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Response to noise from modern wind farms in The Netherlands

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The increasing number and size of wind farms call for more data on human response to wind turbine noise, so that a generalized dose-response relationship can be modeled and possible adverse health effects avoided. This paper reports the results of a 2007 field study in The Netherlands with 725 respondents. A dose-response relationship between calculated *A*-weighted sound pressure levels and reported perception and annoyance was found. Wind turbine noise was more annoying than transportation noise or industrial noise at comparable levels, possibly due to specific sound properties such as a "swishing" quality, temporal variability, and lack of nighttime abatement. High turbine visibility enhances negative response, and having wind turbines visible from the dwelling significantly increased the risk of annoyance. Annoyance was strongly correlated with a negative attitude toward the visual impact of wind turbines on the landscape. The study further demonstrates that people who benefit economically from wind turbines have a significantly decreased risk of annoyance, despite exposure to similar sound levels. Response to wind turbine noise was similar to that found in Sweden so the dose-response relationship should be generalizable.
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I. INTRODUCTION

Community noise is recognized as an environmental stressor, causing nuisance, decreased wellbeing, and possibly non-auditory adverse effects on health (Stansfeld and Matheson, 2003). The main sources of community noise are transportation and industry. Air transport is the most annoying of the dominant means of transport (Miedema and Oudshoorn, 2001), though at comparable sound levels noise from road traffic has the largest impact in terms of number of people affected. Increasing awareness of the adverse effects of noise has led to noise management recommendations, including guideline values to limit health effects in various situations (WHO, 2000) and action plans for reducing noise and preserving quietness (END, 2002), all with the aim of decreasing the overall noise load. Noise impact is quantified based on the relationship between noise dose and response, the latter measured as the proportion of the public annoyed or highly annoyed by noise from a specified source. Several studies have explored the community response to transportation noise. The results of all available studies have been synthesized and modeled to yield polynomials describing the expected proportion of people annoyed by road traffic, aircraft, or railroad noise (Miedema and Oudshoorn, 2001). Dose-response curves have also been modeled for noise from industry and shunting yards (Miedema and Vos, 2004), albeit in relatively few studies. The Lden (day–evening–night) noise exposure metric has been found to best describe the noise load from these sources (Miedema *et al.*, 2000). This metric is based on long-term equivalent sound pressure levels assessed for different times of the day, to which penalties of 5 dB for evening and 10 dB for nighttime hours are added. These penalties reflect the need for quietness at specific times of day when the background sound levels are assumed to be lower.

Wind turbines are a new source of community noise to which relatively few people have yet been exposed. The number of exposed people is growing, as in many countries the number of wind turbines is rapidly increasing. The need for guidelines for maximum exposure to wind turbine noise is urgent: While not unnecessarily curbing the development of new wind farms, it is also important to avoid possible adverse health effects. No generalized dose-response curves have yet been modeled for wind turbines, primarily due to the lack of results of published field studies. To the best of

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the authors' knowledge, there are only four such studies, all of which find different degrees of relationship between wind turbine sound levels and annoyance: (i) a European study carried out in Denmark, The Netherlands, and Germany (Wolsink *et al.*, 1993; Wolsink and Sprengers, 1993); (ii) a complementary Danish study (Pedersen and Nielsen, 1994); (iii) the first Swedish study (Pedersen and Persson Waye, 2004); and (iv) a more recent Swedish study (Pedersen and Persson Waye, 2007). The sizes and heights of wind turbines have increased over the time covered by these studies. The 1994 Danish study included 16 wind turbines of up to 150 kW nominal power with towers under 33 m high, while the latest Swedish study included wind turbines of up to 1.5 MW with towers up to 65 m high. Also, these studies included mostly single wind turbines, while groups of wind turbines, i.e., wind farms, are more common today. The studies all use the *A*-weighted equivalent sound pressure level under specific meteorological conditions (generally winds of 8 m/s at 10-m height and, implicitly, a neutral atmosphere) as the metric for the sound immission levels—the standard for describing the dose of wind turbine noise.

The results of these studies indicate that wind turbines differ in several respects from other sources of community noise. Modern wind turbines mainly emit noise from turbulence at the trailing edge of the rotor blades. The turbine sound power level varies with the wind speed at hub height. It also varies rhythmically and more rapidly as the sound is amplitude modulated with the rotation rate of the rotor blades, due to the variation in wind speed with height and the reduction in wind speed near the tower (Van den Berg, 2005, 2007). Amplitude-modulated sound is more easily perceived than is constant-level sound and has been found to be more annoying (Bradley, 1994; Bengtsson *et al.*, 2004). In addition, sound that occurs unpredictably and uncontrollably is more annoying than other sounds (Hatfield *et al.*, 2002; Geen and McCown, 1984).

Wind turbines are tall and highly visible, often being placed in open, rural areas with low levels of background sound and in what are perceived as natural surroundings. Consequently, wind turbines are sometimes regarded as visible and audible intruders in otherwise unspoiled environments (Pedersen *et al.*, 2007). Furthermore, the moving rotor blades draw attention, possibly enhancing the perception of sound in a multi-modal effect (Calvert, 2001).

In summary, wind turbine noise could be predicted to be easily perceived and—in some environments—annoying, depending on both sound levels and visual aspects. To assess possibly unacceptable adverse health effects, generalized dose-response relationships need to be estimated and related to those of other noise sources. To this end, a field study exploring the impact of wind turbine sound on people living in the vicinity of wind farms was carried out in The Netherlands in 2007. The objectives of this study, reported here, were (i) to assess the relationship between wind turbine sound levels at dwellings and the probability of noise annoyance, taking into account possible moderating factors, (ii) to explore the possibility of generalizing a dose-response relationship for wind turbine noise by comparing the results of this study with those of previous Swedish studies, and (iii) to relate annoyance with wind turbine noise to annoyance with noise from other sources.

II. METHOD

A. Site selection

The site selection was intended to reflect contemporary wind turbine exposure conditions over a range of background sound levels. All areas in The Netherlands with at least two wind turbines of at least 500 kW within 500 m of each other and characterized by one of three clearly defined land-use types (i.e., built-up area, rural area with a main road, and rural area without a main road) were selected for the study. Sites dominated by industry or business were excluded, as these are not representative for residential areas and detailed examination showed that most of the nearest dwellings were not in the industrial areas but far from the wind turbines, thus adding to the already over-populated sound level classes in the study group. In The Netherlands, 1735 wind turbines were operating onshore in March 2006, 1056 of which were of 500 kW or greater nominal electric power. To rule out short-term effects, sites that had changed over the March 2006–March 2007 period (when the study started) were excluded.

B. Study population and sample

The study population consisted of approximately 70 000 adults living within 2.5 km of a wind turbine at the selected sites. The study sample was selected stepwise: (i) The authors identified 4570 postal codes for the selected sites; (ii) for these postcodes, they obtained 17 923 addresses with individual *x* and *y* coordinates from Adrescoördinatenbestand Nederland (the Dutch coordinates file); (iii) these addresses were classified into 5-dB(A) intervals according to *A*-weighted sound immission level due only to wind turbine sound, i.e., <30, 30–35, 35–40, 40–45, and >45 dB(A); and (iv) further classified into the three area types. Statistical power calculations based on the results of previous studies indicated that approximately 150 respondents were required in each of the five immission level groups. As relatively few people were classified as belonging to the highest immission level groups, all people in these groups were assigned to the study sample. In the other groups, the sample was randomly selected, based on an expected response rate of 33%. The final study sample included 1948 people.

C. Assessments of immission levels

A-weighted sound power levels in octave bands (at 8 m/s wind speed at 10-m height in a neutral atmosphere) for all wind turbines ($n=1846$) at the selected sites were obtained from reports from consultancies, manufacturers, and reports used by local authorities, describing the results from sound power level measurements and used as input for calculating sound levels caused by wind turbines. When data were unavailable, which was more often the case for older and smaller wind turbines, the sound power level of a turbine of the same dimensions and electrical output was used. The

TABLE I. Study sample, number of respondents, and response rate according to 5-dB(A) sound level interval.

	Predicted A-weighted sound pressure levels [dB(A)]					
	<30	30–35	35–40	40–45	>45	Total
Study sample	473	494	502	282	197	1948
No. of respondents	185	219	162	94	65	725
Response rate (%)	39	44	32	33	33	37

propagation of sound from the wind turbines toward the dwellings of members of the study population was calculated in accordance with the model legally required in The Netherlands (VROM, 1999), the New Zealand standard as an example of a simple model (NZS, 1998), and the international ISO standard model (ISO, 1996). For all sites, the ground absorption was set to 1 (100% sound absorbing surface) and the receiver height to 5 m. A-weighted sound pressure levels of all wind turbines (including those of <500 kW nominal power) at the dwelling facade were added logarithmically. The values calculated in accordance with ISO will be used as the exposure variable in this paper.

D. Social survey

Subjective responses were obtained through a postal questionnaire presented as a survey investigating general living conditions but also including a section on road traffic and wind turbine noise. The questionnaire was based on one previously used in Swedish studies (Pedersen and Persson Waye, 2004, 2007). Response to wind turbine noise was measured using five different questions, all of which displayed high internal consistency (Cronbach's alpha=0.87). In the present study, response to wind turbine noise was based on the answer to the following question: "Below are a number of items that you may notice or that could annoy you when you spend time outdoors at your dwelling. Could you indicate whether you have noticed these or whether these annoy you?" This question was followed by a list of possible annoyance factors (i.e., olfactory, aural, or visual annoyances from different sources) of which wind turbine sound was one. The question could be answered on a five-point verbal rating scale, where 1="do not notice," 2="notice but not annoyed," 3="slightly annoyed," 4="rather annoyed," and 5="very annoyed." The question was repeated for indoor perception. The scale was dichotomized into "do not notice" (scale point 1) and "notice" (scale points 2–5) when perception was analyzed, into "not annoyed" (scale points 1–3) and "annoyed" (scale points 4–5) for analyzes of annoyance, and into "not very annoyed" (scale points 1–4) and "very annoyed" (scale point 5) for studies of highly annoyed. The whole five-pointed scale was used when correlations between perception and annoyance on one hand, and other variables such as sound pressure levels on the other were studied. Noise sensitivity was measured on a five-point scale ranging from "not at all sensitive" to "very sensitive." Attitudes toward the noise source were measured as the general opinion on wind turbines (general attitude) and on the visual impact of wind turbines on the landscape (visual attitude), as well as with eight polarized items, such as "pretty–ugly" and "dangerous–harmless," all on five-point scales. The questionnaire also contained questions regarding the possibility of hearing the sound under different meteorological conditions, how often the sound was regarded as annoying, whether wind turbines were visible from the dwelling, and whether the respondent benefited economically from the wind farm, either by full or partial turbine ownership, or by being compensated otherwise. The respondents were also asked to choose descriptors of the wind turbine noise from among several alternatives; these descriptors were partly derived from a previous experimental study of the perception of wind turbine sounds (Persson Waye and Öhrström, 2002).

Of the selected study sample, 37% satisfactorily completed and returned the questionnaire (Table I). There was no difference in immission levels between the respondents and non-respondents ($t=-0.38, p=0.703$). A random sample of non-responders ($n=200$) received a short questionnaire comprising only two of the questions from the original questionnaire, questions asking them to rate their annoyance with wind turbine noise outdoors and indoors on a scale of 0–10. There was no statistically significant difference in the answers to these two questions between the responders and followed-up non-responders ($t=-0.82, p=0.412$; $t=-0.74, p=0.458$).

E. Analysis methods

Response to wind turbine noise is presented as proportions of the number of respondents in each 5-dB(A) interval, 95% confidence intervals being calculated in accordance with Wilson (Altman *et al.*, 2000). Differences between proportions were tested using the Mann–Whitney U-test. Correlations between two variables with ordinal scales were explored using Spearman's rank correlation (r_s). Logistic regression analysis was used for the multivariate analyses, with a dichotomous response variable and a continuous scale of the exposure variable (A-weighted sound pressure level). The Hosmer–Lemeshow test was used to determine the fit of the regression models to the data; here a p-value >0.05 indicates a good fit, as no difference between modeled and observed data is desirable. Principal component analysis with Varimax rotation was used in constructing factors. All tests were two-sided and a p-value <0.05 was assumed to indicate statistical significance.

TABLE II. Response to wind turbine noise outdoors or indoors, proportion of respondents ($n=708$) according to 5-dB(A) sound level intervals, and 95% confidence intervals (95%CI).

	Predicted *A*-weighted sound pressure levels [dB(A)]				
	<30	30–35	35–40	40–45	>45
Outdoors, *n*	178	213	159	93	65
Do not notice (%) (95%CI)	75 (68–81)	46 (40–53)	21(16–28)	13 (8–21)	8 (3–17)
Notice, but not annoyed (%) (95%CI)	20 (15–27)	36 (30–43)	41 (34–49)	46 (36–56)	58 (46–70)
Slightly annoyed (%) (95%CI)	2 (1–6)	10 (7–15)	20 (15–27)	23 (15–32)	22 (13–33)
Rather annoyed (%) (95%CI)	1 (0–4)	6 (4–10)	12 (8–18)	6 (3–13)	6 (2–15)
Very annoyed (%) (95%CI)	1 (0–4)	1 (0–4)	6 (3–10)	12 (7–20)	6 (2–15)
Indoors, *n*	178	203	159	94	65
Do not notice (%) (95%CI)	87 (81–91)	73 (67–79)	61 (53–68)	37 (28–47)	46 (35–58)
Notice, but not annoyed (%) (95%CI)	11 (7–17)	15 (11–20)	22 (16–29)	31 (22–31)	38 (28–51)
Slightly annoyed (%) (95%CI)	1 (0–4)	8 (5–12)	9 (6–15)	16 (10–25)	9 (4–19)
Rather annoyed (%) (95%CI)	0 (0–2)	3 (1–6)	4 (2–8)	6 (3–13)	5 (2–13)
Very annoyed (%) (95%CI)	1 (0–4)	1 (0–4)	4 (2–8)	10 (5–17)	2 (0–8)

III. RESULTS

A. Response to wind turbine sound

The degree of perception and annoyance increased with increasing sound level, for both outdoor ($r_s=0.50, n=708, p<0.001$) and indoor annoyance ($r_s=0.36, n=699, p<0.001$). The distribution of the response variables in relation to the sound level intervals is shown in Table II. In the 35–40-dB(A) sound level interval, 78% of respondents noticed sound outdoors from wind turbines, in the 40–45-dB(A) interval 87% noticed, and in the >45-dB(A) interval 92% noticed. As expected, the sound was not as frequently noticed indoors.

The loudness of the wind turbine sound was perceived differently under different meteorological conditions. Of the respondents, 69% reported that the sound was louder than average when the wind was blowing from the wind turbines toward the dwelling (downwind conditions), vs 5% who reported that it was less loud under those conditions. In addition, 67% reported that the sound was louder downwind when the wind was strong vs 18% who reported that it was less loud, and 40% thought the sound was louder at night while 22% thought it was less loud. The rest of the respondents reported that there was no difference between sound levels or that they did not know. "Swishing/lashing" was the most common descriptor of the wind turbine sound used by those who noticed the sound from their dwellings (75% of $n=335$), followed by "rustling" (25%), and "a low-frequency/low-pitch sound" (14%). Less than 10% reported "whistling/screeching," "thumping/throbbing," "resounding," "a pure tone," or "scratching/squeaking."

The proportion of respondents who were annoyed (rather or very) by the sound increased with increasing sound level up to 40–45 dB(A), after which it decreased. 18% were annoyed in the 35–40- and 40–45-dB(A) intervals, and 12%

TABLE III. Description of possible moderating variables in relation to 5-dB(A) sound level intervals: proportion of respondents ($n=725$) per sound level interval and 95% confidence intervals (95%CI) for subjective variables.

	Predicted *A*-weighted sound pressure levels [dB(A)]				
	<30 $n=185$	30–35 $n=219$	35–40 $n=162$	40–45 $n=94$	>45 $n=65$
Economic benefits (%)	2	3	10	34	67
	Situational parameters				
Wind turbine visible (%)	35	60	90	89	100
Rural area (%)	36	30	46	43	52
Rural area with main road (%)	27	32	36	38	46
Built-up area (%)	37	38	17	19	2
	Subjective variables				
Noise sensitive (%) (95%CI)	36 (29–43)	25 (19–31)	31 (24–38)	31 (22–41)	23 (15–35)
Negative attitude (%) (95%CI)	10 (7–16)	14 (10–19)	19 (13–25)	17 (11–26)	9 (4–19)
Negative visual attitude (%) (95%CI)	33 (26–40)	36 (30–43)	45 (37–52)	39 (30–49)	20 (12–41)

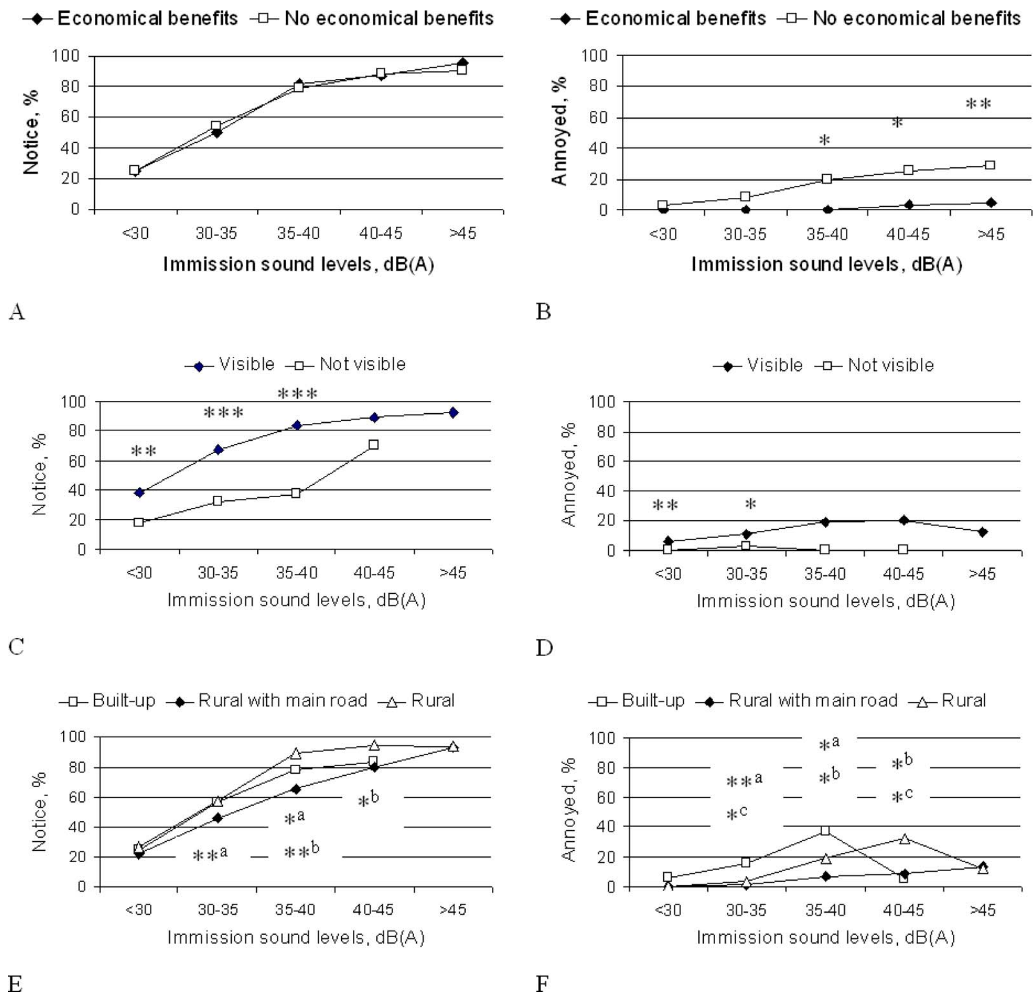

FIG. 1. (Color online) Proportion of respondents in each sound immission interval who noticed sound from wind turbines outside their dwelling (left column) or were annoyed by it (right column); [(A) and (B)] comparison between respondents who benefited economically and those who did not; [(C) and (D)] comparison between respondents who could see at least one wind turbine from their dwelling and those who could not; [(E)–(F)] comparison between respondents living in built-up areas, rural areas with a main road, and rural areas without a main road. $^{*}=p<0.05$, $^{**}=p<0.01$, $^{***}=p<0.001$ (Mann–Whitney U-test), ^{a}=built-up vs rural with main road, ^{b}=rural with main road vs rural without main road, and ^{c}=built-up vs rural without main road.

at levels above 45 dB(A) (Table II, outdoors). Almost all of the respondents that were annoyed by wind turbine sound had also reported that they were annoyed by sound from the rotor blades once a week or more often (92%). The proportions of respondents annoyed indoors were lower: In the sound level intervals below 40 dB(A) less than 10% were rather or very annoyed by the noise indoors, at 40–45 dB(A) 16% reported annoyance, and at levels above 45 dB(A) 6% were annoyed.

B. Moderating factors

Of the respondents, 100 reported that they benefited economically from the wind turbines, either by full or partial turbine ownership, or by receiving other economic benefits. Most of these respondents were subject to higher sound levels (Table III), 76 being subject to a level above 40 dB(A). There was no difference in terms of noticing wind turbine sound between those who benefited economically and those who did not [Fig. 1(A)], though there was a difference in *annoyance* [Fig. 1(B)]. Only 3 of the 100 respondents who benefited economically reported being annoyed by wind turbine sound.

Almost all respondents subject to sound pressure levels above 35 dB(A) could see at least one wind turbine from outside or inside their dwelling (Table III). The proportion of respondents who noticed sound from wind turbines [Fig. 1(C)], as well as the proportion annoyed by the noise [Fig. 1(D)], was larger for those who could see wind turbines from their dwellings than for those who could not. Only a few respondents who could not see any wind turbines were annoyed by the noise, even in the higher sound level intervals.

The distribution of respondents between the three types of area was fairly even in the lower sound level intervals, but at the higher sound intervals only a few people lived in built-up areas (Table III). Figure 1(E) indicates that at higher levels it was easier to notice wind turbine sound in rural areas without any main roads than it was in built-up areas, and that the sound was less noticeable in rural areas with a main road. In the lower sound level intervals, however, annoyance was more common in built-up than in both types of rural areas [Fig. 1(F)]. The proportions of respondents who benefited economically were higher in the two types of rural areas (19%) than in the built-up areas (2%). The wind turbines, on the other hand, were more visible in the rural areas,

TABLE IV. Results of two logistic regression models using the response variables *do not notice/notice* and *not annoyed/annoyed*, respectively; the exposure variable *sound pressure level* (continuous scale) and situational factors were used as moderating variables ($n=680$).

	Estimate (B)[a]	SE[b]	p-value	Exp(b)[c]
Do not notice vs notice (H–L)[d] ($p=0.721$)				
Sound pressure level [dB(A)]	0.17	0.022	<0.001	1.2
Economic benefits (no/yes)	−0.04	0.376	0.911	1.0
Visibility (no/yes)	1.40	0.214	<0.001	4.1
Area type (reference: rural)				
Rural with main road	−0.74	0.231	<0.01	0.5
Built-up	−0.18	0.240	0.451	0.8
Not annoyed vs annoyed (H–L)[d] ($p=0.199$)				
Sound pressure level [dB(A)]	0.13	0.027	<0.001	1.1
Economic benefits (no/yes)	−2.77	0.665	<0.001	0.1
Visibility (no/yes)	2.62	0.740	<0.001	13.7
Area type (reference: rural)				
Rural with main road	−1.07	0.372	<0.01	0.3
Built-up	0.65	0.321	<0.05	1.9

[a]Coefficients of the independent variables in the logistic regression.
[b]Standard errors of the coefficients.
[c]The exponential function of the coefficients of the independent variables in the logistic regression, which corresponds to the odds' ratio.
[d]Hosmer–Lemeshow goodness-of-fit test; p-value >0.05 indicates there is no statistically significant difference between the modeled and the observed data.

where 73% of respondents could see at least one wind turbine from their dwellings vs 54% in built-up areas.

The situational variables were entered simultaneously in logistic regressions. First, "do not notice wind turbine sound" vs "notice" was designated a dependent variable. The probability of hearing the sound was greater if the wind turbines were visible than if they were not. At the same time, living in a rural area with a main road as opposed to an area without decreased the probability (Table IV). Economic benefits had no statistically significant impact on perception of the sound. In the second regression model, the dichotomous variable "not annoyed by wind turbine sound" vs "annoyed" was designated as dependent. As before, the probability of being annoyed by wind turbine sound was higher if wind turbines were visible than if they were not (Table IV). Respondents who benefited economically were less likely to be annoyed than those who did not benefit. Living in a built-up area as opposed to a rural area without a main road increased the probability of being annoyed, while living in a rural area with a main road decreased the probability. Both regression models displayed good fit.

Approximately one of three respondents reported being rather or very sensitive to noise (Table III). There was no statistically significant relationship between noise sensitivity and the sound pressure level of wind turbine noise; there was, however, a positive correlation between noise sensitivity and annoyance (Table V). Noise sensitivity was also correlated with attitude toward the noise source. Of the respondents, 14% were negative (rather or very) toward wind turbines in general (general attitude), and 36% were negative toward the visual impact of wind turbines on the landscape (visual attitude). Attitude was not related to sound levels, but

TABLE V. Correlations between sound pressure levels, response (five-point scale from "do not notice" to "very annoyed"), and subjective variables; Spearman's rank correlation test.

	1	2	3	4
1. Sound pressure level [dB(A)]	⋯			
2. Response (five-point scale)	0.51[a]	⋯		
3. Noise sensitivity (five-point scale)	−0.01	0.14[a]	⋯	
4. General attitude (five-point scale)	−0.03	0.24[a]	0.14[a]	⋯
5. Visual attitude (five-point scale)	−0.01	0.29[a]	0.26[a]	0.65[a]

[a]$p<0.001$.

to annoyance (Table V). The association between noise annoyance on the one hand, and the variables noise sensitivity, general attitude, and visual attitude, on the other, was confirmed by testing in a logistic regression with the dependent variable "not annoyed" vs "annoyed" and adjusting for sound levels (Table VI). Of the three variables, visual attitude (i.e., attitude toward the visual impact of wind turbines on the landscape) had the strongest relationship with annoyance.

According to the eight polarized items, the wind turbines on average tended to be rated as relatively ugly (vs pretty), repulsive (vs inviting), unnatural (vs natural), and annoying (vs blending in); also, they were rated as efficient (vs inefficient), environmentally friendly (vs not environmentally friendly), necessary (vs unnecessary), and harmless (vs dangerous). Principal component analysis revealed that six of these items could be grouped to form two constructed factors: (i) *visual judgments*, comprising "pretty–ugly," "inviting–repulsive," and "natural–unnatural" (Cronbach's alpha=0.850), and (ii) *utility judgments*, comprising "environmentally friendly–not environmentally friendly," "efficient–inefficient," and "necessary–unnecessary" (Cronbach's alpha=0.804). These two factors accounted for 75% of the variance of the included items. The factor visual judgments was highly correlated with visual attitude ($r_s=0.602, p<0.001$) and, to a lesser degree, with general attitude toward wind turbines ($r_s=0.501, p<0.001$). The factor utility judgments was more highly correlated with general attitude ($r_s=0.513, p<0.001$) than with visual attitude ($r_s=0.381, p<0.001$).

TABLE VI. Results of a logistic regression model with the response variables *not annoyed/annoyed*, the exposure variable *sound pressure level* (continuous scale), and individual factors as moderating variables ($n=670$).

	Estimate (B)[a]	SE[b]	p-value	Exp(b)[c]
Not annoyed vs annoyed (H–L)[d] ($p=0.977$)				
Sound pressure level [dB(A)]	0.10	0.025	<0.001	1.1
Noise sensitivity (five-point scale)	0.35	0.138	<0.05	1.4
General attitude (five-point scale)	0.54	0.172	<0.01	1.7
Visual attitude (five-point scale)	1.04	0.215	<0.001	2.8

[a]Coefficients of the independent variables in the logistic regression.
[b]Standard errors of the coefficients.
[c]The exponential function of the coefficients of the independent variables in the logistic regression, which corresponds to the odds' ratio.
[d]Hosmer–Lemeshow goodness-of-fit test; p-value >0.05 indicates there is no statistically significant difference between the modeled and the observed data.

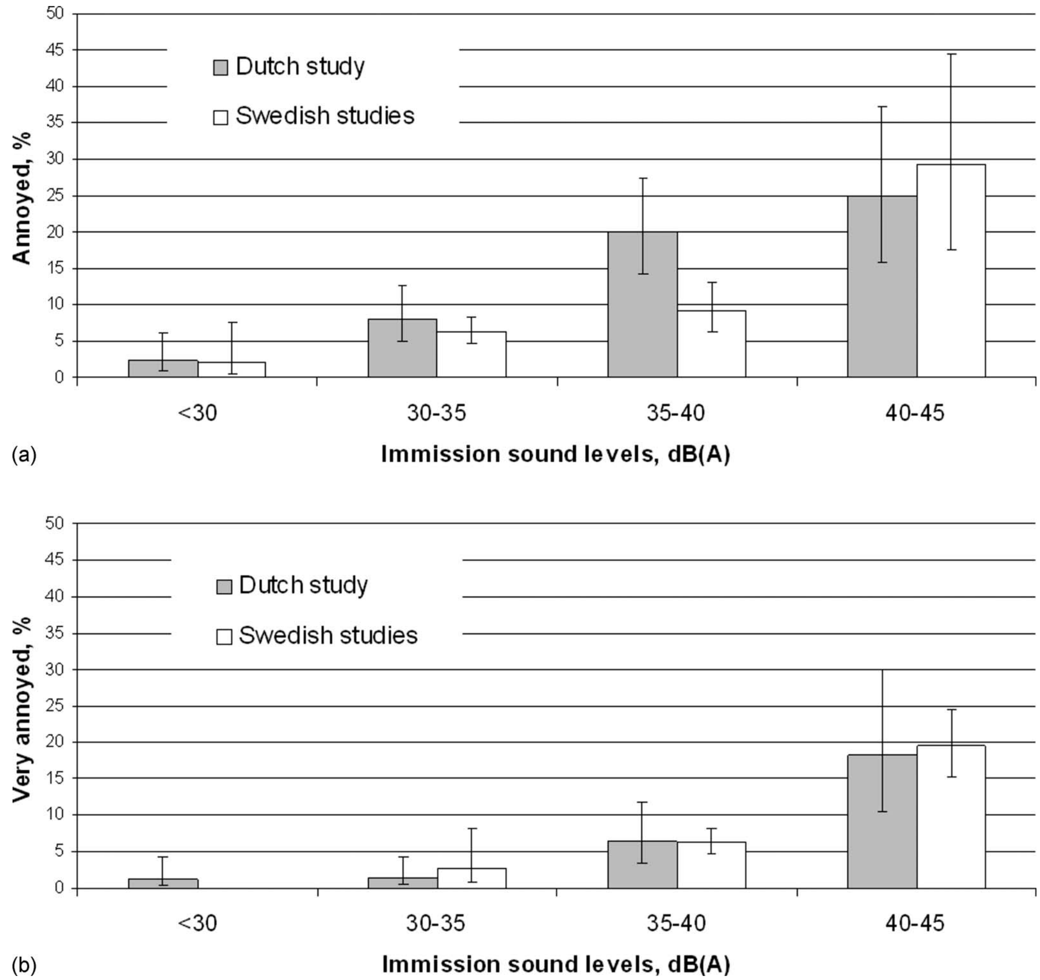

FIG. 2. Proportions of respondents annoyed (a) and very annoyed (b) by wind turbine noise outside their dwellings in four sound level intervals in the Dutch study (only respondents who did not benefit economically, $n=586$) and the Swedish studies ($n=1095$), with 95% confidence intervals.

C. Sound exposures

The calculated immission levels representing the levels of wind turbine sound outside respondent dwellings were similar for all three different calculation methods, and these values were highly correlated with each other ($r^2>0.98$). The differences between the levels calculated in accordance with the ISO standard and those calculated using the Dutch algorithm ranged from −0.8 to 1.4 dB(A), the average difference being 0.3 dB(A). The differences between the levels calculated in accordance with the ISO and the New Zealand standards were somewhat greater, −4.4 to 1.8 dB(A), the average difference being −0.8 dB(A). There were no differences in the exposure-response relationships between the three different methods for calculating the exposure levels; the correlation coefficient for the relationship between sound levels and response to wind turbine noise outdoors was 0.50 in all three cases.

IV. COMPARISONS WITH SWEDISH STUDIES

The proportions of respondents annoyed by wind turbine noise were compared with similar merged data from the two previous Swedish studies (Pedersen and Persson Waye, 2004, 2007) (Fig. 2). In the Swedish studies, the *A*-weighted sound levels were calculated in accordance with the Swedish standard, which uses a simplified algorithm comparable to the New Zealand standard for receiver points 1000 m or less from a wind turbine, and an algorithm based on octave bands for greater distances. The sound power used was the level at a wind speed of 8 m/s at 10-m height assuming a neutral atmosphere, as in the present study. The high degree of agreement between the dose calculations, as demonstrated above, leads to the assumption that calculation of the sound levels in the Swedish study was comparable to those used in the Dutch study. In the Swedish studies, many of the respondents (77% of 1059) could see at least one wind turbine from their dwellings, just as in the Dutch study. However, almost none of the Swedish respondents benefited economically from the turbines. The response to wind turbine noise found in the Swedish studies will therefore be compared with the responses of those not benefiting economically from the turbines in the Dutch study. Annoyance (rather or very) with wind turbine noise displays great agreement between the studies for the lowest sound level intervals [Fig. 2(A)]. For the 35–40-dB(A) interval, annoyance was greater among Dutch than Swedish respondents, the difference being statistically significant for respondents not benefiting economically from the turbines. In contrast, for the 40–45-dB(A) interval, the proportion of respondents annoyed was somewhat smaller in the Dutch study than in the Swedish studies, though this difference was not significant. No Swedish data were available for higher sound levels. No differences between Dutch and Swedish respondents were found when comparing the percentages of very annoyed respondents [Fig. 2(B)].

V. COMPARISONS WITH OTHER SOURCES OF COMMUNITY NOISE

The proportions of respondents annoyed by wind turbine noise were compared with the proportions annoyed by other sources of community noise. For transportation, third-order polynomials with the Lden exposure metric have been formulated by Miedema and Oudshoorn (2001). These models are based on 19 aircraft studies, 26 road traffic studies, and 8 railway studies. The polynomials were forced to zero at Lden=37 dB(A) for moderate annoyance and to 42 dB(A) for severe annoyance, i.e., it was assumed that no moderate/severe annoyance with transportation noise occurred below these levels. For stationary sources, second-order polynomials were used, also with the Lden exposure metric (Miedema and Vos, 2004). The data originate from one study of eight industries (not seasonal) and two shunting yards.

The *A*-weighted sound pressure levels used as the exposure variable in the wind turbine studies must be converted into the Lden metric to enable comparisons. The sound power level of a wind farm changes with wind speed, so the long-term equivalent level depends on the wind speed distribution at the hub. Van den Berg (2008) suggested that *A*-weighted sound pressure levels capturing conditions at a wind of 8 m/s at 10-m height could be transformed into Lden values by adding 4.7 ± 1.5 dB. These findings are based on the long-term measurement of wind speed at hub height of modern wind turbines, also taking into account the atmospheric states (stable, neutral, or unstable) during the day and night and different locations (coastal and inland). As meteorological data from the wind farm sites used in the present study were unavailable, this simplified transformation was used for the exposure variable in this study, i.e., 4.7 dB were added to the calculated immission levels.

To allow comparisons between studies, Miedema and Vos (1998) suggested standardized transformations of the proportion of annoyed respondents measured at different scales. The base is a scale from 0 (no annoyance at all) to 100 (very annoyed). The cutoff point for the proportion of respondents annoyed is 50 and for highly annoyed 72. The scale used in the present study uses two scale points in reporting no annoyance: 1—"do not notice" and 2—"notice, but not annoyed." These two scale points were merged into one, to reduce the five-point scale to a four-point scale. Hence, with a cutoff point of 50 on a 0–100 scale, the proportion of respondents annoyed was represented by those reporting 4—"rather annoyed" and 5—"very annoyed." Similarly, respondents reporting 5—"very annoyed" could be compared to those highly annoyed in previous studies. Only respondents who did not benefit economically from wind turbines were included, as it can be assumed that few respondents benefited economically from these other noise sources. The curves describing the dose-response relationship for sound sources other than wind turbines do not distinguish between outdoor and indoor responses. Here, outdoor annoyance with wind turbine noise was chosen for comparison.

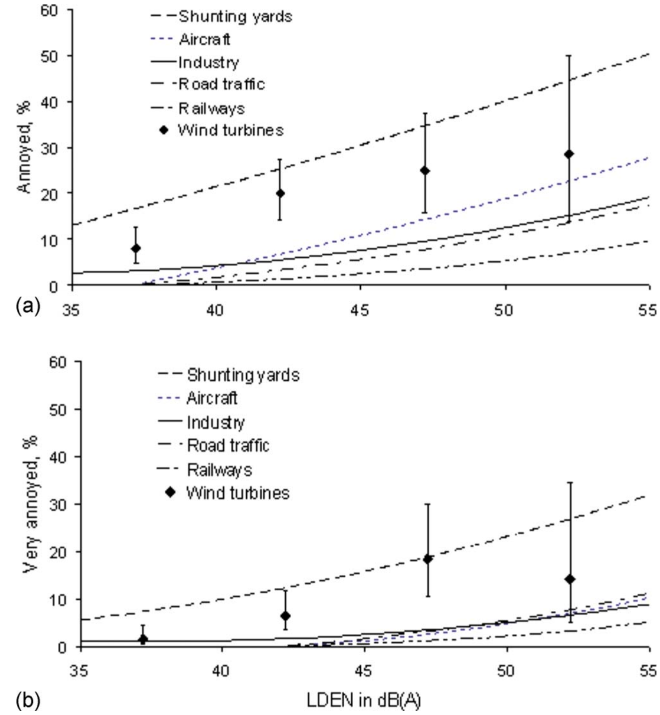

FIG. 3. (Color online) Proportion of respondents annoyed (a) and very annoyed (b) by wind turbine noise outside their dwellings (only respondents who did not benefit economically, $n=586$) compared to the modeled response [(A) percentage annoyed and (B) percentage highly annoyed] to noise from road traffic, aircraft, and railways (Miedema and Oudshoorn, 2001) and from industry and shunting yards (Miedema and Vos, 2004). For wind turbine noise the median of sound immission levels in each 5-dB interval is at the abscissa.

The comparison shows that the proportion of respondents annoyed with wind turbine noise below 50 dB(A) Lden is larger than the proportion annoyed with noise from all other noise sources except shunting yards (Fig. 3). At higher sound levels, this is less certain due to the low number of respondents leading to large confidence intervals.

VI. DISCUSSION

Noise from wind turbines was found to be more annoying than noise from several other sources at comparable Lden sound levels. The proportions of people annoyed by wind turbine noise lie between the proportions expected to be annoyed by noise from aircraft and from shunting yards. Like aircraft, wind turbines are elevated sound sources visible from afar and hence intrude both visually and aurally into private space (Brown, 1987). A strong correlation between noise annoyance and negative opinion of the impact of wind turbines on the landscape was found in early studies of perceptions of wind turbines (Wolsink and Sprengers, 1993); this was confirmed in the present study, as manifested by words such as "ugly," "repulsive," and "unnatural." Three different landscapes were explored. Surprisingly, annoyance was highest in what was classified as built-up area, in this case, mostly small towns and villages. It cannot be excluded that reflections from buildings may have caused higher sound levels than those calculated, though it is more plausible that nearby buildings would have reduced the noise. The higher annoyance levels found in towns could instead be interpreted as an effect of place attachment (Giuliani and Feldman, 1993). In this view, new technical devices being deemed not beneficial for the living environment induce a negative reaction (Lazarus and Cohen, 1977). This theory cannot, however, be confirmed from the present data set.

Previously, the relatively high annoyance with shunting yard noise has partly been explained by the impulsive nature of some yard activities (Miedema and Vos, 2004). Wind turbine sound also varies unpredictably in level within a relatively short time span, i.e., minutes to hours. It can be postulated that it could be even more important that neither type of noise ceases at night. In contrast, in areas with traffic noise and/or industrial noise, background levels usually return to lower levels at night, allowing residents to restore themselves psycho-physiologically. A large proportion of respondents in the present study reported hearing wind turbine sound more clearly at night, an observation supported by previous findings that, due to atmospheric conditions that are common over land in the temperate climate zone, nighttime immission levels can be higher than estimated from 10-m wind speeds using a neutral wind speed profile (Van den Berg, 2007) and also because the average hub height wind speed at night is higher than the same wind in day time (Van den Berg, 2008). In contrast, the near surface wind at night is often weaker in conditions that favor stronger high altitude winds, resulting in less wind-induced background sound from vegetation (Van den Berg, 2007) with less capacity to mask the wind turbine sound or even distract attention for it. Taken together, this implies that nighttime conditions should be treated as crucial in recommendations for wind turbine noise limits.

Using only the subsample that did not benefit economically from wind turbines in the comparisons with other noise sources could be questioned as the databases for the dose-response curves for other sources than wind turbines do not take (perceived) benefits into account. However, in contrast to the other noise sources (in Fig. 3), wind turbines are special because they can provide direct profit to residents in a wind farm area. They could be owned by a single person or by a group of people, or the landowner could receive a yearly income. The benefits from the other noise sources are not as direct and not as clearly economical, but they could be taken into account in future studies with the aim to compare noise annoyance due to different sources considering the benefits of each source.

There was great agreement as to how to describe the wind turbine sound. The dominant quality of the sound was swishing, a quality previously found to be the most annoying (Pedersen and Persson Waye, 2004). Few respondents described the turbine sound as low frequency, in line with recent reports confirming that modern wind turbines do not produce high levels of (audible) low-frequency sound (Jakobsen, 2005).

The proportion of annoyed respondents found by the present study was similar to that found by previous Swedish studies, indicating there were no cultural differences in the perception or appreciation of the sound between these two countries. However, annoyance was found to be significantly higher in the Dutch study in the 35–40-dB(A) interval. At these levels, it could be hypothesized that masking by background sound could have a large influence. The perceived difference could be due to the larger wind turbines included in the present study. Higher towers push the rotors to heights with stronger winds than found lower down, increasing the time a wind turbine operates and increasing differences between immission levels and the background sound levels of wind-induced noise in bushes and trees, especially at night when the atmosphere is stable for part of the time.

This study found a stronger relationship between immission levels of wind turbine noise and annoyance than the previously reported Swedish studies. This could be due to the study design, which, rather than concentrating on sampling participants from only a few areas, sampled participants from all suitable wind farm areas in The Netherlands, thus avoiding the influence of uncontrollable local factors. The non-acoustical factor that had the highest impact on noise annoyance was economic benefit, which substantially decreased the probability of annoyance. As was expected, people benefiting economically from a noise source are less likely to be annoyed by it, though to the best of the authors' knowledge this has not previously been demonstrated as clearly as in this study. The observed gap in annoyance between those benefiting economically and those who do not could be due to a more positive appraisal of the sound if it signifies profit. On the other hand, resentment against profiting neighbors among those not benefiting could have increased the annoyance in this group, also contributing to the gap. The study design with respondents from all over The Netherlands instead of fewer selected study areas should reduce the risk for local disputes to affect the results, unless these disputes, and the resentment they could cause, are occurring everywhere.

VII. CONCLUDING REMARKS

This study enlarges the basis for calculating a generalized dose-response curve for wind turbine noise usable for assessing wind turbine noise in terms of its environmental health impact, the number of people influenced by it, and, by extension, its role from a public health perspective. The study confirms that wind turbine sound is easily perceived and, compared with sound from other community sources, relatively annoying. Annoyance with wind turbine noise is related to a negative attitude toward the source and to noise sensitivity; in that respect it is similar to reactions to noise from other sources. This may be enhanced by the high visibility of the noise source, the swishing quality of the sound, its unpredictable occurrence, and the continuation of the sound at night. The study demonstrates that it is possible to model a highly needed generalized dose-response relationship for Northern Europe, and supposedly also for the rest of Europe and North America, if the different proportions of people benefiting economically from wind turbines in the different regions are taken into account. The study also shows that mitigation measures can be directed to acoustical as well as non-acoustical factors that contribute to the impact of wind farms.

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