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Wind turbines—low level noise sources interfering with restoration?

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Abstract
Wind turbines generate a low level noise and would thus not be expected to cause annoyance and disturb rest. In a society where people are being exposed to an increasing noise load, moderate and low level noise sources may also be perceived as annoying and hence inhibit restoration. This article presents an analysis of two socio-acoustic studies of wind turbine noise with the emphasis on perception, annoyance and consequences for restoration. It is hypothesized that low and moderate stressors such as wind turbine noise could have an impact on health. The risk seems to be higher if restoration is, or is perceived to be, impaired and also for certain groups of individuals. The observations warrant further studies.

Keywords: wind turbine noise, perception, annoyance, restoration

1. Introduction

Human activities have led to increasing noise pollution in residential and occupational settings. The adverse outcomes due to noise (unwanted sound) have previously been extensively reviewed as regards transportation noise (e.g. Schultz 1978, van Kempen *et al* 2002, Babisch 2006) and occupational noise (Zhao *et al* 1993, Passchier-Vermeer and Passchier 2000, Stansfeld and Matheson 2003, Davies *et al* 2005). While an increased risk for ischaemic heart disease is generally found for occupational noise around 85 dB LpAeq 8h, and transportation noise above about a daytime average of 65–70 dB LpA,[1] the picture is heterogeneous for hypertension and even more so for biochemical effects. As regards adverse outcomes of low and moderate noise levels, less information is available. In a society where people are being exposed to an increasing noise load, it can however be hypothesized that moderate and low level noise sources will also be perceived as annoying and hence reduce the restoration needed to recover from daily stress.

Some support for this can be found from studies investigating adverse reactions to sources of low and moderate levels such as low frequency ventilation and compressor noise in living areas (Persson Waye and Agge 2005, Wallenius 2004), noise from neighbours (Stansfeld *et al* 2000) and wind turbines (Pedersen and Persson Waye 2004, 2007). In Persson Waye and Agge (2005) the prevalence of noise annoyance was, apart from the sound pressure level, strongly related to disturbed rest. Noise annoyance was furthermore greater for those with bedrooms facing the yard where the compressor/ventilation units were placed, and negatively associated with the perceived restoration qualities of the yard. Inhibited restoration or hindrance of psychological stress recovery due to disturbance from noise sources is today believed to have an important impact not only on mood but also more long term health consequences (Staats 2003). While research in this area is much needed to fully explore these ideas, it has been found experimentally that exposure to restorative environments facilitates recovery from mental fatigue (Wallenius 2004).

One obvious factor affecting the response to these low and moderate level noise sources is the audibility of the noise, which in turn depends on the inherent sound properties of the source in relation to the sound properties of the ambient sound. It has for example been found experimentally that the same sound played back against different background sounds was rated differently (Fidell *et al* 1979, Persson *et al* 1990), thus supporting the importance of signal detectability for human response. It is also well known that inherent sound properties

[1] Acoustic definitions according to ISO 80000-8:2007.

such as amplitude modulations are easily perceived by the human ear (Fastl and Zwicker 2007) also against different background sounds (Arlinger and Gustafsson 1988). Sounds that are easily perceived and difficult to filter out would be perceived as intrusive. Other factors that would influence the response to noise sources are the opinion of the necessity and the controllability of the noise source (Kjellberg *et al* 1996, Hatfield *et al* 2002), individual noise sensitivity (Öhrström *et al* 1988, Persson Waye *et al* 2001) and the context within which the noise is heard (Schulte-Fortkamp and Fiebig 2006).

While context can be generic such as home and work, it is also closely related to the individual's expectation for that environment and the situation, and formed by e.g. cultural, personal and social parameters. Although the quantitative impact of context is not fully explored, when the context is one's home it can be hypothesized that most intrusive sounds, regardless of level, would interfere with restoration.

Wind turbines are new sources of community noise. They generate a 'broadband' low level sound but with inherently easily perceived modulations. The modulations are caused by the differences in wind velocity at different heights of the area swept by the rotor blades and the effect of the wind being slowed down by the tower, increasing and decreasing the wind-induced sound power level with the pace of the rotation (van den Berg 2006). Turbines are placed mainly in rural areas with low ambient sound pressure levels and in an environment where the intrusion of the sound can be expected to be high.

To explore the impact of this noise source in this special context, two cross sectional socio-acoustic studies were carried out: one in a flat landscape in mainly rural settings (Pedersen and Persson Waye 2004) and another in a landscape with different terrains (complex or flat) and different degrees of urbanization (rural or suburban) (Pedersen and Persson Waye 2007). This article presents an analysis of both studies with the emphasis on perception, annoyance and consequences on restoration.

2. Method

Twelve geographical areas in Sweden were chosen in total for these studies. The study areas all contained one or more wind turbines with at least a nominal power of 500 kW. The 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.

The study population consisted of all people living within an immission level of $\geqslant$30 dB(A) due to wind turbine sound. One person in each household was randomly sampled. The study sample was in densely populated areas further reduced using randomization to avoid unnecessary costs and comprised in total 1822 people of age 18 and older. Questionnaires assessing response were delivered to the study sample. For each respondent, outdoor A-weighted sound pressure levels (SPLs) from the nearest wind turbine were calculated based on wind conditions of 8 m s^{-1} at 10 m height, with the wind direction towards the respondent, according to Swedish Environmental Protection Agency (2001) guidelines.

Subjective responses were obtained through a questionnaire masked to give the impression of investigating general living conditions in the countryside. The questionnaire comprised questions on response to several sources of possible disturbance in the living area. Response to wind turbine noise was assessed with a five-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'. The same scale was used to measure the response to specified sound characteristics of wind turbine noise. These characteristics were defined in a previous experimental study (Persson Waye and Öhrström 2002) and complemented with locally used phrases. The respondents' evaluation of wind turbines in general and of wind turbines' impact on the landscape scenery were measured with a five-point VRS ranging from 1 = 'very positive' to 5 = 'very negative'. The subjects were also asked which of the following terms they thought described wind turbines: efficient, inefficient, environmentally friendly, harmful to the environment, unnecessary, necessary, ugly, beautiful, inviting, threatening, natural, unnatural, annoying, blends in. Demographic data as well as current status of health and well-being were furthermore assessed in the questionnaire, as well as sensitivity to noise, odour, air pollution and litter (four-point VRS from 1 = 'not at all sensitive' to 4 = 'very sensitive'). A subsample of the respondents ($n = 752$) were asked to agree or not agree to ten statements about their living environment (five-point VRS ranging from 1 = 'do not agree at all' to 5 = 'completely agree'). The statements assessed the perception of the background noise in the area, expectations of the environment (for example as a place suitable for resting and gaining strength), and the respondent's feeling of belonging. A factor used to classify the areas either as quiet or as not so quiet were derived from three of the items: (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'.

Associations between variables were assessed using Spearman rank correlation. Covariance analyses were carried out with linear multiple regression. Differences in means between groups were assessed using Student's t-test for continuous variables and with a Mann–Whitney U-test for ordinal variables. Differences between proportions were calculated according to Altman *et al* (2000). All hypothesis tests were two-sided and p-values of <0.05 were considered statistically significant. A sensitivity score was constructed of four items measuring sensitivity to noise, odour, air pollution and littering (alpha = 0.852; all factor loadings >0.7) using principal component analyses; the score reflected 69% of the variance of the four items. Stress scores were constructed for the three items strain/stress, feeling irritable and undue tiredness (alpha = 0.762; all factor loadings >0.7) with the same method. The score reflected 68% of the variances in the initial three items.

3. Results

The questionnaires were satisfactorily returned by 1095 respondents (response rate: 60%). The numbers of respondents in each 1 dB(A) interval are shown in table 1.

Table 1. Number of respondents in relation to estimated A-weighted sound pressure levels outside the dwelling of each respondent.

dB(A)	<28	29	30	31	32	33	34	35	36	37	38	39	40	41	>41
n	9	57	89	148	142	118	162	97	59	64	54	34	32	17	13

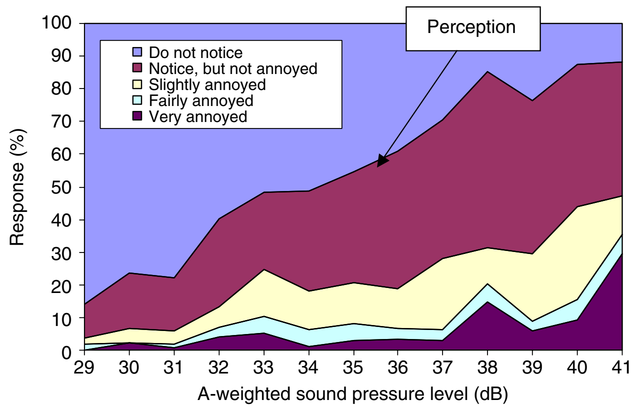

Figure 1. Response to wind turbine noise in relation to A-weighted sound pressure levels outside the dwellings of the respondents ($n = 1095$).

Table 2. Correlations between general response to wind turbine noise ('notice, but not annoyed' to 'very annoyed') and response to specified sound characteristics ('do not notice' to 'very annoyed'), based on respondents who noticed wind turbine sound ($n = 519$).

	r_s	p
Swishing	0.664	<0.01
Whistling	0.508	<0.01
Resounding	0.418	<0.01
Pulsating/throbbing	0.402	<0.01
Scratching/squeaking	0.360	<0.01
Tonal	0.236	<0.01
Lapping	0.215	<0.01
Low frequency	0.200	<0.01

Response to wind turbine noise was correlated with A-weighted SPL ($r_s = 0.401$; $n = 1095$; $p < 0.001$). The proportion of respondents who noticed sound from wind turbines, i.e. had perception of the sound, increased almost linearly with increasing A-weighted SPL (figure 1). A large proportion of the respondents noticed the noise, but were not annoyed. From about 37 dB(A) the proportion of respondents fairly or very annoyed slightly increased. The increase was however not statistically significant. Of those reporting annoyance a small proportion were 'fairly annoyed', while a larger proportion reported that they were 'very annoyed' by wind turbine noise.

Swishing, whistling, resounding and pulsating/throbbing were the sound characteristics that were most highly correlated with annoyance by wind turbine noise among respondents who noticed the noise outside their dwellings (table 2).

Wind turbines were described as environmentally friendly, necessary and efficient, but also as ugly. Response to wind turbine noise was correlated with attitude towards wind turbines in general ($r_s = 0.230$; $n = 1084$; $p < 0.001$) and with attitude towards the impact of wind turbines on the

Table 3. Variables predicting response to wind turbine noise (five-graded scale from 'do not notice' to 'very annoyed') modelled with multiple linear regression. All variables were entered into the model simultaneously ($n = 1070$; $R^2 = 0.31$).

	B^a	β^b	p-values
A-weighted SPL	0.11	0.34	<0.001
Attitude, visual impact	0.40	0.40	<0.001
Attitude, general	0.04	0.04	0.260 (n.s.)

[a] Unstandarized coefficients.
[b] Standardized coefficients.

landscape scenery ($r_s = 0.341$; $n = 1079$; $p < 0.001$); i.e., annoyance with wind turbine noise was associated with a negative attitude towards wind turbines in general and towards their visual impact. When these two attitudinal variables were explored in a linear multiple regression, also adjusting for A-weighted SPL, attitude towards the visual impact of the wind turbines was found to be strongly associated with response to wind turbine noise while the general attitude had no statistically significant impact (table 3). The standardized coefficient for the visual attitude was furthermore in the same range as that of A-weighted SPL.

Response to wind turbine noise was correlated with the respondent's judgment of the possibility for recovery and regaining strength in the current living place. The correlation was negative, meaning that respondents that were annoyed by wind turbine noise did not think of the area as a suitable place for recovery and regaining strength ($r_s = 0.128$; $n = 745$, $p < 0.001$).

About half of the respondents rated themselves as fairly sensitive or sensitive to noise (51%; $n = 540$). Noise sensitivity was not correlated with sound pressure levels ($r_s = 0.000$; $n = 1083$; $p = 0.991$), but with response to wind turbine noise ($r_s = 0.095$; $n = 1083$; $p < 0.01$), although to a low degree; being sensitive to noise increased the risk of noise annoyance or vice versa. The proportion of respondents who were sensitive to noise differed in relation to previous living conditions. The largest proportion of noise sensitivity was found among respondents who had lived in a city and the lowest among those who always had lived at their current residence (table 4). The difference between these two groups was statistically significant.

A small group of respondents reported that they were fairly or very annoyed by wind turbine noise ($n = 84$). This group did not differ from the rest in distribution of age or sex. Respondents who were fairly or very annoyed by wind turbine noise reported that they were sensitive to noise to a higher degree than other respondents (MWU test -4.00; $p < 0.001$). They also had a higher sensitivity score ($t = 3.38$; $df = 1072$; $p < 0.01$); i.e. they were more sensitive to noise, odour, air pollution and littering than other respondents. No differences as regards self-reported hearing

Table 4. Proportion of respondents who rated themselves as fairly or very sensitive to noise in relation to previous living environment.

Previous living	Fairly or very sensitive to noise (%)	Differences between city and other categories (%); (95%CI)
City ($n = 385$)	55	—
Village ($n = 279$)	53	2; (−5.9–9.4)
Countryside ($n = 262$)	50	5; (−2.5–13.0)
Always lived here ($n = 129$)	40	15; (5.9–25.2)

impairment, diabetes or cardiovascular diseases were found between respondents that were fairly or very annoyed versus other respondents. However, respondents who were fairly or very annoyed by wind turbine noise were under more strain and reported stress symptoms; the mean stress scores were statistically significantly higher in this group than among the other respondents ($t = 2.38$; $df = 1038$; $p < 0.05$). The physical environment also differed between the groups. Respondents who were fairly or very annoyed by wind turbine noise more commonly lived in rural areas than in suburban areas in comparison to other respondents (58% versus 28% who lived in rural areas; $p < 0.001$), more commonly lived in flat terrain than in complex terrain (82% versus 63% who lived in flat terrain; $p < 0.001$) and more commonly lived in areas that had been classified as quiet areas (85% versus 59% who had lived in quiet areas; $p < 0.01$). Also, respondents who were fairly or very annoyed by wind turbine noise could all see wind turbines from their dwelling.

4. Discussion

Response to wind turbine noise was significantly related to exposure expressed as A-weighted sound pressure levels dB. Among those who could hear wind turbine sound, annoyance with wind turbine noise was highly correlated to the sound characteristics: swishing, whistling, resounding and pulsating/throbbing. This is noteworthy, as sound characteristics related to the unevenness and the high frequency components in the wind turbine sounds (Persson Waye *et al* 2000, Persson Waye and Öhrström 2002) in experimental studies were found to contribute to unpleasantness and awareness (Persson Waye and Agge 2000). There is thus support both from experimental and field studies that intrusive sound characteristics not fully described by the equivalent A-weighted sound pressure level contribute to annoyance with wind turbine noise.

Nonetheless, it does not entirely explain why some people become very annoyed by these low A-weighted sound pressure levels, as only a small proportion of those who could hear the noise were also annoyed. Some guidance can be found from the finding that the respondents' judgments of the possibility of recovery and regaining strength in their current living places were related to noise annoyance, meaning that respondents annoyed by wind turbine noise did not think of the area as a suitable place for restoration. Restorative experience can be seen as the degree to which an environment can aid recovery from mental fatigue and restoration of attentional capabilities. Kaplan and Kaplan (1989) found that natural environments often have restorative qualities. In the study presented here, the prevalence of noise annoyance was higher among people living in more natural environments, i.e., rural versus urban environments, and also among those who lived in areas where the ambient level was classified as quiet, supporting the idea that inhibited possibilities for restoration were related to noise annoyance. Also visual components making the environment less natural may reduce the restorative experience (Herzog *et al* 2003). Although that finding was based on comparisons between urban and natural environments and hence not directly applicable to the environments investigated in this study, seeing a wind turbine in an otherwise non-industrial environment may reduce the individual's perception of the naturalness of the area and reduce the perception of restoration possibilities. A negative attitude towards the impact of wind turbines on the landscape was in the present study associated with noise annoyance to about the same degree as A-weighted sound pressure levels. Even though the study design did not allow conclusions as regards cause and effect (does a negative attitude lead to noise annoyance or vice versa?), this indicates that the visual properties of wind turbines play an important role in how the noise is perceived. The large impact of visual aspects in studies as regards resistance to local wind turbine projects (Wolsink 2005) shows that not only the noise, but also the prominent appearance of a wind turbine could be perceived as intrusive. The rotor blades of a wind turbine are furthermore almost constantly moving, attracting attention and making it difficult to ignore seeing the wind turbine. Inability to disregard visual and audible intrusion possibly adds to the impression that the environment is unsuitable for restoration.

It has previously been suggested that inhibited restoration could have an impact on health (Staats 2003, Laumann *et al* 2003) and mental recovery (Wallenius 2004). Respondents who were fairly or very annoyed by wind turbine noise were under more strain and reported more stress symptoms. Whether this finding was a result of noise annoyance, poor restoration or due to a general high stress level cannot be concluded from this study as no questions on daily 'hassle' or daily stressors in general were included. In line with the attention restoration theory outlined by Kaplan (1995), it can however be anticipated that people with a need for recovery, for example when coming home from a stressful day at work, would react strongly and with annoyance if their home environment was made unsuitable for restoration by the intrusion of an annoying sound or a visually intrusive object. This should be investigated in further studies.

In accordance with previous studies (e.g. Job 1999, Miedema and Vos 2003), being sensitive to noise was related to noise annoyance. This study did however also show that respondents having moved from the city to the rural area were more sensitive to noise than people who had always lived there, possibly indicating an intentional seeking of naturalness among the former. Interestingly, it was also found that noise annoyance was strongly predicted by a general sensitivity index. Noise sensitivity could thus be a measure of vulnerability to sensory stimuli and a measure of risk of becoming annoyed by any stimuli. Further studies of this are clearly needed.

In this article we have put forward the hypothesis, and some support for the possibility, that low and moderate stressors such as wind turbine noise could have an impact on health. The risk seems to be higher if restoration is, or is perceived to be, impaired and also for certain groups of individuals. There are though many questions still to be answered before conclusions can be drawn. In the light of these findings it seems feasible to carry out further studies on low level stressors, include better measures of daily 'hassle' or daily stress in general and to study the restoration experience more closely.

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