Indoor noise annoyance due to 3–5 megawatt wind turbines—An exposure–response relationship

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The existing exposure–response relationships describing the association between wind turbine sound level and noise annoyance concern turbine sizes of 0.15–3.0 MW. The main purpose of this study was to determine a relationship concerning turbines with nominal power of 3–5 MW. A cross-sectional survey was conducted around three wind power areas in Finland. The survey involved all households within a 2 km distance from the nearest turbine. Altogether, 429 households out of 753 participated. The households were exposed to wind turbine noise having sound levels within 26.7–44.2 dB L_{Aeq}. Standard prediction methods were applied to determine the sound level, L_{Aeq}, in each participant's yard. The measured sound level agreed well with the predicted sound level. The exposure–response relationship was derived between L_{Aeq} outdoors and the indoor noise annoyance. The relationship was in rather good agreement with two previous studies involving much smaller turbines (0.15–1.5 MW) under 40 dB L_{Aeq}. The Community Tolerance Level (*CTL*), $CTL_{20} = 50$ dB, was 3 dB lower than for two previous studies. Above 40 dB, a small number of participants prevented a reliable comparison to previous studies.

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I. INTRODUCTION

Wind turbine noise has become an important scientific and political issue, especially in countries where wind power is increasingly being used to replace conventional sources of electricity production. According to present scientific understanding, noise annoyance has remained the only health effect of wind turbine noise (Schmidt and Klokker, 2014). A number of studies have presented exposure–response relationships describing the association between the sound level of wind turbine noise and the percentage of highly annoyed in residential environments (Table I). The studies agree that noise annoyance increases with increasing sound level. However, new research is important because different exposure–response relationship have been obtained from different countries and even from different provinces of, e.g., Sweden (Pedersen and Persson Waye, 2004, 2007) and Canada (Michaud *et al.*, 2016a, 2016b).

From the perspective of community health, the exposure–response relationship dealing with indoor noise annoyance is of primary importance because people spend most of their time at home indoors, especially in Finland. The time spent outdoors is usually shorter than the time spent indoors. Second, the activities indoors (relaxing, restoring, reading, sleeping, etc.) set much stronger limits for tolerable sound level. Wind turbine noise annoyance indoors has also been associated with sleep disturbance (Pedersen, 2011), although the level indoors is not expected to be very high. Sleep disturbance can lead to more severe health effects (Muzet, 2007). Although noise regulations for outdoor noise levels are given in many countries, noise annoyance outdoors can be considered more as a discomfort or restoration issue than a health issue. The sound level of wind turbines is usually relatively low in residential yards, under 45 dB L_{Aeq}, but the amplitude-modulated low frequency components of wind turbine noise may be noticeable indoors and produce indoor noise annoyance at levels far below the regulated sound levels of indoor noise. Therefore, authorities are highly interested in the exposure–response relationships and *CTL*s regarding indoor noise annoyance. In spite of this, only few studies of Table I have reported the indoor noise annoyance.

The field survey of Møller and Pedersen (2011) showed that the relative amount of low frequency noise was higher for large turbines (2.3–3.6 MW) than for small turbines (0.075–2 MW). The spectral difference was not large but statistically significant. They made a reference to the night-time sound level regulations of the World Health Organization (WHO) (WHO, 1999), according to which environmental noise that includes a large proportion of low frequency noise might deserve tighter indoor noise limits than 30 dB L_{Aeq}. Their results have raised strong expectations among scientists, citizens, and authorities that large turbines might cause more annoyance than small turbines even if the A-weighted sound level, L_{Aeq}, is the same. Therefore, special regulations have been given for the low frequency noise, e.g., in Denmark (Jakobsen, 2012).

The height of wind turbines increases with increasing nominal electric power [International Energy Agency (IEA, 2013)]. While the hub height of a 300 kW turbine, which was typical in 1995, was approximately 30 m, the hub height of a modern 5 MW on-shore turbine is 125 m or more. Pedersen *et al.* (2009) showed that the visibility of wind turbines was associated with significantly higher noticeability of noise below 40 dB and annoyance of noise below 35 dB L_{Aeq}. This

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TABLE I. Comparison of previous studies involving exposure–response relationships. N is the number of participants. Indoors and outdoors refer to indoor and outdoor noise annoyance, respectively. **Annoyance question and response scale: A.** Specify for each of the inconveniences below whether you notice it or are annoyed by it (A1: indoors, A2: outdoors at your dwelling). 1 Do not notice; 2 Notice, but not annoyed; 3 Slightly annoyed; 4 Rather annoyed; 5 Very annoyed. **B.** Below are a number of items that you may notice or that could annoy you when you spend time (B1: indoors, B2: outdoors at your dwelling). 1 Do not notice; 2 Notice, but not annoyed; 3 Slightly annoyed; 4 Rather annoyed; 5 Very annoyed. **C.** Thinking about the last 12 months or so, when you are here at home, how much does each noise listed below bother or annoy you? 1 Not at all; 2 Slightly; 3 Moderately; 4 Very; 5 Extremely. **D.** Occurrence and degree of annoyance experienced from wind turbine noise: (D1: Indoors, D2: Outdoors) 1 Not at all annoying; 2 A little annoying; 3 Rather annoying; 4 Annoying; 5 Extremely annoying. **E.** Thinking about the last 12 months or so, when you are here at home, how much does noise [FROM SOURCE] bother, disturb or annoy you? (E1: indoors, E2: outdoors). 1 Not at all; 2 Slightly; 3 Moderately; 4 Very; 5 Extremely. **F.** How annoying do you find the following sound? [LIST OF SOURCES] (F1: indoors, F2: outdoors) 1 Do not notice; 2 Notice, but not annoyed; 3 Slightly annoyed; 4 Rather annoyed; 5 Very annoyed.

Study	N	Dose–response relationship		Turbine power [MW]	Response collection method
		Indoors	Outdoors		
Pedersen and Persson Waye (2004)	341	A1[a]	A2	0.15–0.65	In-mail
Pedersen and Persson Waye (2007)	754	A1[a]	A2	0.40–1.50	In-mail
Pedersen and Persson Waye (2008)[b]	1095	A1[a]	A2	0.15–1.50	In-mail
Pedersen *et al.* (2009), Bakker *et al.* (2012)	725	B1	B2	0.50[c]	In-mail
Janssen *et al.* (2011)[d]	1820	A1&B1	A2&B2	0.15–1.50[e]	In-mail
Kuwano *et al.* (2014)	747	C	C	0.4–3.0	Home interview
Pawlaczyk-Luszczynska *et al.* (2014a)	361	D1	D2	0.1–2.0	In-mail
Michaud *et al.* (2016a)	1238	E1	E2	0.66–3.0	Home interview
Our study	429	F1	F2	3.0–5.0	In-mail & home interview

[a] This item was neither mentioned nor reported in this particular study but Janssen *et al.* (2011) reported these results later.

[b] Combinatory analysis of Pedersen and Persson Waye (2004, 2007).

[c] Wind turbine areas included at least two turbines sizing 0.50 MW. The power span was not reported.

[d] Aggregate analysis of Pedersen and Persson Waye (2004, 2007) and Pedersen *et al.* (2009).

[e] Referring to c, the largest size remains unknown.

finding would imply that noticeability and annoyance might increase when the turbines' physical size and visibility increases. However, there is no scientific evidence about that.

Current assumptions and guidelines on suitable setback distances and/or sound level limits for wind turbines are based largely on exposure–response relationships derived from turbines with rated power below 3 MW (Table I). At the moment, new turbines are mainly larger than 3 MW. According to the IEA (2013), the size of the largest commercially available onshore wind turbines has increased approximately by 1 MW every five years, being 5 MW in 2015. There is a strong need in both scientific venues and society to know whether the exposure–response relationship of large wind turbines (e.g., $>$3 MW) differs from that obtained from smaller wind turbines (e.g., $<$3 MW).

Noise-related complaints of wind turbines started to increase in Finland in 2012 around existing wind power areas, and noise concerns were common around wind power areas under planning. As a consequence of the strong pressure from the citizens, operators, and authorities, a new governmental regulation for wind turbine noise came into effect in 2015 (Ministry of the Environment, 2015). A literature review preceding the regulatory work (Hongisto, 2014) revealed that the most reliable exposure–response relationships of that time (Janssen *et al.*, 2011) were based on turbine sizes below 1.5 MW. There were strong beliefs that the relationships would not apply to Finnish climate and building envelopes and larger turbines. A Finnish survey was needed, focusing on households living within a 2 km distance from the wind turbines. This is because Shepherd *et al.* (2011) had recently suggested a setback distance of 2 km to protect people from wind turbines' health effects in hilly terrains, and some Finnish municipalities started to apply this setback distance. Another study found adverse health effects among people living closer than 1.4 km from the turbines (Nissenbaum *et al.*, 2012). Their conclusions have been reasonably criticized (Ollson *et al.*, 2013; McCunney *et al.*, 2014).

CTL has been increasingly used to compare the exposure–response relationships. According to Schomer *et al.* (2012): "*CTL value corresponds to the DNL value at which half of the people in a community describe themselves as highly annoyed by noise exposure*." Michaud *et al.* (2016b) reported *CTL* values regarding outdoor noise annoyance for several studies. *CTL* values for indoor noise annoyance have not been reported in the studies of Table I.

The main purpose of our study was to determine the exposure–response relationship between the sound level outdoors and indoor noise annoyance when the turbine size is 3–5 MW. *CTL* was determined to facilitate the comparison to previous studies. Similar analysis was also presented for outdoor noise annoyance. Comparison was made to the previous studies regarding indoor noise annoyance. The secondary purpose was to determine how the indoor noise annoyance depends on the distance to the nearest wind turbine.

II. MATERIALS AND METHODS

A. Design

This is a cross-sectional socio-acoustic survey which was conducted in residential dwellings near wind power areas. The independent variable was the *sound level*, L_{Aeq}. It refers to the equivalent A-weighted sound pressure level (SPL) outdoors caused by the turbines of the wind power area during the maximum sound emission of the wind power area. Maximum emission takes place when the wind speed normalized to 10 m height is 8 m/s (see Sec. II E). In such conditions, the electric power output of turbines is usually at or almost at maximum, and the sound emission should be at maximum level. The *sound level* was a continuous variable in the correlation analyses. The exposure assessment was based on four outdoor sound level categories: [25–30) dB; [30–35) dB; [35–40) dB, and [40–45] dB, and four distance categories: [400–800) m, [800–1200) m; [1200–1600) m, and [1600–2000] m.

The dependent variable was the *indoor noise annoyance* caused by wind turbines. The variable is explained in Table I (response scale F). For comparison, we reported also the *outdoor noise annoyance* results.

B. Wind power areas

The study was conducted in three wind power areas A, B, and C (Table II). The study areas represent the other wind power areas in Finland well. The areas were located in the forest more than 10 km away from the nearest city center, and reasonably close (0.3–10 km) to the nearest main highway (2 to 4 lanes, speed limit 100–120 km/h). The topography was relatively flat: the height variations were less than 30 m in every area and the turbines were surrounded by forests. Dense urban areas were not involved. Upwind turbines were used in all areas. Such turbines are expected to emit much less low-frequency sounds in comparison to downwind turbines (Jakobsen, 2005). However, large turbines (>2.3 MW) are expected to emit slightly more low-frequency sounds than small turbines (<2 MW) as found by Møller and Pedersen (2011).

We used important background information to identify three highly populated wind power areas which differed from each other with respect to three important factors: the general resistance against turbines (complaints were strong in area A according to the media), population density (area C was more dense than A and B), and history of land use (area A was built in an industrial area while areas B and C were built in a recreational area). The areas were far away from each other so that there was very little interaction between the residents. Therefore, our study areas are expected to collectively represent Finnish wind power areas.

The participants lived mainly in single-family houses, but also a couple of row houses and apartment buildings were involved from area C. Facade constructions in Finland vary with respect to the surface mass of the load-bearing wall (30–500 kg/m^2), the thickness of the wall (150–450 mm), the existence of window towards the wind

TABLE II. Description of the three wind power areas A–C.

	Wind power area			
	A	B	C	Total
Number of wind turbines in the area	12	11	3	
Nominal electric power of each turbine	4.5	3.0/3.3	5.0	
Wind turbine manufacturer and type	Gamesa G128	Vestas V112/V126	Gamesa G132	
Hub height [m]	140	140	140	
Sound power level of each turbine, L_{WA} [dB]	108.8	106.7/107.6	109.6	
Time of deployment	Dec 2013	Dec 2012	Dec 2014	
Time of our survey	Jan 2015	May 2015	Sept 2015	
Locality	Pori, Peittoo	Ii, Olhava	Salo, Märynummi	
Mid-point to sea coast distance [km]	2	3	45	
No. of households within 2 km	107	189	457	753
No. of participants	70	91	268	429
Response rate [%]	65.4	48.1	58.6	57
No. of valid participants[a]	64	78	258	400
Vacation homes [%]	46	59	5	23
Age of participants [yr]				
Mean (standard deviation)	61 (13)	58 (15)	53 (15)	55 (15)
Range	24–85	23–85	17–89	17–89
Female participants [%]	41	37	49	47
Education [%]				
Ground school (mandatory levels)	17	40	21	20
Professional or upper secondary school	18	33	25	46
Applied or scientific university (highest level)	20	44	34	34
No. of economical benefiters	[b]	[b]	[b]	10
Sound level on participants' yard, L_{Aeq} [dB]				
Mean (standard deviation)	37.6 (2.9)	35.3 (2.3)	33.6 (2.8)	34.6 (3.1)
Range	33.0–44.2	31.5–40.7	26.7–43.0	26.7–44.2
Distance to the nearest turbine [m]				
Mean (standard deviation)	1490 (350)	1460 (340)	1540 (244)	1520 (290)
Range	600–2000	790–2000	480–2000	480–2000

[a] Both *sound level* and *indoor noise annoyance* available.

[b] Values cannot be reported due to ethical reasons (number of individuals is less than 10 within each cell).

power area, the number of glass panes (2–4 pcs), thickness of glass panes (3–8 mm), cavities between the glass panes, window area (5% to 100% of floor area), the quality of window and door seals, and the presence of ventilation holes. These numerous factors affect the overall sound reduction index of the facade in a very complex way. Most participants are unable to precisely declare these building physical factors precisely. Even if they could, the sound leaks in the facade may significantly affect the sound transmission loss (Hongisto *et al.*, 2000). In addition, sound can also transmit indoors through the facade elements not facing the wind power area. Due to this complexity, we did not inquire about details of the facade construction.

C. Survey methods

The survey was conducted in each wind power area using the same questionnaire (see supplementary material[1]). The questionnaire was based on methods published in previous studies (Table I). The questionnaire inquired on, e.g., basic demographic information, noise sensitivity, experiences concerning, e.g., the satisfaction with living in the area, attitudes towards wind turbines, visibility of the turbines, and trust towards authorities or operators. Most of the questions, and the title of the survey ("Experiences of living nearby wind turbines"), were not dealing with noise. Thus, it is probable that most participants could not expect our primary purpose of doing noise effect research.

Our study focuses only on the relationship between outdoor *sound level* and *indoor noise annoyance*. The association between non-acoustic factors and noise annoyance is a topic of a subsequent study. The *indoor noise annoyance* question and response scale is shown in Table I (scale F1). The scale has basically four steps and it agrees with Pedersen and Persson Waye (2004, 2007) and Pedersen *et al.* (2009). When our data collection methods were decided in October 2014, the exposure–response relationships regarding indoor noise annoyance had been published only by Pedersen *et al.* (2009) and Janssen *et al.* (2011). We decided to adopt their four-step annoyance response scale although a five-step response scale of ISO/TS 15666 (2003) has become very popular (scale C of Table I). *Outdoor noise annoyance* was measured using the response scale F2 of Table I.

The number of households within 2 km from the wind turbines (the sample) and the number of responding households (later: participants) in each wind power area are given in Table II among other descriptive information. In areas A and B, the procedure of the survey was the same. Postal addresses and phone numbers of all households within a 2 km distance from the turbines were requested from the municipal authorities. A letter was sent to the owner of each household's dwelling to inform about the forthcoming interview survey. One week later, we started to call the owners to ask for their interest in an interview at home. If the owner was not willing, we inquired about the owner's interest to respond to the in-mail questionnaire. If this option was not accepted, we inquired about the owner's interest to respond immediately to a short phone interview, including the question for *indoor noise annoyance*. A non-response household was recorded if none of the three options were successful. In-mail questionnaire was also applied if the owner could not be reached by phone. In area C, the procedure was the same as in areas A and B, but the number of interviews was limited to 30 randomly selected households. An in-mail questionnaire was sent to the rest of the households. Overall, out of 429 participants, 125 were interviewed at home, 269 responded to the in-mail questionnaire, and 35 responded in phone to the four main questions. Reminders were not used.

In each wind power area, the results were disseminated two months after the survey ended. The participants were sent a letter which included a link to the internet page presenting the results, and a phone number where the hard copy of the results could be requested.

The study was carried out in accordance with the requirements of the national ethical principles (National Advisory Board on Research Ethics, 2009).

D. Sound level predictions

The sound levels at participants' yards, as defined in Sec. II A, were determined by well-established commercial prediction methods (CadnaA version 4.0.135, DataKustik GmbH, Gilching, Germany). The propagation of sound from the wind turbines was predicted in 1/1-octave bands within 31.5–8 000 Hz according to an international standard (ISO, 1996), which is embedded in the software. The atmospheric conditions were 70% humidity and 15 °C temperature. Wind speed was 0 m/s so that the propagation of sound from the turbines was omnidirectional. The ground absorption was 0.4. The maximum order of reflection was 3. These details follow the Finnish recommendations (Ministry of the Environment, 2014a). Ground absorption value disagrees with the suggestion of Öhlund and Larsson (2015), but we decided to hold on to national recommendations because both values resulted in similar A-weighted sound levels.

The topographic information was obtained from the file service of open data (National Land Survey of Finland, 2016). The information was imported to the software as a map info file (*.mif). All the irrelevant information from the files was omitted, except the elevation contours, roads, and buildings. The total area of water was negligible. The locations of the wind turbines were obtained from the operator of the wind power area.

The sound power level of the wind turbines was obtained from the manufacturer in 1/3-octave bands from 25 Hz to 10 kHz. The levels had been determined according to an international standard (IEC 61400-11, 2012) in downwind conditions when the wind speed normalized to 10 m height was 8 m/s. The operator had performed some sound power level measurements and the results were in good agreement with the manufacturer's values (difference less than 1 dB in L_{WA}). The wind turbines were treated as omnidirectional point sound sources in the model.

The SPL at receiver positions was calculated to the geometrical center of each participant's main building at a height of 4 m. The locations of the participants were obtained from the municipal authorities. The buildings were modeled using zero height from the ground so that they did not affect the propagation of sound.

The outcome of the prediction was A-weighted SPL at a height of 4 m from the ground, and without the reflecting effect of the houses or other obstacles. These values corresponded to the *sound level*, L_{Aeq}, which was assigned to the participant. Noise measurements are usually conducted at a height of 4.0 m from the ground according to ISO 1996-2 (ISO, 2007). The height of 1.5 m can be applied in residential areas with one-floor-high buildings. The differences in L_{Aeq} between these two heights is negligible in areas where the density of buildings is small, which was the case in our study.

L_{Aeq} was used as a primary quantity of *sound level* because it is used in Finnish legislation like in many other countries. The determination of L_{den} is possible if the annual distribution of wind speed could be taken into account in each wind turbine area. In the absence of data that would permit a more precise estimate, the conversion equation $L_{\mathrm{den}} = L_{\mathrm{Aeq}} + 4.7$ dB recommended by van den Berg (2008) was applied. By comparison, Kuwano *et al.* (2014) used a correction constant +6 dB and Keith *et al.* (2016a) derived a constant +1.9 dB.

E. Sound level measurements

The predicted sound levels were verified by measurements in each wind power area according to the national regulations (Ministry of Environment, 2014b) and international standards (ISO 1996-2, 2007; IEC 61400-11, 2012). The measurement times and positions were selected so that downwind condition prevailed and the wind power output was at maximum so that the sound power levels were also at maximum. This condition corresponds with the predicted sound levels in this specific direction. Positions were selected from moderate distances to avoid strong background noise problems. The positions were within the allowed sector ±45% from the downwind direction.

Measurements were conducted in collaboration with the operator to obtain the electric output power and the wind direction and wind speed at the hub height, and to be able to shut down the turbines during background noise measurements. These data were obtained in 10 s intervals (averages).

Measurement positions labeled "*M*" were equipped with a precision sound level meter at a height of 1.5 m from the ground (Nor150 analyzer, NOR1217 microphone). Measurement positions labeled "*K*" were equipped with a digital data recorder (Tascam HD-P2, NTI Audio M2010 microphone). Data were collected in 10 s periods ($T = 10$ s). The time synchronization of all data sources (wind turbine, noise measurement devices) was made using the national time standard (VTT Mikes Metrology, 2016).

In each measurement position, the equivalent sound levels, L_{Aeq}, were plotted as a function of wind speed v_{10} (normalized from wind speed at hub height to wind speed at 10 m height) separately in two conditions: ON (total noise including both turbine noise and background noise) and OFF (only background noise). Linear fitting was applied to both datasets. The corresponding levels, $L_{\mathrm{Aeq,WB}}$ (ON) and $L_{\mathrm{Aeq,B}}$ (OFF), were determined from the linear fit at the normalized wind speed value $v_{10} = 8$ m/s. The measurement result, $L_{\mathrm{Aeq,M}}$, was determined after the background noise correction. Thereafter, the predicted value, $L_{\mathrm{Aeq,P}}$, at the measurement position was determined using the sound propagation model of Sec. II D. The uncertainty value U (dB) of the measurement was determined according to the principles of ISO 1996-2. The value depends on the variation of sound levels, number of data points, size of the background noise correction, and instrumentation. The predicted and measured values were in agreement if $L_{\mathrm{Aeq,P}} - U < L_{\mathrm{Aeq,M}} < L_{\mathrm{Aeq,P}} + U$.

It is normal that the datasets ON and OFF overlap significantly when the distance to the nearest wind turbine increases. This is because the level of wind turbine noise gets close to the background noise caused by wind noise and vegetation noise. When the difference between levels $L_{\mathrm{Aeq,WB}}$ and $L_{\mathrm{Aeq,B}}$ was less than 3 dB, the background noise correction to $L_{\mathrm{Aeq,WB}}$ was at most −3 dB.

F. Exposure–response relationships

Careful analysis of previous exposure–response relationships was conducted after a literature review (Table I). When our study design was decided, the response scale used by Janssen *et al.* (2011) was found to be the most relevant. Their study used the data collected by Pedersen and Persson Waye (2004, 2007) and Pedersen *et al.* (2009). However, only Pedersen *et al.* (2009) and Janssen *et al.* (2011) reported the indoor noise annoyance in such a form that we could perform a meaningful comparison.

The literature of Table I is very inconsistent regarding the methods of deriving the exposure–response relationships. In our study, the dichotomization of *indoor noise annoyance* responses was made according to two different definitions:

(1) Percentage of highly annoyed *%HA* corresponds to the percentage of participants who responded 5 on our annoyance scale (scale F1 of Table I). This definition enables direct comparison to the results of Pedersen *et al.* (2009), who used an equal annoyance measurement method (see Table I). The exposure–response relationship was presented as a function of L_{Aeq}.

(2) Percentage of highly annoyed *%HA* corresponds to the percentage of participants whose responses were above the cut-off point of 72% in a transformation, where the responses from 1 to 5 were equally distributed on a scale from 0 to 100. The definition conforms to Schultz (1978). We used the procedure explained on page 3748 of Janssen *et al.* (2011) to transform our four-point annoyance responses [scale F1 of Table I, where responses (1) and (2) were combined] to a scale from 0 to 100. This definition enables direct comparison to the results of Janssen *et al.* (2011). The exposure–response relationship was presented as a function of L_{den}.

We could not present a comparison to Kuwano *et al.* (2014) because they did not explicitly enquire the annoyance indoors. Comparison to Pawlaczyk-Luszczyńska *et al.* (2014) could not be done either because they reported only the percentage of moderately annoyed participants indoors (percentage of participants reporting annoyance rating 3, 4, or 5 on scale D of Table I). Figure 3 of Michaud *et al.* (2016a) reported the fitted percentage of highly annoyed participants indoors (L_{Aeq}). However, they defined *%HA* as the percentage of responses 4 or 5 on scale E of Table I. It was not found meaningful to transform the data of Pawlaczyk-Luszczyńska *et al.* or Michaud *et al.* to meet the definitions used in our study.

G. Other analyses

Bivariate Spearman's correlation coefficient, r_S, was determined between three variables: the absolute *distance* to the nearest wind turbine, absolute predicted *sound level*, and *indoor noise annoyance*. In this analysis, annoyance responses were transformed to a 4-step response scale where the original responses (1) and (2) (scale F1 of Table I) were merged since they both indicate the absence of annoyance. The coefficients are statistically significant if $p < 0.01$ (two-tailed).

CTL was determined according to Schomer *et al.* (2012) by finding the best fit of the following fitting function over the data points of exposure–response relationship [*%HA* in the ordinate vs L_{den} in the abscissa]:

$$\%HA = 100 \cdot \exp\left[-\left(1/\left[10^{(L_{den} - CTL_{50} + 5.306)/10}\right]^{0.3}\right)\right], \quad (1)$$

where CTL_{50} represents the L_{den} value where *%HA* is expected to reach the level of 50%. CTL_{20} was determined from the fitting function at the point where $\%HA = 20\%$.

The original model requires the determination of yearly average L_{dn} (day–night level), where 10 dB penalty is given for the A-weighted equivalent SPL from 10 p.m. to 7 a.m. Based on van den Berg (2008), L_{dn} is nearly equivalent with L_{den} (day–evening–night level), where 5 dB penalty is given between 7 p.m. and 10 p.m. The yearly average day–night sound power level of a wind power area depends on yearly wind conditions of the area because the sound power level depends on the rotation speed, and, finally, on wind speed at hub height. *CTL* was determined using the *%HA* definition 2 in Sec. II F for our data, and the previous data of Pedersen *et al.* (2009) and Janssen *et al.* (2011).

III. RESULTS

The comparison of measured and predicted *sound levels* in eight positions are shown in Table III.

A demographic description of the aggregate study sample of wind power areas A–C is presented in Table II. The distribution of *indoor noise annoyance* responses in each sound level category is depicted in Table IV.

Spearman's correlation coefficient between *indoor noise annoyance* and *sound level* was $r_S = 0.27$ ($p = 2.4 \times 10^{-8}$). Correlation coefficient between *indoor noise annoyance* and *distance* to the nearest wind turbine was $r_S = -0.20$ ($p = 8.5 \times 10^{-5}$). *Sound level* and *distance* were strongly correlated ($r_S = -0.79$, $p = 1.5 \times 10^{-87}$). *Indoor noise annoyance* was larger when the *sound level* was larger or the *distance* to the turbines was shorter. The corresponding coefficients of determination (square of r_S) were 0.08 and 0.04, respectively, indicating that only 8% of the variance in *indoor noise annoyance* ratings could be explained by *sound level* and 4% by *distance*.

TABLE III. Comparison of measured and predicted *sound levels* in eight positions. The measured and predicted values were in agreement if $L_{\mathrm{Aeq,M}} < L_{\mathrm{Aeq,P}} + U$. Agreement was observed in every position. *d* is the distance to the nearest wind turbine. $L_{\mathrm{Aeq,WB}}$ is the measured A-weighted equivalent SPL of total noise, wind turbines ON. $L_{\mathrm{Aeq,B}}$ is the measured A-weighted equivalent SPL of background noise, wind turbines OFF. $L_{\mathrm{Aeq,M}}$ is the background noise corrected A-weighted equivalent SPL of wind turbine noise. *U* is the estimated measurement uncertainty of $L_{\mathrm{Aeq,M}}$. $L_{\mathrm{Aeq,P}}$ is the predicted A-weighted equivalent SPL of wind turbine noise. SPL is the sound pressure level (dB re 20 μPa).

Wind power area/Position	*d* (m)	$L_{\mathrm{Aeq,WB}}$ (dB)	$L_{\mathrm{Aeq,B}}$ (dB)	$L_{\mathrm{Aeq,M}}$ (dB)	*U* (dB)	$L_{\mathrm{Aeq,P}}$ (dB)
A/M1	660	47.8	44.7	44.8	4	44.1
A/K1	630	48.4	44.7	45.9	4	44.6
B/M1	447	42.8	38.1	41.0	4	43.0
B/K1	244	47.6	39.0	47.6	3	46.6
B/K2	600	42.1	39.5	39.1	5	41.3
B/K3	383	46.6	38.2	46.6	4	44.7
C/M1	772	47.2	45.4	44.2	5	43.2
C/K1	889	47.7	46.9	44.7	5	42.0

The exposure–response relationship and related confidence intervals are shown in Fig. 1. Comparison to the previous exposure–response relationships reporting *indoor noise annoyance* are shown in Fig. 2 and Fig. 3. The *CTL* values of our study, Pedersen *et al.* (2009) and Janssen *et al.* (2011) are shown in Table V. The *CTL* plots according to Eq. (1) are shown in Fig. 4.

TABLE IV. Description of study characteristics and indoor noise annoyance responses in four sound level categories.

	L_{Aeq} [dB]					
	[25–30]	[30–35]	[35–40]	[40–45]	Total	Total [%]
Response rate [%]	61.8	61	59.9	42.5	42.5	
Female participants [%]	45.5	51.7	41.8	37.5	37.5	
Mean age [yr]	58.6	54.4	55.8	57.3	57.3	
Age range [yr]	34–77	17–86	23–89	37–85		
No. of responses	21	209	153	15	398	
Way of responding:						
Interview at home	8	188	57	12		
In-mail questionnaire	6	21	81	3		
Short phone interview	7	0	15	0		
Vacation homes [%]	0	19	29	23		
Indoor noise annoyance						
Total no. of responses	21	209	153	15	398	
1. Do not notice	17	160	93	2	272	68.3
2. Notice, but not annoyed	3	25	26	3	57	14.3
3. Slightly annoyed	0	17	18	5	40	10.1
4. Rather annoyed	1	4	11	2	18	4.5
5. Very annoyed	0	3	5	3	11	2.8
Outdoor noise annoyance						
Total no. of responses	20	208	156	16	400	
1. Do not notice	7	78	13	0	98	24.5
2. Notice, but not annoyed	10	85	81	2	178	44.5
3. Slightly annoyed	3	27	30	4	64	16.0
4. Rather annoyed	0	14	23	3	40	10.0
5. Very annoyed	0	4	9	7	20	5.0

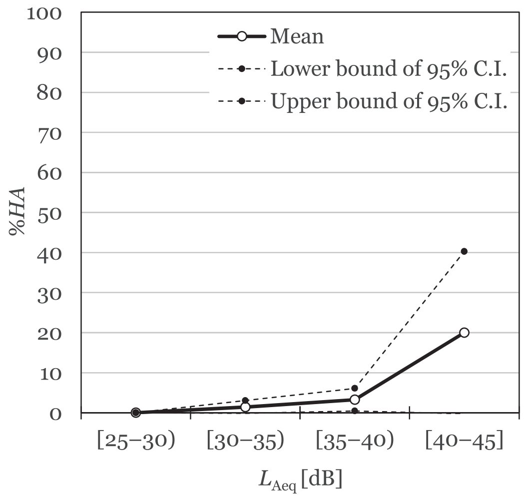

FIG. 1. The exposure–response relationship for indoor noise annoyance and the related confidence interval ($N = 398$) in four sound level categories. L_{Aeq} corresponds to the predicted equivalent A-weighted sound level of wind turbine noise outdoors during maximum sound emission from the wind power area. *%HA* is the percentage of highly annoyed participants by wind turbine noise indoors according to definition 1 of Sec. II F. The expected uncertainty of L_{Aeq} is negligible based on the results of Table III.

Ten participants were economically benefiting from the wind turbines. Detailed information about them cannot be given due to ethical reasons. Four of them belonged to the sound level category [30–35) dB L_{Aeq} and four to [35–40) dB. These eight participants reported that the wind turbine sound is inaudible. By comparison, 70% of all participants within the sound level categories [30–40) dB reported that the sound is inaudible. The difference between the benefiters and non-benefiters was statistically significant but the effect on the exposure–response relationship is negligible. Therefore, we did not exclude these ten benefiters from the analyses.

The relation between the categorized *distance* and percentage of highly annoyed indoors is shown in Fig. 5.

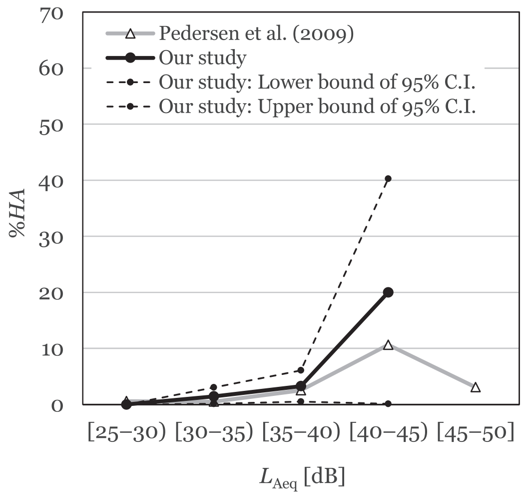

FIG. 2. Comparison of our exposure–response relationship to Pedersen *et al.* (2009, Table II). Our curve is based on the data of Table IV and Fig. 1. *%HA* is the percentage of highly annoyed participants by wind turbine noise indoors according to definition 1 of Sec. II F. L_{Aeq} is described in Fig. 1. The curve of Pedersen *et al.* (2009) bends down in the sound level category [45–50] dB. A possible explanation was that the majority of respondents (67%) benefited economically from the turbines in this category.

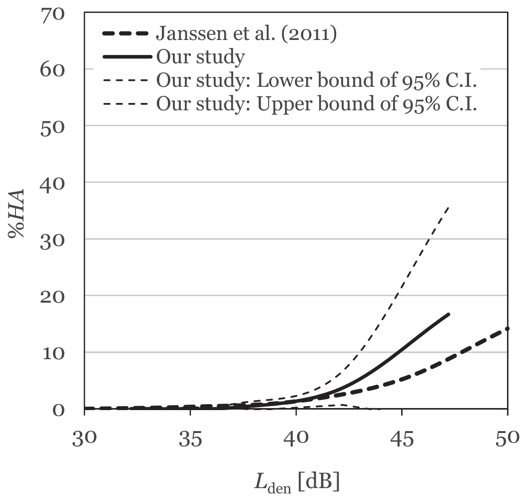

FIG. 3. Comparison of our exposure–response relationship to Janssen *et al.* (2011, Fig. 1, left panel). *%HA* is the percentage of highly annoyed participants by wind turbine noise indoors determined according to definition 2 of Sec. II F. L_{den} is the predicted day–evening–night level ($T = 24$ h) of wind turbine noise outdoors during maximum sound emission from the wind power area. The curve of Janssen *et al.* (2011) excluded participants who benefited economically from the wind turbines.

The distribution of *outdoor noise annoyance* responses in each sound level category is depicted in Table IV. The exposure–response relationship and related confidence intervals are shown in Fig. 6. The *CTL* regarding *outdoor noise annoyance* were $CTL_{20} = 48$ dB and $CTL_{50} = 60$ dB.

IV. DISCUSSION

A. Exposure–response relationship

Indoor noise annoyance was significantly, albeit weakly, associated with the *sound level*. This is in agreement with previous studies (Pedersen and Persson Waye 2004, 2007; Pedersen *et al.*, 2009).

Our exposure–response relationship agreed strongly with Pedersen *et al.* (2009) up to the sound level category [35–40) dB L_{Aeq}, and with Janssen *et al.* (2011), up to 42 dB L_{den}. Above these limits, our exposure–response relationship seems to increase faster with *sound level* than the previous ones. When the confidence interval of our relationship is taken into account, it is not possible to suggest that there is a disagreement between the relationships below sound level category [40–45] dB L_{Aeq} (Fig. 2) or below 47 dB L_{den} (Fig. 3).

Møller and Pedersen (2011) showed that large wind turbines (>2.3 MW) emit significantly more low frequency noise than small wind turbines (0.075–2 MW), which could increase annoyance indoors since low frequencies can more

TABLE V. The *CTL*s determined from Fig. 4 regarding *indoor noise annoyance*.

	CTL_{20} [dB]	CTL_{50} [dB]
Our study	50	62
Pedersen *et al.* (2009)	53	66
Janssen *et al.* (2011)	53	65

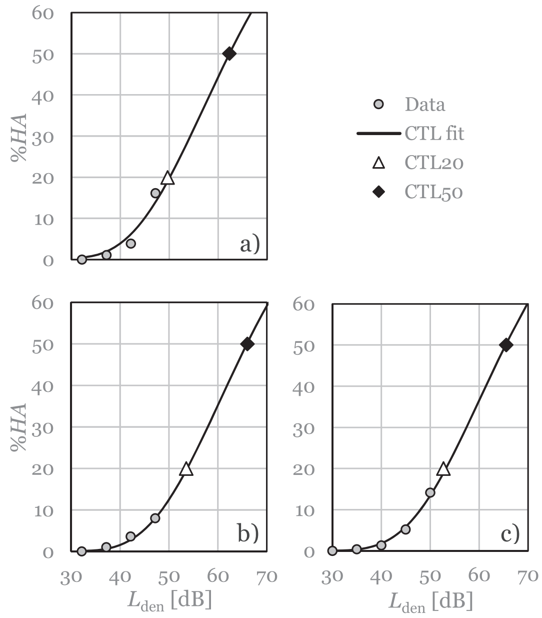

FIG. 4. The determination of CTL_{20} and CTL_{50} values for (a) our study, (b) Pedersen *et al.* (2009), and (c) Janssen *et al.* (2011). The data points (grey circles) represent the percentage of highly annoyed participants by wind turbine noise indoors determined according to definition 2 of Sec. II F. The fitting was made to the data points according to Eq. (1). The data points of (a) and (c) are based on the corresponding curves of Fig. 3. The data points of (b) were derived from Fig. 2 using the definition 2 in Sec. II F. The uncertainty of *%HA* of (a) follows the confidence intervals of Fig. 3. The data of Pedersen *et al.* in the sound level category [45–50] dB shown in Fig. 2 was not used in the derivation of *CTL* because the majority of respondents (67%) benefited economically from the turbines.

easily penetrate through the facade constructions. Our study does not suggest that exposure to large turbines would lead into larger annoyance indoors than exposure to smaller turbines. Our study suffered from a small number of respondents above 40 dB L_{Aeq} so that strong conclusions regarding the annoyance difference of large (3–5 MW) and small wind turbines (<1.5 MW) cannot be made. It should be noted that the mean difference of the emission spectra of large and small turbines was only 2–4 dB within 63–125 Hz (Fig. 14 of Møller and Pedersen, 2011): such a small difference does not usually result in statistically significant annoyance changes even in carefully designed laboratory experiments.

The width of the confidence interval was large in the sound level category [40–45] dB L_{Aeq} because it involved only 15 participants. As a result of the Finnish noise policy, residential houses are mainly located below the 40 dB limit after the year 2012. Another Finnish survey suffered also from the lack of respondents close to the turbines (Turunen *et al.*, 2016a, 2016b). There are not many other wind power areas in Finland where the residents are exposed to levels above 40 dB L_{Aeq}. Therefore, the number of participants in the category [40–45] dB could only be increased by conducting a follow-up survey only in the vicinity of a large number of wind power areas erected before 2012.

Our exposure–response relationship is valid for the pool of areas A–C. The results should be applied to specific other wind power areas with care because different exposure–response relationships have been observed in different areas (see Sec. I). Therefore, it is not justified to suggest that the

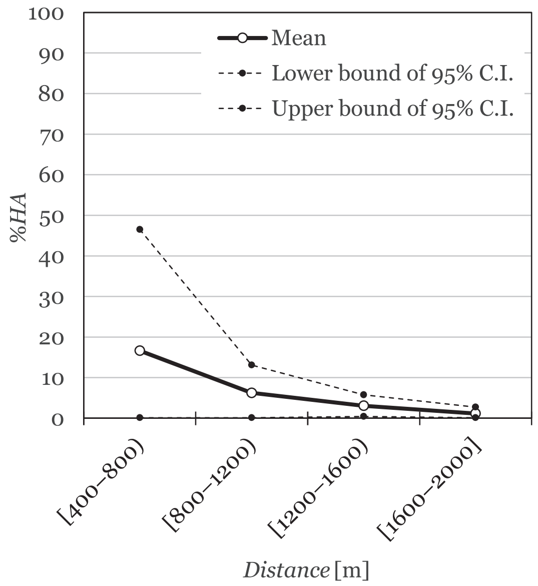

FIG. 5. The relationship between *%HA* and the *distance* to the nearest wind turbine in four distance categories. *%HA* is the percentage of highly annoyed participants by wind turbine noise indoors according to definition 1 of Sec. II F.

minor differences between the curves in Figs. 2 and 3 above 40 dB are explained solely by the power supply of the wind turbines or their size.

The *CTL* values of our study were 3–4 dB lower than those derived for the data of Pedersen *et al.* (2009) and Janssen *et al.* (2011) involving indoor noise annoyance data (Table V). This could be expected from Figs. 2 and 3, where our exposure–response relationship was at a slightly higher position than previous studies above 40 dB L_{Aeq}. Our *CTL* values involve a large uncertainty since the value is based on the mean annoyance values of four sound level categories. The mean of the highest sound level category [40–45] dB had a wide 95% confidence interval. Therefore, our *CTL* values involve a large uncertainty.

Comparison of Figs. 1 and 6 reveals that the *%HA* curve of *outdoor noise annoyance* was at a higher level than the

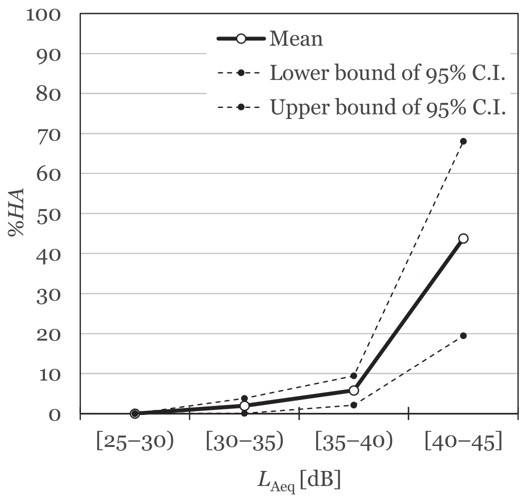

FIG. 6. The exposure–response relationship for *outdoor noise annoyance* and the related confidence interval ($N = 400$) in four sound level categories. L_{Aeq} and *%HA* were described in Fig. 1.

%HA curve of *indoor noise annoyance*. The difference was similar as observed by, e.g., Janssen *et al.* (2011). Correspondingly, the *CTL* were 2 dB lower for *outdoor noise annoyance* than for *indoor noise annoyance*. Our result regarding *outdoor noise annoyance* ($CTL_{50} = 60$ dB) falls to the range of previously determined values (57–65 dB) reported by Michaud *et al.* (2016b) for wind turbines smaller than 3 MW.

B. Distance

Indoor noise annoyance was slightly better explained by the *sound level* than by the *distance* to the nearest wind turbine. However, 92% of variance in *indoor noise annoyance* is still explained by other factors than *sound level*. Low correlation coefficient between *indoor noise annoyance* and *sound level* is partially explained by small percentage of annoyed respondents: only 17.3% of all respondents rated 3, 4, or 5 in scale F1 of Table I. The finding supports the further research of the role of, e.g., non-acoustic factors and alternative descriptors of noise exposure. The research of the latter option is very important because the land use and appropriate setback distances will probably be based on the sound level predictions also in the future.

The three study areas A–C represent typical Finnish wind power areas well. Therefore, it was justified to analyze the dependence of *%HA* on the *distance* using coarse distance categories separated by 400 m (Fig. 5). The *indoor noise annoyance* was systematically reduced with increasing distance. It is usual in noise control policies that *%HA* values above 10%–20% should be avoided. In our data, *%HA* was under 10% already in the distance category [800–1200) m and reached almost zero in the distance category [1600–2000] m: two participants out of 173 (1.2%) reported to be very annoyed in the distance category [1600–2000] m. Our results do not give support the suggestions of Nissenbaum *et al.* (2012) or Shepherd *et al.* (2011), according to which fixed setback distances (1400 or 2000 m, respectively) to wind turbines should be applied to protect the residents from adverse health effects. The reason is obvious: environmental policies cannot be based on the target that no-one reports "very annoyed." Our interpretation is also justified because high noise annoyance, including indoor noise annoyance, is the only health effect of wind turbine noise (Schmidt and Klokker, 2014). The other potential health effects suggested by Nissenbaum *et al.* (2012) or Shepherd *et al.* (2011) have not been supported by a much larger study (Feder *et al.*, 2015).

The use of fixed setback distances cannot be supported from physical reasons either. Wind farms involving high emission wind turbines produce much wider noise areas than wind farms involving low emission wind turbines. The number of wind turbines in the wind farm plays also an important role. Therefore, the setback distance should be determined for each wind farm separately using sound propagation models and regulated noise limits. In spite of these arguments, some communities have made political decisions about the application of fixed setback distances.

Although the *indoor noise annoyance* depended on the *distance*, the curve of Fig. 4 shall not be generalized. If the sound power level of the wind turbines is lower than in the wind power areas of our study, or the density of wind turbines is lower, the height of the columns in Fig. 4 are expected to decrease because the noise exposure is lower.

C. Sound levels

The measured sound levels of wind turbine noise in eight positions were on average 0.6 dB larger than the predicted values (Table III). The largest difference between the predicted and measured sound level was +2.7 dB (position *C/K*1). The differences in all eight positions were smaller than the measurement uncertainty (3–5 dB) of sound level. The predicted sound levels agreed well with measured sound levels and major errors related to the *sound level* can be ruled out.

By comparison, the measurement uncertainty within a single laboratory for repeated measurements of a calibrated wide-band steady-state sound source is at least 1 dB (Hongisto *et al.*, 2016). The uncertainty for the same sound source is at least 1.5 dB between different laboratories (different apparatus, technicians, and practices). In field environments, the uncertainties are always larger than in controlled laboratory conditions because it is impossible to achieve equivalent levels of the vegetation and wind noise during the subsequent measurement of $L_{\mathrm{Aeq,WB}}$ and $L_{\mathrm{Aeq,B}}$. Therefore, the estimated uncertainty values of U in Table III may be even underestimated.

The previous studies of Table I have presented very little or no quantitative analysis regarding the differences between predicted and measured sound levels at distances where the dwellings are located. An exception is the survey of Kuwano *et al.* (2014), where the predicted sound levels assigned to the participants were based on night-time measurements described in Tachibana *et al.* (2014). Although the uncertainty of prevailing prediction methods has been shown to be small (Evans and Cooper, 2012), and the sound power levels reported by the manufacturers have been found to be reliable (Keith *et al.*, 2016b), the absence of prediction errors in specific wind power areas cannot be ruled out without measurements. Therefore, the quantitative analysis of the reliability of predicted sound level is a strength of our study.

Our measurements were conducted in the distance range 244–889 m from the turbines, although the questionnaire survey concerned distances up to 2000 m. The increment of measurement positions above 1 km would not give much added value, because the value of U is larger than 5 dB due to the strong overlap of background noise and wind turbine noise. In some circumstances, background noise, $L_{\mathrm{Aeq,B}}$, can be even higher than the total noise, $L_{\mathrm{Aeq,WB}}$, because of the random occurrence of the vegetation and wind noise. In such cases, the declared result $L_{\mathrm{Aeq,M}}$ is an overestimate of the true result, the measurement uncertainty upwards is negligible and indefinitely large downwards. A negative signal-to-noise ratio could be interpreted as the harmlessness of the signal, i.e., wind turbine noise. On the other hand, the psychoacoustic experiment of Van Renterghem *et al.* (2013)

demonstrated that wind turbine sound could still be detected by the subjects when the L_{Aeq} of wind turbine noise was 20 dB below the L_{Aeq} of intermittent road traffic noise. Because the most sensitive inhabitants can report high annoyance right after the sound is noticeable, actual sound level L_{Aeq} may have very little to do with the dweller's subjective perception of the sound.

We focused on the *indoor noise annoyance*, although the sound levels concern the levels outdoors. Using outdoor sound levels is a standard practice in environmental epidemiology. It was not meaningful to conduct indoor sound level measurement because the measurement uncertainties are unsustainable. Measurements require a downwind condition as explained in Sec. I. It may take several years until the wind blows in the direction of a specific dwelling with sufficient strength. The evacuation of the residents is necessary, which might not be accepted by everyone. Based on our experiences of wind turbine noise measurement in various homes, indoor measurements would be strongly contaminated by background noise of home appliances and the electric background noise of measurement apparatus because the estimated SPL of wind turbine noise is far less than 25 dB L_{Aeq} inside most residences of our study. The estimated upper limit of 25 dB is based on the expectation that the building envelope reduces the wind turbine noise at least by 20 dB when the windows and doors are closed.

The prediction of indoor sound levels would be an easier alternative because the outdoor levels are always predicted in octave bands. Such a procedure is already applied in Denmark (Jakobsen, 2012) and also in Finland. Hoffmeyer and Jakobsen (2010) have reported typical level differences of the facades of typical Danish houses in third octave bands. However, the building envelope constructions may be different in Finland than in Australia or Denmark. Keränen *et al.* (2017) have recently reported a large number of sound insulation measurements of the facades of Finnish single-family houses and cottages within 5–5000 Hz. The data can be used to estimate indoor sound levels and spectra.

D. Other methodological questions

Non-acoustic factors such as noise sensitivity, attitudes towards the landscape effects of wind turbines, visibility of wind turbines, attitudes towards wind turbines in general, and economical benefitting have been stronger when associated with noise annoyance than the sound level itself (Pedersen and Persson Waye, 2004, 2007; Pedersen *et al.*, 2009; Pawlaczyk-Luszczynska *et al.*, 2014; Kuwano *et al.*, 2014; Michaud *et al.*, 2016b). Such findings have been supported by a preliminary analysis concerning wind power areas A and B (Hongisto *et al.*, 2015). However, the detailed analysis of non-acoustic factors was beyond the scope of this study. We focused on the sound level because it is an objective variable used in environmental protection and legislation, unaffected by subjective variables. Environmental protection and design are primarily based on simple physical quantities, such as distances and sound levels. Political decisions will be based more or less on available exposure–response relationships and preferably also on *CTL* values.

In spite of this, understanding the associations between various non-acoustic variables and noise annoyance is necessary to understand the large individual differences of annoyance ratings and to be able to develop noise control processes which aim to reduce noise annoyance, not only sound level (Guski, 1999). For example, if the concerns of possible health effects of wind turbines are associated with noise annoyance, it is important for the developers to distribute scientific facts dealing with the issue to the residents. Distribution of fact-based information is expected to reduce gratuitous health concerns and non-specific health symptoms (Crichton *et al.*, 2014).

The role of more sophisticated descriptors of noise exposure shall not be underestimated. It is possible that adjusted *sound level* L_{Aeq} involving an adequate penalty for, e.g., tonality (Oliva *et al.*, 2017) or amplitude modulation (Schäffer *et al.*, 2016) might result in better correlation with indoor noise annoyance.

New wind power areas in Finland are usually owned by large energy companies: locals are seldom given the possibility to invest in the local wind energy business. Economical compensations to locals are usually not given. Receiving land rent, involvement on building and maintenance business, or local secondary services are the most typical ways of economically benefiting from the wind power industry. Therefore, it was not a surprise that our study involved only ten economically benefiting participants. By comparison, the exposure–response relationship of Janssen *et a*l. (2011) in Fig. 3 involved an exclusion of 138 benefiters out of 1820 participants. Most of the economically benefitting participants originated from the sub-study conducted in the Netherlands (Pedersen *et al.*, 2009) where 104 out of 725 participants benefited economically from the turbines. In their study, economic benefit was negatively associated with noise annoyance but not with audibility. They found almost no annoyance among economically benefitting participants, independent on the sound level. It is possible that the annoyance might be larger in equivalent wind power areas where the residents would not benefit economically. This is the reason why we ignored the highest sound level category of Pedersen *et al.* (2009) while determining the corresponding *CTL* values (see Figs. 2 and 4). Because Janssen *et al.* (2011) did not publish the exposure–response relationship including the economically benefitting participants, the comparison shown in Fig. 3 may be partially misleading.

Our data was mainly collected by interviews in wind power areas A and B, and mainly by in-mail questionnaires in area C. It is possible that different methods of collecting responses in different areas caused some bias in the results. However, it is impossible to suggest the direction of a possible bias. In addition, we cannot guarantee that we could mask our intention of studying the perception of wind turbines. Although most of the questions in our questionnaire did not deal with wind turbine noise, we do not find it plausible that these attempts masked our true intention among all participants because the wind turbine noise issue was frequently released in the news in 2014 and 2015. In addition, wind power activists distributed non-scientific information about the negative health effects of wind turbines in many wind power areas. Masking could be achieved in such studies where the questions are not dealing with the noise source but only with, e.g., health, symptoms, and general environmental perceptions. Another option is registry-based health studies involving residents from wind turbine areas and control areas.

V. CONCLUSIONS

The first exposure–response relationship between outdoor sound level and indoor noise annoyance was derived for large wind turbines (3–5 MW) based on a sample of 429 participants around three wind power areas. The relationship was in relatively good agreement with those obtained for significantly smaller wind turbines (sizes 0.15–3.0 MW) when the sound level was under 40 dB L_{Aeq}. The CTL, $CTL_{20} = 50$ dB L_{den}, was 3–4 dB lower than those determined for previous surveys involving smaller turbines. The prevalence of high annoyance was less than 4%, when the sound level was under 40 dB L_{Aeq}. It seems that large wind turbines (>3 MW) produce pretty similar indoor noise annoyance than smaller ones (<1.5 MW) below 40 dB L_{Aeq}. However, future studies are needed to confirm or question our findings because of a limited sample size above 40 dB L_{Aeq}.

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[1] See supplementary material at http://dx.doi.org/10.1121/1.5006903 for the original questionnaire (available only in Finnish).

Bakker, R. H., Pedersen, E., van den Berg, G. P., Stewart, R. D., Lok, W., and Bouma, J. (**2012**). "Impact of wind turbine sound on annoyance, self-reported sleep disturbance and psychological distress," Sci. Total Environ. **425**, 42–51.

Crichton, F., Chapman, S., Cundy, T., and Petrie, K. J. (**2014**). "The link between health complaints and wind turbines: Support for the nocebo expectations hypothesis," Front. Publ. Health **2**, 220.

Evans, T., and Cooper, J. (**2012**). "Comparison of predicted and measured wind farm noise levels and implications for assessments of new wind farms," Acoust. Australia **40**(1), 28–36.

Feder, K., Michaud, D. S., Keith, S. E., Voicescu, S. A., Marro, L., Than, J., Guay, M., Denning, A., Bower, T. J., Lavigne, E., Whelan, C., and van den Berg, F. (**2015**). "An assessment of quality of life using the WHOQOL–BREF among participants living in the vicinity of wind turbines," Environ. Res. **142**, 227–238.

Guski, R. (**1999**). "Personal and social variables as co-determinants of noise annoyance," Noise Health **3**, 45–56.

Hoffmeyer, D., and Jakobsen, J. (**2010**). "Sound insulation of dwellings at low frequencies," J. Low Freq. Noise Vibr. Act. Control **29**(1), 15–23.

Hongisto, V. (**2014**). *Health Effects of Wind Turbine Noise* (Finnish Institute of Occupational Health, Helsinki, Finland).

Hongisto, V., Keränen, J., and Lindgren, M. (**2000**). "Sound insulation of doors—Part 2: Comparison between measurement results and predictions," J. Sound Vib. **230**(1), 149–170.

Hongisto, V., Keränen, J., Virjonen, P., and Hakala, J. (**2016**). "New method for determining sound reduction of furniture ensembles in laboratory," Acta Acust. united Acust. **102**, 67–79.

Hongisto, V., Suokas, M., Varjo, J., and Yli-Kätkä, V.-M. (**2015**). "Tuulivoimalamelun häiritsevyys kahdella tuulivoima-alueella" ("Annoyance of wind turbine noise in two wind power areas"), Ympäristö ja Terveys -lehti **6**, 54–59.

IEA (**2013**). "Technology roadmap: Wind Energy," 2013 edition (International Energy Agency, Paris, France), available at http://www.iea.org/publications/freepublications/publication/technology-roadmap-wind-energy—2013-edition.html (Last viewed October 10, 2017).

IEC (**2012**). IEC 61400-11, *Wind Turbines – Part 11: Acoustic Noise Measurement Techniques* (International Electrotechnical Commission, Geneva, Switzerland).

ISO (**1996**). ISO 9613-2, *Acoustics—Attenuation of Sound During Propagation Outdoors. Part 2: General Method of Calculation* (International Organization for Standardization, Geneva, Switzerland).

ISO (**2003**). ISO/TS 15666, *Acoustics—Assessment of Noise Annoyance by Means of Social and Socio-Acoustic Surveys* (International Organization for Standardization, Geneva, Switzerland).

ISO (**2007**). ISO 1996-2, *Acoustics—Description, Measurement and Assessment of Environmental Noise. Part 2: Determination of Environmental Noise Levels* (International Organization for Standardization, Geneva, Switzerland).

Jakobsen, J. (**2005**). "Infrasound emission from wind turbines," J. Low Freq. Noise Vibr. Act. Control **24**(3), 145–155.

Jakobsen, J. (**2012**). "Danish regulation of low frequency noise from wind turbines," J. Low Freq. Noise Vibr. Act. Control **31**(4), 239–246.

Janssen, S. A., Vos, H., Eisses, A. R., and Pedersen, E. (**2011**). "A comparison between exposure–response relationships for wind turbine annoyance and annoyance due to other noise sources," J. Acoust. Soc. Am. **130**(6), 3746–3753.

Keith, S. E., Feder, K., Voicescu, S. A., Soukhovtsev, V., Denning, A., Tsang, J., Broner, N., Leroux, T., Richarz, W., and van den Berg, F. (**2016a**). "Wind turbine sound pressure level calculations at dwellings," J. Acoust. Soc. Am. **139**(3), 1436–1442.

Keith, S. E., Feder, K., Voicescu, S. A., Soukhovtsev, V., Denning, A., Tsang, J., Broner, N., Richarz, W., and van den Berg, F. (**2016b**). "Wind turbine sound power measurements," J. Acoust. Soc. Am. **139**(3), 1431–1435.

Keränen, J., Hakala, J., and Hongisto, V. (**2017**). "Pientalojen ääneneristävyys ympäristömelua vastaan taajuuksilla 5–5000 Hz–infraäänitutkimus" ("Sound insulation of single-family houses against environmental noise at frequencies 5–5000 Hz–an infrasound study"), in *Proceedings of Akustiikkapäivät 2017*, August 24–25, Espoo, Finland, pp. 123–128, available at http://www.akustinenseura.fi/wp-content/uploads/2017/08/akustiikkapaivat_2017_eprosari.pdf (Last viewed October 10, 2017).

Kuwano, S., Yano, T., Kageyama, T., Sueoka, S., and Tachibana, H. (**2014**). "Social survey on wind turbine noise in Japan," Noise Control. Eng. J. **62**(6), 503–520.

McCunney, R. J., Mundt, K. A., Colby, W. D., Dobie, R., Kaliski, K., and Blais, M. (**2014**). "Wind turbines and health—A critical review of the scientific literature," J. Occup. Environ. Med. **56**(11), e108–e130.

Michaud, D. S., Feder, K., Keith, S. E., Voicescu, S. A., Marro, L., Than, J., Guay, M., Denning, A., McGuire, D., Bowe, T., Lavigne, E., Murray, B. J., Weiss, S. K., and van den Berg, F. (**2016a**). "Exposure to wind turbine noise: Perceptual responses and reported health effects," J. Acoust. Soc. Am. **139**(3), 1443–1454.

Michaud, D. S., Keith, S. E., Feder, K., Voicescu, S. A., Marro, L., Than, J., Guay, M., Bower, T., Denning, A., Lavigne, E., Whelan, C., Janssen, S. A., Leroux, T., and van den Berg, F. (**2016b**). "Personal and situational variables associated with wind turbine noise annoyance," J. Acoust. Soc. Am. **139**(3), 1455–1466.

Ministry of the Environment. (**2014a**). "Modelling of wind turbine noise," https://helda.helsinki.fi/handle/10138/42937 (Last viewed October 10, 2017).

Ministry of the Environment. (**2014b**). "Measurement of wind turbine noise levels in exposed areas," https://helda.helsinki.fi/handle/10138/42939 (Last viewed October 10, 2017).

Ministry of the Environment. (**2015**). "Government Decree on the Outdoor Noise Level Guide Values caused by wind turbines," http://www.finlex.fi/en/laki/kaannokset/2015/en20151107.pdf (Last viewed October 10, 2017).

Møller, M., and Pedersen, C. (**2011**). "Low frequency noise from large wind turbines," J. Acoust. Soc. Am. **129**, 3727–3744.

Muzet, A. (**2007**). "Environmental noise, sleep and health," Sleep Med. Rev. **11**, 135–142.

National Advisory Board on Research Ethics. (**2009**). *Ethical Principles of Research in the Humanities and Social and Behavioural Sciences and Proposals for Ethical Review* (National Advisory Board on Research Ethics, Helsinki, Finland).

National Land Survey of Finland. (**2016**). "File service of open data," https://tiedostopalvelu.maanmittauslaitos.fi/tp/kartta (Last viewed October 10, 2017).

Nissenbaum, M. A., Aramini, J. J., and Hanning, C. D. (**2012**). "Effects of industrial wind turbine noise on sleep and health," Noise Health **14**(60), 237–243.

Öhlund, O., and Larsson, C. (**2015**). "Meteorological effects on wind turbine sound propagation," Appl. Acoust. **89**, 34–41.

Oliva, D., Hongisto, V., and Haapakangas, A. (**2017**). "Annoyance of low-level tonal sounds—Factors affecting the penalty," Build. Environ. **123**, 404–414.

Ollson, C. A., Knopper, L. D., McCallum, L. C., and Whitfield-Aslund, M. L. (**2013**). "Letter to Editor: Are the findings of 'Effects of industrial wind turbine noise on sleep and health' supported?," Noise Health **15**(63), 148–150.

Pawlaczyk-Luszczyńska, M., Dudarewicz, A., Zaborowski, K., Zamojska-Daniszewska, M., and Waszkowska, M. (**2014**). "Annoyance related to wind turbine noise," Arch. Acoust. **39**(1), 89–102.

Pedersen, E. (**2011**). "Health aspects associated with wind turbine noise—Results from three field studies," Noise Con. Eng. J. **59**(1), 47–53.

Pedersen, E., and Persson Waye, K. (**2004**). "Perception and annoyance due to wind turbine noise—a exposure–response relationship," J. Acoust. Soc. Am. **116**, 3460–3470.

Pedersen, E., and Persson Waye, K. (**2007**). "Wind turbine noise, annoyance and self-reported health and well-being in different living environments," Occup. Environ. Med. **64**(7), 480–486.

Pedersen, E., and Persson Waye, K. (**2008**). "Wind turbines—Low level noise sources interfering with restoration?," Environ. Res. Lett. **3**, 015002.

Pedersen, E., van den Berg, F., Bakker, R., and Bouma, J. (**2009**). "Response to noise from modern wind farms in The Netherlands," J. Acoust. Soc. Am. **126**(2), 634–643.

Schäffer, B., Schlittmeier, S. J., Pieren, R., Heutschi, K., Brink, M., Graf, R., and Hellbrück, J. (**2016**). "Short-term annoyance reactions to stationary and time-varying wind turbine and road traffic noise: A laboratory study," J. Acoust. Soc. Am. **139**(5), 2949–2963.

Schmidt, J. H., and Klokker, M. (**2014**). "Health effects related to wind turbine noise exposure: A systematic review," PLoS One **9**(12), e114183.

Schomer, P., Mestre, V., Fidell, S., Berry, B., Gjestland, T., Vallet, M., and Reid, T. (**2012**). "Role of community tolerance level (CTL) in predicting the prevalence of the annoyance of road and rail noise," J. Acoust. Soc. Am. **131**(4), 2772–2786.

Schultz, T. J. (**1978**). "Synthesis of social surveys on noise annoyance," J. Acoust. Soc. Am. **64**, 377–405.

Shepherd, D., McBride, D., Welch, D., Dirks, K. N., and Hill, E. M. (**2011**). "Evaluating the impact of wind turbine noise on health-related quality of life," Noise Health **13**, 333–339.

Tachibana, H., Yano, H., Fukushima, A., and Sueoka, S. (**2014**). "Nationwide field measurements of wind turbine noise in Japan," Noise Con. Eng. J. **62**(2), 90–101.

Turunen, A., Tiittanen, P., and Lanki, T. (**2016a**). "Meluhaittojen kokeminen ja oireilu yhdeksällä tuulivoima-alueella Suomessa" ("Experiences of noise detriments and symptoms in nine wind power areas in Finland"), Ympäristö ja Terveys-lehti **5**, 76–81.

Turunen, A. W., Yli-Tuomi, T., Tiittanen, P., Taimisto, P., and Lanki, T. (**2016b**). "Noise annoyance and sleep disturbance in the vicinity of five wind farms in Finland," in *Proceedings of Internoise 2016*, August 25–28, 2008 (Hamburg, Germany), pp. 2692–2695.

van den Berg, F. (**2008**). "Criteria for wind farm noise: Lmax and Lden," in *Proceedings of Acoustics 08*, June 29–July 4, 2008 (Paris, France), pp. 4043–4048.

Van Renterghem, T., Bockstael, A., De Weirt, V., and Botteldooren, D. (**2013**). "Annoyance, detection and recognition of wind turbine noise," Sci. Tot. Environ. **456–457**, 333–345.

VTT Mikes Metrology (**2016**). http://www.mikes.fi/.

WHO. (**1999**). *Guidelines for Community Noise*, edited by B. Berglund, T. Lindvall, and D. H. Schwela (World Health Organization, Geneva, Switzerland).