

Can road traffic mask sound from wind turbines? Response to wind turbine sound at different levels of road traffic sound

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ABSTRACT

Wind turbines are favoured in the switch-over to renewable energy. Suitable sites for further developments could be difficult to find as the sound emitted from the rotor blades calls for a sufficient distance to residents to avoid negative effects. The aim of this study was to explore if road traffic sound could mask wind turbine sound or, in contrast, increases annoyance due to wind turbine noise. Annoyance of road traffic and wind turbine noise was measured in the WINDFARM perception survey in the Netherlands in 2007 ($n=725$) and related to calculated levels of sound. The presence of road traffic sound did not in general decrease annoyance with wind turbine noise, except when levels of wind turbine sound were moderate (35–40 dB(A) Lden) and road traffic sound level exceeded that level with at least 20 dB(A). Annoyance with both noises was intercorrelated but this correlation was probably due to the influence of individual factors. Furthermore, visibility and attitude towards wind turbines were significantly related to noise annoyance of modern wind turbines. The results can be used for the selection of suitable sites, possibly favouring already noise exposed areas if wind turbine sound levels are sufficiently low.

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1. Background

Wind power plays a small but significant role in the ongoing conversion to renewable energy sources. Installed electric wind power is increasing with an annual rate of 27% globally (IEA, 2008), meaning that the number of operational wind turbines is rapidly growing. Wind power is generally favoured by the public, though at the same time wind turbines often are opposed in the local community (Ek, 2005; Breukers and Wolsink, 2007). Wind turbines are by some viewed upon as visual and audible intruders, destroying the landscape scenery and emitting noise (Pedersen et al., 2007). Remote places with a low population density were considered suitable locations for wind farms, but long distances to the existing power grid are costly. Also, remote places often are otherwise unspoiled landscapes with high values for recreation and tourism that could decrease with the construction of a wind farm. Suitable places for wind farms are therefore more often sought after also in populated areas.

One of the parameters to assess the suitability of a location could be the existing background sound level due to natural or man-made sources. It seems plausible that high levels of

background sound can reduce annoyance by masking the noise from a wind farm, either physically when the sound cannot be heard, or cognitively when the sound is perceived as attracting less attention. If this is true, a row of turbines could cause less noise annoyance when placed next to a motorway instead of a quiet agricultural area. One modern 2–3 MW turbine at high speed produces a sound power level (105–108 dB(A)) that is approximately equal to a car on a motorway (see road traffic sound power levels in Jabben et al., 2001). Siting wind turbines next to a motorway could thus be an attractive alternative, certainly if they then also would be perceived as visually less intrusive as they serve as visible ‘milestones’ along the motorway. However, it is not yet clear if road traffic can indeed mask wind turbine sound and to what extent. Physical masking of wind turbine sound by wind induced noise in vegetation has been investigated by Bolin (2007) and masking by sea waves by Appelqvist et al. (2007). The capacity for masking will change with time as high turbine sound levels can occur at low levels of vegetation or wave noise, either on a short time scale during wind gusts or on a longer time scale associated with changes in the vertical wind profile. Also, wind turbine sound can be audibly amplitude modulated due to differences in wind speed over the area swept by the rotor blades (van den Berg, 2005). Amplitude modulations in a sound are more easily detected by the human ear (Fastl and Zwicker, 2007) than a constant sound. Masking will

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also depend on the spectral distribution of the masking sound relative to the masked sound. Wind turbine and road traffic sound are not very different in this respect as both have high levels of sound at roughly 1–2 kHz (due to trailing edge and tyre noise respectively) at close distance and high levels at low frequencies due to inflow turbulent sound and engine sound. Here we assume that road traffic sound needs to exceed the actual level of wind turbine sound in order to be able to mask wind turbine noise.

When placing a wind farm close to another noise source, the other source could (at least for part of the time) mask the sound from the wind farm, but synergetic effects cannot be excluded: the response to exposure from one noise source could be enhanced due to exposure from another noise source. The prevalence of annoyance due to road traffic noise has been found to be significantly *higher* in areas with high exposure of both road traffic and railway noise, in comparison with areas with only high exposure of road traffic (Ahlstrom et al., 2007). On the other hand, the prevalence of annoyance due to high levels of railway noise was *lower* when high levels of road traffic sound were present compared to when they were not (Lercher et al., 2007). Vos (1992) found no synergetic effect when people were simultaneously exposed to sound from gunfire, aircraft and/or road traffic: the annoyance was shown to depend on the total sound level (logarithmic summation of sound level from each source), though sound levels were corrected with penalties to account for the difference in dose–response relations. Synergetic effects, if present, hence appear to depend on the character or origin of the sounds, or other circumstances related to the source, and can differ for each type and perhaps level of sound exposure.

Observed synergetic effects could also be due to confounders. Variables known to moderate the response to noise are noise sensitivity (Miedema and Vos, 2003) and attitude towards the noise source (Job, 1988). An association between annoyances with two noise sources could hence be due to individual factors that change the threshold for a negative appraisal and not actually to a synergetic effect. For wind turbines, the prevalence of annoyance with the noise increased if the wind turbines could be seen from the dwelling or outside the dwelling by the receiver (Pedersen and Larsman, 2008), is possibly due to a multi-sensory effect where the ability to detect and recognize external stimuli is enhanced when more than one sense is involved (Calvert, 2001). Also road traffic noise has been found to be more annoying if the road is visible than if it is not (Bangjun et al., 2003). It could be presumed that in landscapes where the noise sources are easily visible the possibility of noise annoyance increases due to the multi-modal stimuli, rather than annoyance with one noise source enhancing annoyance with a second source. Thus, situational factors also have to be taken into account when a possible synergetic effect is studied.

The objective of this paper is to explore if road traffic sound can mask wind turbine sound. To put it more precisely: Is perception and annoyance with wind turbine sound reduced when road traffic sound dominates the wind turbine sound?

2. Methods

The analyses are based on data from a large cross-sectional study that was carried out in the Netherlands (Pedersen et al., 2009). The objective was to evaluate human responses to exposure from wind turbines, especially for people living close to modern wind farms. The study included three different settings in order to vary background sound levels: built-up areas, rural areas with a main road (within 500 m from a selected wind turbine) and rural areas without a main road. Wind turbines were selected (from all wind turbines in the Netherlands) when they

had a nominal power of 500 kW or more and another turbine within 500 m, and were not (re)placed in the previous year. A stratified sample of 1948 people living within different levels of wind turbine sound outside their dwellings was chosen for the study. Of those, 725 completed and returned a questionnaire (response rate 37%) measuring perception and annoyance with environmental factors, including wind turbine and road traffic sounds. The questionnaire also comprised questions about attitude towards the noise sources and individual factors such as health symptoms and perceived stress. A follow-up survey found no differences between respondents and non-respondents regarding the main annoyance question (Pedersen et al., 2009).

2.1. Assessments of sound levels

Coordinates for all respondents were available from the sampling process and used for calculating the distance to all wind turbines within 20 km of each respondent's dwelling. Emission (sound power) levels of wind turbines were obtained from technical specifications published by manufacturers and consultancies. Equivalent immission levels in dB(A) of wind turbine sound outside the dwelling of each respondent were calculated in accordance with ISO-9613 (1993) for a wind speed of 8 m/s at 10 m height and a wind profile in a neutral atmosphere. The sound levels at each respondent's dwelling due to all wind turbines in the area were summarized logarithmically.

In the European Union, two time averaged sound levels are now recommended: Lden and Lnight. Lden is the average sound pressure level (A-weighted) over a longer period of time, including a penalty of 5 dB(A) in the evening and 10 dB(A) at night; Lnight is the average sound pressure level (A-weighted) over the night time period only (EU, 2003). We will use the difference between Lden from wind turbines and Lden from road traffic, as Lden is the usual metric related to annoyance. Lnight would be a more proper choice when investigating sleep disturbance. The calculated immission levels (at 8 m/s wind speed) were transformed into levels of day–evening–night values (Lden) by adding 4.7 dB as proposed by van den Berg (2008). In this article all sound levels are expressed in dB(A) Lden.

The Dutch National Institute for Public Health and the Environment (RIVM) supplied calculated day–evening–night sound immission levels (Lden) due to road, air and rail traffic in 5 dB intervals and for a 25 m by 25 m grid over the entire country. The levels are based on traffic volumes in 2002. Mopeds, motor bicycles, and local traffic on minor roads are not included in the road traffic sound level, and overflying (i.e. not taking off or landing) aircraft are not included in the aircraft sound level. For (nearly) all respondents there is no railroad or airport nearby, so road traffic will dominate the Lden value. The Lden values of background (=not wind turbine) sound, thus, are an approximation of the road traffic sound level. For each respondent the value at the nearest grid point has been used. To obtain a best approximation for the road traffic sound level, the midpoint value of each interval (2.5 dB below the maximum value of the interval) is used.

2.2. Statistical analyses

In the questionnaire annoyance was measured with several questions. It was therefore possible to derive factor scores for annoyance with turbine sound (5 items, Cronbach's alpha=0.892) and for annoyance with road traffic sound (6 items, Cronbach's alpha=0.863). Such factor scores are a more reliable measurement of annoyance than if only the response to one question is used. In this case, principal component analyses were used. The

derived factors have a mean value of 0 and a standard deviation of 1. A factor score below 0 means lower than average of the total sample, a factor score above 0 higher than average.

Symptoms of stress were also measured with several items of which six were suitable for constructing a factor score as described above (Cronbach's $\alpha=0.840$). The six items were: feeling tense or stressed, feeling irritable, having mood changes, being depressed, suffering from undue tiredness and having concentration problems.

The study sample was divided into three sub-samples corresponding to the difference between the level of wind turbine and road traffic sounds. In the 'WT dominant' sub-sample the level of wind turbine sound for each respondent was more than 5 dB higher than the level of road traffic sound. In the 'RT dominant' sub-sample the reverse is true. In the 'No dominant source' sub-sample the difference between the two sound levels was 5 dB or less. The 5 dB cut-off approach has previously been used by, for example, *Cremezi et al. (2001)* and *Lim et al. (2008)*.

Differences between sub-samples were tested with ANOVA for continuous variables and Chi-square test for binary variables. Associations between two variables were tested with the Pearson's moment correlation (r) for continuous variables, the Spearman's rank correlation (r_s) for ordinal scales and with the Mann-Whitney U -test for differences between sub-samples (Z_{MWU}). The association between several independent variables and one dependent variable was tested in models using multiple linear regression. The association between several independent variables and two dependent variables was tested with multivariate general linear model. A p -value <0.05 was taken as an indication of statistical significance, though the number of tests were carried out calls for precaution. All respondents had not answered all questions in the questionnaire. Missing cases were not substituted in any way, while some analyses include a lower number of respondents than the total number in the study. The number of respondents are noted in the tables listing the results of multiple or multivariate modelling.

2.3. Overview of variables used in the analyses

The following variables were used in the analyses:

- WT sound: wind turbine sound outside the dwelling of the respondent; WT sound level is Lden in dB(A) on a continuous scale.
- RT sound: road traffic sound outside the dwelling of the respondent; RT sound level is Lden in dB(A) in 5 dB intervals, but here treated as a continuous scale.
- WT annoyance: annoyance with wind turbine sound. Factor score, continuous scale. Five items: (i) "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." (sound from wind turbines; 5-point verbal scale from "do not notice" to "very annoyed"), (ii) same question but indoors, (iii) "To what extent are you affected by wind turbines in your living environment? Please indicate for each item whether you notice or are annoyed by it in your living environment." (sound from rotor blades; 5-point scale verbal from "do not notice" to "very annoyed"), (iv) "To what extent are you annoyed by the sound of wind turbines when you are outdoors at your dwelling?" (11-point scale from 0="I am not at all annoyed" to 10="I am extremely annoyed"), and (v) the same but for indoors.
- RT annoyance: annoyance with road traffic sound. Factor score, continuous scale. Six items: (i) "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." (road traffic sound; 5-point verbal scale from "do not notice" to "very annoyed"), (ii) same question but sound indoors, (iii) "To what extent are you affected by busy roads in your living environment? Please indicate for each item whether you notice or are annoyed by it in your living environment." (sound indoors; 5-point scale verbal from "do not notice" to "very annoyed"), (iv) same question but sound outdoors, (v) "To what extent are you annoyed by the sound of busy roads when you are outdoors at your dwelling?" (11-point scale from 0="I am not at all annoyed" to 10="I am extremely annoyed"), and (vi) the same but for indoors.

- Hear wind turbines: no or yes as answer of the question "Can you hear a wind turbine from your dwelling or your garden/balcony?"
- Hear busy road: no or yes as answer to the question "Can you hear the sound of busy roads from your residence or garden/balcony?"
- WT visibility: no or yes as answer to the question "Can you see a wind turbine from your dwelling or your garden/balcony?"
- RT visibility: no or yes as answer of the question "Can you see a busy road from your residence or garden/balcony?"
- WT attitude: attitude towards wind turbines, measured with the question "What is your opinion on the impact of wind turbines on the landscape scenery?" on a 5-point scale from "very positive" to "very negative" and dichotomized into "not negative" (point 1, 2 or 3) and "negative" (point 4 or 5).
- RT attitude: attitude towards road traffic, measured with the question "What is your opinion on the impact of busy roads on the landscape scenery?" on a 5-point scale from "very positive" to "very negative" and dichotomized into "not negative" (point 1, 2 or 3) and "negative" (point 4 or 5).
- Noise sensitivity: noise sensitivity measured on a 5-point scale from "not at all sensitive" to very sensitive and dichotomized into "not sensitive" (scale point 1, 2 or 3) and "sensitive" (scale point 4 or 5).
- Stress: factor score constructed from six items with a 4-point scale rated from "(almost) never" to "(almost) daily". Continuous scale with zero as mean value and standard deviation 1.

3. Results

3.1. Descriptive

The mean levels of wind turbine and road traffic sound in each of the three sub-samples are shown in Table 1 together with response to the sounds and variables possibly influencing the response. The mean Lden of wind turbine sound as well as road traffic sound differed significantly among the sub-samples (all $p < 0.001$) with the highest WT sound levels in the WT dominant sub-sample and the highest RT sound levels in the RT dominant sub-sample. In the WT dominant sub-sample a larger proportion of respondents could hear the wind turbine sound ($p < 0.001$), was annoyed by the sound ($p < 0.001$), and could see wind turbines from their dwellings ($p < 0.001$), in comparison to the other two sub-samples. Also a larger proportion of respondents was negative to the impact of wind turbines on the landscape scenery in the WT dominant sub-sample than in the other sub-samples ($p < 0.001$), and, vice versa, a larger proportion of respondents in the RT dominant sub-sample was negative to the visual impact of busy roads ($p < 0.001$). No significant differences

Table 1

Description of sound levels, response to sound and variables possibly influencing the response in the three sub-samples.

	WT dominant (n=150)	No dominant source (n=230)	RT dominant (n=338)
WT sound Lden in dB(A), mean (SD)	46.5 (5.5)	40.7 (5.6)	36.2 (4.3)
RT sound Lden in dB(A), mean (SD)	31.6 (4.9)	40.9 (5.5)	42.5 (5.5)
Difference between WT and RT sound Lden, mean (SD)	15.1 (4.9)	-0.2 (4.0)	-14.7 (4.9)
Age, mean (SD)	50 (13)	53 (15)	57 (15)
Gender, %male	47	56	46
Hear wind turbines, %yes	82	49	28
Hear busy road, %yes	32	50	59
WT annoyance, mean (SD)	0.29 (0.96)	0.08 (1.06)	-0.21 (0.93)
RT annoyance, mean (SD)	-0.34 (0.65)	-0.08 (0.93)	0.20 (1.12)
Noise sensitive, %sensitive	24	31	30
WT visibility, %yes	91	71	53
RT visibility, %yes	48	50	41
WT attitude, %negative	30	34	40
RT attitude, %negative	13	18	21
Economical benefits from WT, %yes	41	11	3
Stress, mean (SD)	0.01 (1.02)	-0.06 (0.89)	0.03 (1.06)

Table 2

Difference between levels of WT sound and RT sound at 5-Lden intervals of WT sound in the three sub-samples.

WT sound intervals Lden	WT dominant			No dominant source			RT dominant		
	WT sound mean Lden	RT sound mean Lden	Diff	WT sound mean Lden	RT sound mean Lden	Diff	WT sound mean Lden	RT sound mean Lden	Diff
30–35				33.4	35.4	2.0	32.9	48.7	15.8
35–40	37.5	27.5	10.0	37.2	38.6	1.4	37.7	50.2	12.5
40–45	42.0	28.8	13.2	42.4	41.8	0.5	41.9	56.7	14.8
45–50	47.4	32.7	14.7	47.4	46.1	1.4	47.4	59.6	12.1
50–55	52.3	34.2	18.1	51.8	50.0	1.8			

between the sub-samples were found for noise sensitivity and stress. More than 40% of the respondents in the WT dominant sub-sample benefited economically from the wind turbines, in comparison with 11% in the no dominant source ($p < 0.001$) and 3% in the RT dominant sub-sample ($p < 0.001$). Economical benefits decreased the possibility for noise annoyance, but not the possibility to hear the sound (Pedersen et al., 2009). Economical benefits are thus an important moderating factor and should therefore be considered in the analyses when annoyance is explored.

Table 2 shows the differences between levels of WT and RT sounds in relation to 5-dB(A) intervals of wind turbine sound. The WT sound levels clearly exceeded the RT sound levels at all intervals in the WT dominant sub-sample. Similar, the RT sound clearly exceeded the WT sound in the RT dominant sub-sample.

3.2. Possibility to hear wind turbine sound in different levels of background sound

The proportion of respondents that could hear a wind turbine from their dwelling or garden/balcony increased with increase in levels of wind turbine sound as expected. However, in the WT dominant sub-sample the possibility of hearing the wind turbine sound remained constant for WT sound levels up to 50 dB(A) and at levels up to 45 dB(A) the proportion of respondents that could hear the sound was larger than in the other sub-samples (Fig. 1). At levels below 45 dB(A) the difference between the WT dominant sub-sample and the others was statistically significant ($Z_{MWU} = -3.01, p < 0.01$; $Z_{MWU} = -3.22, p < 0.01$). Fig. 1 looks the same when respondents who benefited economically are excluded (data not shown).

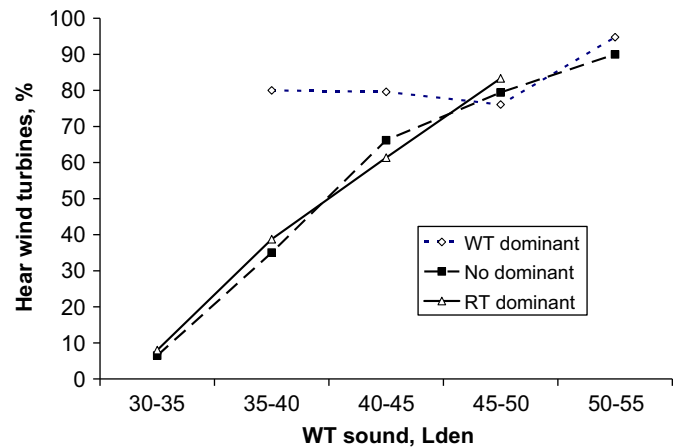


Fig. 1. Proportion of respondents that could hear wind turbine sound at their dwelling or garden/balcony (%) related to levels of wind turbine sound (Lden) for sub-samples with either WT or RT sound as the dominant sound or none of both. All respondents (n=706). Only points representing >5 respondents are depicted.

3.3. Annoyance with wind turbine noise in different levels of background sound

Annoyance with wind turbine noise increased with increase in levels of wind turbine sound ($r=0.374, n=622, p < 0.001$) and was approximately the same in the three sub-samples at lower levels (< 45 dB(A)) of wind turbine sound (Fig. 2). Although annoyance was highest in the sub-sample dominated by road traffic sound at 45–50 dB(A) WT sound levels, this difference was not statistically significant.

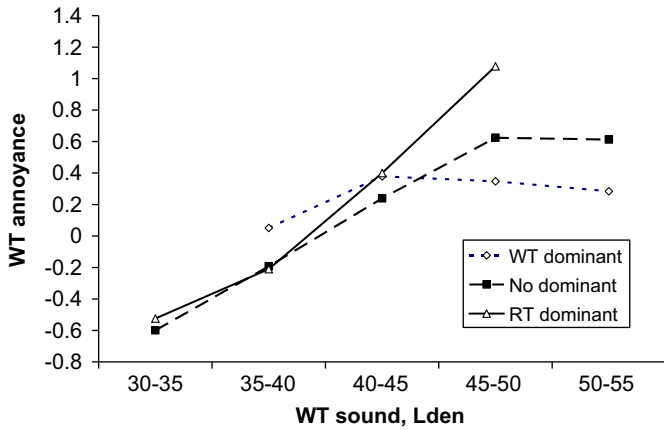


Fig. 2. Mean annoyance score for wind turbine noise in relation to sound levels of wind turbine sound (Lden) for sub-samples with either WT or RT sound as the dominant sound or none of both. All respondents ($n=617$). Only points representing > 5 respondents are depicted.

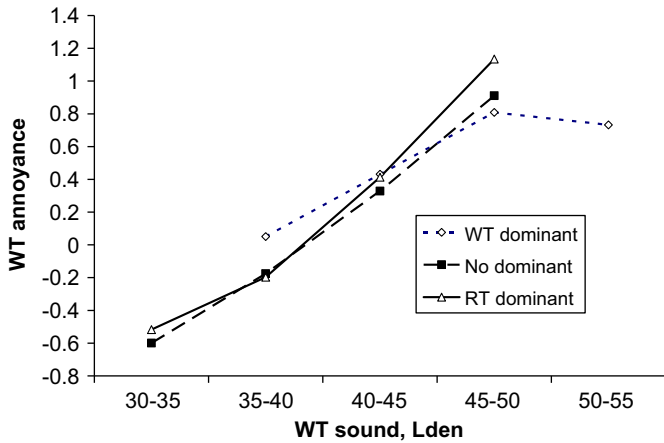


Fig. 3. Mean annoyance score for wind turbine noise in relation to levels of wind turbine sound (Lden) for sub-samples with either WT or RT sound as the dominant sound or none of both. Only respondents that did not benefit economically from wind turbines ($n=511$). Only points representing > 5 respondents are depicted.

Of the respondents that owned wind turbines or otherwise had economical interests in wind turbines ($n=100$), 64% belonged to the sub-sample dominated by wind turbine sound (Table 1). These respondents showed very little or no annoyance from WT sound. When they were withdrawn from the sample no differences in annoyance scores remained between sub-samples at any level of wind turbine sound (Fig. 3); differences of mean annoyance scores were tested for each interval of sound level and found to be not statistically significant. A comparison between Figs. 2 and 3 shows that the mean value of annoyance with wind turbine sound is in both figures is the same in the RT dominant sub-sample but higher in Fig. 3 than in Fig. 2 for the two other sub-samples. This is in agreement with the fact that almost no one in the RT dominant sub-sample benefited economically from wind turbines and therefore this annoyance score was indifferent to the withdrawal of respondents with economical benefits.

The observation that annoyance with wind turbine noise was not lower in the sub-sample dominated by road traffic sound could be due to differences between the sound levels being too small for a masking effect to occur. Also, the average differences between the two sound levels were rather similar for all intervals of WT sound. To investigate this the no dominant sound and RT dominant sub-samples were taken together and divided into

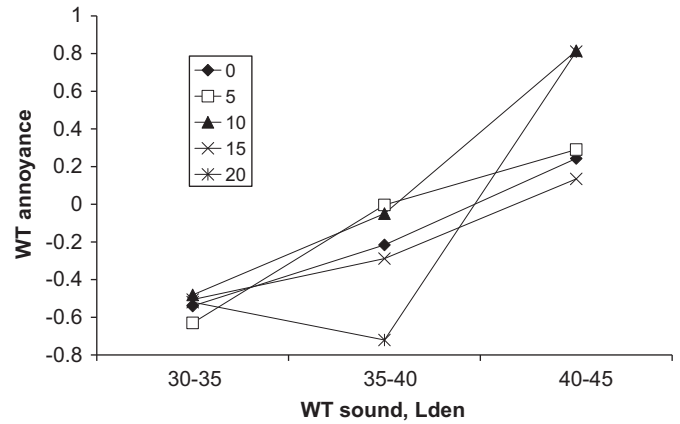


Fig. 4. Mean annoyance score for wind turbine noise in relation to levels of wind turbine sound (Lden) for five situations where RT sound level exceeds WT sound level with 0–5, 5–10, 10–15, 15–20 or > 20 dB(A) Lden.

groups with levels of RT sound exceeding those of WT sound with 0–5, 5–10, 10–15, 15–20 or > 20 dB(A) in order to explore a possible masking effect when the difference increased. Fig. 4 shows that WT annoyance was reduced when the RT sound level exceeded WT sound level with 20 dB(A), but only in the WT sound interval 35–40 dB(A). This reduction in WT annoyance was significantly different only with respect to the WT annoyance where RT sound exceeded WT sound with 5–10 dB(A) ($t = -0.69$, $p < 0.05$); no other differences were statistically significant.

Thus, Fig. 4 indicates that there is a decrease in the WT annoyance and thus a possible masking effect from RT sound at an intermediate level of WT sound, but this masking effect vanishes at higher levels of WT sound for all levels of RT sound studied. A possible synergetic effect at these high levels is explored in the next paragraph.

3.4. Interaction effects between annoyance with wind turbine and road traffic noise

The influence of annoyance with road traffic noise on the relationship between sound levels and wind turbines was modelled with multiple linear regression within the total sample and the three sub-samples. Both respondents that benefited economically and those that did not were included, but all models were adjusted for economical benefits from wind turbines. The continuous annoyance score for wind turbine noise was assigned as dependent variable. The direct influences of the two sound levels were first explored for WT sound only, then WT sound and RT sound simultaneously. Annoyance with wind turbine noise increased with increase in levels of wind turbine sound in the total sample, and road traffic sound at higher or lower levels had no influence on this (Table 3, model 2) as already seen in Fig. 3. Annoyance with road traffic noise was in the third model entered into the regression to explore a possible enhancing effect on annoyance with wind turbine noise (Table 3, model 3). Annoyance with road traffic noise was correlated with sound levels of road traffic ($r=0.387$, $n=587$, $p < 0.001$), but this correlation did not change the outcome of the regression: WT annoyance did not change substantially when RT sound level was removed (Table 3, model 4). When exploring the sub-samples, road traffic sound level was found to have a negative effect, i.e. a masking effect, on annoyance (Table 3, model 3) with wind turbine noise in the sub-sample dominated by road traffic sound, but not in the others. This reduction due to RT sound level was, however, balanced by an increase in WT annoyance caused by RT annoyance. Noise annoyance with road traffic was associated with noise

Table 3

Linear regression models exploring the influence of wind turbine sound, road traffic sound and annoyance from road traffic sound, on annoyance with wind turbine sound. Independent variables in the models are wind turbine sound level and/or road traffic sound level and/or road traffic noise annoyance.

	Total		WT dominant		No dominant		RT dominant	
	Beta	p	Beta	p	Beta	p	Beta	p
Model 1 ^a , R-square ^b	0.20 (n=609)		0.07 (n=145)		0.22 (n=201)		0.21 (n=263)	
WT sound	0.53	< 0.001	0.19	0.054	0.152	< 0.001	0.047	< 0.001
Model 2 ^a , R-square ^b	0.20 (n=609)		0.09 (n=145)		0.25 (n=201)		0.22 (n=263)	
WT sound	0.53	< 0.001	0.13	0.220	0.39	< 0.001	0.51	< 0.001
RT sound	0.02	0.571	0.11	0.260	0.18	< 0.05	-0.09	0.166
Model 3 ^a , R-square	0.25 (n=525)		0.08 (n=122)		0.29 (n=159)		0.27 (n=244)	
WT sound	0.50	< 0.001	0.21	0.087	0.35	< 0.001	0.51	< 0.001
RT sound	-0.06	0.137	0.04	0.712	0.08	0.433	-0.17	< 0.05
RT annoyance	0.24	< 0.001	0.10	0.283	0.30	< 0.001	0.23	< 0.001
Model 4 ^a , R-square	0.25 (n=525)		0.08 (n=122)		0.29 (n=159)		0.26 (n=244)	
WT sound	0.51	< 0.001	0.24	< 0.05	0.40	< 0.001	0.43	< 0.001
RT annoyance	0.22	< 0.001	0.10	0.102	0.32	< 0.001	0.18	< 0.01

^a Adjusted for economical benefits from wind turbines.

^b R-square for the model, i.e. the proportion of variation in the dependent variable explained by all the independent variables in the model.

Table 4

Associations between explorative variables (tested one by one) on the one hand and annoyance with wind turbine and road traffic noises on the other hand, respectively.

	WT annoyance		RT annoyance	
WT sound	$r=0.374$	$p < 0.001$	$r=0.027$	$p=0.513$
RT sound	$r=-0.029$	$p=0.474$	$r=0.387$	$p < 0.001$
Age	$r=0.012$	$p=0.775$	$r=0.002$	$p=0.965$
Gender	$Z_{MWU}=-1.20$	$p=0.231$	$Z_{MWU}=-0.06$	$p=0.956$
Noise sensitive	$r_s=0.127$	$p < 0.01$	$r_s=0.343$	$p < 0.001$
WT visibility	$Z_{MWU}=-12.99$	$p < 0.001$	$Z_{MWU}=-1.51$	$p=0.131$
RT visibility	$Z_{MWU}=-5.57$	$p < 0.001$	$Z_{MWU}=-9.34$	$p < 0.001$
WT attitude	$r_s=0.289$	$p < 0.001$	$r_s=0.153$	$p < 0.001$
RT attitude	$r_s=0.118$	$p < 0.01$	$r_s=0.279$	$p < 0.001$
Economical benefits from wind turbines	$Z_{MWU}=-3.14$	$p < 0.01$	$Z_{MWU}=-2.06$	$p < 0.05$
Stress	$r=0.128$	$p < 0.01$	$r=0.177$	$p < 0.001$

annoyance due to wind turbines in the sub-sample dominated by road traffic sound and that with no dominance, but not in the WT dominant. Also, none of the models explained more than 9% of the variance of annoyance with wind turbine noise in the WT dominant sub-sample meaning that other factors must be of importance in this sub-sample. In the total sample WT sound predicted 20–25% of the WT annoyance, but there was also a relationship between annoyances with the two sounds so that an increase in annoyance with road traffic sound increased annoyance with wind turbine sound. This could be a synergetic effect, or the effect of common confounders such as noise sensitivity leading to annoyance with both sounds. Possible confounders were therefore investigated in the next step.

3.5. Possible confounders

The association between annoyance with wind turbine noise and road traffic noise that was found in the regression models could be due to other underlying factors influencing both. Possible factors are listed in Table 4 with their relation to WT and RT annoyances, respectively. As expected, levels of wind turbine sound and visibility of wind turbines were correlated with annoyance due to wind turbine noise, but not with annoyance due to road traffic noise. Age and gender were not associated to either annoyance score. Noise sensitivity, stress and being negative to the visual impact of wind turbines and/or roads on

the landscape scenery were variables that were all positively correlated with both the annoyance scores. Both annoyance scores were also higher for those who could see busy roads, in comparison with those who could not, but WT annoyance was related to the visibility of wind turbines only. Also, both annoyance scores were higher for those who did not benefit economically from wind turbines.

Variables that were found to be associated with one or both the annoyance scores in Table 4 were tested in a multivariate general linear model in which the association between explorative and two dependent variables were tested simultaneously, including all respondents. Dose–response relationships between sound levels and annoyance were found for wind turbines and road traffic, respectively, but levels of one sound did not influence annoyance with the other sound (Table 5). Visibility of a source did only influence annoyance with that source, and, similar, attitude towards a source was only related to annoyance with that specific source. Noise sensitivity and symptoms of stress were associated with both annoyance due to wind turbine and road traffic sounds.

4. Discussion

The expectation that the presence of road traffic sound would reduce the prevalence of annoyance due to noise from wind turbines in general was not confirmed in this systematical

Table 5

Result of multivariate general linear model where the association between possible explorative variables (column 1) and the two measurements of annoyance were tested simultaneously ($n=480$).

	WT annoyance		RT annoyance	
	Adj. R-sq. ^a =0.43		Adj. R-sq. ^a =0.38	
	P eta ^b	p	P eta ^a	p
WT sound	0.12	< 0.001	0.01	0.140
WT visibility	0.06	< 0.001	0.00	0.865
WT attitude	0.17	< 0.001	0.00	0.413
RT sound	0.00	0.615	0.13	< 0.001
RT visibility	0.00	0.253	0.11	< 0.001
RT attitude	0.00	0.942	0.04	< 0.001
Noise sensitive	0.01	< 0.05	0.06	< 0.001
Stress	0.01	< 0.05	0.01	< 0.05

^a R-square for the dependent variable, i.e. the proportion of variation in the dependent variable explained by all the independent variables in the model.

^b Partial eta-squared value; describes the proportion of total variability attributable to a factor; adjusted for economical benefits from wind turbines.

analysis of a large data set. The relationships between sound levels and annoyance with the noise were in most cases separate for wind turbine and road traffic, respectively, and not interacting. Several interesting findings could however guide future planning for wind farms.

Wind turbine sound is, as found in other studies (Pedersen and Persson Waye, 2004; 2007), very easily perceived and about 80% of the respondent in this study could hear the sound at levels as low as 35–40 dB(A) Lden when background sound levels were low. Wind turbines were less easily heard when road traffic sound dominated over wind turbine sound, but this did not result in a change in annoyance: the dose–response relationship between levels of wind turbine noise and annoyance were about the same despite levels of road traffic sound. The exception is that high levels of road traffic sound (> 55 dB(A)) did seem to have a masking effect on wind turbine sound, but only at moderate levels of wind turbine sound (35–40 dB(A)). This statistically significant finding was confirmed in the regression models where an increase in road traffic noise led to a decrease in annoyance of wind turbine noise in the sub-sample dominated by road traffic noise. This is consistent with previous findings (for the same data set) of a reduction of annoyance with wind turbine noise in rural areas with a main road as opposed to areas without (Pedersen et al., 2009). The effect at 35–40 dB(A) vanished when the wind turbine sound level increased further. It is hence possible to reduce the prevalence of annoyance with wind turbine noise if the turbines are placed in areas with high levels of road traffic noise, but the levels of wind turbine noise need to be held back even at these sites. The reduction as yet cannot be predicted due to the low number of respondents with road traffic noise exceeding wind turbine noise with more than 20 dB(A). An explanation for the low masking potential of even relatively high levels of background sound may be that the Lden background level in fact averages over fluctuations in traffic intensity and daily patterns (rush hour) and over slower variations related to weather (down/upwind). Wind turbine sound may not be masked at times of low background sound levels (the ‘troughs’ in the level over time) and these times may determine annoyance, perhaps independent of the time length of the exposure. Wind turbine sound levels do not follow the same behaviour as road traffic noise levels. Road traffic usually calms at night, whereas modern, tall wind turbines may produce more sound at night than in daytime. Also, there is less difference between downwind and upwind audibility due to

the fact that the source is high above ground and thus for an upwind situation the sound shadow is further away than it is for a low source (road traffic). Only at relatively very high background sound levels, the troughs are not deep enough to reach the level of the wind turbine sound.

Except for the masking at 35–40 dB(A) wind turbine sound, no other effects were found. This study shows that being exposed to road traffic noise as well, did not lead to more annoyance related to wind turbine noise. The observed relation between annoyance with road traffic and wind turbine noises could be explained by common confounders, in this case noise sensitivity and stress. Noise sensitivity is usually not seen as a result of annoyance, but as a personal trait independent of exposure (Job, 1999). It is reasonable to believe that individual factors enhance the possibility of annoyance both with wind turbine and road traffic noises, and that no other interaction between annoyances with the two noise types takes place.

5. Application to wind farm planning

In the sometimes heated local debates about wind farm proposals it is important to consider the qualities of the proposed sites if the conversion from electricity generation based on fossil fuels to that of wind is to be successful and not cause adverse effects on residents and local communities. The presence of other noise sources such as road traffic is one of these qualities.

Residents near busy roads are less likely to oppose potential wind farm developments (van den Horst, 2007). Placing wind farms in areas with low background levels is more delicate. This is not unique for wind turbines; also annoyance due to aircraft noise is higher in low background sound regions in comparison to those with high background levels (Lim et al., 2008). It is not clear if indeed the differences in background levels between areas cause the difference in noise annoyance or another, possibly related factor such as landscape type. Landscape values are strongly related to the acceptability to wind farms; industrial areas and military grounds are considered suitable, while landscapes with natural and cultural preservation values are rated as not suitable (Wolsink, 2007).

The present study shows that road traffic noise can provide a significant masking of wind farm noise, but only at intermediate levels of wind turbine sound (35–40 dB(A)), not at higher or lower levels. This only occurs if the road traffic is substantially louder (+20 dB) than the wind turbines. These intermediate levels are within the range where most countries have noise limits for wind turbines (35–45 dB(A)). Thus, one would expect less noise annoyance from a not too near wind farm if residents are already exposed to road traffic sound levels of 55–60 dB(A).

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References

- Appelqvist, P., Almgren, M., Bolin, K., Åbom, M., 2007. Masking of wind turbine noise by sea waves. In: Proceedings of Second International Meeting on Wind Turbine Noise, Lyon, France, September 20–21.
- Bangjun, Z., Lili, S., Guoqing, D., 2003. The influence of the visibility of the source on the subjective annoyance due to its noise. Applied Acoustics 64, 1205–1215.

- Bolin, K., 2007. Investigating the audibility of wind turbines in the presence of vegetation noise. In: Proceedings of Second International Meeting on Wind Turbine Noise, Lyon, France, September 20–21.
- Breukers, S., Wolsink, M., 2007. Wind power implementation in changing institutional landscapes: an international comparison. *Energy Policy* 35, 2727–2750.
- Calvert, G.A., 2001. Crossmodal processing in the human brain: insights from functional neuroimaging studies. *Cerebral Cortex* 11, 1100–1123.
- Cremezzi, C., Gautier, P.E., Lambert, J., Champelovier, P., 2001. Annoyance due to combined noise sources —advanced results. In: Proceedings of 17th International Congress of Acoustics, Rome, September 2–7.
- Ek, K., 2005. Public and private attitudes towards “green” electricity: the case of Swedish wind power. *Energy Policy* 33, 1677–1689.
- EU, 2003. Commission Recommendation of 6 August 2003 concerning the guidelines on the revised computation methods for industrial noise, aircraft noise, road traffic noise, and related emission data. *Official Journal L* 212, 49–64.
- Fastl, H., Zwicker, E., 2007. *Psychoacoustics: Facts and Models*. Springer-Verlag, New York.
- IEA, 2008. *Global Wind Energy Outlook*. International Energy Agency.
- ISO, 1993. *Acoustics—Attenuation of Sound During Propagation Outdoors*, 9613. ISO, Geneva, Switzerland.
- Jabben, J., Potma, C.J.M., Swart, W.J.R., 2001. Continuous monitoring of noise emission from roadways. In: Proceedings of the INTER-NOISE, the Hague, August 28–30.
- Job, R.F.S., 1988. Community response to noise: a review of factors influencing the relationship between noise exposure and reaction. *Journal of the Acoustical Society of America* 83, 991–1001.
- Job, R.F.S., 1999. Noise sensitivity as a factor influencing human reaction to noise. *Noise & Health* 3, 57–68.
- Lercher, P., Botteldooren, D., de Greve, B., Dekoninck, L., Rüdusser, J., 2007. The effects of noise from combined traffic sources on annoyance: the case of interactions between rail and road noise. In: Proceedings of the INTER-NOISE, Istanbul, Turkey, August 28–31.
- Lim, C., Kim, J., Hong, J., Lee, S., 2008. Effect of background noise levels on community annoyance from aircraft noise. *Journal of the Acoustical Society of America* 123, 766–771.
- Miedema, H.M.E., Vos, H., 2003. Noise sensitivity and reactions to noise and other environmental conditions. *Journal of the Acoustical Society of America* 104, 3432–3445.
- Öhrström, E., Barregård, L., Andersson, E., Skånberg, A., 2007. Annoyance due to single and combined sound exposure from railway and road traffic. *Journal of the Acoustical Society of America* 122, 2642–2652.
- Pedersen, E., Hallberg, L.R.-M., Persson Waye, K., 2007. Living in the vicinity of wind turbines—a grounded theory study. *Qualitative Research in Psychology* 4, 49–63.
- Pedersen, E., Larsman, P., 2008. The impact of visual factors on noise annoyance among people living in the vicinity of wind turbines. *Journal of Environmental Psychology* 28, 379–389.
- Pedersen, E., Persson Waye, K., 2004. Perception and annoyance due to wind turbine noise: a dose-response relationship. *Journal of the Acoustical Society of America* 116, 3460–3470.
- Pedersen, E., Persson Waye, K., 2007. Wind turbine noise, annoyance and self-reported health and wellbeing in different living environments. *Occupational and Environmental Medicine* 64, 480–486.
- Pedersen, E., van den Berg, F., Bakker, R., Bouma, J., 2009. Response to noise from modern wind farms in the Netherlands. *Journal of the Acoustical Society of America* 126, 634–643.
- van den Berg, G.P., 2005. The beat is getting stronger: the effect of atmospheric stability on low frequency modulated sound of wind turbines. *Journal of Low Frequency Noise and Vibration* 24, 1–24.
- van den Berg, F., 2008. Criteria for wind farm noise: L_{max} and L_{den}. In: Proceedings of the 7th European Conference on Noise Control, EURONOISE, Acoustics'08, Paris, June 30–July 4.
- van den Horst, D., 2007. NIMBY or not? Exploring the relevance of location and the politics of voiced opinions in renewable energy siting controversies. *Energy Policy* 35, 2705–2714.
- Vos, J., 1992. Annoyance caused by simultaneous impulse, road-traffic, and aircraft sounds: a quantitative model. *Journal of the Acoustical Society of America* 91, 3330–3345.
- Wolsink, M., 2007. Planning of renewable schemes: deliberative and fair decision-making on landscape issues instead of reproachful accusations of non-cooperation. *Energy Policy* 35, 2692–2704.