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Listening test comparing A-weighted and C-weighted sound pressure level as indicator of wind turbine noise annoyance

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Abstract:

A listening test was conducted to investigate whether A- or C- weighed sound levels are most suitable as indicator of annoyance due to wind turbine noise. The tests consisted of fifteen different wind turbine noises presented at eight sound levels together with pink noise signals as reference sounds. A total number of 31 persons performed the listening test divided into two subgroups. The first group comprising of 20 students conducted the test in a semi anechoic chamber, and the second group of 11 residents annoyed by wind turbine noise in their homes, conducted the test in their own homes. Results from both subgroups showed that A-weighed sound levels were a more accurate description of wind turbine noise annoyance than C-weighed sound levels. The residents found the same wind turbine noises more annoying than the students,

indicating a higher sensitivity to wind turbine noise among persons a priori annoyed by this noise and exposed to this source in their residential settings.

1. Introduction

A dramatic increase of wind power is anticipated worldwide, due to the need to decrease the dependence on fossil fuels and thereby try to limit the effects of the ongoing global warming. Public attitude towards wind power is generally positive because it is recognized as an environmentally friendly power source. However, plants of wind turbine often concern neighbors because of anticipated disturbance of the visual and acoustic environment. Among residents living close to wind turbines, their noise is typically a source of annoyance [1-3].

Hearing is a remarkable and intriguing sense with nonlinear frequency response depending on the sound intensity. This property can be described by equal loudness contours showing the perceived loudness as a function of frequency and sound pressure. For facilitating estimations of loudness different weighting curves like the A-and C-weight have been created and are commonly used to specify guidelines for community noises. Traditionally, the A-weighted curve is an approximation of the 40 phon equal loudness contour and the C-weighted is an approximation of a significantly louder sound at the 90 phon equal loudness contour. The choice of weighting filter for wind turbine noise might thus seem obvious as permitted wind turbine noise levels usually are much closer to the lower level. However, low frequency noise from wind turbines raise concern that A-weighting might attenuate the low frequencies to much and be a less suitable descriptor of noise annoyance from wind turbines. Therefore it is considered interesting to investigate if the C-weighting curve could be justified as a noise annoyance descriptor or if a combination of the two weighting curves might be a more suitable indicator of annoyance and loudness compared with just using one weight. Moreover, the development of wind turbines has been rapid in recent years. Sizes have increased from around 25 m average height in the 1990's to above 100 m today and the average rated power from wind turbines has increased from 250 kW to 2 MW in the same period. The sound from modern wind turbines is mainly generated from the turbulent boundary layer at the blade's trailing edges [4] and is commonly described as a "swishing" sound by nearby residents [2]. In an earlier study, Persson-Waye and Öhrström [5] investigated how several psycho-acoustic parameters influence the perception of wind turbine noise. Since that article was published in year

2002, the size and power of new wind turbines have increased, which has been shown to increase the relative level of low-frequency components of the noise [6]. A comparison of A- and C-weighted sound pressure levels as indicators of annoyance is therefore warranted, because these indicators weigh the low-frequency components differently. In addition, noise guidelines are typically applied by some standardized weighing curve of which A- and C-weighing are among the most common.

With an increasing occurrence of wind turbines accompanied by a shift to raised exposure to lower frequencies, noise guidelines based on the A-weighing filter might be less suitable than those based on C-weighing as the latter do not attenuate low frequencies as much as the former. The A-weighed sound levels have also been questioned as a measure of noise annoyance for other community noise sources containing relatively high levels of low frequency noise [7- 9]. Consequently, the main purpose of this study was to investigate which of A-weighted or C-weighted sound pressure levels that are most accurately correlated to the perceived annoyance of wind turbine noise so that accurate regulations of the noise source can be facilitated. A second objective was to compare naïve listeners' annoyance response to wind turbine nose with response from residents exposed to and annoyed by wind turbine noise in their homes. It was hypothesized that the latter group would find the noise more annoying than the naïve group of listeners.

2. Experiment

2.1 Binaural recordings

Wind turbine noise was recorded with a manikin (Brüel and Kjær Head and Torso Simulator type 4100) with in ear microphones (Brüel and Kjær type 4190, and preamplifiers type 2669). These were connected to a preamplifier (Brüel and Kjær type 2672) with a high pass filter at 20 Hz to reduce wind disturbances and then linked to a sound card Digigram VXpocket440 inserted into a laptop computer (Fujitsu Siemens lifebook S7110). Recordings were performed with a sampling frequency of 44.1 kHz and analyzed in the frequency range from 20 Hz to 10 kHz.

Five different turbine sounds were recorded with binaural recording technique, information of these sites are shown in Table 1. Whenever possible, measurements were conducted in accordance to the ISO1996 standard [10]. All measurement sites were in flat rural areas. The sites were chosen to represent both older turbines and modern with higher output of power as well as single turbines and small wind farms. The distances from the closest turbine to the immission point varied between 180 m and 660 m. Recordings were performed in cloudy conditions in October 2009 (site 1 & 2) and at nighttime April 2011 (site 3-5) with presumably neutral or stable atmospheric conditions.

Site no	**No of WTs**	**Power [MW]**	**Distance [m]**
1	1	0.85	180
2	3	2.0	300
3	2	2.0	470
4	1	2.0	660
5	1	0.85	220

Table 1: Specification of the measurement sites.

2.2 Experimental sounds

The five sound samples from the immission measurements were recorded at relatively close distances from the turbines. However, wind turbine noise is often annoying at longer distances than these, see e.g. [11]. We did not increase the measurement distances (up to a few kilometers) from the wind farms due to expected decrease in signal-to-noise ratios as background sound substantially would influence the recordings. Instead, atmospheric attenuations for 1/3 octave bands between 20 Hz and 10 kHz at 1 km and 2 km distance were calculated according to the ISO 9613-1 algorithm [12] (assuming 20 °C (293 K), 70% relative humidity and 101.325 kPa atmospheric pressure). The immisson measurements were adjusted with these excess attenuations using digital filters created in the software Audacity (version 1.3), it should be noted that the geometrical spreading of the sound was disregarded. The filters were then applied to the measured sounds and consequently 15 different sounds were available for the test. These samples are considered by the authors to represent wind turbine sites from single turbines to small wind farms at different distances and with different spectral content.

The played sounds had stimuli duration of four seconds which would fall within the "psychological presence" [13, 14] and consequently facilitate comparison between consecutive stimuli and would not be affected by cognitive biases occurring at longer durations [15]. All reported sound levels and spectra in this paper refer to free field levels but the binaural recordings implies that the microphone membranes are positioned at the entrance of the ear canals which means that the recorded third octave levels have been adjusted to free field levels according to ISO 11904-2 [16]. Both A- and C- weighed sound levels ($L_{Aeq4s\ FF}$=L_A and $L_{Ceq4s\ FF}$=L_C) of recoded and filtered experimental sounds are given in Table 2.

Distance	Im					+1km					+2km						
WT	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	Mean	Std Dev
L_A (dB)	45,6	45,7	48,1	48,4	48	45,1	45,1	45,5	47,1	45,7	46,6	46	45,5	45,1	45,7	46,2	1,1
L_C (dB)	62,9	56,2	68	67,5	59,8	63,6	57,7	67,8	68,3	59,4	66,5	60,2	69,8	68,3	61,1	63,8	4,5

Table 2: Sound levels (A- and C-weighed) from the 15 sound stimuli used in the listening test.

Third octave band frequency spectra are shown for the sound samples in Figure 1. As can be seen from the figure the highest levels of each noise are observed between 160 Hz and 500 Hz and all sources seem to be of relative broadband character. Furthermore, emission spectra presented by Møller & Pedersen [6] are also shown in the figure aligned with the measured turbines by setting the total sound power to 48 dB A-weighted. The general shape of the used sound stimuli agrees to the average spectrum, although it is noted that ground interaction and atmospheric attenuation is not included in the emission spectrum while these effects affect the measured sounds. If these considerations would be included the high frequency component would decrease relative to the lower frequencies at typical distances to immisson points and would thus be more similar to the immission levels. Thus the spectral range of stimuli in this paper is considered by the authors to be representative of noise from wind turbines of today (as of 2013).

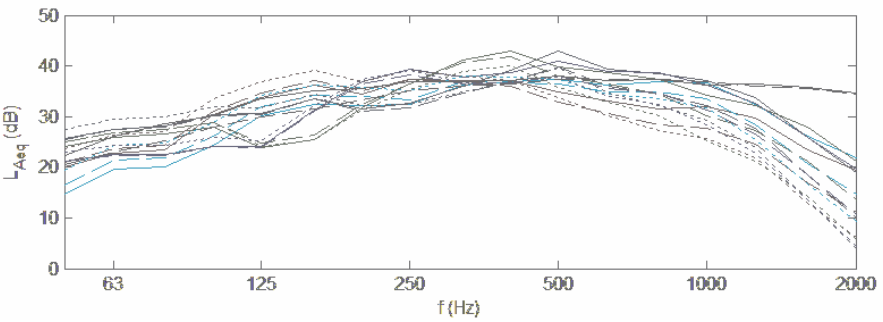

Figure 1: Showing the third octave band spectra for the used wind turbine noises at the immission points (solid curves), +1km (dashed curves) and +2km (dotted curves). Turbines are denoted by 1 (-), 2 (-), 3 (-), 4 (-) and 5 (-) and the emmission spectra from Møller and Pedersen [6] at 48 dB(A) by the black curves rated power ≤2MW solid and > 2MW dashed.

2.3 Listeners

Thirty one listeners participated in the study. The subjects were separated into two subgroups. The first "reference" group consisted of 20 staff members and students from the Royal Institute of Technology, Stockholm, Sweden (median age = 25, 6 females and 14 males). The second field group consisted of 11 persons living close to wind turbines and who had reported annoyance due to wind turbine noise at home (median age 49 years, 7 females and 4 males).

An audiometric test was administered to each participant prior to the listening test in the reference group. All listeners' hearing threshold levels were below 25 dB in their best ear in the tested frequencies 0.5, 1, 2, 4 and 8 kHz. The audiometric test was not administered for the field group as silent conditions could not be guaranteed. However, they all reported to have normal hearing.

2.4 Procedure

A training session with twelve sounds was administrated prior to the first session, to assure that the listener had understood the test and to familiarize them with the sounds and test procedure. Perceived annoyance was assessed with the method of free number magnitude estimation [17]. The participants entered their magnitude estimates in a graphical user interface programmed in MATLAB and the responses were collected. If the subjects could not detect the wind turbine noise or experienced no annoyance of the wind turbine noise they were instructed to respond "zero".

The test presented 132 sounds repeated four times each. The stimuli consisted of the 15 different noises at eight different levels (120 samples) and twelve pink noises at different levels. In the first session half of the signals were presented followed by the remaining in the next session all in random order. This procedure was repeated four times (i.e. eight sessions in total). The presented levels of the stimuli varied from the given in table 2 to 14 dB lower in 2 dB steps.

Pink noise stimuli were used as a reference sound and were presented in 2.5 dB steps from 27.5 dB(A) to 55 dB(A). This was a wider interval than the wind turbine noise, to provide a context in which the wind turbine noises could be scaled. The wider range also avoided extrapolation when calculating the "Perceived Pink Noise Equivalent", described in section 2.6.

After each session the subjects were instructed to take off the headphones and have a rest of self determined duration but at least 20 seconds. The total duration of the test was therefore varying but usually around 45 minutes of which minimum 140 seconds were breaks.

In the test for the reference group the subjects were seated in a semi-anechoic soundproof room in front of a computer screen connected to a laptop computer shielded by a 10 cm thick foam screen from the listener. In the field group persons were in their home environments situated in what they considered to be the quietest room in their homes.

2.5 Equipment

In these experiments two different headphones were used. For the reference group the headphones AKG501k and for the field group active sound cancellation headphones BOSE QC15. The presented sounds were first convoluted by the reciprocal of each headphone's frequency response in the audio software Audacity 2.0.3. Thereafter the convoluted sounds were played from a laptop computer into the headphones via a Creative Sound Blaster X-Fi HD soundcard. The frequency response functions of each system (laptop-Soundcard-Headphone) were estimated by submitting white noise through the system and using the artificial head Brüel and Kjær Head and Torso Simulator type 4100 with the same measurement setup as in the recordings and calculating the measured frequency spectrum. Post processing of the measurements was performed in MATLAB R2010a using the software Vibratool to calculate acoustic quantities and the convoluted filters as earlier mentioned created in Audacity 2.0.3. Thus, similar frequency content should be presented to the subject's as measured in the ear canal's enterece on the manikin.

Active sound cancellation headphones (BOSE QC15) were employed in the field experiment to reduce the amount the exposure of external noise in the test. The sound attenuation of a diffuse field was measured using a reference sound source (Brüel and Kjær Type 4204) placed in a reverberation room. The Brüel and Kjær 4100 dummy head was placed inside the chamber and recordings were performed with and without the headphones mounted on the head. The resulting difference of the two spectra can be seen in Figure 2 showing the narrow band (bandwidth 10.8 Hz) attenuation of the active noise cancellation technique. As can be seen the attenuation is above 20 dB for frequencies above 200 Hz while the performance at lower frequencies seems to be less good, especially at 100 Hz.

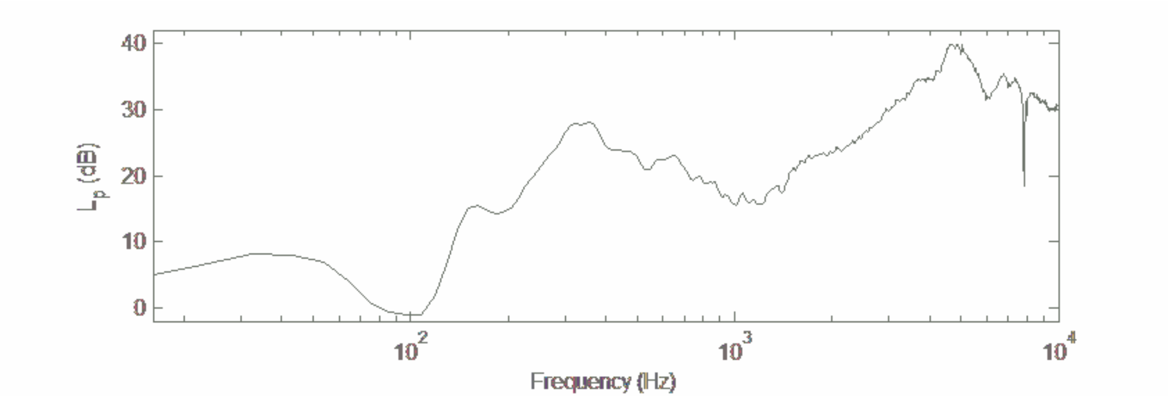

Figure 2: Showing the diffuse field attenuation with respect to narrow band (10.8 Hz) frequency bands for the BOSE QC15 active noise cancellation headphones used in the field study.

The frequency response of the whole listening system was flat within ±2dB in third-octave-band levels from 20 to 10 000 Hz.

2.6 Pink Noise Equivalent sound level (*PNE*)

The perceived annoyance of each wind turbine sound was expressed as the pink-noise equivalent sound level (*PNE*). The *PNE* of a wind turbine sound is the sound level of an equally annoying pink noise. The main advantage of expressing annoyance as *PNE* is (a) that it gives annoyance a meaningful unit (pink-noise A-weighed sound level in dB), (b) that it does not presuppose that listeners are able to produce magnitude estimates with ratio scale properties, and (c) it facilitates straightforward comparisons between results from different experiments. The only assumption is that, on average, equal numbers (magnitude estimates) means equal annoyance (cf. Refs. [18, 19, 20]). *PNE* -values were determined by first calculating the geometric mean magnitude estimate (R_{PN}) for each listener and pink-noise sound level (L_{PN}). These geometric means were used to derive individual psychophysical functions,

$$\ln(R_{PN}) = a + bL_{PN} \tag{1}$$

where *a* and *b* are constants unique to each listener and represent the line in Figure 3.

Second, for each listener and wind turbine noise, the geometric mean magnitude estimate (R_{WT}) was calculated. These geometric means were then transformed into pink-noise equivalent sound levels, using each listener's unique set of constants (*a* and *b*). The logic behind the transformation was as follows: Equal annoyance of a wind turbine noise and a pink-noise sound level would imply that a listener, on average, would give the two sounds the same magnitude estimate. Thus, *PNE* can be calculated from Eq. (2),

$$\text{PNE} = \frac{\ln(R_{WT}) - a}{b} \tag{2}$$

To illustrate the procedure Figure 3 shows an individual's average annoyance estimates of pink noise (R_{PN}, crosses) as a function of the sound level (L_A). The black line shows the individual's psychophysical annoyance function for pink noise (Eq. 1, least square fit). The square indicates the participant's average annoyance estimate of a wind turbine noise at 42 dB (R_{WT}). This magnitude estimate corresponds to a pink noise equivalent sound level of 39 dB L_A, as can be seen by following the vertical dashed lines.

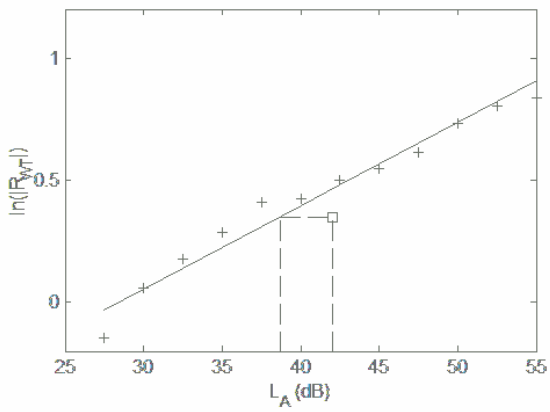

Figure 3: Magnitude estimates of wind turbine sound as a function of wind turbine sound level (L_A). The crosses represent the magnitude estimates of one listener of pink noise (R_{wt}). The solid line is the least square approximation by Equation (1). The square denotes a magnitude estimate of 42 dB wind turbine noise with corresponding PNE of 39 dB.

3. Results

Intra-individual correlation between average values of the two first and the two last judgments were performed to control the ability of the subjects to reproduce their magnitude estimates. The average intra-individual correlation coefficient was 0.65 with minimum value 0.43 and 0.91 as maximum. Two persons in the field group had correlation coefficients of 0.04 and 0.17, these were considered to have misinterpreted the test and their responses were excluded from the results.

A Lilliefors test was conducted to control for normal distributed of each stimuli for each group with a significance level of 5% which showed that at 8 stimuli in the field group and 19 stimuli in the reference group the hypothesis of a normal distributions were rejected. The stimuli that were not normally distributed were excluded from the following ANOVA procedure described below. For those stimuli, where normal distributions were not rejected, one-way factorial ANOVA was calculated. A statistically significant (5%) difference between the two test groups existed for all but four stimuli. The across subject average PNE as a function of A- and C- weighed sound levels are shown in Figure 4. An advantage by introducing PNE is obvious when comparing the results from the two subgroups. It is easily observed from these results that a shift occurs in PNE between the responses of the two subgroups for the same sound levels. The field group show an increased annoyance compared to the reference group of 9.3 dB in both A-weight and C-weight and which is interpreted as increased sensitivity to this noise source compared to pink noise.

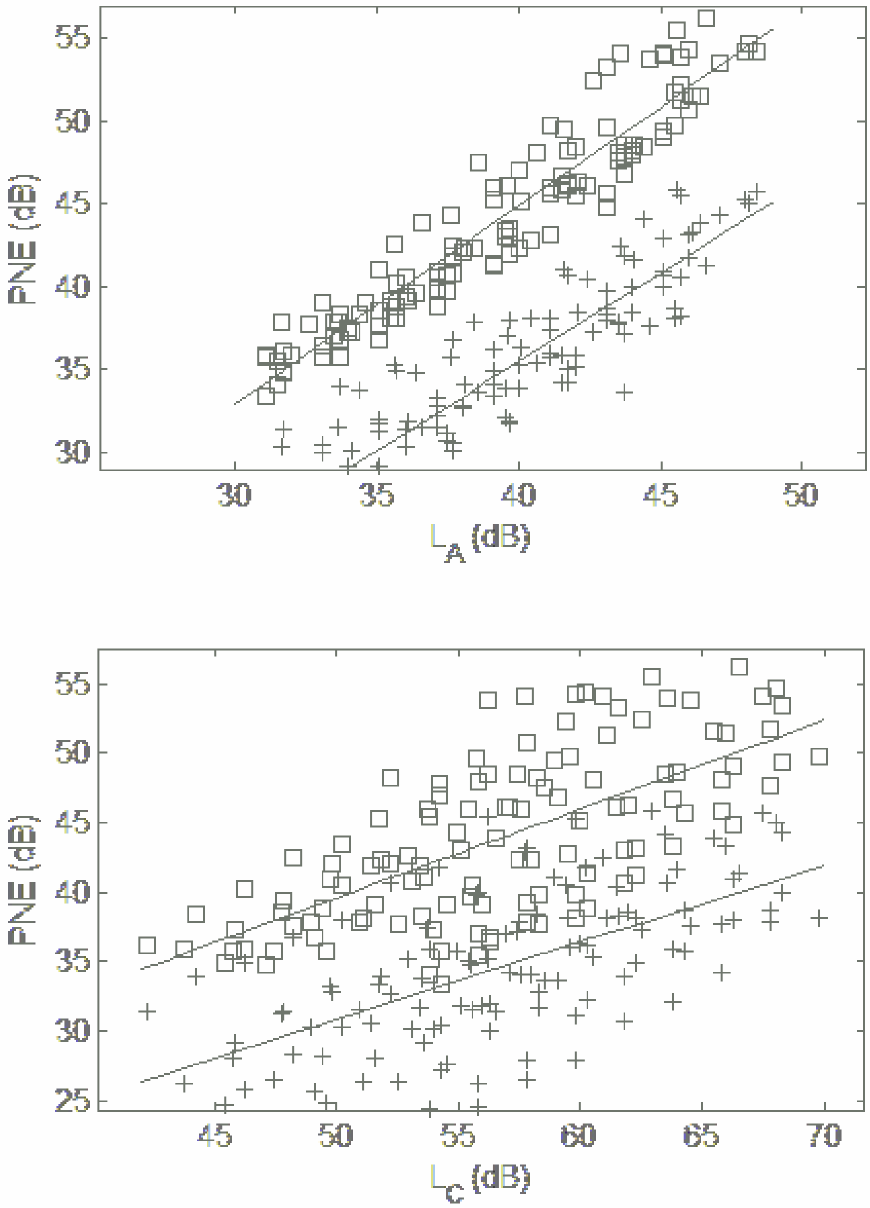

Figure 4: The graphs show the average A-weighed PNE at the ordinate as a function of L_A in the upper subfigure and L_C in the lower figure. Results from the reference subgroup are shown as (+) and the field subgroup as (□).

Linear regression analysis was performed to investigate A- and C-weighted sound levels correlation to PNE using the latter as dependent variable and L_A, L_C and L_C–L_A =$L_{C\text{-}A}$ as independent variables. The linear coefficient between PNE and L_A, L_C and $L_{C\text{-}A}$ are shown in table 3 (all coefficients statistically significant $p<0.01$). As seen, the slope of the annoyance functions were marginally higher for the field group, perhaps because these persons recognize wind turbine noise and thus find the sound more annoying than the reference group even at the lower sound levels. The R^2 fit of the annoyance data are shown for both subgroups and the average RMS errors are also shown in table 3. As can be seen the R^2-values are higher for A-weighed levels than for C-weighed for both groups (0.45 and 0.49) which suggests that A-weighed sound levels are more suitable predictors of annoyance cased by wind turbine noise. When both L_A and $L_{C\text{-}A}$ levels are included in the fit the R^2 value only increases marginally (0.01 for both groups) when compared to the R^2 value of A-weighed levels alone which indicates that L_A solely is a sufficient indicator of short term annoyance of wind turbine noise.

		PNE∝	R^2	E_{RMS}
Reference	L_A	$1.07 \cdot L_A$	0.83	2.3
	L_C	$1.20 \cdot L_C$	0.40	4.7
	L_A & $L_{C\text{-}A}$	$1.17 \cdot L_A - 0.10 \cdot L_{C\text{-}A}$	0.83	2.2
Field	L_A	$0.55 \cdot L_A$	0.90	1.8
	L_C	$0.64 \cdot L_C$	0.46	4.8
	L_A & $L_{C\text{-}A}$	$1.25 \cdot L_A - 0.06 \cdot L_{C\text{-}A}$	0.91	1.8

Table 3: Showing the R^2 values for and the average PNE for the respective subgroups and weighting filters.

4. Discussion and Conclusion

The main finding of this study was that A-weighted sound pressure level was a better indicator of wind turbine noise annoyance than the C-weighted sound pressure level. This was true for both groups of listeners. A second finding was that residents annoyed by their nearby wind turbine showed an increased sensitivity to any wind turbine noise compared to naïve listeners. It could be that the increased annoyance of the residents is a consequence of a generally higher noise sensitivity of that group but such tendencies should be counteracted by the PNE procedure unless the pink noise is excepted from the increased noise sensitivity. Moreover, the residents group can not be considered representative for people in general living near turbines as the majority of the population exposed to wind turbine noise are not bothered [1, 2].

Results and conclusions in this paper is restricted to short term annoyance from wind turbine noise as the stimuli duration was relatively short in order to facilitate recollection of the recent magnitude estimates and also to restrict the test time to one listening session. From a methodological point of view the PNE approach reveals an interesting observation that could not have been detected by free number magnitude estimation without this reference sound, namely the increased sensitivity to wind turbine noise by the field group compared to a reference group. Consequently the justification for using this method is considered straightforward by the authors.

It would naturally be presumptuous to extend the current findings to long term annoyance from wind turbine noise as the mechanisms activating discomfort might change for prolonged exposure times. However, the main conclusion in this test is that A-weighed sound levels are more suitable as a predictor of short term wind turbine noise annoyance compared to C-weighed sound levels in both studied subgroups. This conclusion is perhaps not surprising considering that the sound stimuli were presented at loudness levels where the auditory system is similar to the A-weighing filter. One advantage from these results would be that current guidelines usually refer to A-weighed sound levels and such procedures are supported by the results from this test.

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