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## **Human response to wind turbine noise – annoyance and moderating factors**

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### **Summary**

Wind turbines are regarded as industrial sources of noise and as such, guidelines based on knowledge originate from situations rather different from those normally connected to wind turbines are used. A rural setting, constantly moving rotor blades, unpredictable incidences of noise, and easily perceived sound properties are examples of factors that indicate the need for new regulation. In an ongoing project on human responses to wind turbines, the relationship between A-weighted sound pressure level (SPL) and self-reported annoyance with wind turbine noise is studied together with moderating factors. In an initial cross-sectional field study among people living in a rural area with several wind turbines close by, a dose-response relationship between A-weighted SPL and noise annoyance was found ( $r_s=0.40$ ;  $n=341$ ;  $p<0.001$ ). When comparing the findings with dose-response relationships for other stationary noise sources, the proportion annoyed by wind turbine noise increased more rapidly with exposure. Of the possible moderating factors measured in the study, the attitude to wind turbines' visual impact on the landscape scenery seemed to be most important. To deepen the understanding of why the noise sometimes causes severe reactions and explore the influence of non-audible factors, a qualitative study was completed. In-depth interviews with people ( $n=15$ ) living in the vicinity of wind turbines were analyzed according to Grounded Theory. The wind turbine noise was by some of the informants perceived as intruding into private domain, physically into the garden and the home, but also as intruder into themselves. The informants' conception of the countryside as either a place of peace and quietness or a place for development and economic growth seemed to influence the adverse effect of the noise, together with feelings induced by the experience of lacking control, being subjected to injustice, lacking influence, and/or not being believed.

## 1. Introduction

Wind turbines are regarded as industrial sources of noise and as such, guidelines based on knowledge originate from situations rather different from those normally connected to wind turbines are used. A rural setting, constantly moving rotor blades, unpredictable incidences of noise, and easily perceived sound properties are examples of factors that may require a new base for regulation. A dose-response relationship between A-weighted sound pressure levels (SPLs) of wind turbine noise at the dwellings of people in wind turbine areas and responses as proportion annoyed by the noise should be established. Such relationships have been established for other types of community noises, e.g. transportation noise [Miedema and Voss 1998], and recently for stationary (industrial) sources [Miedema and Voss 2004] although that study did not include wind turbines.

In developing dose-response relationship for wind turbines moderating factors known from studies of other community noise sources (road traffic, railways, aircraft, and industries) should be taken into account. Two factors that more consistently has been found to be of importance for noise response are noise sensitivity and attitude to the noise source. In a review of factors influencing the relationship between community noise exposure and reaction, research from ten different countries and nine different types of noise sources were examined [Job1988]. The mean correlation between reaction and noise sensitivity was 0.30 and between reaction and attitude 0.41. The correlation between the noise exposure and noise sensitivity was low ( $r=-0.01$ ), and between noise exposure and reaction 0.15. Job suggests that there is a cause-effect relation between sensitivity and reaction even if the direction of causality is not established. The influence of attitude to the source is somewhat more complicated; it seems to be in part, a genuine factor of reaction, and in part, a result of the reaction itself. The results were supported by a meta-analysis of 136 community noise surveys with the objective to evaluate 22 personal and situational variables hypothesised to influence noise annoyance [Fields 1993]. In this study, none of the nine demographical variables (age, sex, social status etc.) could be associated to noise annoyance. Noise annoyance was related to five factors; general noise sensitivity, fear of danger from the noise source, noise prevention beliefs, beliefs about the importance of the noise source, and annoyance with non-noise impacts of the noise source (e.g. air quality). Of special interest for the case of wind turbines was the findings that noise annoyance was not affected to an important extend by ambient noise levels. It should though be noted that only a few studies on community noise annoyance have been carried out in areas with ambient noise levels as low as 40 dB ( $L_{Aeq}$ ). Interesting was also that even at low noise levels (in Fields meta-analysis defined as below DNL 55), a small percentage of the respondents were highly annoyed and that the extent of annoyance was related to noise exposure. This indicates that a dose-response relationship between noise and reaction could be found even for sources producing low level noise.

Other moderating factors not so frequently studied could also be of interest when exploring the effects of wind turbine noise. Visual interference of relationships between noise exposure and noise annoyance has been found in experimental studies of traffic noise [e.g. Kastka and Hangartner 1986, Viollon *et al.* 2002], findings highly relevant for large, tall objects as wind turbines. The visual variables were though in these studies not the actual noise sources. Wind turbines are not only visual objects, but sources of visual stimuli in addition to noise. Flashing shadows occur if the sun is shining behind the wind turbine in relation to a dwelling and the rotor

blades are directed perpendicular to the sun rays. When the sun rays are cut off by the rotor blades, a strobe-like light can be perceived at the dwelling. The number of events and the lasting of the events could be calculated out of astronomical data and expressed as hours per year. The value is dependent of the distance between the wind turbine and the receiver as the noise exposure, but it also depends on the geographical direction, hence the two types of exposures are only to a part correlated. The effect of both visual and audible stimuli from the same source could be hypothesised to influence the response.

As wind turbines are new sources of noise and visual annoyance it is important also to study the occurrence of hitherto unknown moderating factors.

The most relevant previous study on human responses to wind turbine noise when exploring dose-response relationships, to our knowledge, was performed in Denmark, the Netherlands, and Germany in the early 1990's. [Wolsink *et al.* 1993]. The main aims of that study were to explore the correlation between noise exposure from wind turbines and noise annoyance among residents and to find other variables of importance for the annoyance. The sampling of study subjects were done so that the average A-weighted SPL due to wind turbines that subjects were exposed to was approximately 35 dB with a standard deviation of 5 dB from an almost normal distribution. Of the 574 residents who responded to a questionnaire, 93.6% answered that they were not at all annoyed by wind turbine noise; remaining 6.4% (n=37) reported some degree of annoyance. Most of the noise was experienced outdoors and between 16.00 pm and midnight. 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).

An attempt to find more of the knowledge needed was done within an ongoing project on human responses to wind turbines. In an initial cross-sectional field study, Study I, the aims were

- to evaluate the prevalence of annoyance due to wind turbine noise
- to study dose-response relationships between calculated A-weighted SPL and noise annoyance
- to describe interrelationships between noise annoyance and individual factors such as noise sensitivity and attitude to the source

To further describe the response and reveal new factors influencing the dose-response relationship, people whom experienced audio and visual exposures from wind turbines in their homes were interviewed and their reports analysed qualitatively in Study II.

Study I has previous been presented in Pedersen and Persson Waye [2004]. A summary of the main result and some new aspects of the data analysis will be presented here. The results of Study II have not yet been published.

## 2. Method

Study I was carried out in the south of Sweden in the summer 2000 and comprised respondents exposed to different SPLs from wind turbines. In the study areas, 16 wind turbines (14 of nominal power 600 kW) were situated. The study population consisted of one randomly selected subject between the ages of 18 and 75 in each household living in the vicinity of at least one wind turbine (n=518). Subjective responses were obtained through a questionnaire, which purpose was masked. Among questions of living conditions in the countryside, questions directly related to wind turbines were included. Annoyance perceived outdoors was rated on five categories verbal scales ranging from "do not notice" to "very annoyed". The term "annoyed" in this paper refers to respondents that rated themselves "rather annoyed" or "very annoyed". Noise sensitivity was measured with four categories from "not sensitive at all" to "very sensitive". Attitude questions comprised of five categories from "very positive" to "very negative". A total of 356 respondents were included (response rate 69%). For each respondent outdoor A-weighted SPL (free field) from nearby wind turbines were calculated based on wind conditions of 8 m/s with the wind direction towards the respondent according to [The Swedish Environmental Protection Agency 2001]. The calculations are summarised in Pedersen and Persson Waye [2004]. The value represents an equivalent SPL for a period of 5-10 minutes under the described conditions. It is not known how often these sound pressure levels occur and therefore the equivalent SPL for 24 hours is not possible to estimate. The respondents were divided into 6 SPL-intervals; <30dB (n=15), 30.0-32.5 (n=71), 32.5-35.0 (n=137), 35.0-37.5 (n=63), 37.5-40.0 (n=40), >40.0 (n=25). Note that there were few respondents in the lowest and in the highest intervals and hence results from these intervals should be treated with care. All significance tests presented in this paper were two-sided and  $p < 0.05$  was considered statistically significant.

In Study II, data were collected through 15 interviews that was taped and transcribed verbatim. Subjects were first chosen strategically among those who in the questionnaires of Study I stated that they were willing to be contacted for further questioning and gave their telephone numbers. The objective of the strategic sampling was to obtain a heterogeneous group by regarding self-rated noise annoyance of wind turbine noise in relation to calculated SPLs from wind turbines as well as gender. As a model emerged the sampling became more theoretical, seeking variance within the identified categories. Subjects were at this stage also chosen from among those who had complained to local authorities concerning various aspects of wind turbines. The interviews were analysed according to the constant comparative method for discovering Grounded Theory [Glaser and Strauss 1967]. The transcribed interviews were coded line-by-line using the subject's own words or immediate expression. The codes were associated with each other to form clusters, categories were identified, and relationships between categories established. Constant comparison among and between transcribed interviews, memos, and categories led to reflections, confirmations, and adjustments in formulating the emerged model.

The results from Study I and Study II will here be presented thematically, but with references to which study they originate from.

### 3. Results

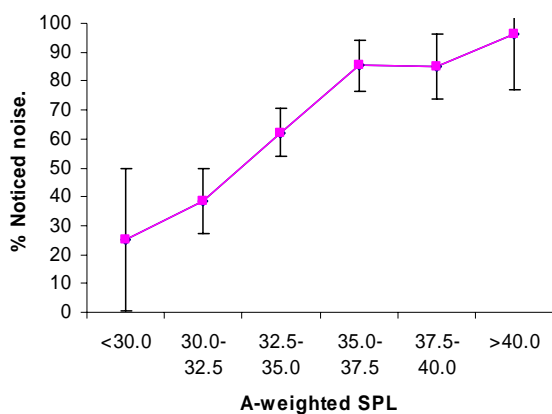
#### 3.1. Perception

Most informants interviewed in Study II described noise as the dominating *not chosen stimulus* of wind turbines, adding blinking shadows, shadows sweeping over the garden, or the constant movement of the rotor blades as a second source of annoyance. The noise was often described as a swishing sound, but throbbing (dunkande), resounding (rungande), rattling (skramlande), and howling (tjutande) were also used as descriptors. Incidents that accidentally increased the noise were remembered (e.g. loose parts) and seemed to increase the negative affection even after they were taken care of. The noise was perceived as constant, not just passing by as a car on the road:

”Well, it’s this that it is never really quiet. It sort of swishes all the time.” (IP9, p.2).

The informants' descriptions of their feelings when exposed to wind turbine noise, as well as shadows and the rotating movement of the rotor blades, were in the analysis interpreted as an *intrusion into private domain*. The noise was physically perceived in the living environment, e.g. in the garden, in spite of bushes and fences put up to keep out invaders, and was to those who could not mentally shut it out, an obstacle to pleasant experiences decreasing the joy of daily life at home. For some of the informants the intrusion went further into the most private domain, themselves, creating a feeling of violation that was expressed as anger, uneasiness, and tiredness.

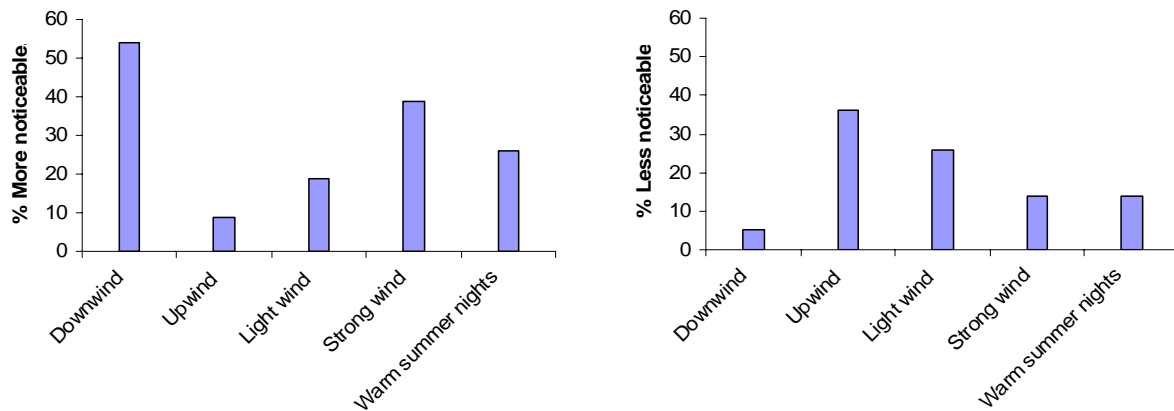
Noise was also the most noticed exposure from wind turbines when measured in Study I and related to the dose. The proportion of respondents who noticed noise from wind turbines outdoors increased with increasing A-weighted SPLs (Figure 1). At SPLs exceeding 35.0 dBA, 85% or more reported that they could hear the noise.



**Figure 1.** The proportion of respondents who noticed noise from wind turbines related to A-weighted SPLs with 95% confidence intervals.

Of those respondents who noticed the sound, 54% (n=103) stated that the noise was more noticeable at downwind conditions (when the wind was blowing from the wind turbine towards their dwelling), 39% (n=68) at strong wind, and 26% (n=44) at warm summer nights. There was

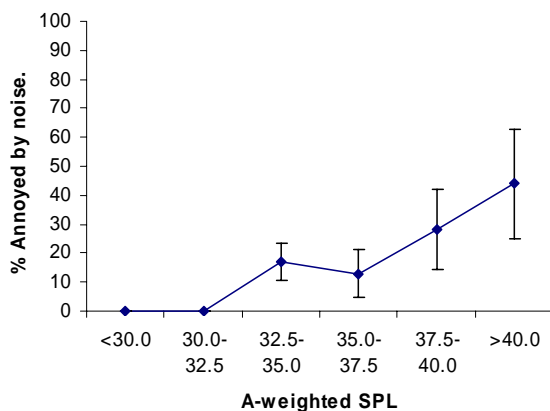
though a variation; some respondents stated that the noise was less noticeable at strong wind and downwind conditions as seen in Figure 2.



**Figure 2.** Proportion of respondents who noticed the wind turbine noise more or less in different situations.

### 3.2. Dose-response

Study I showed that the proportions of outdoor annoyance (rather and very annoyed) due to wind turbine noise increased with increasing A-weighted SPL at SPLs exceeding 35.0 dB (Figure 3). No respondent stated them selves annoyed at A-weighted SPLs below 32.5 dB. At A-weighted SPL of 37.5-40.0 dB the proportion annoyed was 28% (n=11; 95%CI: 14 - 41%) and above 40 dB it was 40% (n=11; 95%CI: 19 - 57%).



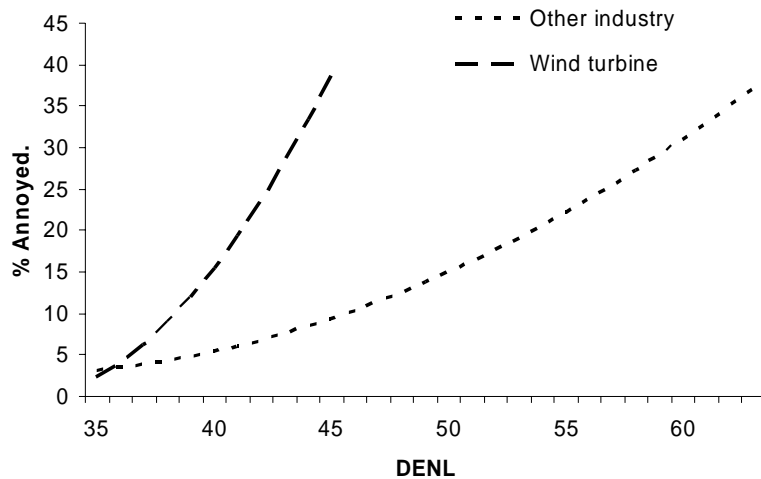
**Figure 3.** Proportion of respondents annoyed by wind turbine noise related to A-weighted SPLs with 95% confidence intervals.

To compare the dose-response relationship for wind turbine noise and response with that for other stationary sources (excluding shunting and seasonal industry) presented by Miedema and Voss [2004], noise exposure metrics day-evening-night levels (DENL) were calculated out of the hypothetical assumption that the SPLs presented above represented the noise exposure  $L_{Aeq24hours}$ .

A polynomial approximation of the dose-response relationship (eq.1) was plotted together with the annoyance curve for other stationary sources (eq. 2) in Figure 4.

$$\text{Wind turbine noise: \%A} = 224.77 - 13.625 \text{ DENL} + 0.2057 \text{ DENL}^2 \quad (\text{eq. 1})$$

$$\text{Other stationary sources: \%A} = 36.854 - 2.121 \text{ DENL} + 0.03270 \text{ DENL}^2 \quad (\text{eq. 2})$$

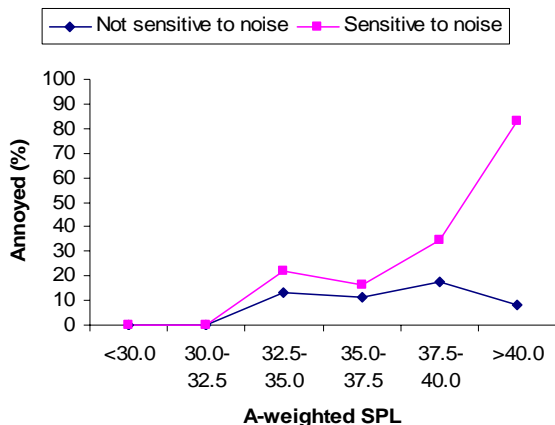


**Figure 4.** *The proportion annoyed persons as a function of DENL for noise from wind turbines and for noise from other industry (not shunting or seasonal industry).*

Figure 4 shows that the proportions of annoyed respondents were comparable between wind turbines and other industries at the starting point of 35 DENL. At higher SPLs the proportion annoyed by wind turbine noise increased more rapidly with exposure than the proportion annoyed by noise from other stationary sources.

### 3.3. Noise sensitivity

Of the respondents in Study I, 50% (n=169), stated that they were "rather sensitive" or "very sensitive" to noise. No association between noise sensitivity and A-weighted SPL was found ( $r_s=0.07$ ;  $p=0.204$ ); the proportion of noise sensitive varied somewhat between the six SPL-intervals, but no trend towards a higher proportion of noise sensitive at higher SPL was seen. Noise sensitivity was statistically significantly related to noise annoyance ( $r_s=0.20$ ;  $p<0.001$ ). Noise sensitivity seemed to influence the dose-response relationship especially at higher SPLs (Figure 5).



**Figure 5.** Proportion of respondents annoyed by wind turbine noise related to A-weighted SPLs comparing respondents not sensitive to noise (not sensitive at all, slightly sensitive) and respondents sensitive to noise (rather sensitive, very sensitive).

Some of the interviewed informants in Study II spontaneously stated that they did not want to get used to the exposure, even though they did not relate this behaviour to being noise sensitive.

“I never wanted to get used to it. We have bought far too expensive cars just so that they would be quiet. [...] No, I am not unusually sensitive. I have been at construction sites all my life [...] But I have been better at using hearing protectors than most people. So I have. [...] We totally agree, me and my wife. We value silence. We seek it.” (IP12, p.9)

### 3.4. Attitude to source

Of the respondents in Study I, 13% stated that they were "rather negative" or "very negative" to wind turbines. Attitude to wind turbines was positively correlated to noise annoyance ( $r_s=0.33$ ;  $p<0.001$ ) and seemed to influence the dose-response relationship (Figure 6). It could not though be excluded that the noise exposure caused part of the annoyance response. No statistically significant association between attitude to wind turbines and A-weighted SPL was found ( $r_s=0.07$ ;  $p=0.170$ ), but the proportion negative to wind turbines were somewhat higher at higher SPLs. Of the respondents living in areas with SPLs > 35 dBA, 16% were negative to wind turbines compared to 11% among those living at lower SPLs.

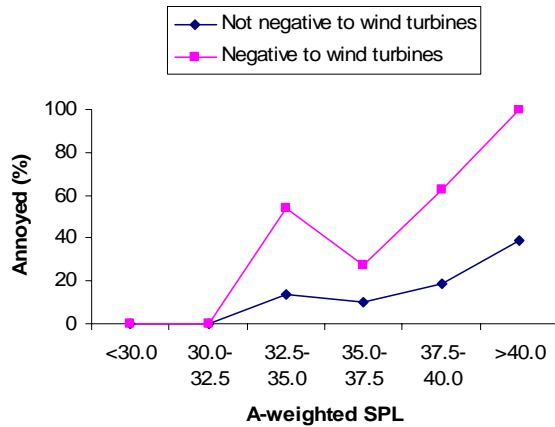
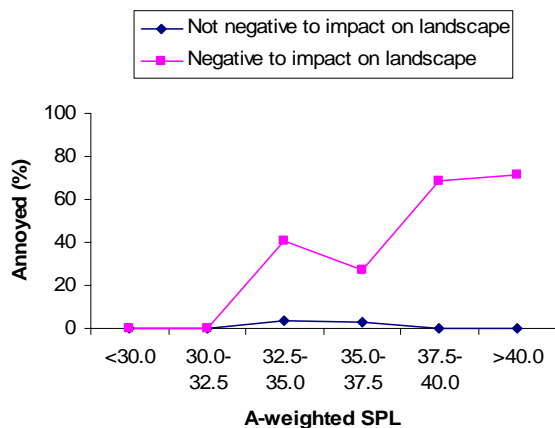


Figure 6. Proportion of respondents annoyed by wind turbine noise related to A-weighted SPLs comparing respondents not negative to wind turbines (very positive, positive, neither positive nor negative) and respondents negative to wind turbines (negative, very negative).

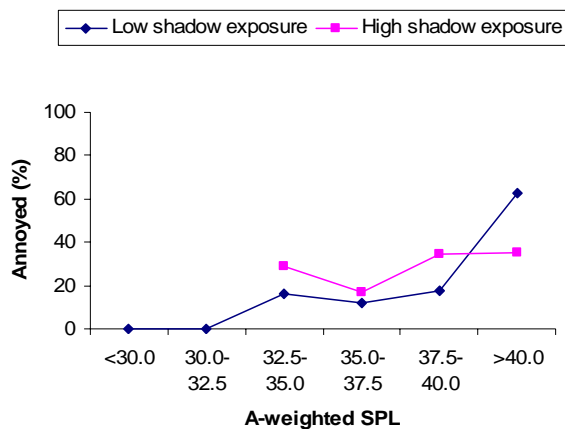
Attitude was also measured in a question regarding the respondent's attitude to wind turbines' impact on the landscape scenery. This factor was related both to SPL ( $r_s=0.15$ ;  $p<0.01$ ) and to noise annoyance ( $r_s=0.51$ ;  $p<0.001$ ); hence attitude to the wind turbines' impact on the landscape scenery could explain the variation in noise annoyance (Figure 7) or it could be that being annoyed by the noise caused a negative attitude to the wind turbines' visual impact. When modelling the dose-response and the influence of attitude in a logistic regression, the noise exposure was still a statistically significant variable for predicting noise annoyance ( $\text{Exp}(b)=1.74$ ; 95% CI:1.29-2.34), even though the attitude to wind turbines' visual impact influenced the prediction highly ( $\text{Exp}(b)=5.05$ ; 95% CI:3.22-7.92).



**Figure 7.** Proportion of respondents annoyed by wind turbine noise related to A-weighted SPLs comparing respondents not negative to wind turbines' impact on the landscape scenery (very positive, positive, neither positive nor negative) and respondents negative to wind turbines' impact on the landscape scenery (negative, very negative).

### 3.5. Visual exposure

Some of the respondents in Study I were exposed to shadows as well as noise from wind turbines. There was a correlation between shadow exposure (hour/year) and A-weighted SPL ( $r_s=0.62$ ;  $p<0.001$ ), but among the respondents exposed to higher A-weighted SPLs the intensity of shadow exposure varied. Of those respondents exposed to wind turbine noise  $> 35$  dBA ( $n=128$ ), 41% were exposed to shadows more than 10 hours/year and hence 59% were exposed to less than 10 hours/year. Among those exposed to lower A-weighted SPLs ( $n=217$ ), almost no one (3%) were exposed to shadows more than 10 hours/year. The shadow exposure did not seem to influence the dose-response relationship between A-weighted SPL and noise annoyance (Figure 8). Noise annoyance and shadow annoyance were correlated ( $r_s=0.50$ ;  $p<0.001$ ).



**Figure 8.** Proportion of respondents annoyed by wind turbine noise related to A-weighted SPLs comparing respondents subjected to low shadow exposure ( $< 10$  h/year) and respondents subjected to high shadow exposure ( $> 10$  h/year).

Several of the interviewed informants in Study II were annoyed by the movement of the rotor blades; a factor not thought about when designing Study I. They described the movement as something that involuntarily attracted the eye. The rotor blades were almost always rotating, leaving no rest from the stimulus to the receivers.

“Every time you walk in the garden or look at that direction, it is spinning. It just spins and spins. It gets you irritated. [...] If you are walking around looking down on the ground, you sort of have it in front of you so that you see it whisk around.” (IP3, p.2)

### 3.6. The rural setting

Some of the interviewed informants in Study II expressed that wind turbines were foreign objects that did not belong in the landscape and that one should be able to expect peace and quietness in the countryside.

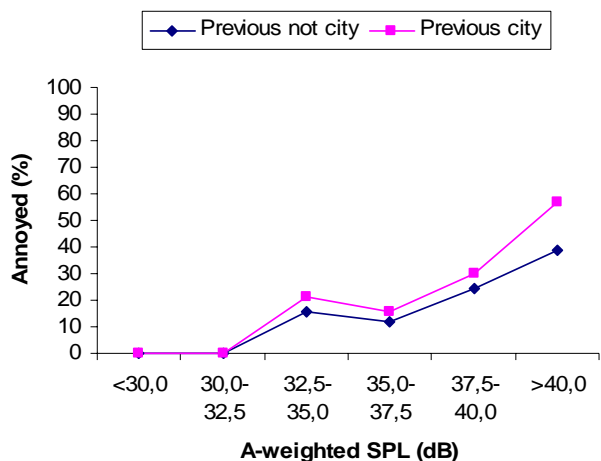
”It is quiet and peaceful in the countryside in spite of tractors and the rail way. I mean, these are occasional sounds. A tractor passes and you know what it sounds like. And a train passes and that sounds too. The neighbours have the hay fans operating, but that is certain weeks and you have to accept that, as they of course need to dry the hay. There

are sounds in the countryside, but some sounds are natural and some are not. It is novel this with wind turbines, that is to say the sound.” (IP13, p.9)

Other informants thought of their living environment as a place for technical achievements and economical growth, and did not perceive the wind turbine noise as obstruct for a good quality of life. The informants hence had different *conception of the living environment*; a factor that might influence the response to wind turbine noise. Some of the informants stated that they had actively chosen to live in the countryside, seeking a place for recovery, even though they were brought up or had temporary lived in a city.

“Where you live is where you should feel well and regain strength in the breaks. We have moved to the countryside because it suits us, you know. Down-to-earth and all that.” (IP9, p11)

Reanalysing the data of Study I, some indications of the importance of the concepts of the living environment could be found. The respondents were asked were they lived before moving to their present residence. About 30% (n=102) had lived in a city before moving to the countryside and the remaining 70% had either lived at the same address as now, in another place in the countryside or in a small town. Former city-residents were slightly more annoyed by wind turbine noise (Figure 9), but the difference was not statistically significant. The main difference in attitude between the two groups was found regarding the attitude to wind turbines impact on the landscape scenery. Of the former city-residents 55% (n=56) had a negative view compared to 33% (n=80) among the others. The difference was statistically significant (Mann Whitney U:  $Z_{MU}=-3.746$ ,  $p<0.001$ ).



**Figure 9.** Proportion of respondents annoyed by wind turbine noise related to A-weighted SPLs comparing respondents that had not previously lived in a city and respondents that had previously lived in a city.

The respondents in the two groups also described the wind turbines slightly different. The respondents were asked to agree or not agree on 14 adjectives as descriptors of the phenomenon wind turbines. Both group rated "Environmentally friendly" the highest, but then the former city-

residents chose "Ugly" (48%) and "Unnaturally" (38%), while the other group rated "Necessary" (39%) and "Effective" (33%) as second and third.

### **3.7. Other variables formed out of experiences**

The extent of intrusion by stimuli from wind turbines felt by the interviewed informants in Study II seemed to in part be determined by the informants' experiences of the situation. The experiences formed four categories, all comprising feelings of inferiority and all somewhat related. Feeling *lack of control* when the wind turbines were built, not being aware of the development plans or the impact the wind turbines would make on the living environment was common. Also the unpredictable occurrences of noise exposure and the impossibility to stop the wind turbines when reacting to audible and visual stimuli, created a feeling of no control of the situation. When trying to take control of the situation by contacting local authorities, a feeling of *lack of influence* sometimes occurred. Most of the informants did not believe that they had any say in the planning of new wind turbines or that complains about the noise would be treated seriously. They felt that they were *being subjected to injustice*, not only by the authorities, but also by the owners of the wind turbines that sometimes lived in other areas, not exposed to audible and visual stimuli themselves. For some informants, the feeling of *not being believed* was the most frustrating; friends and authorities had no understanding for the implication of living close to a wind turbine and the strong reactions the low levels of noise raised.

## **4. Concluding comments**

A dose response-relationship between A-weighted SPL and noise annoyance was found. The results suggest that the proportion annoyed increases more rapidly with increasing SPL than for other stationary sources. The influence of hypothesised moderating factors showed high consistency with previous studies on community noise [Job 1988]; both noise sensitivity and attitude were associated with noise annoyance, especially when attitude was expressed as attitude to the wind turbines' impact on the landscape scenery. The latter indicates that the rapid increase of annoyance could be due to interference of visual factors on the audio perception. Visual aspects could be merely esthetical but the feelings of intrusion found in Study II point towards a complex influence of the wind turbines with a possibility of multi modal and/or interacting effects between audio and visual exposure. The visual stimuli of the rotor blades' constant movement might be a factor that enhances adverse effects. The rapid growth of noise annoyance could also be explained by an appraised incongruence between wind turbine noise and the respondent's conception of his or her living environment in a rural surrounding; the latter a factor probably firmly rooted within a personality and therefore difficult to change. Negative feelings induced by contacts with local authorities and owners of wind turbines also seem to be of importance for the reaction to wind turbine noise, but should be feasible to avoid with proper regulation and appropriate planning process.

In the next phase of the ongoing project on human responses to wind turbines, more data will be collected to achieve a larger base for evaluating dose-response relationships between wind turbine noise and noise annoyance. It would be of great interest if similar studies would be carried out in other countries to enlarge the data base, but also to study possible cultural differences. To evaluate sound propagation algorithms used to calculate the dose, measurements

of sound and meteorological data should also be carried out. The effect of simultaneous audible and visual exposures from the same source is of special interest for future research on responses to wind turbines.

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