive påverkan från vindkraftverk (n = 513; svarsfrekvens: 68%). A-vägda ljudtrycksnivåer (ljud från vindkraftverk utanför bostaden vid vindhastigheten 8 m/s på 10 meters höjd vid medvind) beräknandes för varje person. För att få en djupare förståelse för hur det är att bo i närheten av vindkraftverk så intervjuades 15 personer. Intervjuerna analyserades med den kvalitativa metoden Grounded Therory. I en uppföljande tvärsnittstudie prövades även betydelsen av geografiska faktorer för människors störningsreaktioner och studien utfördes därför i sju områden som varierade i topografi och urbaniseringsgrad (n = 765; svarsfrekvens: 58%). För att ytterligare undersöka hur visuella faktorer påverkar störning av vindkraftsbuller så testades en teoretisk modell med analysmetoden Structural Equation Modelling.

Avhandlingen visar att det finns ett samband mellan A-vägd ljudtrycksnivå och andelen närboende som hör och/eller störs av ljud från vindkraftverk – risken att störas ökar med ökad ljudtrycksnivå. Även om antalet personer som störs av vindkraftsljud var få, så var andelen störda högre än förväntat utifrån studier om störning av andra bullerkällor. Risken att störas av vindkraftsljud var större om man såg vindkraftverk från sin bostad än om man inte kunde se några verk. Risken var också större i landsbygdsmiljöer jämfört med i villaområden. Ljudet uppfattades av en del människor som ett intrång i deras privata sfär. De förväntande sig lugn och ro, och önskade att deras bostad skulle vara en plats lämplig för vila och återhämtning. Negativa erfarenheter i kontakten med grannar, myndigheter och projektörer var förknippat med obehagskänslan. Mest störande var de ljudkaraktärer som beskrev det aerodynamiska amplitudmodulerade ljudet: svischande, vinande och pulserande/dunkande. Vindkraftverken beskrevs som miljövänliga, effektiva och nödvändiga, men också som fula och onaturliga. Att vara negativt inställd till vindkraftverkens påverkan på landskapsbilden var i högre grad relaterat till störning av vindkraftsbuller än att vara negativ till vindkraftverk i allmänhet. Det fanns inget samband mellan självrapporterat hälsotillstånd och A-vägd ljudtrycksnivå, men sänkt välbefinnande var relaterat till störning av vindkraftsbuller. Indikationer på minskad möjlighet till återhämtning observerades också.

Vindkraftsljudets speciella karaktär och verkens placering i tysta miljöer gör att ljudet är lätt hörbart, men också störande. Amplitudmodulerat ljud är mer störande än icke-amplitudmodulerat ljud. Dessutom är vindkraftverken synliga objekt med en roterande rörelse som drar blicken till sig. En multimodal effekt kan därför uppstå, vilket innebär att det visuella intrycket kan förstärka hörselintrycket. Vindkraftverkens synlighet gör att de värderas utifrån en estetisk aspekt och de kan då uppfattas som objekt som inte passar in i landskapet. En negativ attityd till bullerkällan ökar risken för störning.

Vindkraftverk är en bullerkälla som skiljer sig från andra bullerkällor i samhället vad gäller ljudkaraktär, placering och synlighet. Det är därför nödvändigt att upprätta specifika dos-responssamband för vindkraftsljud så att bullerstörning kan undvikas. Eftersom faktorer relaterade till omgivningen påverkar hur ljudet uppfattas så behövs dessutom olika dos-responssamband för skilda typer av miljöer, t.ex. för jordbrukslandskap och för villaområden. Även om inga negativa hälsoeffekter kunde kopplas direkt till vindkraftsljudet, så kan det finnas risk för att psyko-fysiologisk återhämtning hindras, vilket på lång sikt kan leda till ohälsa.

List of Papers

This thesis is based on the following four papers:

I Pedersen, E., and Persson Waye, K. Perception and annoyance due to wind turbine noise – a dose-response relationship. Journal of the Acoustical Society of America, 2004, 116, 3460–3470.

II Pedersen, E., Hallberg, L.R.-M., and Persson Waye, K. Living in the vicinity of wind turbines – a grounded theory study. Qualitative Research in Psychology. In press.

III Pedersen, E., and Persson Waye, K. Wind turbine noise, annoyance and self-reported health and wellbeing in different living environments. Occupational and Environmental Medicine. Published online, 1 Mar 2007; doi:10.1136/oem.2006.031039.

IV Pedersen, E., and Larsman, P. The impact of visual factors on noise annoyance among people living in the vicinity of wind turbines. Submitted.

Contents

Abbreviations

ANOVA	analysis of variance
CFI	comparative fit index
CI	confidence interval
DENL	day-evening-night level; a descriptor of noise level based on equivalent sound pressure levels (SPLs) over a year for different times of the day, with a penalty of 10 dB(A) for night-time noise (22.00–7.00 hours) and an additional penalty of 5 dB(A) for evening noise (19.00–23.00 hours)
DNL	day-night level; a descriptor of noise level based on equivalent sound pressure levels (SPLs) over a year for different times of the day, with a penalty of 10 dB(A) for night-time noise (22.00–7.00 hours)
GT	Grounded Theory
LSD	Least Significant Different, a post hoc test
OR	odds ratio
RMSEA	root mean square error of approximation
SD	standard deviation
SEM	structural equation model
SPL	sound pressure level
VRS	verbal rating scale

1. Introduction

Wind consists of large amounts of energy originating from the sun and transferred to Earth every day, energy that will not cease in time imaginable. This large amount of energy is devastating when it hits us as storms or hurricanes, weather situations prophesied to increase with the increased net emission of carbon dioxide. However, the energy in wind is also beneficial, if it is captured and transformed into forms of kinetic or potential energy that can be utilized by humans. Wind has been used for transportation up rivers and over the seas for 6,000 years and has in this function only just recently been substituted by fossil fuels. Wind has also been a helper for strenuous mechanical work where no hydropower has been available. Windmills, with sails that rotated the heavy millstone when it was time to grind the crops, dominated some flat agricultural landscapes in Europe 500 years ago. Wind wheels pumping up water were a common sight on the Great Plains in North America during the last century.

Today the need for highly efficient and flexible forms of energy requires transformation of wind energy into electricity, rather than into mechanical work. Wind turbines for electricity generation have undergone rapid development and after experiments with different designs have found their present shape, three rotor blades sweeping a large area, a generator placed downwind from the rotor blades and a steel tower high enough to reach steady winds not influenced by the ground. The awareness of the limited resources of fossil fuels and the rising concern for the effects of the increased amount of greenhouse gases in the atmosphere have given the wind turbine industry a push forward. Wind turbines are now being produced on a large scale in countries such as Denmark, Germany, the USA, India and Spain, and the demand at the moment is larger than the production.

Wind turbines have, however, not been welcomed in all places where they have been planned to operate. Although wind power has been favoured by the public in general opinion polls, in comparison with other electricity production alternatives, projects have often been opposed locally. People living in areas pointed out as suitable for generation of wind power have expressed a fear of being disturbed by noise and have defended their landscape from what they believe is an intrusion of the environment. Opposition to planned projects, often reported in the media, is not unique to wind turbine development. It is difficult to say whether the voices against potential disturbers of the peace are raised higher today than in the past, when the windmills for grain crops were built. The overall increased sound levels in our environment, together with other demanding stressors, may, however, have enhanced the need for quiet in our home environment, a need that triggers opposition to potential noise sources such as wind turbines.

On the one hand, there is therefore a social (and economic) requirement for erecting more wind turbines so that electricity can be generated without harm to the environment and hence also to humans. On the other hand, there is an individual need for quiet and peace in the home environment. Both these demands have to be met in the future development of wind power. The probability of adverse reactions to wind turbine noise in relation to noise levels, with all its implications, should carefully be taken into account in the planning process. This will help avoid inappropriate placement of wind turbines. If areas more suitable for wind power are chosen, there will be less of an issue of disturbing the public and the public will not have to worry about disturbance, being confident that this aspect would have been included in the planning. This thesis is an attempt to contribute to the knowledge of response to wind turbines as community noise sources.

2. Background

A brief overview of what is known about response to community noise (other than wind turbine noise) including moderating factors and health effects is presented initially. Results from previous studies on response to wind turbine noise are then presented and the special features of the sound from wind turbines discussed.

2.1. Response to community noise

Perception and annoyance

The most observed adverse reaction to community noise is annoyance. A prerequisite of noise annoyance is that the sound can be perceived (i.e. it can be noticed, or heard). Perception of low and moderate levels of sounds is initiated by sensoneural responses of the hair cells in the cochlea, responses that are recognized and interpreted by the central structure of the brain. Whether or not a sound is perceptible depends on the character of the sound, for example the frequency content, and the present background sound.

Noise annoyance is described as a feeling of displeasure evoked by a noise [Berglund and Lindvall 1995]. The occurrence and magnitude of noise annoyance is not only related to the sound pressure levels (SPLs) and sound properties, but depends also on individual, situational and noise source-related factors. Measurements of annoyance in surveys are today standardized [ISO/TS 15666 2003] and the outcome is typically expressed as percentage of annoyed or highly annoyed and constitutes the response in dose-response relationships.

Response to transportation (aircraft, road traffic and railway) noise and noise from industrial sources has been explored in several studies. Attempts have been made to construct joint dose-response models that could be used as predictors for community noise annoyance. Schultz [1978] started with data from 18 studies dealing with response to transportation noise and found that eleven of these showed similar relationships between A-weighted day-night level (DNL) and proportion of respondents highly annoyed by the noise. Suggested explanations for observed differences between the eleven studies were differences in measurement procedures, the time of year when the measurements took place, the size of the communities and the effect of background sound. The work was updated with 15 new studies of transportation noise [Fidell et al. 1991], resulting in one curve illustrating a common dose-response relationship for transportation noise. However, Miedema and Vos argue that different curves have to be used for different modes of transportation, which they illustrated by using the same studies as Fidell et al., with an added 34 datasets [Miedema and Vos 1998]. This work resulted in synthesized dose-response curves based on polynomials as models of the relation between DNL or A-weighted day-evening-night level (DENL) and proportion of annoyed or highly annoyed respondents. In addition to noise from aircraft, road traffic and railways [Miedema and Oudshoorn 2001], annoyance due to noise from stationary sources has also been modelled using two shunting yards, one seasonal industry and eight other industries [Miedema and Vos 2004]. Examples of these synthesized curves are shown in Figure 1.

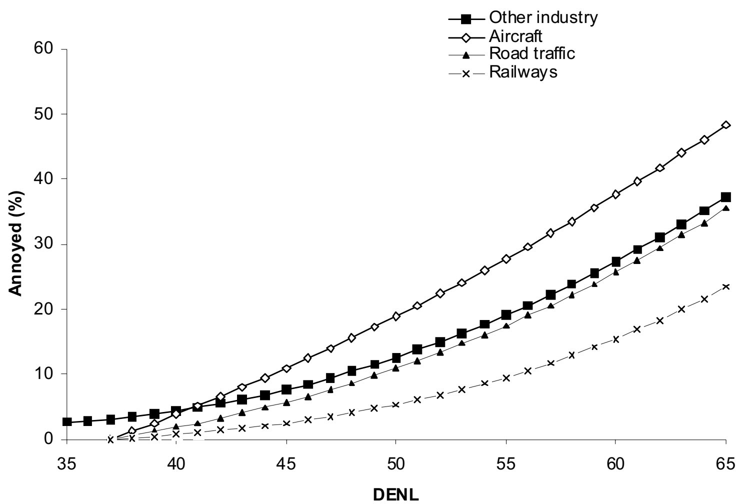

Figure 1. Polynomial approximations of dose-response relationships between day-evening-night level (DENL) and annoyance of noise from industry other than seasonal industry and shunting [Miedema and Vos 2004], and between DENL and annoyance from transportation noise [Miedema and Oudshoorn 2001]. The curves describing response of transportation noise were forced through zero at 37 DENL [Miedema and Oudshoorn 2001].

It is important to note that even though dose-response relationships between noise and response can be derived, only a small percentage of the variation in individual reaction to the noise is accounted for by noise exposure. In a review of almost 40 community noise studies from different countries and involving different noise sources, Job found that the average correlation between noise and annoyance was 0.42, indicating that only 18% of the variation in reaction is accounted for by noise exposure [Job 1988]. This could be explained by errors in dose estimations, inaccurate response measures or moderating variables influencing the response.

Moderating factors

The relationship between noise and response is moderated by several factors. A moderating factor in this study is defined as a factor changing the impact of the noise on the response so that the degree of annoyance would be lessened or enhanced. The moderating factor is therefore not correlated to the noise, but to the response. Several such factors have been found in community noise studies and the most consistent will be discussed here.

No difference in response to noise has been reported between the sexes [Miedema and Vos 1999]. In a meta-analysis, age was not found to be linearly related to noise annoyance [Fields 1993], but people between 20 and 50 years of age tend to report a higher degree of annoyance than other respondents [Miedema and Vos 1999].

Self-reported noise sensitivity has been associated with noise annoyance. Noise sensitivity is defined in several different ways, for example as a general negative attitude towards noise or strong reactions to specific noise situations [Miedema and Vos 2003] or as a personality trait [Ellermeier et al. 2001]. A definition adopted by several researchers in the field [e.g. Van Kamp et al. 2006] was suggested by Job [1999]; "noise sensitivity", according to Job, refers to the internal states of an individual (physiological, psychological, or life style-determined), which increases their degree of reactivity to noise in general. In a review of 27 community noise studies the mean correlation between noise sensitivity and noise annoyance was found to be 0.30 [Job 1988]. In a meta-analysis of 15 studies on response to traffic noise, noise-sensitive respondents reported a higher degree of annoyance than did non-sensitive respondents [Miedema and Vos 1999]. Further analyses of 29 studies showed that noise sensitivity influences the dose-response relationship between noise and annoyance inasmuch as the rate of increase in annoyance with increasing sound level (i.e. the slope of a regression line) was greater among noise-sensitive than among non-sensitive respondents [Miedema and Vos 2003].

The attitude of an individual towards the noise source has in several community noise studies been found to be associated with response to noise. In a review of twelve studies regarding noise from traffic and rifle ranges, the mean correlation between attitude towards the noise source and noise response was 0.41 [Job 1988]. The definition of attitude towards the source differed between the studies, which makes comparisons difficult. Attitude is often measured as fear of the noise source [Fields 1993, Miedema and Vos 1999] and sometimes also includes noise sensitivity. Guski has pointed to general attitude as a distinct factor, comprising the variance of evaluation of the source between individuals [Guski 1999]. Attitude towards the noise source has been possible to manipulate in experimental studies, which shows that people react more negatively to a sound from a less preferred noise source (traffic vs. ocean waves) [Djokvucic et al. 2004] and more negatively if a negative attitude towards the noise source (aircraft and road traffic) is created [Jonsson and Sörensen 1970].

The visual appearance of a noise source influences noise annoyance. In field studies, seeing the noise source has been found to increase noise annoyance [Bangjun et al. 2003]. This finding was only partly confirmed in an experimental study. Loudness was judged to be lower when there was a barrier partially obscuring the sound source than when there was no barrier, but greater when the sound source was totally obscured [Aylor and Marks 1976]. A reduction in noise annoyance due to a positively evaluated visual appearance has furthermore been observed [Kastka and Hangartner 1986, Kastka and Noack 1987], also when the object is evaluated in the context of the surrounding landscape [Viollon and Lavandier 2002]. Visual stimuli that are appraised as natural, rather than urbanized, seem to reduce negative ratings of sound [Viollon et al. 2002].

Health effects and coping

Sleep disturbance and hindrance of rest and relaxation are the most observed direct effects of traffic noise [Öhrström et al. 2005]. Sleep disturbance has been found, in laboratory studies, to depend on the number of noise events, and occurs at indoor noise levels of 45 dB(A) and more [Öhrström 1995]. Psychological and physiological stress-related symptoms have also been associated with noise exposure [Evans et al. 1995]. Increased risk of cardiovascular diseases, associated directly with noise exposure or with noise annoyance, has been reported in several field studies [Van Kempen et al. 2002, Babisch et al. 2005, Willich et al. 2005]. The observation thresholds for hypertension and ischaemic heart disease in the community have been estimated to be 70 DNL [Passchier-Vermeer and Passchier 2000], even if lower levels have been associated with hypertension in single studies [Rosenlund et al. 2001].

Noise may directly influence health. Physiological activation such as increase in heart rate and blood pressure, and increased peripheral vascular resistance are known acute effects of noise exposure. Endocrine responses, i.e. raised levels of noradrenaline, adrenaline and cortisol, have in some studies been observed as an effect of noise exposure. The thresholds for these autonomous responses are found between 60 and 70 dB(A) during waking hours and 50 and 60 dB(A) during sleep, but are modified by personal characteristics and by other stimuli received simultaneously with the noise [Griefahn 2000]. Prolonged arousal of physiological activation could lead to resignation and induce either psychological or physiological fatigue, or metabolic syndromes [Ljung and Friberg 2004]. Adverse health effects, other than hearing impairment, could also occur as an indirect effect of noise. Noise annoyance may lead to stress responses, which could be measured as stress-related symptoms, and possibly also to illness [Stansfeld and Matheson 2003]. This pathway has, however, not been confirmed. It is also plausible that illness decreases the ability to cope with the noise; an undesirable shortcoming as it is of great importance to be able to cope successfully with a stressor. According to Lazarus and Folkman's cognitive stress theory [1984], an individual appraises an environmental stressor, such as noise, as beneficial or not at the first encounter. If the noise is appraised as goal incongruent, for example threatening life quality or lowering well-being, a coping process takes place. The individual can then alter the behaviour to reduce the noise exposure or the effects of the noise exposure. After this, a second appraisal takes place. If the coping is not successful, it could lead to adverse psychological effects. Action- or problem-oriented coping style has in noise studies been found to be negatively associated with health complaints, while denial or avoidance has been found to be positively correlated with lowered sleep quality, somatic symptoms and depression [Van Kamp 1990]. People who adopted active problem-solving behaviour when exposed to increased traffic noise had lower systolic blood pressure than people who did not take any action [Lercher 1998].

2.2. Wind turbine noise

In Sweden, about 750 wind turbines are operating on land (January 2007). The number of people living in the vicinity of a wind turbine is not known. Based on demographic data from Geographical Information Systems it could be estimated that no more than 20,000 people live within 1 km of a wind turbine.

Response to wind turbine noise

Few studies have investigated human response to wind turbine noise. One of the most important was carried out in Denmark, The Netherlands and Germany [Wolsink et al. 1993]. The main aims of the study were to explore the correlation between noise exposure from wind turbines and noise annoyance among people living near wind turbines, and to find other variables of importance for the annoyance. Only a weak correlation between A-weighted SPL and noise annoyance was found (Kendall's coefficient for correlation rank order variables $t = 0.09$; $p<0.05$). Variables reported to be related to noise annoyance were stress caused by wind turbine noise, daily hassles, perceived effects of wind turbines in the landscape (visual intrusion), and the age of the turbine site (the longer it had been operating, the less annoyance).

The Danish part of the study was enlarged [Pedersen and Nielsen 1994] adding several dose and response variables. An objective variable called "visual angle", measured in degrees from the respondent's dwelling to the hub, with the ground as the horizontal line, was included as a measure of visual impact. A dose-response relationship between wind turbine noise and noise annoyance was found ($r = 0.26$), but the visual angle also influenced the annoyance ($r = 0.34$), i.e. a larger angle corresponded to a higher degree of annoyance. Other variables related to noise annoyance were perception of shadows ($r = 0.48$), perception of blinking shadows ($r = 0.50$) and the attitude towards the impact of wind turbines on the landscape ($r = 0.48$), all aspects of visual impact. The findings are interesting, but of the 16 wind turbines in the study, all were of nominal power 150 kW or smaller, so it is not positive that the results are applicable to modern wind turbines.

Sounds from wind turbines

There are two main types of sounds from a wind turbine: mechanical sound and aerodynamic sound. Mechanical sound is mainly generated by the gearbox, but also by other parts such as the generator [Lowson 1996]. Mechanical sound has a dominant energy within the frequencies below 1,000 Hz and may contain discrete tone components. Noise including tones is known to be more annoying than noise without tones, but both the mechanical sound and any tones that may occur can be efficiently reduced [Wagner et al. 1996]. In the turbines erected during the last 10 years, the manufacturers have been able to decrease the mechanical sound to a level below the aerodynamic sound. This is also due to the fact that the size of the turbines has increased and mechanical sound does not increase with the dimensions of the turbine as rapidly as does aerodynamic sound.

Aerodynamic sound is typically the dominating part of wind turbine noise today. It comprises a broadband sound (a continuous distribution of sound pressure over a frequency range) and an amplitude modulation (when the SPL rises and falls with time). The aerodynamic sound from wind turbines originates mainly from the flow of air around the outer part of the blades. It is directly linked to the production of power and therefore inevitable [Lowson 1996] even though it could be reduced to some extent by altering the design of the blades [Wagner et al. 1996]. For an older wind turbine with two constant rotational speeds, the sound power level will remain almost constant as long as the turbine is operating at the lower rotational speed, but it will increase sharply with a change to the higher speed [Van den Berg 2006]. For a wind turbine with variable rotational speed, the sound power level generally increases with increasing wind speed up to the rotational maximum. The amplitude modulation is an effect of differences in wind velocity at different heights of the area swept by the rotor blades and an effect of the wind being slowed down by the tower, increasing and decreasing the wind-induced sound power levels with the pace of the rotation [Van den Berg 2006].

Amplitude modulations in a sound are easily detected by the human ear, but best at the modulation frequency 2–4 Hz [Zwicker and Feldtkeller 1967; Landström et al. 1996]. The modulation frequency for a three-blade 600 kW turbine, a common size in Sweden today, with a steady speed of 26 rpm, is 1.3 Hz. A more modern wind turbine with variable rotational speed typically has a modulation frequency of 0.5 Hz at the wind speed 4 m/s and 1.0 Hz at 20 m/s. All examples are within the span where modulations can easily be detected. In one experimental study the threshold for detection of a sound with a modulation frequency of 1 Hz was found to be 1–2 dB below a masking noise (white noise) [Arlinger and Gustafsson 1988]. The masking noise had its energy within the same frequency band as the modulated sound, thus providing optimal possibilities for masking.

Amplitude-modulated sound has also been found to be more annoying than sound without modulations. In an experimental study it was found that a 30 Hz tone, amplitude modulated with a modulation frequency of 2.5 Hz, generally caused higher annoyance, symptoms and change in mood. However, the difference compared with a non-modulated tone at 30 Hz was only statistically significant for subjective reports of drowsiness [Persson et al. 1993]. In another study, subjects given the possibility to change the modulation frequency avoided the start value of 2 Hz and chose either higher or lower modulation frequencies [Bengtsson et al. 2004]. Furthermore, combining equivalent SPLs and a weighting function that gave a penalty for amplitude modulations of 0.5–4 Hz successfully predicted annoyance in an experimental setup [Bradley 1994]. Experimental studies exploring response to wind turbine noise have shown consistent findings. In a study where 25 subjects were exposed to five different wind turbine sounds with an A-weighted equivalent SPL of 40 dB, differences between the noises regarding annoyance were found [Persson Waye and Öhrström 2002]. The most annoying noises were predominantly described as “swishing”, “lapping” and “whistling”. These could all be seen as being related to the aerodynamic sound and as descriptions of a time-varying (modulated) sound with high frequency content.

Sound pressure levels of noise from wind turbines are difficult to measure at distances where the noise levels are just above the background SPLs. Weather conditions largely influence the outcome. The dose is therefore often estimated by modelling the sound propagation. This is not uncomplicated. Prediction models available in software programs give significantly different results, especially at longer distances [Tickell 2005]. Wind turbines are highly placed noise sources, and sound propagation models used for other noise sources are not suitable. It is therefore important to use a model specifically developed for propagation of wind turbine sound, which assumes spherical spreading and takes ground conditions into account. Even when a proper model is chosen, accurate considerations related to the unique situation have to be made.

Recent reports have indicated yet another complication. The common hub height of the operating wind turbines today in Sweden is 40–50 m, but the new, larger turbines are often placed on 80–90 m towers. The wind speed at this height compared with the wind speed on the ground may be underestimated when a logarithmic wind profile is assumed, which is often the case when the sound power level for the sound propagation modelling is assessed. In stable atmospheric conditions with horizontal layers of air and little vertical movement, a condition sometimes occurring at night, the wind velocity has been found to be 1.8 times higher than expected at hub height [Van den Berg 2006].

Topography is of importance for the degree to which the noise from wind turbines is masked by the wind. Dwellings that are located in deep valleys or that are sheltered from the wind in other ways may be exposed to low levels of background sound, even though the wind is strong at the position of the wind turbine [Hayes 1996]. The noise from the turbine may under these conditions be perceived at lower SPLs than expected. Current recommendations are that measures and sound propagation calculations should be based on a wind speed of 8 m/s at 10 m above the ground, downwind conditions, creating a "worst case" scenario. However, this recommendation does not consider the case described above.

2.3. Summary

Wind turbines are new sources of noise and little is known about the impact on people living in the vicinity of the wind turbines. Previous studies are few and were carried out on smaller wind turbines than those of interest today. Findings from studies regarding noise sources other than wind turbines presumably also apply to response to wind turbine noise. Perception and annoyance due to wind turbine noise could be hypothesized to increase with increasing SPL. Individual factors such as noise sensitivity and attitude towards the source could be predicted to influence noise annoyance. However, wind turbines differ from other noise sources in several respects. Wind turbines are often placed in rural areas with low background sound. This, together with the amplitude modulation in the sound, leads to the hypothesis that wind turbine noise could easily be perceived and possibly is also annoying at SPLs lower than those known to be annoying for other noise sources. Furthermore, wind turbines are prominent objects in the landscape and have rotor blades that are almost constantly moving, visual aspects that could influence noise annoyance. There is therefore a need to study the impact of wind turbine noise on people living in the vicinity of wind turbines.

The response can, in accordance with the definition of noise annoyance, not be studied in isolation (Figure 2), since it is directly linked to exposure and the effects. Properties of wind turbine noise and possible adverse effects on health and well-being caused by a negative response must therefore also be considered when studying the response.

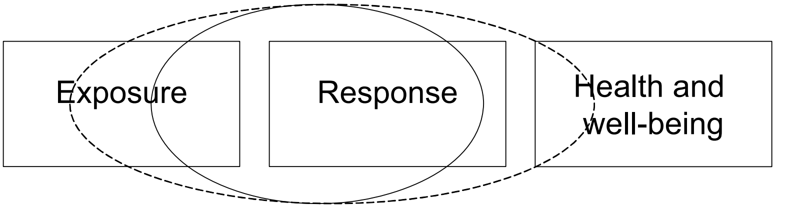

Figure 2. A conceptual model of the focus of this thesis (unbroken line) and related themes discussed (dashed line).

3. Aims of the thesis

The objectives of this thesis were –

to gain an understanding of how people living in the vicinity of wind turbines experience, and are affected by, wind turbine noise;

to determine the prevalence of perception of and annoyance with wind turbine noise and to describe possible adverse health effects;

to examine dose-response relationships between A-weighted SPLs and response to wind turbine noise; and

to explore the influence of moderating factors (individual, situational and visual) and sound properties on response to wind turbine noise.

4. Method

4.1. Study design – considerations

Cross-sectional studies are commonly used in community noise studies to determine occurrence of annoyance among populations exposed to various levels of exposure. It is an efficient approach when descriptive data are required. A cross-sectional design was therefore chosen for Study I. Cross-sectional studies have some limitations, the main one being that no conclusions about cause and effect can be drawn from the results. This is not a problem when a dose-response relationship is assessed, as noise is a physical parameter that cannot be influenced by the response. However, this limitation has to be taken into account when moderating variables are investigated. An observed correlation between response, measured as self-reported noise annoyance, and self-reported noise sensitivity, for example, could only lead to the conclusion that there is a direct or indirect association between the two variables. Another limitation is the time-period problem; only information about the exposure at one point in time is available [Rothmann and Greenland 1998]. In the studies presented here, the wind turbines had been operating for some time and the properties of the wind turbine noise had not changed to any large extent over time.

In Study I it was found that a proportion of people exposed to wind turbine noise of lower levels than known from other community noise studies to cause annoyance, were annoyed by the noise. Variables known to moderate dose-response relationships between noise and annoyance (for example, attitude and noise sensitivity) had been taken into account in Study I, but could only partly explain the prevalence of annoyance. The objective of Study II was therefore to explore new aspects that had not been thought of beforehand. The constant comparative method of Grounded Theory (GT) was chosen for the study design as this approach is known to be useful when new phenomena are explored and prior applicable theory is lacking. By setting aside prejudices and systematically analysing data step by step as they are collected, a model describing relevant categories and their relationships is developed. Grounded Theory was originally developed by the social scientists Glaser and Strauss [1967] and later revised by Strauss and Corbin [1998]. However, GT has developed into new fields, and has been adapted to other research traditions and hence used by researchers representing different views of reality. Glaser and Strauss believed in realist ontology and positivist epistemology assuming an external reality possible for researchers to discover and record [Charmaz 2000]. Later Strauss, together with Corbin, gave voice to the respondents as individuals and included their views of reality in the method [Dellve et al. 2002]. Charmaz [2000] introduced a constructivist version of GT, as opposed to the objective GT, which recognizes the mutual creation of knowledge between the researcher and the subject. The aim of constructive GT is to interpret how subjects construct their realities [Dellve et al. 2002]. Constructive GT has become common in research fields close to environmental medicine, such as public health and nursing. However, as the discipline of medicine rests on a strict realistic ontology, an approach close to the original one of Glaser and Strauss was chosen for Study II, i.e. objective GT.

Glaser and Strauss have stressed the importance of the theory emerging from data, independent of existing theories [1967]. Therefore the researcher should take an unprejudiced approach, setting aside his or her knowledge and beliefs, and not turn to previous research until all categories are saturated. The need to relate the research to its context was later recognized and today it is acceptable to review relevant literature before starting a new study [Hallberg 1998; Dellve et al. 2002]. An open mind is still necessary, however, and pre-designed categories should not be used. Even though Study II was carried out after the results of Study I had been analysed, and therefore some knowledge of response to wind turbine noise had already been gained, no hypotheses or theories were set up in advance.

Informants in a GT study are chosen strategically. Strategic sampling, as originally described by Glaser and Strauss [1967], is the process of systematically seeking useful data, and choosing the next comparison group as the analysis goes on. Two selection criteria are similarity and differences, providing maximization and minimization. The number of subjects could not be determined beforehand, as the collection of data and the analysis continues until saturation is reached, i.e. until no new information contributing to the developed theory emerges. Additional interviews, typically one to five, are often performed to confirm the result. The choice of informants should be motivated as the work proceeds, but is otherwise fairly free. Later research has distinguished open from theoretical sampling; the former term is used for the initial sampling where a large variation between subjects is sought while the latter term is used for sampling with the aim to test the emerging theory [Hallberg 2006]. This approach was used in Study II.

Study II, and its results, has its own value as a complement to a quantitative understanding of annoyance due to wind turbine noise. However, some of the findings of the qualitative Study II were suitable for quantitative testing to establish whether they would be valid at a more generalized level. Study III was therefore a new cross-sectional study designed so that it would be possible to explore differences of perception of and annoyance with wind turbine noise in living environments with various characteristics. Measurements of additional individual factors were included and therefore the questionnaire was modified and tested in a pilot study. The overall design and main questions of response were, however, left unchanged to allow comparison with Study I.

Several visual factors possibly influencing the dose-response relationship between wind turbine noise and annoyance had been observed in studies I–III. These were factors related to the visibility of the wind turbines, to the wind turbine and the surrounding landscape, and to the subjects' appraisal of the wind turbines as prominent objects. The visual factors could be predicted to interact. Therefore, in Study IV a theoretical model comprising dose, response and visual variables was tested within a joint dataset of studies I and III. To explore presumed factors of influence on the response to noise, which are not easily captured by a single measurement (for example, visual attitude), and to allow variables to interact (for example, visual attitude and visibility of wind turbines), a structural equation model (SEM) approach was chosen. In structural equation modelling a theoretical model comprising latent constructs with manifest variables and a structure of relations between the constructs is tested simultaneously with confirmatory factor analysis and multiple linear regression technique, also taking measurement errors into account. The model can be tested in different groups, with variance of regression coefficients between groups (for example, wind turbines being visible vs. not being visible), indicating interaction effects between the group characteristic and the structure of interest [Rigdon et al. 1998]. Maximum likelihood estimation (MLE), which is the standard estimation of structural equation modelling, treats ordinal data as continuous data and assumes normal distribution of residuals. The analysis in Study IV should therefore be regarded as explorative and the results should be treated with caution.

4.2. Overview of study designs

A matrix overview of the study designs is presented in Table 1.

Table 1. Overview over the studies included in the thesis.

Study	Method	Year of data compilation	Study sample	Subjects included	Response rate
I	Cross-sectional	2000	513	351	68%
II	Grounded theory	2003	–	15	–
III	Cross-sectional	2005	1,309	754	58%
IV	Synthesis	2006	1,822	1,095	60%

Study I

Study I was a cross-sectional study comprising respondents exposed to different SPLs from wind turbines, carried out in the summer of 2000 in a flat agricultural landscape in southern Sweden. Subjective responses were obtained through a questionnaire. Of 513 delivered questionnaires, 351 were satisfactorily returned (response rate 68%) (Table 1). For each respondent, outdoor A-weighted SPLs from the nearest wind turbine were calculated based on wind conditions of 8 m/s at 10 m height, with the wind direction towards the respondent, according to Swedish Environmental Protection Agency [2001] guidelines. The calculated values were divided into 2.5 dB(A) intervals. Comparisons were made of the extent of annoyance between respondents living at different dB(A) intervals.

Study II

In Study II, which was carried out during 2003, data were collected through 15 interviews that were tape-recorded and transcribed verbatim. Subjects were first chosen strategically among those who had stated in the questionnaires of Study I that they were willing to be contacted for further questioning and had given their telephone numbers. The objective of this open sampling was to obtain a heterogeneous group by studying self-rated noise annoyance of wind turbine noise in relation to calculated SPLs from wind turbines. As a model emerged the sampling became more theoretical, the aim being to seek variance within the identified categories. Subjects were then chosen also among people who had complained to the local authorities concerning different aspects of wind turbines. The transcribed interviews were coded line by line using the subjects' own words or immediate expression. The codes were compared and clusters between similar codes were formed. Categories were identified, and relationships between categories were established. Constant comparison among and between transcribed interviews, memos and categories led to reflections, confirmations and adjustments in formulating the emerged model.

Study III

Study III was another cross-sectional study with the same study design as used in Study I. The study was carried out in areas with different terrain (flat or complex) and degrees of urbanization (rural or suburban). The questionnaire used in Study III was modified. Questions regarding evaluation of the living environment, feelings evoked by the wind turbines, and coping strategies were added. The new questionnaire was tested in a pilot study in the summer of 2004. Small adjustments were made. In the summer of 2005 the revised questionnaires were sent out to 1,309 subjects and satisfactorily returned by 754 (response rate 58%) (Table 1). A-weighted SPLs were calculated in accordance with the Swedish Environmental Protection Agency [2001] as in Study I, but kept as a continuous scale. Another variable of exposure, vertical visual angle from the respondent to the wind turbine, was calculated as a measure of closeness and height. The data were analysed using an epidemiological approach.

Study IV

Study IV was a synthesis study. The study was based on the data sets from the two cross-sectional studies, Study I and Study III. To form a homogenous database, additional calculations were made. A-weighted SPLs were re-calculated for Study I as only interval data were available from this study and a continuous scale was desired. Vertical visual angle was calculated for the respondents in Study I. With the exception of ten respondents who had not answered the main response question used in the analyses of Study IV, all respondents from Study I and Study III were included in the new database. Out of a total of 1,822 subjects chosen for the two original study samples, 1,095 respondents were included in Study IV (response rate 60%) (Table 1). Data were analysed using descriptive statistics and multivariate statistical methods.

4.3. Power calculations

No power calculations were carried out prior to Study I as the prevalence was not known. In Study III the power calculations were based on a 95% confidence level and a statistical power of 80%. The size of the study sample had to be large enough so that (i) differences in proportions of annoyed respondents could be detected between four exposure groups (2.5 dB(A) intervals from <32.5 to 40.0 dB(A); it was assumed that no people were exposed to >40 dB(A)); (ii) a difference of 20% in proportion of respondents annoyed with wind turbine noise between two exposure groups would be statistically significant; and (iii) the number of respondents in each group would be large enough to allow dichotomization when exploring moderating variables. In total, 352 respondents were needed, distributed so that each of the four exposure groups would comprise 88 respondents. With an estimated response rate of 60%, the size of the study sample was set to 600 subjects. The calculations were performed using the Epi Info software.

4.4. Study areas

All studies were carried out in southern Sweden (Figure 3).

Figure 3. Map of southern Sweden including the twelve study areas A–L.

The municipality of Laholm was chosen for Study I since it is a community with several wind turbines situated in populated areas and has a homogenous landscape. At the time of the study most of the wind turbines had been operating for 1–3 years. Five study areas within Laholm were found to be suitable for a cross-sectional study (areas A–E), all comprising at least one wind turbine with the nominal power of 500 kW or more (Table 2). Subjects in Study II were also later chosen within these five areas. For Study III, areas varying in terrain and degree of urbanization were sought. Areas with rocky or hilly terrain were found in Bohuslän on the Swedish west coast. Areas classified as suburban were found in Bohuslän, Halland and Skåne. Seven study areas were included in Study III (areas F–L).

Table 2. Overview of the study areas.

Area	Commu-nity	Wind turbines				Terrain	Degree of urbaniza-tion
		Wind turbines	Hub height (m)	Nominal power (kW)	Starting year		
A	Laholm	2	50	600	1998	Flat	Rural
B	Laholm	3	50	600	1998	Flat	Rural
C	Laholm	8	50	600	1998	Flat	Rural
D	Laholm	1	47	600	1999	Flat	Suburban
		1	40	150	1995		
E	Laholm	1	65	500	1999	Flat	Rural
F	Öckerö	1	50	660	1999	Complex	Suburban
G	Tjörn	1	60	850	2004	Complex	Rural
H	Orust	1	65	600	2001	Complex	Rural
I	Lysekil	2	55	750	2000	Complex	Suburban
		2	40	550	1995		
J	Varberg	3	41	600	1995	Flat	Rural
		1	30	250	1993		
		7	30	225	1991		
		2	30	225	1994		
K	Lands-krona	2	65	1,500	2002	Flat	Rural
		2	41	550	1996		
L	Simris-hamn	1	42	500	1996	Flat	Suburban
		3	32	225	1993		

The main problem in finding suitable study areas was the lack of areas comprising both wind turbines and a large enough population so that the requirements of the power calculations could be met, especially for the higher exposure groups. In the preparations for Study III, all wind turbines larger than 500 kW operating on land in Sweden at the beginning of 2004 were marked on maps. The number of people living within 1 km of the turbines was estimated using a Geographical Information System provided by the National Board of Housing, Building and Planning. Possible study areas were visited to ensure that the wind turbine was still operating and that the area was not dominated by any other noise source and also, to obtain variability of terrain and degree of urbanization. Some areas with a fairly low number of inhabitants were included to meet the other criteria. The requirement of the power calculations was not met for the exposure interval 37.5–40.0 dB(A) in

Study III; instead of 88 respondents, it comprised 71 respondents. This was because the number of subjects in the study sample was lower than desired, and also, because the response rate was somewhat lower than expected (58%).

4.5. Study samples

Sampling

The study populations of the cross-sectional studies comprised one selected subject over the age of 18 in each household situated within a preliminarily calculated A-weighted SPL of more than 30 dB of wind turbines in the selected areas. For Study I, all households meeting the criteria were included in the study sample. In Study III all households were included except those located at SPL <35 dB(A) in areas with a study population of more than 500 (areas F, I and L) where every other household was randomly selected to avoid unnecessary costs. An overview of study samples, response and response rates related to study areas is shown in Table 3.

Table 3. Overview of study samples, responses and response rates related to study areas.

Area	Study sample n	Response n	Response rate (%)
A	75	54	72
B	33	24	73
C	59	48	81
D	325	208	64
E	21	17	81
F	396	206	52
G	24	16	67
H	23	12	52
I	221	141	64
J	148	87	59
K	112	70	63
L	385	222	58
Total	1,822	1,105	61

An upper age limit of 75 was used in Study I. This limitation was based on experiences from other community noise studies, but was later found not to be relevant for these studies. Therefore no upper age limit was used in Study III. Of the respondents in Study III, 4% (n = 30) were aged 76 and above.

In Study I, no names were used. Instead, the households were identified on maps and the questionnaires delivered directly in the mailboxes of the subjects, together with a letter asking one person in the household with their birth date closest to 20 May to answer the questionnaire. In Study III, which was carried out in a larger geographical area, this approach was not possible. Addresses of people living in the areas were therefore bought from a postal delivery company. One person from each household over the age of 18 was randomly selected from this list.

Among the subjects chosen for Study II, three declined participation, two mentioning lack of time combined with no opinion on wind turbines, and one for unknown reasons.

Respondents and informants

Table 4 shows the main characteristics of the respondents in Study I and Study III, and also in the joint database of Study IV, by exposure levels in 2.5 dB(A) intervals. Sex, age, occupation and length of time in current dwelling were fairly consistent throughout the studies and the exposure levels. A lower proportion of respondents living in detached houses were found in the intervals 32.5–35.0 dB(A) (all studies) and 35.0–37.5 dB(A) (Study III), meaning that a higher proportion of respondents living in rented or owned apartments could be found at these sound levels. A larger proportion of respondents in Study I compared with Study III had at least one wind turbine visible from their dwelling. Noise sensitivity, being negative towards wind turbines, self-rated health and self-rated sleep did not differ to any extent between the studies or between the intervals of exposure. However, being negative about the impact of wind turbines on the landscape scenery was more common in Study I than in Study III, and also increased with increasing intervals of SPL.

In Study II, 15 subjects were interviewed, eight female and seven male, aged 32–75 (median 54) years. Two of the subjects were a married couple. All subjects lived in detached houses in the countryside and could see more than one wind turbine from their house. Two subjects were farmers, five were self-employed or worked in a small family business, seven were employees, and one was a senior citizen. Ten of the informants were clearly annoyed by the noise while five were not.

Table 4. Characteristics of the respondents, by A-weighted sound pressure level (SPL), for studies I, III and IV.

	Study	<32.5 dB(A)	32.5–35.0 dB(A)	35.0–37.5 dB(A)	37.5–40.0 dB(A)	>40.0 dB(A)	Total
Respondents (n)	I	86	137	63	40	25	351
	III	356	204	103	71	20	754
	IV	445	332	168	106	44	1,095
Male sex (%)	I	33	39	50	50	48	42
	III	45	45	37	47	55	44
	IV	43	43	41	49	52	44
Age (yrs), mean (SD)	I	47 (13.5)	47 (14.3)	50 (14.6)	48 (13.1)	48 (14.3)	48 (14.0)
	III	52 (15.0)	50 (14.6)	51 (16.1)	49 (15.0)	49 (15.0)	51 (15.0)
	IV	51 (14.8)	48 (14.7)	51 (15.3)	49 (14.4)	48 (14.6)	50 (14.8)
Occupation (% employed; % retired)	I	61 15	58 28	53 19	69 15	67 13	60 21
	III	58 28	60 20	52 26	58 20	60 35	57 25
	IV	60 26	61 23	56 25	64 19	63 23	60 24
Housing type (% detached)	I	86	61	100	97	96	81
	III	82	77	73	82	95	80
	IV	83	70	83	88	93	80
Length of time in current dwelling (yrs), mean (SD)	I	15 (12.5)	13 (12.1)	18 (14.2)	19 (14.9)	19 (12.2)	15 (13.1)
	III	16 (13.6)	15 (12.7)	16 (14.4)	14 (11.6)	13 (13.2)	15 (13.2)
	IV	16 (13.3)	14 (12.6)	16 (13.9)	16 (13.2)	16 (12.9)	15 (13.2)
Visibility (% could see at least one wind turbine)	I	87	94	100	98	100	94
	III	60	72	85	93	95	71
	IV	66	80	92	94	98	78
Noise-sensitive (%)	I	46	49	53	58	50	50
	III	52	53	53	48	35	51
	IV	50	51	54	50	44	51
Negative towards wind turbines (%)	I	10	11	18	20	8	13
	III	10	5	5	10	15	8
	IV	10	8	8	16	11	10
Negative towards visual impact (%)	I	35	38	41	40	58	40
	III	18	13	12	20	26	16
	IV	22	22	22	29	45	23
Self-rated health (% with chronic disease)	I	27	28	16	30	24	26
	III	34	28	38	30	30	32
	IV	32	28	30	30	25	30
Self-rated sleep (% not good)	I	5	8	5	8	0	6
	III	8	6	6	1	0	6
	IV	7	7	6	3	0	6

4.6. Calculated variables

Noise exposure

It is not clear which parameter of sound best describes the received exposure of wind turbine noise. For one thing, the SPL varies significantly over time owing to variations in sound power levels at the source and to changes in the propagation paths from the wind turbine to the receiver. Variation in background SPL also influences the audibility of the wind turbine sound. With those respondents who stated that they noticed wind turbine sound, the sound could be predicted to vary from not being noticeable, to being just detectable to being clearly audible. It was therefore necessary to choose a specific condition. In accordance with the Swedish regulations for calculations of SPL at a dwelling nearby a wind turbine, downwind conditions of 8 m/s at 10 m height were chosen [Swedish Environmental Protection Agency 2001]. The origin of this choice of wind speed and direction is not known, but it was presented in the Danish legislation of wind turbines in 1989 [Danish Ministry of the Environment 1989]. It is presumed to represent a case where the sound generation of the wind turbine is at its maximum, or almost at its maximum, while the background sound levels at a dwelling may not mask the wind turbine sound.

The wind turbines were regarded as stationary point sound sources with a hemispherical sound propagation, as per equation 1:

$$L_{pAT} = L_{WA} - 10\log(2\pi r^2) - Dc - A \text{,} \qquad \text{(Eq. 1)}$$

where L_{pAT} = A-weighted equivalent SPL at the receiver (dB); L_{WA} = A-weighted equivalent sound power level of the source (dB); r = the distance between the source and the receiver (m); Dc = directivity correction (dB); and A = attenuation during propagation from the source to the receiver (dB).

For most of the wind turbines in these studies, the A-weighted sound power level of the source, L_{WA}, was derived from data provided by the wind turbine companies concerned. Measurements of the noise emission had been carried out by the manufacturers in accordance with the International Electrotechnical Commission’s standard [IEC 61400-11 1998]. The results of the measurements were available as sound power levels over third octaves at different wind speed measured at 10 m height. According to the standard, the measurements are carried out on flat terrain. Therefore, the relation between the wind speed at 10 m height and the wind speed at hub height (proportional to the sound power level) is only valid in such terrain as the ground influences the wind. For calculation of sound propagation from a wind turbine placed in another type of terrain, additional emission measurements have to be made in situ or the declared sound power levels need to be corrected for the differences in wind speed. The corrected sound power level was calculated in accordance with the Swedish Environmental Protection Agency [2001] –

$$L_{WA,corr} = L_{WA} + k \cdot v_h \left(\frac{\ln(H/z_0)}{\ln(h/z_0)} \frac{\ln(h/0.05)}{\ln(H/0.05)} - 1 \right), \qquad \text{(Eq. 2)}$$

where k = the relation between sound power level and wind speed at hub height; v_h = wind speed at 10 m height (m/s); H = height of the hub (m); h = 10 m; and z_0 = surface roughness length (m).

In Study I, all study areas were situated in flat terrain, so no corrections were made (z_0 = 0.05 m). In Study III, four of the study areas consisted of fairly complex terrain. For area G, measurements in situ had been made and hence the results of these measurements were used [Thorsson 2004]. For three of the sites (F, H and I), the correction described above was carried out. The surface roughness length was decided to be calculated as 0.3 m.

For all cases, the directivity correction was set to 0 as the sound intensity from a wind turbine is almost the same in all directions; only a small decrease has been found just perpendicular to the wind direction (personal communication with Professor Sten Ljunggren). The attenuation during the propagation from the wind turbine to the receiver depends on a number of parameters, the most important of which are absorption of sound in air, non-uniformity of the propagation due to meteorological conditions, ground interaction, and obstacles between the source and the receiver. The absorption of sound in air depends on the frequency of the sound, the temperature, the relative humidity and the pressure. As a function of these four variables, attenuation coefficients valid for different conditions have been derived and standardized [ISO 9613-1 1993]. However, it has been found that if mean temperature and mean air humidity for a location in Sweden are used as criteria for attenuation coefficients, the SPLs will be biased by about 0.5 dB/km for 500 Hz and 4 dB/km for 4,000 Hz [Larsson 1997]. To avoid underestimations of noise emissions, the attenuation coefficients for calculations in these studies were based on the 95th percentile of air absorption in Ljungbyhed in southern Sweden, meaning the air absorption is higher than this value 95% of the time. This is also the assumption of the simplified model describing sound propagation of wind turbine noise proposed by the Swedish Environmental Protection Agency [2001] and therefore this algorithm was used.

For distances <1,000 m between the wind turbine and the respondent, the algorithm used was –

$$L_{AeqT} = L_{WA} - 8 - 20\log(r) - 0.005r \qquad \text{(Eq. 3)}$$

The horizontal distance between the base of the wind turbine and the respondent in Study I was obtained from property maps, scale 1:10,000. In Study III geographical coordinates for the dwelling of each respondent were provided with the addresses, allowing calculations of the distances. The distance between the hub of the wind turbine and the respondent, *r*, was calculated from the horizontal distance and the vertical distance, i.e. the hub height of the wind turbine and the altitude difference between the wind turbine and the dwelling of the respondent. The altitudes were derived using digital maps. The attenuation coefficient of 0.005 used in the model is assumed mainly to account for atmospheric absorption, but it also includes a minor attenuation related to porous ground.

At larger distances, the attenuation differences between frequencies of the sound spectrum have an impact on the equivalent SPL that cannot be neglected. Therefore, for distances >1,000 m between the wind turbine and the respondent, the attenuation was calculated for each octave band, using the equation –

$$L_{AeqT} = L_{WA} - 10 - 20\log(r) - [10\log(\Sigma 10^{(Li + Ai)/10}) - 10\log(\Sigma 10^{(Li + Ai - r \cdot ai)/10})], \qquad \text{(Eq. 4)}$$

where L_i is the measured sound power level (dB) for octave band *i*; A_i is the A-weighting; and a_i is the attenuation for the same octave band [Swedish Environmental Protection Agency 2001].

In areas with several wind turbines (areas A, B, C, I, J, K and L) the L_{AeqT} from each wind turbine outside the dwelling of a respondent was added logarithmically. For those respondents in area F who lived on the opposite side of a small bay on which the wind turbine is located, 1.5 dB(A) were added to the calculated A-weighted SPL (personal communication with Sten Ljunggren). The same was done for respondents living in area G where the level from the wind turbine to the respondents was fairly steep, which is known to enhance sound propagation [Bass et al. 1998].

The common exposure metric in community noise reports today is DENL, a noise exposure metric also proposed by the European Union [2003]. It is based on the A-weighted equivalent SPLs during the daytime (12 hours), evening (4 hours) and night (8 hours), respectively, and adds a penalty of 5 dB to noise in the evening and 10 dB to noise in the night. It has been found to predict annoyance due to transportation noise fairly well [Miedema and Oudshoorn 2001]. However, for studies on response to wind turbine noise, DENL was considered to be unsuitable. Firstly, it could be questioned whether DENL is a proper measure for exposure to low sound levels that mainly cause annoyance during seasons and under weather conditions which allow people to spend time outdoors. A penalty for night-time noise is also difficult to motivate for noise that is rarely heard indoors. Secondly, the sound power level of the turbine varies with the wind and since no data of local conditions at each turbine were available it would not be possible to estimate equivalent values over such long periods as a day or a night. Instead, L_{AeqT} was chosen. L_{AeqT} is the continuous A-weighted equivalent SPL (dB) within the time interval T at the respondent, i.e. over the time period when the wind speed is 8m/s at 10 m height. In this thesis, A-weighted SPLs are divided into 2.5 dB intervals in some of the analyses. This was done for illustrative purposes.

Vertical visual angle

Vertical visual angle was defined in this study as the angle between the horizontal plane and an imaginary line from the dwelling of a respondent to the hub of the nearest wind turbine, expressed in degrees. The angle was calculated as –

$$\alpha = \tan^{-1}\left(\frac{h_h + (a_w - a_r)}{d}\right), \qquad \text{(Eq. 5)}$$

where h_h = the hub height of the wind turbine; a_w = the altitude of the base of the wind turbine; a_r = the altitude of the respondent; and d = the distance between the respondent and the wind turbine.

4.7. Variables obtained by questionnaires

Response to wind turbine noise

Response to wind turbine noise (and other environmental stressors) was assessed by the question, “Specify for each of the inconveniences below whether you notice it or are annoyed by it outside your dwelling”, with a 5-point verbal rating scale (VRS), where 1 = “do not notice”; 2 = “notice but not annoyed”; 3 = “slightly annoyed”; 4 = “fairly annoyed”; and 5 = “very annoyed”. In this thesis, the phrase “response to wind turbine noise” refers to the total 5-point scale. For separate analyses of perception and annoyance, points 2–5 were classified as perception and points 4–5 as annoyance. The scale has previously been used in several community noise studies [e.g. Öhrström and Skånberg 1996]. However, the 5-point VRS that is standard for community noise questions ranges from 1 = “not at all annoyed” to 4 = “very annoyed” and 5 = “extremely annoyed” [ISO/TS 15666 2003]. The questions do not distinguish between not noticing the noise and not being annoyed by it. In the case of wind turbines, it could be predicted that several people living fairly close to the turbines would not be able to hear the noise because of local conditions and for that reason would not be annoyed. Both scales were used in a community noise study regarding annoyance with road traffic noise [Öhrström et al. 2006b]. A comparison between the response to these two questions shows that 65% of those who said on the standardized scale that they were “not at all annoyed” answered “do not notice” on the scale used in our studies (Figure 4). Using the standardized scale in our studies would consequently have meant that information about perception of wind turbine noise would be missed. It could also be questioned whether the wording “extremely annoyed” is applicable for annoyance with noise of fairly low levels. In the community study using both scales described above, 23% of the respondents who on the scale we used had chosen “very annoyed”, chose “extremely annoyed” on the standardized scale (Figure 4). Transferred to the joint data in Study IV, out of those 45 respondents who answered “very annoyed”, ten would have reported “extremely annoyed”, corresponding to 1% of all respondents in the study. The 5-point VRS starting with “do not notice” has also been tested and recommended by the Nordic Method working group for assessing annoyance with vibrations from road and rail traffic in dwellings [Klaeboe et al. 2003], an exposure that also depends on local conditions.

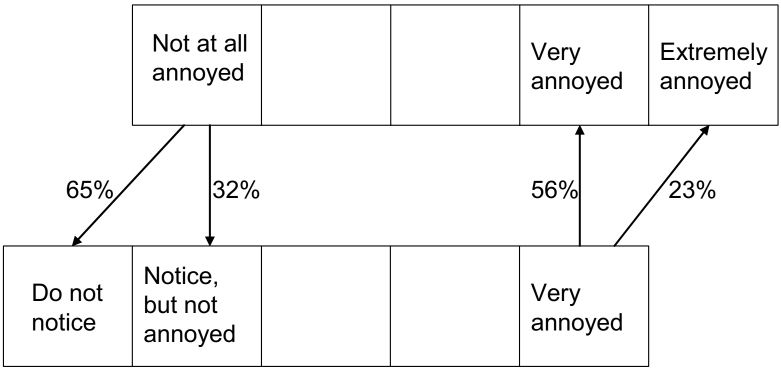

Figure 4. Comparison between two different scales used in a community noise study [Öhrström et al. 2006b].

Response to sound from rotor blades and sound from machinery, respectively, was assessed with the same VRS as was the main question discussed above (Study I).

Responses to 14 perceptual characteristics of wind turbine noise were also measured with this scale (studies I and III). Most of the characteristics were obtained from previous experimental studies in which subjects verbally described their perception of annoying sound properties in played-back wind turbine sounds [Persson Waye and Öhrström 2002]. These descriptions were complemented with regionally used phrases.

The frequency of annoyance occasions was asked for in both Study I and Study III with the question, “If you are annoyed by noise, how often does this happen?” The following answer alternatives were available: never/almost never; some/a few times a year; sometimes/a few times a month; sometimes/a few times per week; daily/almost daily. Respondents were also asked to describe whether the sound was heard more, less or the same under different weather conditions and at different times of the day.

Moderating factors

Several individual factors were measured in studies I and III: age, sex, employment (working at home, employed, on parental leave, on sick leave, retired, student, or currently unemployed), type of housing (farm, detached house, rented or owned apartment) and whether wind turbines were visible from the dwelling of the respondent. The respondents in Study III were also asked to agree or not agree to descriptions of their living environment (ten items) derived from the results of Study II (5-point VRS ranging from 1 = “do not agree at all” to 5 = “completely agree”).

Noise sensitivity was measured on a 4-point VRS ranging from 1 = “not sensitive at all” to 4 = “very sensitive” in both Study I and Study III. Two measurements of attitude were included in the studies: attitude towards wind turbines in general and attitude towards the impact of wind turbines on the landscape scenery. Both were assessed on a 5-point VRS ranging from 1 = “very positive” to 5 = “very negative”. The subjects were also asked which of the following 14 words or phrases they thought described wind turbines: efficient, inefficient, environmentally friendly, harmful to the environment, unnecessary, necessary, ugly, beautiful, inviting, threatening, natural, unnatural, annoying, blends in. These descriptors were developed by Karin Hammarlund, of the Department of Human and Economic Geography, Göteborg University, and used with her permission. In Study IV, opposite adjectives were put together in pairs so that new 3-point scales were formed.

Sleep quality was assessed in both Study I and Study III with the questions, “How would you describe your sleep?” (5-point VRS from 1 = “very good” to 5 = “very bad”) and “Is your sleep interrupted by a noise source?” (“no” or “yes”). The respondents were also asked whether they slept with their window open. Health was measured as prevalence of long-term or chronic disease, followed by the alternatives diabetes, high blood pressure, tinnitus, hearing impairment, and cardiovascular disease. Migraine was added for Study III. Well-being was measured as presence of symptoms on a 5-point VRS ranging from 1 = “rarely/never” to 5 = “daily or almost daily”. The symptoms were, for both Study I and Study III, headache, undue tiredness, pain and stiffness in the back, neck and/or shoulders, strain/stress, and feeling irritable; for Study III, they also included feeling sad/depressed, feeling unsocial and wanting to be alone, and feeling resigned.

Coping was measured in Study III. General coping was assessed by 15 items originally developed by Lercher [2001] and in our study translated and slightly modified for Swedish conditions. Questions on coping with wind turbines (eleven items) were derived from Study II (5-point VRS ranging from 1 = “do not agree at all” to 5 = “completely agree”). Respondents were also asked about their emotions when thinking about wind turbines (happy, angry, stressed, curious, resigned, indifferent, envious, knowledgeable, afraid, unaffected, proud, violated, and tired).

4.8. Classification of study areas

Topography and degree of urbanization

The twelve areas were classified as either flat or complex, the latter referring to areas with rocky ground and/or a hilly terrain. They were also classified as either rural (comprising agricultural fields and scattered houses) or suburban. The classifications were based on subjective ratings by the author when visiting the areas.

Subjective background sound

Using principal component analysis the variable “subjective background sound” in Study III was derived from three items in the questionnaire. Respondents were asked to agree or not agree on a 5-point VRS to the following statements: (i) “When outside on a calm summer morning, I can hear only bird song and other nature sounds”; (ii) “A background sound from road traffic is almost always present outdoors”; and (iii) “It is never really quiet in the area.” The mean values of the factor scores differed between the areas ($F = 4.137$; $p<0.001$). Three quiet areas (areas I, K and L) and two areas that were not quiet (areas F and J) were identified in a post hoc test (Least Significant Different, LSD). Areas G and H were excluded as they did not significantly differ from areas in either group.

4.9. Data collection

Questionnaires

A questionnaire with the masked purpose of assessing the response to wind turbine noise was developed for Study I from similar questionnaires as used by the Environmental Medicine Research group at Göteborg University [see, e.g., Persson Waye and Rylander 2001]. The questionnaire was called “Living in the countryside” and gave the impression of focusing on general living conditions in rural areas. A pre-stamped envelope for mailing back the questionnaire was provided together with the questionnaire. Households that did not respond by mail were visited twice and offered the opportunity to hand in the questionnaire in person.

The modified questionnaire in Study III still had the same masked purpose as in Study I. All questionnaires were sent out on the same day. One reminder letter and one reminder letter with an additional copy of the questionnaire were sent out 14 and 21 days, respectively, after the first sending.

Interviews

The 15 interviews in Study II took place either at the home of the participant or at Halmstad University and lasted between 30 minutes and 1 hour. An open-ended approach was used in the first six interviews, i.e. informants were asked what they thought when the first wind turbines were erected in their neighbourhoods, what they thought of them now, and how they would describe the implications of living near them. Follow-up questions were used for clarification and to reveal thoughts and feelings. This open-ended approach was kept for the remaining interviews, but with added questions related to the emerging concepts. The interviews were audio-taped and transcribed verbatim by an independent research assistant.

4.10. Analysis

Statistical treatment

Measurements were carried out with several types of scales. A-weighted SPL was treated as a continuous scale, even though ratios could not be formed owing to the underlying logarithmic transformation. Other continuous scales used measured the age of the respondents and the vertical visual angle. In the results, these data are given in means and standard deviation (SD). Differences between groups were tested with Student's t-test or analysis of variance (ANOVA), followed by the post-hoc test LSD.

Ordinal scales (e.g. for response, attitude and noise sensitivity) and nominal scales (e.g. sex, and type of housing) were used for several of the measurements. The results of these measurements were presented as proportions of respondents and tests were carried out using non-parametric methods. Correlations were tested using Spearman's rank test and differences in distribution between groups were tested using the χ^2 test or Mann-Whitney's U-test. Ordinal scales were treated as continuous scales when used in factor analysis and structural equation modelling (see below).

Confidence intervals (CIs) for proportions in Study I were calculated in accordance with Altman [1991, p. 230]. However, this method is based on an approximation not suitable for proportions close to 0% or 100%. In a later textbook Altman therefore recommends using Wilson's method. This gives an asymmetric CI (except for the proportion 50%) which better describes the properties of such an interval [Altman et al. 2000, p. 46]. This method was used for Study III and also for the results presented in this thesis.

Moderating factors of the relationship between A-weighted SPL and noise annoyance were tested in binary logistic regressions, dichotomizing annoyance into "not annoyed" (points 1–3) and "annoyed" (points 4 and 5) in both Study I and Study III. Furthermore, in Study III moderators of perception of wind turbine noise were tested in the same way by dichotomizing the response into "do not notice" (point 1) and "notice" (points 2–5).

Factors were derived from items measuring coping, well-being and health, using principal component analysis with Varimax in studies III and IV. In accordance with Hair et al. [1998], items were excluded if they did not meet the following criteria: extraction communality <0.5, measure of sampling adequacy >0.5, not loading more than 0.2 on two factors. Derived factors with Cronbach's alpha <0.6 for the included items were rejected.

In Study IV a number of fit indices were considered in testing the fit of the proposed model to the empirical data, viz. χ^2 test, the normed χ^2, the root mean square error of approximation (RMSEA) and the comparative fit index (CFI). The χ^2 statistic is a goodness-of-fit measure that assesses the magnitude of the discrepancy between the sample covariance matrix and the estimated covariance matrix [Hu and Bentler 1995] with a large, statistically significant value relative to the degrees of freedom indicating poor model fit. The normed χ^2 is the ratio of the χ^2 to its degrees of freedom. There is no consensus on what precisely represents a good fit [Bollen 1989], but values larger than 2.0 and the more liberal limit of 5.0 indicate that the model does not fit the observed data and needs improvement. Root mean square error of approximation is a measure of the discrepancy per degree of freedom for the model [Browne and Cudeck 1993], with values of about 0.05 or less indicating close fit of the model to the data. The CFI is an incremental fit index [Kline 1998], with values greater than 0.90 indicating acceptable model fit.

All tests were two-sided. P-values <0.05 were considered statistically significant for hypothesis tests. For estimations, 95% CIs not including 0 (for differences) or 1 (for odds ratios (ORs)) were considered significant. For the measurement of fit RMSEA, 90% CIs were obtained [Kline 1998, p. 139]. Many tests were carried out and consequently some are likely to show statistical significance by chance. Bonferroni's method for avoiding mass significance was used in Study I where appropriate. However, this is a fairly rigid approach and in studies III and IV the problem was discussed without establishing an absolute p-value.

Comparative method of Grounded Theory

All codes found in the first six transcribed interviews were listed together with the interviewer's free reflections and ideas related to each code. As codes were associated with each other to form clusters, categories were identified and the coding became more focused. Theoretical reflections on data and assumptions as to conceptual relationships between categories were continuously recorded in memos, mostly as running text. Saturation was reached after ten interviews, i.e. when we could not foresee finding any more data that would contribute to the study.

Model of the influence of visual factors

A structural model was developed for Study IV (Figure 5). This model consisted of the independent variables noise level (manifest variable) and visual and general attitude towards wind turbines (latent variables), as well as the dependent variable noise annoyance (latent variable). Visual attitude was measured in terms of the respondents' attitude towards the impact of wind turbines on the landscape scenery, and the bipolar descriptions "beautiful"–"ugly" and "natural"–"unnatural". General attitude was measured by the respondents' opinion of wind turbines in general, and the bipolar descriptions "efficient"–"inefficient" and "necessary"–"unnecessary". The model was tested among those who could and those who could not see at least one wind turbine from their home. The model was also tested among those living in a flat terrain and those living in a complex terrain. The proposed model is based on the following hypotheses: (i) variations in noise annoyance depend on variations in A-weighted SPLs from the wind turbine (path 1 (p1)); (ii) variations in noise annoyance also depend on the individual's attitude towards the noise source, comprising two aspects, namely visual attitude (p2) and general attitude (p3); (iii) there is a moderating effect of visibility, i.e. the effect of noise and general and visual attitude on noise annoyance is different for individuals who can see at least one wind turbine from their dwelling than for those who cannot; and (iv) there is a moderating effect of type of terrain, i.e. the effect of noise and general and visual attitude on noise annoyance is different for individuals who live in flat terrain than for those who live in complex terrain.

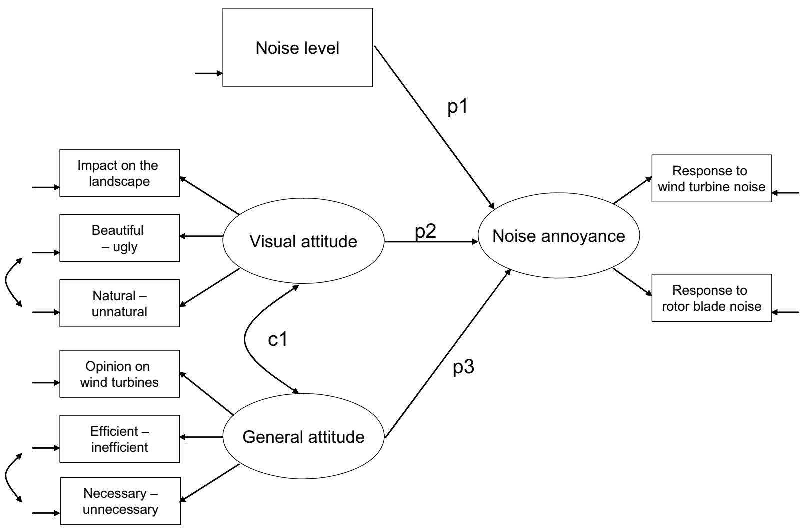

Figure 5. The structural equation model (SEM) tested in Study IV. "Noise level" refers to calculated A-weighted sound pressure levels (SPLs) outside the dwellings of the respondents due to wind turbine noise. Visual attitude, general attitude and noise annoyance are latent constructs. Regression weights (paths) are labelled "path 1 (p1)" to "path 3 (p3)" and the correlation between visual and general attitude is labelled "c1".

4.11. Ethical considerations

The studies were carried out in accordance with the requirements of the national regional ethics committees in Sweden. For studies based on questionnaires (studies I and III), no proposal to an ethics committee is required. Study II was approved by the Ethics Committee at Lund University as the study was carried out in Laholm. All informants in Study II consented in writing to participate in the study and were informed that they could withdraw from the interview or the study at any time.

5. Results

5.1. Response to wind turbine noise

Perception and annoyance

Response to outdoor wind turbine noise was statistically significantly correlated to A-weighted SPL both in Study I and in Study III (cf. Table 9). The distributions of the response related to 2.5 dB(A) intervals are shown in Table 5. The proportions of respondents who noticed wind turbine noise (points 2–5) were higher in Study I than in Study III at all sound levels. The proportions of respondents who were annoyed by wind turbine noise (points 4 and 5) were also higher in Study I than in Study III, except in the lowest sound intervals. The observed differences in the proportion of respondents who were annoyed between the studies remained when the proportions were calculated as ratios with only those who noticed the sound as denominator, excluding respondents who did not hear wind turbine noise (data not shown). At high sound level intervals in Study I, the number of respondents reporting the highest possible degree of annoyance (point 5) exceeded the number of respondents reporting the second highest degree (point 4) (Table 5).

Table 5. Response to wind turbine noise, i.e. perception and annoyance, outdoors, in relation to A-weighted SPLs in 2.5 dB intervals.

Study I	**<32.5 dB**	**32.5–35.0 dB(A)**	**35.0–37.5 dB(A)**	**37.5–40.0 dB(A)**	**>40.0 dB(A)**
	n = 82	**n = 132**	**n = 62**	**n = 40**	**n = 25**
	% (95% CI)	**% (95% CI)**	**% (95% CI)**	**% (95% CI)**	**% (95% CI)**
1. Do not notice	63 (53–73)	38 (30–46)	15 (8–25)	15 (7–29)	4 (1–20)
2. Notice, but not annoyed	24 (16–35)	28 (21–36)	47 (35–59)	35 (22–50)	40 (23–59)
3. Slightly annoyed	12 (7–21)	17 (11–24)	26 (17–38)	23 (12–38)	12 (4–30)
4. Fairly annoyed	0 (0–4)	10 (6–16)	6 (3–15)	8 (3–20)	8 (2–25)
5. Very annoyed	0 (0–4)	8 (4–13)	6 (3–15)	20 (10–35)	36 (20–55)
Study III	**<32.5 dB**	**32.5–35.0 dB(A)**	**35.0–37.5 dB(A)**	**37.5–40.0 dB(A)**	**>40.0 dB(A)**
	n = 356	**n = 204**	**n = 103**	**n = 71**	**n = 20**
	% (95% CI)	**% (95% CI)**	**% (95% CI)**	**% (95% CI)**	**% (95% CI)**
1. Do not notice	75 (71–79)	60 (53–67)	47 (37–56)	24 (16–35)	10 (3–30)
2. Notice, but not annoyed	18 (15–23)	25 (20–31)	43 (34–52)	58 (46–69)	45 (26–66)
3. Slightly annoyed	3 (2–5)	11 (8–16)	7 (3–13)	13 (7–22)	30 (15–52)
4. Fairly annoyed	2 (1–4)	2 (1–6)	2 (1–7)	1 (0–8)	10 (3–30)
5. Very annoyed	2 (1–4)	1 (0–4)	2 (1–7)	4 (1–12)	5 (1–12)

CI = confidence interval.

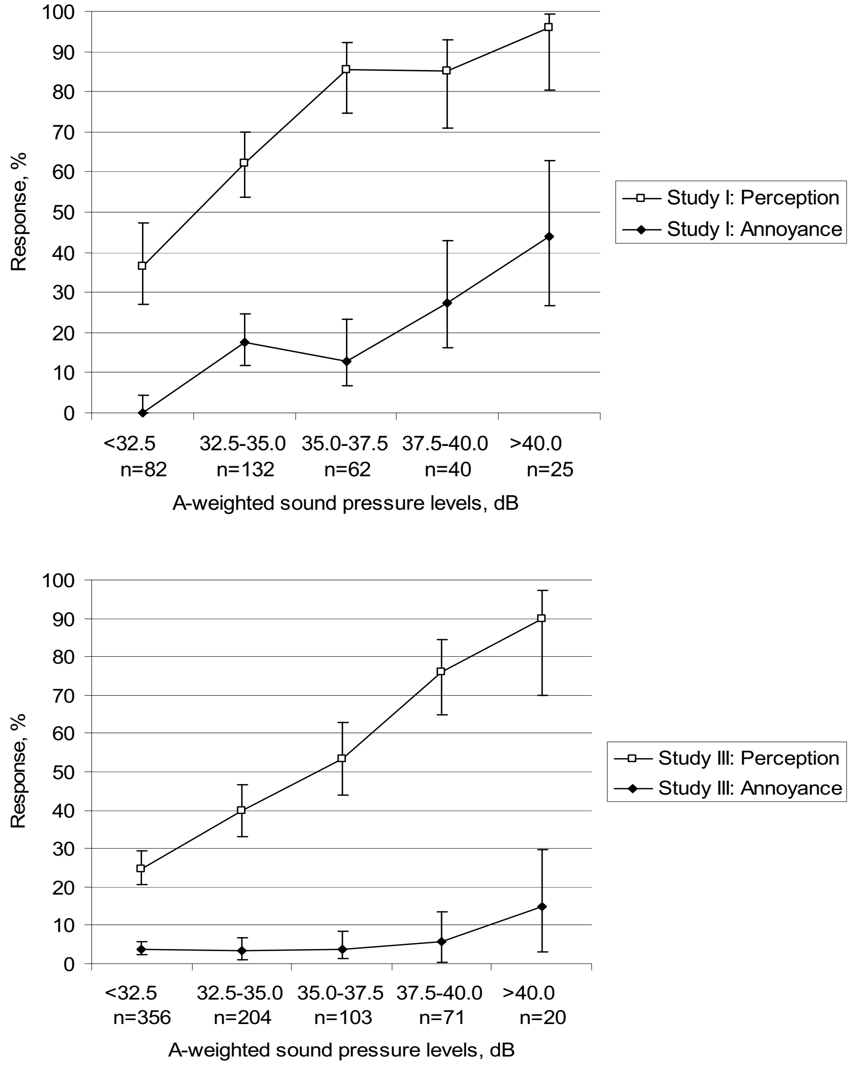

Figure 6. Proportion of respondents who noticed sound and/or were annoyed by noise from wind turbines outside their dwellings in Study I and Study III, respectively, in relation to A-weighted SPLs in 2.5 dB intervals. Vertical bars indicate 95% confidence intervals (CIs) and n = total numbers of respondents at each interval.

Perception (points 2–5) of and annoyance (points 4 and 5) due to wind turbine noise are also illustrated in Figure 6. The proportion of respondents who noticed sound increased with increasing A-weighted SPLs in both Study I and Study III, but a higher proportion of respondents who noticed the sound was found at lower A-weighted SPLs in Study I than in Study III. In Study I, 85% or more reported that they noticed the sound at SPLs ≥35.0 dB(A). In Study III the same proportion of respondents noticing the sound was not found until SPLs of almost 40.0 dB(A).

The proportions of outdoor annoyance due to wind turbine noise also increased with increasing A-weighted SPLs in Study I (Figure 6). Statistically significant differences were found between respondents at the sound intervals <35.0 dB(A) and >40.0 dB(A). In Study III only few respondents were annoyed by wind turbine noise. A small increase in the proportion of annoyed respondents could be observed among respondents at >40 dB(A), but the increase was not statistically significant.

When perception of wind turbine noise was tested in a binary logistic regression, the odds of noticing wind turbine noise increased 1.4 times (95% CI 1.25–1.52), i.e. by 1 dB(A), in Study I, and 1.3 times (95% CI 1.25–1.40) in Study III (not adjusted for other variables). When testing annoyance with wind turbine noise, the odds for annoyance increased 1.2 times (95% CI 1.12–1.34), by 1 dB(A), in Study I, and 1.1 times (95% CI 1.01–1.25) in Study III (not adjusted for other variables). In Study IV an increase of 1 dB(A) corresponded to a theoretical increase of 0.12 on the 5-point response scale (b = 0.12; 95% CI 0.104–0.140; $r^2 = 0.13$).

Occurrence of noise perception and noise annoyance

Among those who noticed wind turbine noise in Study I (n = 223), 25% reported that they were disturbed every day or almost every day and 17% said they were bothered by the noise once or twice a week. The proportions were somewhat lower in Study III (n = 296); 16% were disturbed every day or almost every day, and 12% once or twice a week. Annoyance in Study I was most frequently reported when relaxing outdoors and at barbecues (not measured in Study III).

Perception of wind turbine noise was influenced by weather conditions and time of the day. Of the respondents who noticed wind turbine noise in Study I and Study III, more than 50% stated that they could hear the noise more clearly when the wind was blowing from the turbines towards their dwelling (Table 6). A smaller proportion of respondents reported that the noise was heard more clearly when the wind came from the opposite direction. The noise was also heard more clearly when a fairly strong wind was blowing and on warm summer evenings. In Study III, 24% reported that the noise was more noticeable at night, while 12% thought it was less noticeable at night (not measured in Study I).

Table 6. Weather conditions and time of day when the wind turbine noise was reported to be heard more clearly, less clearly or no differently among respondents who noticed wind turbine noise. The proportion of respondents who answered "do not know" is not shown.

Wind turbine noise	**Study I n = 223**			**Study III n = 296**		
	More %	Less %	No diff. %	More %	Less %	No diff. %
Wind blowing from wind turbine towards dwelling	54	5	5	58	7	11
Wind blowing from dwelling towards wind turbine	9	36	13	6	47	18
Wind is low	18	26	16	19	31	22
Wind is fairly strong	39	14	11	43	18	17
Warm summer evenings	26	14	14	27	15	27
Night-time wind turbine noise	–			24	12	30

5.2. Individual factors

Demographic and socio-economic factors

Age or sex was not associated with response to wind turbine noise in any of the studies.

Table 7. Association between perception of noise from wind turbines and socio-economic variables in Study I and Study III, respectively, expressed as odds ratios (ORs), with 95% confidence intervals (CIs).

Sound pressure level (dB(A))	**Study I Do not notice (point 1; n = 118) vs. notice (points 2–5; n = 223)**	
OR (95% CI)	**Variable of interest (ref; tested category)***	**OR (95% CI)**
1.4 (1.25–1.52)	Employment (employed; not employed)	0.8 (0.46–1.23)
1.4 (1.24–1.52)	Housing (apartment; detached house)	2.3 (1.32–4.15)
Sound pressure level (dB(A))	**Study III Do not notice (point 1; n = 458) vs. notice (points 2–5; n = 296)**	
OR (95% CI)	**Variable of interest (ref; tested category)***	**OR (95% CI)**
1.3 (1.26–1.42)	Employment (employed; not employed)	0.7 (0.48–0.92)
1.3 (1.26–1.41)	Housing (apartment; detached house)	1.6 (1.04–2.33)

*Variables were entered one by one into a binary logistic regression, always keeping sound pressure level (SPL) in the regression as the main factor of importance for perception.

Being employed or not was not associated with response to wind turbine noise in Study I, but to perception of noise in Study III, where being employed increased the odds of noise perception (Table 7). Living in a detached house, in comparison with a rented or owned apartment, increased the odds of perceiving the noise in both Study I and Study III. It also increased the odds of noise annoyance in Study I (Table 8).

Table 8. Association between annoyance with noise from wind turbines and socio-economic variables in Study I and Study III, respectively, expressed as odds ratios (ORs), with 95% confidence intervals (CIs).

Sound pressure level (dB(A))	**Study I Not annoyed (points 1–3; n = 288) vs. annoyed (points 4 and 5; n = 53)**	
OR (95% CI)	Variable of interest (ref; tested category)*	OR (95% CI)
1.2 (1.11–1.35)	Employment (employed; not employed)	0.7 (0.34–1.27)
1.2 (1.09–1.31)	Housing (apartment; detached house)	5.5 (1.28–23.54)
Sound pressure level (dB(A))	**Study III Not annoyed (points 1–3; n = 723) vs. annoyed (points 4 and 5; n = 31)**	
OR (95% CI)	**Variable of interest (ref; tested category)***	**OR (95% CI)**
1.1 (1.01–1.25)	Employment (employed; not employed)	1.3 (0.61–2.61)
1.1 (1.01–1.25)	Housing (apartment; detached house)	2.5 (0.75–8.40)
Valuation of the current living environment†		
1.1 (1.01–1.25)	“I live in a place where I can recover and gain strength.” (disagree; agree)	0.3 (0.13–0.74)
1.1 (1.02–1.25)	“I have renovated my dwelling.” (no; yes)	2.6 (1.03–6.33)

*Variables were entered one by one into a binary logistic regression, always keeping sound pressure level (SPL) in the regression as the main factor of importance for perception.
†Only items that were positively or negatively associated with noise annoyance are shown.

Of the ten items measuring the respondents’ description of the living environment in Study III, the following two were associated with annoyance: (i) having renovated the dwelling was positively associated with noise annoyance; while (ii) looking upon the current living environment as a place for relaxation, recovery and gaining strength was negatively associated with noise annoyance (Table 8).

Noise sensitivity

The proportion of respondents who reported that they were fairly sensitive or very sensitive to noise was consistent throughout the studies. Of all the respondents in Study IV, 51% reported that they were fairly or very sensitive to noise. Noise sensitivity was not related to age. Women were somewhat more sensitive to noise than men (54%), but the difference was not statistically significant. There was no significant difference in noise sensitivity between respondents living in rural areas and respondents living in suburban areas. Noise sensitivity was correlated to response to wind turbine noise in Study IV, but only to a low degree (r_s = 0.095; n = 1,083; p<0.01). The strongest association was found among respondents in the exposure group >40.0 dB(A) (r_s = 0.521; n = 43; p<0.001). Noise sensitivity was not correlated to the general attitude towards wind turbines (r_s = -0.007; n = 1,072; p = 0.830), but to attitude towards the impact of wind turbines on the landscape (r_s = 0.119; n = 1,067; p<0.001). Correlation coefficients separated for Study I and Study III are shown in Table 9.

Table 9. Correlations, using Spearman's rank correlation test, between A-weighted sound pressure level (SPL) and subjective variables in studies I and III.

	A-weighted SPL		Response to wind turbine noise		Attitude towards visual impact		Attitude towards wind turbines	
Study	**I**	**III**	**I**	**III**	**I**	**III**	**I**	**III**
A-weighted SPL (continuous scale)	–	–						
Response to wind turbine noise (5-point scale)	0.377**	0.354**	–	–				
Attitude towards visual impact (5-point scale)	0.131*	-0.089*	0.512**	0.194**	–	–		
Attitude towards wind turbines (5-point scale)	0.095	-0.069	0.334**	0.162**	0.564**	0.618**	–	–
Noise sensitivity (4-point scale)	0.065	-0.023	0.197**	0.056	0.182**	0.100**	0.008	-0.013

*p<0.05; **p<0.01.

Attitude towards the source

In Study I, 13% of the respondents were negative or very negative to wind turbines; in Study III this percentage was 8%. Being negative to wind turbines was not associated with A-weighted SPL (Study IV), but with annoyance due to wind turbine noise (r_s = 0.230; n = 1083; p<0.001). The association was stronger in Study I than in Study III (Table 9).

Of the respondents in Study I, 40% were negative or very negative to the impact of wind turbines on the landscape scenery. Sixteen per cent of the respondents in Study III were negative or very negative to this impact. There was no difference between respondents living on flat terrain and respondents living on complex terrain in Study III (all respondents in Study I lived on flat terrain). Respondents living in rural areas were somewhat more negative than respondents living in suburban areas. In Study I, 45% (n = 66/146) of those living in a rural area vs. 35% (n = 67/193) of those living in a suburban area were negative to the impact of wind turbines on the landscape. The difference in proportions was only just statistically significant (d = 10%; 95% CI 0–21%). In Study III, 20% (n = 36/180) of respondents living in a rural area vs. 15% (n = 84/560) of respondents living in a suburban area were negative (non-significant difference). Respondents who could see at least one wind turbine from their dwelling were more negative to the impact of wind turbines on the landscape. In Study IV, 26% (n = 213/835) of respondents who could see wind turbines from their dwelling vs. 16% (n = 37/232) of those who could not see any wind turbines were negative. Being negative to the impact of wind turbines on the landscape scenery was not associated with A-weighted SPL in Study IV, but when the analyses were carried out separately for Study I and Study III, statistically significant associations were found, positively in Study I and negatively in Study III (Table 9). Attitude towards the impact of wind turbines on the landscape scenery was associated with noise annoyance ($r_s = 0.341$; n = 1,079; p<0.001), to a higher degree in Study I than in Study III (Table 9).

Table 10. Adjectives and phrases used to describe wind turbines in studies I and III.

	Study I %	Study III %	Difference % (95% CI)
Environmentally friendly	78	80	3 (-2.4–7.9)
Necessary	37	45	8 (1.7–14.0)
Ugly	36	28	-8 (-13.9– -2.0)
Efficient	30	34	5 (-1.4–10.3)
Unnatural	27	19	-8 (-13.6– -2.8)
Annoying	25	10	-15 (-19.9– -10.0)
Natural	20	23	4 (-1.3–8.9)
Inefficient	14	10	-4 (-8.5–0.0)
Blends in	14	19	5 (0.2–9.4)
Unnecessary	11	6	-5 (-9.1– -1.7)
Beautiful	9	14	5 (0.8–8.7)
Harmful to the environment	7	3	-4 (-7.4– -1.4)
Inviting	5	7	2 (-1.0–4.9)
Threatening	4	1	-3 (-5.6– -1.0)

Wind turbines were most frequently assessed to be “environmentally friendly”, “necessary”, “ugly” and “efficient” (Table 10). Statistically significant differences in proportions of respondents between the studies were found for some of the adjectives/phrases used to describe the turbines. A higher proportion of respondents in Study I compared with Study III had chosen “ugly”, “unnatural”, “annoying”, “inefficient”, “unnecessary”, “harmful” and “threatening”. In Study III, “blends in”, “necessary” and “beautiful” were more often chosen (all p-values <0.05).

Personal values about the living environment

In Study II the experiences and consequences of living close to a wind turbine differed between the informants who were interviewed, even though they were all exposed to audible and visual stimuli from the wind turbines. The differences were captured in a conceptual model (Figure 7) describing how the personal values of the informants regarding their living environment (core category) led to diverse meanings of living close to a wind turbine for them.

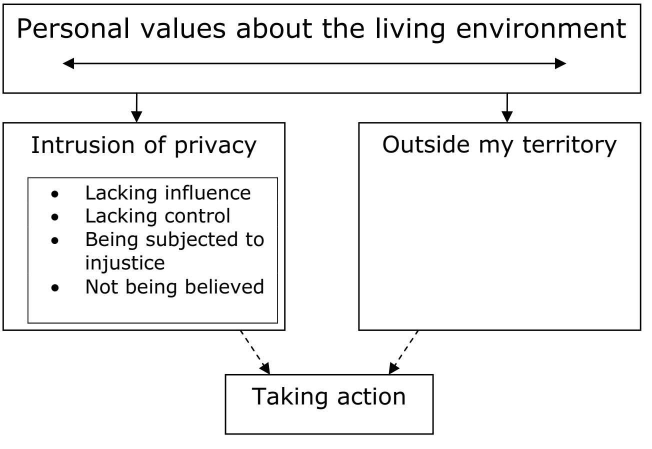

Figure 7. Conceptual model illustrating the relationships between categories and sub-categories (Study II).

Some of the informants thought of the wind turbines as something placed outside of their territory and themselves; these informants said that the countryside could serve as a base for earning a living or as a place for society to develop through technical achievements and economic growth. They thought that the landowner had the right to decide how he or she would use the land and that one must accept disturbances typical of the countryside, including noise from wind turbines and shadows caused by their blades. Other informants perceived the wind turbines as intruders. The audio and visual stimuli, described as a swishing noise and a constant rotation, entered into their gardens, sometimes into their living rooms, and became an intrusion of privacy. Expectations of peace and quiet together with a strong feeling of home, demonstrated by great care devoted to both the interior and the exterior of the house, seemed to increase the risk of feeling intruded by wind turbine exposure. The force of the intrusion was also influenced by the four categories “lacking control”, “being subjected to injustice”, “lacking influence”, and “not being believed”, all comprising feelings of inferiority.

5.3. Area-related factors

Background sound, subjectively assessed as quiet or not quiet, was associated with perception of noise from wind turbines when tested in a binary logistic regression together with A-weighted SPL in Study III (Table 11).

Table 11. Association between perception of noise from wind turbines and area-related variables in Study III, expressed as odds ratios (ORs), with 95% confidence intervals (CIs).

Sound pressure level (dB(A))	**Study III Do not notice (point 1; n = 458) vs. notice noise (points 2–5; n = 296)**	
OR (95% CI)	**Variable of interest (ref; tested category)***	**OR (95% CI)**
1.3 (1.22–1.38)	Subjective background sound (not quiet; quiet)	1.8 (1.25–2.51)
1.3 (1.24–1.40)	Terrain (complex; flat)	1.1 (0.81–1.56)
1.3 (1.25–1.41)	Urbanization (suburban; rural)	1.8 (1.27–2.64)
1.3 (1.24–1.41)	Terrain and urbanization	
	Suburban and flat ground (n = 222)	1.0
	Suburban and complex ground (n = 347)	1.0 (0.65–1.48)
	Rural and flat ground (n = 157)	1.6 (1.01–2.53)
	Rural and complex ground (n = 28)	4.8 (1.65–13.72)

*Variables were entered one by one into a binary logistic regression, always keeping sound pressure level (SPL) in the regression as the main factor of importance for perception.

The terrain (complex or flat) was not associated with perception; however, living in a rural area compared with a suburban area increased the likelihood of noticing the sound. When further exploring the influence of terrain, respondents living in rural areas with a complex ground were more likely to notice the sound than respondents living in rural areas with a flat ground, but the difference was not statistically significant.

Variables associated with perception of wind turbine noise were also associated with noise annoyance (Table 12).

Table 12. Association between annoyance with noise from wind turbines and area-related variables in Study III, expressed as odds ratios (ORs), with 95% confidence intervals (CIs).

Sound pressure level (dB(A))	**Study III** **Not annoyed (points 1–3; n = 723) vs. annoyed (points 4 and 5; n = 31)**	
OR (95% CI)	**Variable of interest (ref; tested category)***	**OR (95% CI)**
1.1 (0.91–1.21)	Subjective background sound (not quiet; quiet)	3.6 (1.21–10.67)
1.1 (1.02–1.26)	Terrain (complex; flat)	0.8 (0.39–1.76)
1.1 (0.99–1.21)	Urbanization (suburban; rural)	3.8 (1.80–7.83)
1.1 (0.98–1.23)	Terrain and urbanization	
	Suburban and flat ground (n = 222)	1.0
	Suburban and complex ground (n = 347)	2.1 (0.63–7.28)
	Rural and flat ground (n = 157)	5.2 (1.62–16.65)
	Rural and complex ground (n = 28)	10.1 (2.46–41.61)

*Variables were entered one by one into a binary logistic regression, always keeping sound pressure level (SPL) in the regression as the main factor of importance for perception.

5.4. Sound characteristics

Noise from the rotor blades was in Study I noticed more than was noise from the machinery (Figure 8). The proportion of respondents who noticed noise from rotor blades was similar to the proportion of respondents who noticed noise from wind turbines in general (cf. Figure 6).

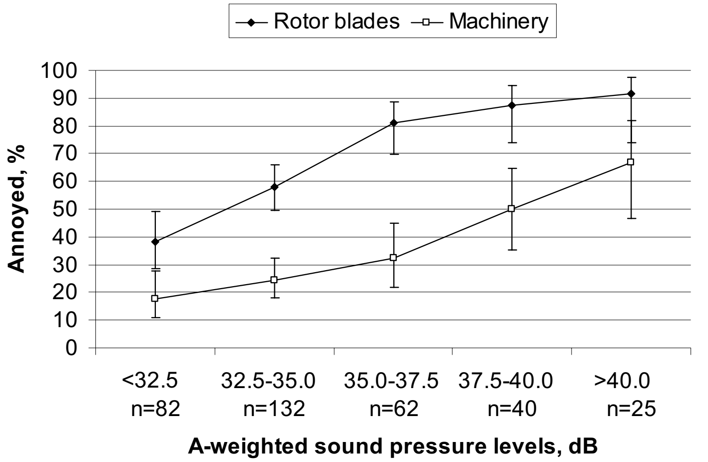

Figure 8. Proportion of respondents who noticed sound from rotor blades and machinery, respectively, outside their dwelling in Study I, in relation to A-weighted SPLs in 2.5 dB intervals.

Descriptors of sound characteristics related to the sound from the rotor blades were also highly correlated with noise annoyance, both in Study I and in Study III, and included “swishing”, “whistling”, “pulsating/throbbing” and “resounding” (Table 13).

Table 13. Correlations, using Spearman's rank correlation test, between noise annoyance and sound characteristics of wind turbine noise in Study I and Study III, respectively, based on respondents who noticed wind turbine sound.

Correlation with noise annoyance	Study I n = 223	Study III n = 296
Swishing	0.718**	0.590**
Whistling	0.642**	0.381**
Pulsating/throbbing	0.450**	0.387**
Resounding	0.485**	0.321**
Scratching/squeaking	0.398**	0.290**
Tonal	0.335**	0.122
Low frequency	0.292**	0.109
Lapping	0.262**	0.162*

**p<0.01; *p<0.05.

5.5. Visual factors

Visibility and visual attitude

Of the respondents in Study I, 93% could see one or more wind turbines from their dwelling. In Study III, this figure was 71%. Seeing wind turbines in Study III was associated with perception (OR: 2.2; 95% CI 1.47–3.18) and also with annoyance (OR: 10.9; 95% CI 1.46–81.92) when tested in a binary logistic regression together with A-weighted SPL.

In Study IV a model of response to wind turbine noise was tested among respondents who saw at least one wind turbine from their dwelling and among those who could see no wind turbines from their home (Figure 9). The model showed good fit in both groups in accordance with the setup criteria. In both groups the visual attitude influenced noise annoyance while the general attitude did not. The impact of A-weighted SPL was larger among respondents who could see wind turbines from their home than among those who could not.

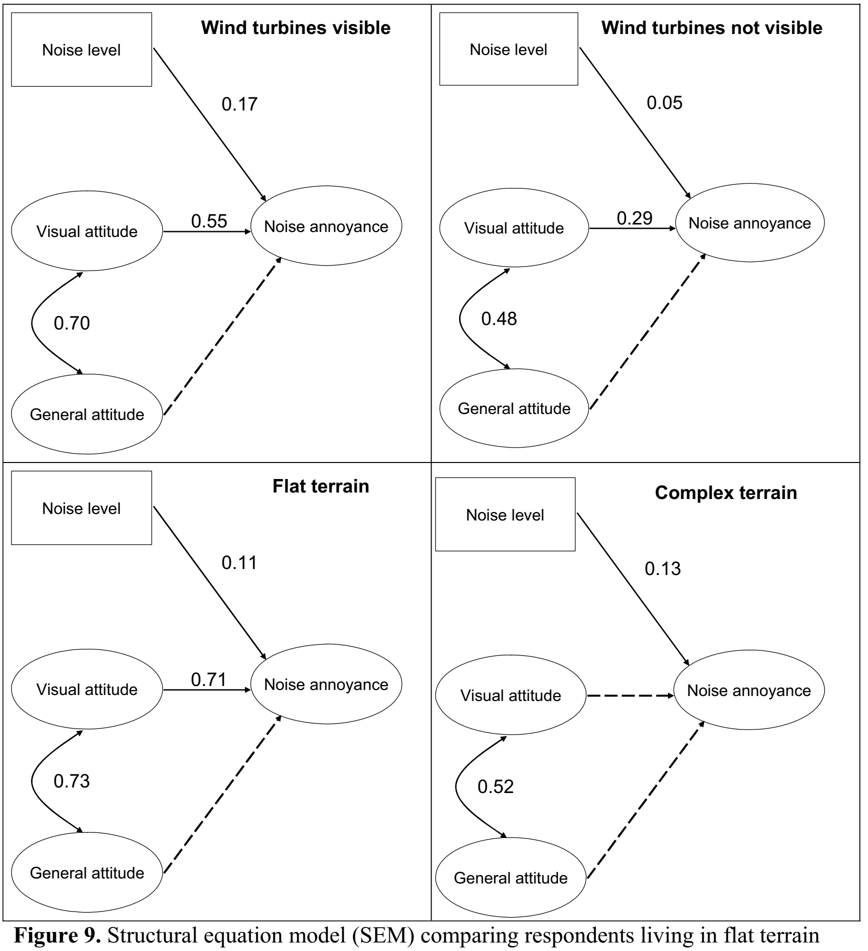

Figure 9. Structural equation model (SEM) comparing respondents living in flat terrain (randomized sub-sample: n = 375) with respondents living in complex terrain (n = 375), and respondents who could see at least one wind turbine from their dwelling (randomized sub-sample: n = 256) with respondents who could not see any wind turbines from their dwelling (n = 237). Statistically significant paths and correlations are annotated with unstandardized estimates ($p<0.01$). Insignificant paths are marked with dashed lines, and are not annotated.

The impact of A-weighted SPL was approximately the same for respondents living in flat terrain as it was for respondents living in complex terrain (Figure 9). Visual attitude had a large influence on noise annoyance among respondents living on flat terrain, but no statistically significant influence in the group of respondents living on complex terrain. The model showed good fit both for respondents living in flat terrain and for respondents living in complex terrain.

Vertical visual angle

Vertical visual angle in Study III was associated with noise annoyance when tested together with A-weighted SPL in a binary logistic regression (OR: 1.2; 95% CI 1.03–1.42). However, A-weighted SPL in this model was no longer statistically significant. This could be due to the dependency between SPL and vertical visual angle as both were calculated from the distance between the wind turbine and the dwelling of the respondent. In Study IV a modified vertical visual angle was tested among respondents who could see at least one wind turbine from their dwelling. The distance was removed from the vertical visual angle when the variable was tested together with A-weighted SPL in a multiple regression, with the response to wind turbine noise (5-point scale) as dependent variable. The test was carried out separately for respondents living in flat terrain ($n = 619$) and for respondents in complex terrain ($n = 231$). A-weighted SPL in this regression was statistically significantly associated with response to wind turbine noise among respondents living in flat terrain ($b = 0.12$; 95% CI 0.093–0.148). Also, the new variable derived from the vertical visual angle was statistically significant, but to a low degree ($b = 0.04$; 95% CI 0.026–0.045). The two variables explained 14% of the variance in response to wind turbine noise. No association between vertical visual angle and response to wind turbine noise was found in complex terrain.

5.6. Health

Sleep

A-weighted SPLs were associated with sleep disturbance in Study I. At sound intervals below 35 dB(A), no respondents were disturbed in their sleep by wind turbine noise, but 16% of the 128 respondents living at sound exposure above 35.0 dB(A) stated in an open question that they were disturbed in their sleep by wind turbine noise. Of these, all except two slept with an open window in the summer. No association between A-weighted SPL and sleep disturbance was found in Study III.

In both Study I and Study III noise annoyance was associated with sleep disturbance. Of the 53 respondents in Study I who were annoyed by wind turbine noise, 64% reported that their sleep was disturbed by a noise source, compared with 15% of the 288 respondents who were not noise-annoyed ($p<0.001$). In Study III, 36% of the 31 respondents who were annoyed reported that their sleep was disturbed by a noise source, compared with 9% among the 723 respondents who were not noise-annoyed ($p<0.001$). In Study III, respondents who were annoyed by wind turbine noise also felt more tired ($p = 0.05$) and tense ($p<0.05$) in the morning, feelings not asked for in Study I.

Health and well-being
Only few respondents reported impaired health or well-being. No association between A-weighted SPL and health was found (Study IV). Only two of the items measuring health and well-being were correlated with annoyance due to wind turbine noise in Study IV, viz. strained/stressed ($r_s = 0.071$; n = 1,055; $p<0.05$) and irritable ($r_s = 0.087$; n = 1,058; $p<0.01$). Three factors explaining 57% of the variation in the original variables were constructed with principal component technique. They were decreased well-being (strained/stressed, irritable, unusually tired, pain in the neck, back and/or shoulders), health (long-term illness, diabetes, cardiovascular disease, high blood pressure) and hearing impairment (hearing impairment, tinnitus). Two of the factors were only just significantly correlated to noise annoyance: decreased well-being was positively ($r_s = 0.065$; n = 1,026; $p<0.05$) and hearing impairment was negatively correlated to noise annoyance ($r_s = -0.067$; n = 1,026; $p<0.05$).

In Study III, respondents who were annoyed by the wind turbine noise (n = 31) felt resigned (29%), violated (23%), strained (19%) and tired (19%) when thinking about wind turbines to a statistically significantly higher degree compared with those who were not annoyed (all p-values <0.001). These feelings were not related to self-reported health status, except for feeling violated, which was associated with lowered sleep quality ($p<0.01$).

5.7. Coping

The informants interviewed in Study II had different coping strategies for avoiding the wind turbine exposure. Some informants did not do anything although they felt negatively affected by the exposure, while others temporarily moved to other parts of the garden or the dwelling, or even carried out major changes such as rebuilding their house or moving. Most informants declared that there was no point in protesting against the wind turbine developments to the local authorities, while some had instituted legal proceedings even though they did not think that they would win their case.

None of the 15 items measuring general coping were correlated to annoyance with wind turbine noise. Several of the eleven items measuring coping specific to wind turbine noise in Study III were correlated to noise annoyance. Two factors, which explained 72% of the variance in the original variables, were derived, viz. (i) taking active steps to avoid the negative impact ("I have changed my living environment because of the wind turbines"; "I have changed my behaviour because of the wind turbines"; "I consider moving if more wind turbines are erected"); and (ii) discussing and seeking information ("I have gathered information about wind power"; "I discuss wind power with people around me"). Both factors were positively correlated to noise annoyance (for (i), $p<0.001$; for (ii), $p<0.01$). "Taking active steps to avoid the negative impact" was not correlated to any of the questions assessing well-being. "Discussing and seeking information" was negatively correlated to three out of five items assessing stress or strain (unhappiness/depression, irritability, feelings of hopelessness; all p-values <0.05), indicating that this coping behaviour is suitable for reducing strain.

5.8. Models predicting perception and annoyance

Perception

In Study III, a developed model predicting perception of wind turbine noise showed that A-weighted SPLs had a statistically significant influence on perception (Table 14).

Table 14. Model predicting perception of noise from wind turbines (dependent variable "do not notice" (n = 457) or "notice" (n = 307)) and variables hypothesized to influence the perception, expressed as odds ratios (ORs), with 95% confidence intervals (CIs) (Study III).

Prediction of perception of wind turbine noise in Study III (Hosmer and Lemeshow test: 0.703)*	**OR (95% CI)**
Sound pressure level (dB(A))	1.3 (1.21–1.39)
Employment (employed; not employed)	0.6 (0.40–0.83)
Terrain (complex; flat)	0.6 (0.38–0.97)
Urbanization (suburban; rural)	2.3 (1.34–3.88)
Subjective background sound (not quiet; quiet)	2.6 (1.72–3.95)
Visibility of turbines (no; yes)	2.3 (1.51–3.47)

*Adjusted for age and sex.

Being employed and living in a complex terrain, living in a rural area, living in a quiet area and having wind turbines visible from the dwelling were factors that all increased the odds of perceiving wind turbine noise.

When the same variables were tested among all respondents (Study IV), the influence of the terrain on perception of wind turbine noise was no longer statistically significant and therefore removed from the model. Being employed, living in a rural area and having wind turbines visible from the dwelling still increased the odds for perceiving the noise (Table 15). Subjective background sound was not available for respondents from Study I and could therefore not be included.

Table 15. Model predicting perception of noise from wind turbines (dependent variable "do not notice" (n = 576) or "notice" (n = 519)) and variables hypothesized to influence the perception, expressed as odds ratios (ORs), with 95% confidence intervals (CIs) (Study IV).

Prediction of perception of wind turbine noise in Study IV (Hosmer and Lemeshow test: 0.512)*	OR (95% CI)
Sound pressure level (dB(A))	1.3 (1.27–1.42)
Employment (employed; not employed)	0.6 (0.46–0.85)
Urbanization (suburban; rural)	1.6 (1.15–2.12)
Visibility of turbines (no; yes)	2.3 (1.61–3.37)

*Adjusted for age and sex.

Annoyance

The low number of respondents annoyed by wind turbine noise in each study did not allow prediction models with more than one or two variables. An attempt to predict annoyance among all respondents who could see at least one wind turbine from their dwelling (Study IV) showed bad fit (Table 16).

Table 16. Model predicting annoyance with noise from wind turbines among respondents who could see at least one wind turbine from their dwelling (dependent variable "not annoyed" (n = 762) or "annoyed" (n = 81)) and variables hypothesized to influence the perception, expressed as odds ratios (ORs), with 95% confidence intervals (CIs).

Prediction of perception of wind turbine noise in Study IV (Hosmer and Lemeshow test: 0.011)	OR (95% CI)
Sound pressure level (dB(A))	1.2 (1.06–1.26)
Urbanization (suburban; rural)	2.7 (1.56–4.79)
Attitude towards visual impact (5-point scale from "not at all negative" to "very negative")	5.2 (3.76–7.19)

Living in a rural area and being negative to the wind turbines' visual impact on the landscape influenced noise annoyance in the model. Employment, type of dwelling, noise sensitivity and attitude towards wind turbines in general were not statistically significantly associated with annoyance when tested simultaneously in the model.

6. Discussion

6.1. Method

Reliability and validity

The observed increase in perception of wind turbine noise with increasing A-weighted SPL indicates high validity of the overall study designs of Study I and Study III. A-weighted equivalent SPL as dose measurement reflected the exposure gradient in an appropriate way. The algorithm used for calculations of sound propagation has been found to estimate the emission levels within 1 dB of a measured value in flat terrain [Swedish Environmental Protection Agency 2001]. However, it has some limitations. The accuracy of the algorithm in non-flat terrain is not known and it does not take special weather conditions into account. Some adjustments of the doses in areas with complex terrain were therefore made, but it is not known whether these were sufficient. Furthermore, more precise dose estimations would have been obtained if the physical situation at the dwelling of each respondent had been taken into account, presumably leading to more distinct dose-response relationships.

Measurements obtained by the questionnaire were of high validity. The response to several subjective variables showed high similarity between the studies. Furthermore, in Study I the questions detected annoyance with odour from industrial plants in an area where a biogas plant was located and annoyance with noise from trains in the areas where trains passed. In Study III the questions detected annoyance with sound from agricultural machines and odour from manure in rural areas.

The internal consistency reliability of the questionnaire was satisfactory for both questionnaires used in the studies. Cronbach's alpha was 0.885 (n = 326) for four questions in Study I, which we had assumed would be likely to be answered, and 0.864 (n = 734) for the same test in Study III.

Several attempts have been made to capture the reliability and validity of qualitative studies such as Study II. Generalizability, validity, reliability and precision have for example been expressed as applicability, concordance, security and accuracy [see, e.g., Lindgren and Fridlund 1999, Granskär et al. 2001] or as credibility, dependability, confirmability and transferability [see, e.g., Hamberg 1998]. This approach was not found to be appropriate as GT has its own "built-in" way of dealing with reliability and validity. Reliability, for instance, is reached when similar relationships between phenomena emerge from data, and a theory or model is valid when identified categories emerge repeatedly from added data. In Study II, data and emerging theories were discussed with the co-authors throughout the analysis. After the categories and the relationships between the categories were saturated, the model was tested in five additional interviews. One of the co-authors read the transcribed interviews after the model was established, and approved the model.

Non-respondents

Since records of non-respondents were not available for Study I, demographic data for the area were used to confirm that the respondents did not differ from the total population. The distribution of age among the respondents was similar to that of the population in the area. However, the proportion of women was higher than expected (58%). In Study III it was possible to compare respondents and non-respondents. The same gender difference was found as for Study I; 56% of the respondents were females compared with 47% of the non-respondents. The same tendency has been observed in other community noise studies in Sweden: 53% of 1,953 respondents were women in a study on health effects of traffic noise [Öhrström et al. 2005], 59% of 493 in a study on the effects of traffic changes [Öhrström et al. 2006a] and 57% of 956 in a study on the benefits of access to quietness [Öhrström et al. 2006b]. The higher proportion of women in the studies presumably had no impact on the results since no differences between men and women regarding annoyance with wind turbine noise were found. It has also previously been shown that annoyance is not related to sex [Miedema and Vos 1999].

Other possible bias

No analysis of the proportion of individuals who were annoyed by wind turbine noise among non-respondents was carried out, and therefore it is not known whether the results were biased by a higher willingness among noise-annoyed individuals to complete the questionnaire than among individuals who were not noise-annoyed. However, masking the questionnaire to give an impression of a survey concerning general living conditions in the countryside very likely prevented such bias. The respondents could of course browse through the questionnaire before answering the first questions, making it difficult to hide the objective of the survey. A comparison between a Norwegian study with a similar study design, where respondents were interviewed by telephone and hence did not see the questions in advance, and a Swedish postal study using the same questions did not show any difference in degree of annoyance, however [Klaeboe et al. 2003]. Also, when comparing respondents in Study III who returned the questionnaire shortly after receiving it, with respondents who required one or two reminders, we found no differences in proportion of respondents annoyed by wind turbine noise. It could therefore be assumed that there was no over-reporting of noise annoyance in the studies presented here.

Study III comprised areas where wind turbines had been operating longer at the time of the survey than in Study I. The lower rate of annoyance in Study III could be seen as an adaptation to the sound. Adaptation to community noise has, however, not been found in other field studies [Vallet et al. 1978, Weinstein 1982]. The studies presented here were not designed to compare annoyance over time and the observation could be due to other differences between the areas, such as degree of urbanization (Table 2).

6.2. Results

Noise annoyance increased with increasing A-weighted SPL. However, some of the factors that were found to influence response to wind turbine noise must be taken into account when the prevalence of annoyance at different SPLs is estimated. Moderating factors will therefore first be discussed here, in relation to descriptions of the response. This will be followed by an attempt to assess the prevalence of perception of and annoyance with wind turbine noise by outlining a dose-response relationship. The latter will then be compared with that of other community noise sources.

Wind turbine noise and background sound

An increased risk of perception of wind turbine noise was naturally found in areas that were rated as quiet compared with non-quiet areas (Table 11). Low levels of background sound make noise from wind turbines easily perceived. However, not only the equivalent SPL of the background sound, but also, the frequency content is important for masking possibilities. As an example, listening tests have shown that wind-induced noise from coniferous trees better masks wind turbine noise than does the noise from deciduous trees or sea waves [Bolin 2006]. The background sound SPLs need to be 2.5 dB(A) higher than the wind turbine noise for coniferous trees and 3.5 dB(A) for deciduous trees if the wind turbine noise is not to be detected.

Also, the risk of annoyance was increased in quiet areas, indicating that the contrast between the wind turbine noise and the background sound makes it not just easily detectable, but also annoying. The special sound characteristics of wind turbine noise, generated by the rotation of the blades, were found to be perceived as especially annoying (Figure 8 and Table 13). Experimental studies have shown that background sound influences annoyance, so that the same sound played back against different background sounds would be rated differently [see, e.g., Fidell et al. 1979]. The predicted detectability of a sound in those studies was strongly associated with annoyance. Reaction to low-level noises, for example expressed as annoyance, could therefore not be regarded without taking the probability of perception into account.

The higher risks of perception and annoyance in quiet areas were reflected in the differences found between rural and suburban areas. The results showed higher risks of both perception and annoyance in rural landscapes compared with suburban areas, findings consistent also when other moderating factors were taken into account (Tables 15 and 16). A rural area presumably comprises background sounds of lower levels than found in a suburban area. In addition, the character of the sounds is different. The background sound of a rural area mainly contains natural sounds with only occasional incidents of anthropogenic noise, leading to large contrasts between the wind turbine noise and the background sound. A constant swishing noise could in this sound context be experienced as intrusive, and may also be incongruent with sounds normally expected to be heard in that surrounding.

Visual intrusion

The visual appearance of the wind turbine could likely be perceived as incongruent with the background. Attitude towards the visual impact of the wind turbines was correlated with noise annoyance, especially in Study I which was carried out in a flat, mainly rural, landscape where the wind turbines were highly visible (Table 9). The magnitude of the correlation coefficient is comparable with that of the correlation coefficient found in the previous study, carried out in a similar landscape in Denmark ($r_s = 0.51$ vs. $r = 0.48$) (Table 9 and Section 2.2). More systematic analyses in Study IV, based on a theoretical model, showed that negative visual attitude towards wind turbines increased the risk of noise annoyance in a flat landscape, but not in complex terrain (Figure 9). This indicates that an aesthetic response [Ulrich 1983] to wind turbines moderates the response to noise. Wind turbines are human-made vertical objects placed in a semi-natural surrounding dominated by horizontal lines. They could therefore be judged as aesthetically incongruent with the landscape. The same has been observed for other built features such as utility poles [Brush and Palmer 1983; Priestly and Evans 1996].

Not only the contrasting appearance, but also, the moving of the rotor blades attracts vision. Informants annoyed by wind turbine noise in Study II described the constant rotation as annoying and impossible to ignore. Humans are equipped with multiple sensory channels through which we experience the environment [Stein and Meredith 1993]. By using our cross-modal capabilities we enhance our ability to recognize and detect external stimuli [Calvert 2001]. The visual attention that wind turbines demand, with their prominent appearance and rotating movement, could therefore increase the risk that a person will be alerted by the noise and hence appraise it as annoying.

Personal values

The influence of the surroundings in which wind turbines operate is also related to individual factors that determine the response to wind turbine noise. Wind turbines are placed in environments that are usually not explored in community noise studies. These environments may have special value for some people. In Study II informants who regarded their living environment as a quiet and peaceful place for rest and recovery were found to perceive the wind turbines as intrusive (Figure 7). Noise and visual stimuli had entered the home environment in spite of boundaries, such as fences and personal markers, which had been put up to indicate a private territory. The home is part of the self-identity [Smith 1994] and therefore an intrusion could be experienced as an offence to the individual and lead to a strong reaction. It was also found in Study III that people who had put an effort into their homes and had renovated their dwellings were more likely to be annoyed by wind turbine noise than others (Table 8). The feeling of intrusion can be enhanced by the fact that wind turbines are tall objects, especially if they are placed on a hill. Vertical visual angle had an influence on noise annoyance, even when the variable was moderated so that the height of the wind turbine was considered, rather than the distance, which also influences estimations of noise levels (Section 5.5).

The frequency of respondents did not decrease with increasing annoyance rates at all 2.5 dB(A) intervals (Table 5). A small group of respondents reported that they were very annoyed by wind turbine noise at SPLs not found to be annoying in other studies of community noise. The strongly adverse reactions against the noise indicate that the wind turbines were appraised as goal incongruent by some of the respondents. If possibilities to rest and recover are considered to be important qualities of the living environment, as for some of the informants in Study II, noise and visual stimuli from wind turbines would threaten these values (Section 5.5). Respondents annoyed by the noise in Study III did not find their living environment suitable for recovery and gaining strength, indicating that these respondents thought of the wind turbine noise as a hindrance to psychophysiological restoration (Table 8).

Being employed predicted perception of wind turbine noise in Study III, contrary to the hypothesis, possibly because individuals who leave the house for work are more observant of stressors that could interfere with their recovery needs at home (Table 7). Wind turbine noise was most frequently reported as annoying when relaxing outdoors and at barbecues, conditions that are meant to be comforting (Section 5.1). Hindrance to psychophysiological restoration on a long-term basis could lead to stress-induced health impairment. However, no direct association between A-weighted SPL and health was found in the studies. Noise annoyance was, however, associated with decreased well-being and lowered sleep quality (Section 5.6). It could be that a person with decreased well-being or bad sleep more easily appraises wind turbine noise as annoying, but the observed variation could also be due to indirect effects of noise exposure. It is therefore important to decrease the undesirable influence of wind turbine noise on psychophysiological restoration qualities of the home, as adverse effects on well-being cannot be excluded at this stage.

Adverse feelings aroused by the wind turbine noise in Study II were also influenced by feelings of lacking control, being subjected to injustice, lacking influence, and not being believed (Figure 7). Not being able to control the noise source is known to increase the risk of noise annoyance [Hatfield et al. 2002], possibly due to prevention of constructive coping [Törestad et al. 1990] such as tuning off the noise. Findings from experimental studies indicate that uncontrollable noise induces higher levels of physiological arousal than does controllable noise [Geen and McCown 1984], a possible explanation for the strong reactions observed, but also a risk factor for adverse health effects. Appraising an exposure to noise as an unfair social situation has in experimental studies been shown to increase the risk of noise annoyance [Maris et al. 2006]. These findings are of importance for future wind farm developments. The process would possibly be rated as fair if it is experienced as transparent, i.e. if all information is given to the public, if possibilities for discussions between developers and the public are provided, and also, if alternative placements of the wind turbines are offered, from which the public can choose the most favourable, from their point of view. Giving the public real influence would likely lessen the strain if the wind turbine noise is found to be annoying at a later stage. Preferably this should be combined with the possibility for people living nearby the wind turbine to control the noise; how this should be arranged is, however, not within the scope of this thesis.

Attitude towards the source, known from other community noise studies to influence annoyance, was found to be associated with noise annoyance in these studies (Table 9). The designs of the studies do not allow conclusions about causality, and for this reason, it is not known whether a negative evaluation of the wind turbines enhances noise annoyance, or vice versa. The successful changing of annoyance ratings through manipulation of attitude in experimental studies indicates, however, that attitude, at least in part, precedes evaluation of the source (Section 2.1). The wind turbines were judged to be environmentally friendly by most of the respondents, followed by positive evaluation of the utility ("necessary" and "efficient") and negative evaluation of aesthetic appearance ("ugly" and "unnatural") (Table 10). More negative adjectives were chosen among respondents in Study I, in which we also found a higher frequency of noise annoyance than in Study III, supporting the observed association between a negative attitude and noise annoyance. The correlation coefficients between the general attitude towards wind turbines and noise annoyance in these studies were, however, lower than those found in other community noise studies (Section 2.1). The general attitude towards wind turbines was of less importance than visual attitude. This, together with positive ratings of the utility of the wind turbines and negative ratings of the aesthetic appearance, implies that attitude towards a noise source is not something unspecified, but that it is directed towards significant features of the noise source. This should be taken into account when other community noise sources are studied, as it could possibly explain some of the differences found between studies of different noise sources.

Other implications
Experiences made on special occasions could possibly also influence the ratings of noise annoyance. The dose levels in the dose-response relationships, shown below in Figures 10 and 11, assume a wind speed of 8 m/s at 10 m height, downwind, a situation representing a "worst case" scenario. As expected, the respondents reported that the wind turbine noise was more noticeable than usual when the wind was blowing from the wind turbine towards their dwelling and when the wind was fairly strong (Table 6). However, the sound was also easier to perceive on warm summer evenings, and also to some degree at night; times when the temperature gradient from the ground to the hub height could be predicted to be inversed. Inversion induces a higher difference in wind speed between the wind turbine and the ground than accounted for in the used sound propagation model (Section 2.2). The sound emission levels on these occasions will therefore be higher than calculated at the dwelling of a person living near a turbine, at the same time as the sound is poorly masked by wind-induced noise in trees and bushes because of low wind speeds on the ground. The same situation could arise where the topography and wind direction lead to high wind speeds at hub height while a person nearby is sheltered from the wind. Such events could possibly be remembered and increase the overall rating of annoyance with wind turbine noise. The increased risk of perception and annoyance in a rural area with complex terrain in comparison with a rural area with flat ground could be attributed to these kinds of experiences (Tables 11 and 12). Annoyance with wind turbine noise would possibly be decreased if the situation could be avoided, for example by reducing the production of the wind turbine under defined weather conditions.

6.3. Models of dose-response relationships and estimations of prevalence

Factors related to the physical environment were taken into account when dose-response relationships were examined between A-weighted SPL and perception of and annoyance with wind turbine noise. Respondents who could not see any wind turbines from their dwelling were less frequently annoyed by the noise than were those who could see at least one wind turbine (Section 5.5). They also less frequently reported that they noticed the sound (Table 14 and 15). It could not be excluded that there was a physical boundary between their dwelling and the wind turbine, which hindered not just the sight, but also the sound propagation. The physical conditions at each respondent's dwelling were not considered in the calculations of sound emission levels. The SPLs could therefore have been overestimated for respondents who saw no wind turbines from their dwelling. Furthermore, the frequency of perception and of annoyance was higher in some types of landscapes than in others. The main difference was found between rural and suburban areas, but living in an area that had been rated as quiet also increased the probability of both perception and annoyance (Tables 11 and 12). Living in an apartment, which was not common in rural areas, decreased the risk of hearing the noise (Table 7). Two models of the relationship between exposure and perception were therefore developed, one for a rural area with low background sound levels (type A) and one for a suburban area at the edge of a city or a small village in the countryside (type B). Figure 10 shows the estimated probabilities of perception of wind turbine noise related to A-weighted SPLs from wind turbines.

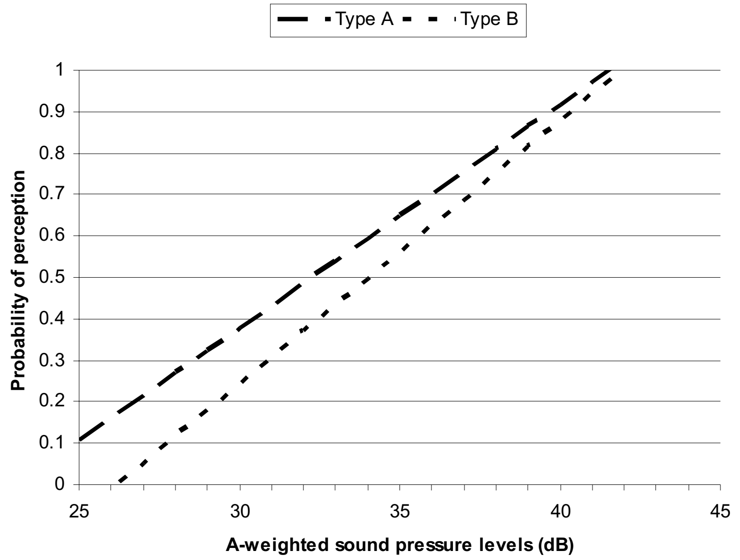

Figure 10. Estimated probability of perception of wind turbine noise outdoors, related to A-weighted SPLs in landscapes of type A (rural, with low background sound levels) and type B (suburban).

The sound levels refer to free field values outside the dwelling of a person receiving the sound at a wind speed of 8 m/s at 10 m height downwind. It is assumed that the wind turbine is visible and that the dwelling is a detached house. The model is derived from probabilities calculated from ORs assessed in binary logistic regressions, using data from studies I and III (cf. Table 5 and Figure 6).

At SPLs of 30 dB(A), the prevalence (in Figure 10 expressed as probabilities) of perception is around 35% for a landscape of type A and around 20% for one of type B. At SPLs of 40 dB(A), which is the recommended limit of exposure to wind turbine noise in Sweden today, around 85% could be predicted to hear the sound in both types of landscapes.

Two models were also created for the relationship between exposure and annoyance (Figure 11), with the same procedures and assumptions as for the models of perception. The relationships were found to be best described by a polynomial function of the third degree. The prevalence for noise annoyance is around 10% at SPLs of 30 dB(A) in landscapes of type A and nil in landscapes of type B. At SPLs of 40 dB(A), the prevalence of annoyance is still higher in landscapes of type A, i.e. around 25%, than in landscapes of type B where the prevalence is around 15%.

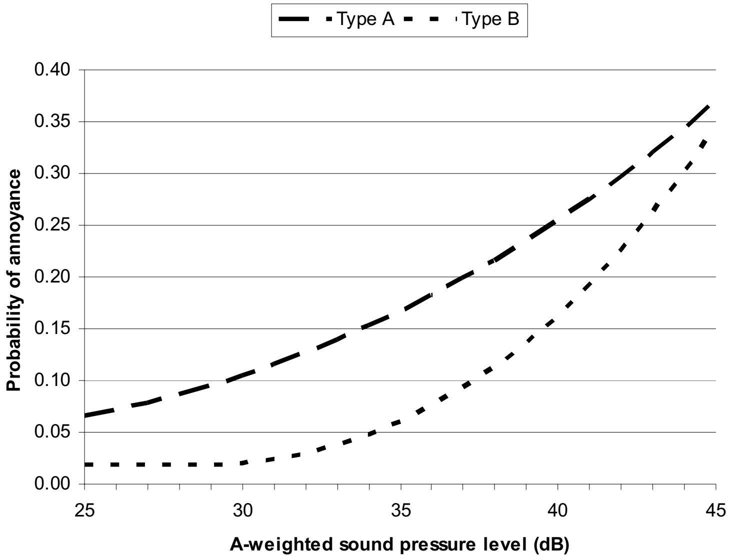

Figure 11. Estimated probability of annoyance with wind turbine noise outdoors, related to A-weighted SPLs in landscapes of type A (rural, with low background sound levels) and type B (suburban).

6.4. Comparison with dose response for other community noise sources

Comparisons between dose-response relationships for wind turbines and those for other community noise sources are difficult to make. Other community noise sources have not been studied at such low SPLs. The response is also often related to DENL, which is not relevant in the case of wind turbines. However, it appears that wind turbines induce an overall higher rate of annoyance in comparison with other community noise sources at low noise levels (Figures 1 and 11). The difference is possibly due to differences in background sound. Already Schultz [1978] explained part of the differences between the community noise studies in his review with differences in background sound levels and sizes of the investigated communities (Section 2.1). Even if dose-response relationships for two different landscapes with different background sounds were derived in this thesis, none of these comprise urban or industrial areas, which is the case with the curves shown in Figure 1. This could lead to the assumption that the annoyance ratings of wind turbine noise would show a higher similarity to other community noise sources if the doses were calculated as differences between the A-weighted SPL of the studied noise and background sound levels. It is, however, important to remember that it is not just the sound levels, but the differences in frequency content and time variation of the studied sound and the background sound that lead to differences of detectability and perceived loudness, and therefore also to differences in annoyance ratings.

Response to wind turbine noise seems to agree most closely with that to noise from aircraft. It is closest in frequency of annoyance and some similarities in the gradient can be found. When comparing Figure 11 with Figure 1, an increase from 10% to 30% in the probability of annoyance requires an increase of 10–15 units (dB(A) or DENL) both for wind turbine noise in a type A landscape and for aircraft noise. It is possible that airplanes entering and leaving an airport at low height over a residential area, with unpredictable occurrence of noise events, could be perceived as visual and audible intruders in the same way as wind turbines.

The influences of variables other than noise are approximately the same for wind turbines as for other community noise sources. The variance in noise levels explained around 13–14% of the variance in annoyance due to wind turbine noise (Table 9), which could be compared to 18% in the studies analysed by Job [1988] (Section 2.1). Differences in which moderating variables are of high importance for noise annoyance could be explained not just by the special features of wind turbines, but also, by differences in noise level range. The association between noise sensitivity and noise annoyance for wind turbine noise (Table 9) was not as strong as in other community noise studies. It could be that noise sensitivity is not so important for response to low-level noise, a hypothesis supported by the findings of Miedema and Vos [2003] (Section 2.1). Annoyance increases more rapidly with increasing sound levels for noise-sensitive respondents than for respondents who are not noise-sensitive, so the difference in annoyance risk between the groups will be more pronounced at higher sound levels. That was also the case in these studies; noise sensitivity was more strongly associated with noise annoyance at SPLs >40 dB(A) (Section 5.2). Dose-response relationships for low-level noise should therefore be studied as a special case and not be derived from studies carried out at higher SPLs.

7. Conclusion

In this work, wind turbine noise induced annoyance at SPLs below those known to be annoying for other sources of community noise. The noise was easily perceived due to the special sound character but probably also due to the moving rotor blades demanding visual attention, making it difficult to ignore the noise. The audible and visual exposure from the wind turbines was experienced as an intrusion of the private sphere and therefore evoked severe reactions, among them noise annoyance. The results indicate that wind turbine noise could reduce possibilities of psychophysical restoration, and adverse effects on health and well-being can therefore not be excluded. The risk of perception of and annoyance with wind turbine noise was, however, different in different situations, and it is consequently not possible to estimate the overall prevalence or find a universal dose-response relationship. Situational factors of great importance were degree of urbanization and visibility of the turbines. Higher proportions of annoyance were found in rural areas, in comparison with suburban areas, where the background sound levels are low and the wind turbine noise interferes with individual values of the living environment. The risk of noise annoyance also increased when the wind turbines were visible, in comparison with when they were not visible. This could in part be explained by the demanding visual attention and in part by differences in noise emission levels not taken into account in the calculations of the dose. The main individual factor that influenced response to wind turbine noise was also a visual factor, which could be expressed as a visual aspect of the attitude towards the noise source. Wind turbines were judged as ugly and unnatural, besides being assessed to be environmentally friendly, necessary and efficient. Negatively appraising the impact of the wind turbines on the landscape scenery was highly associated with noise annoyance, indicating that the special feature of wind turbines as prominent objects enhances the feeling of intrusion and therefore also of noise annoyance.

Wind turbine developments would be facilitated if wind turbines were planned in such a way as to minimize intrusion into people's living environment. To avoid unnecessary adverse effects it is advisable that the special features of the environment where a proposed wind farm is planned be taken into account and that the public be given a significant role in the planning process.

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