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PSYCHO-ACOUSTIC CHARACTERS OF RELEVANCE FOR ANNOYANCE OF WIND TURBINE NOISE

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The knowledge of annoyance and perception of wind turbine noise is limited, although some previous studies have found that the relationship between the equivalent noise level and annoyance was weak. The hypothesis for this study was that different sound characters in the noise not fully described by the equivalent noise level, are of importance for annoyance and noise perception. In total, 25 subjects were exposed to five different wind turbine noises at the level of 40 dB L_{Aeq}. Subjective ratings of annoyance, relative annoyance and for how long they were aware of the noises were carried out after 10 min exposures. This was followed by 3 min exposures where perception and annoyance of 14 psycho-acoustic descriptors were evaluated. The results showed that the rating of annoyance, relative annoyance and awareness was different between the wind turbine noises, although they had the same equivalent noise level. A psycho-acoustic profile was obtained for each noise, which subjectively described the most and the least annoying sound parameters. None of the psycho-acoustic parameters, sharpness, loudness, roughness, fluctuation strength or modulation could explain the differences in annoyance response.

1. BACKGROUND AND AIM

Noise may be one critical factor for the public acceptance of wind turbines. The knowledge on noise disturbance from wind turbines is, however, based on a limited number of field studies. One of the more extensive studies was performed around different sites in Holland, Germany and Denmark [1]. A total of 574 interviews were carried out among people living within the noise levels of 25–60 dB L_{Aeq}. Of those, 70% lived in the range of noise levels of 30–40 dB L_{Aeq} and 16% lived in areas with a noise level above 40 dB L_{Aeq}. The results showed that 6·4% reported some annoyance from noise from wind turbines. No clear relationship was found between annoyance and equivalent noise level, but persons who complained about noise reported a higher occurrence of acoustical components in the noise. Most complaints were directed to noise from the rotor blades and unspecific noise from the turbines.

A weak relationship between annoyance and the equivalent noise level (L_{Aeq}) has also been found in other studies [2]. The weak relationship with the equivalent noise levels may be due to a strong influence of other factors not related to the noise, such as attitude and visual intrusion. It is also possible that different sound characters in the noise not fully described by the equivalent noise level, are of importance for annoyance and noise perception. In wind turbine noise, there are a number of sound parameters that may enhance the perception and annoyance, i.e., modulations, tonality and frequency balance and which may be easily noticeable if the turbines are situated in areas with a low

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TABLE 1

Some technical data of the five wind turbines in the study

Wind turbine	Rated power (kW)	Number of rotor blades	Special characteristics	Hub height (m)	Rotor diameter (m)
Bonus	450	3	Stall regulation	35	35
Zephyr	250	2	Passive regulation	32	28
NWP	400	2	No stall regulation	40	35
Vestas	600	3	Opti tip feature pitch regulated	40	44
WW	490	3	Stall regulation	40	37

background noise. An increased knowledge on how sound characters in wind turbine noise influence annoyance and perception is thus important in order to obtain a more valid dose–response relationship.

The aim of this study was to evaluate awareness and annoyance from different wind turbine noises at the same L_{Aeq} level and to see whether the subjects' perception of acoustical parameters in the noises were of importance for awareness and annoyance. A further aim was to see how analysis of psycho-acoustic parameters developed by Zwicker and Fastl [3] related to reported annoyance and awareness.

2. METHODS

2.1. NOISE RECORDINGS

Noise from five of the most frequently occurring middle sized wind turbines in Sweden 1997, Bonus, Vestas, Zephyr, Nordic Wind Power (NWP) and Wind World (WW), were recorded at site. Some data from the five turbines are given in Table 1. Recordings were carried out using a stereo microphone (Senneheiser MKE44P) that was connected to a low noise amplifier (Marenius SMF-5) and a tape recorder (Sony TCD-7DAT). The microphone was fastened on a 1×1 m board placed flat on the ground. A secondary wind shield, with a diameter of 0·40 m, made it possible for recordings to be obtained up to 11 m/s. Recordings were carried out at a distance of 25, 100, 200 m, and when practically feasible at 300 and 400 m, at a wind speed of 7–10 m/s and with the wind direction from the wind turbine. The recordings made at a distance of 100 m were used in the experimental study.

2.2. EXPOSURE NOISES

The tape recordings were analyzed for time intervals where the background noise from, e.g., bird twitter and wind was low. The remaining disturbing sounds were edited using a sound processing system. Sections of 20 s of the wind turbine noise were then played back using a continuous loop. In this way, exposure noises were obtained with very small variations of the background noise over any time period chosen. In this study, exposure times of 3 and 10 min were used. Figures 1 and 2 show equivalent 1/12-octave band sound pressure levels from the five recorded wind turbines used as exposure noises.

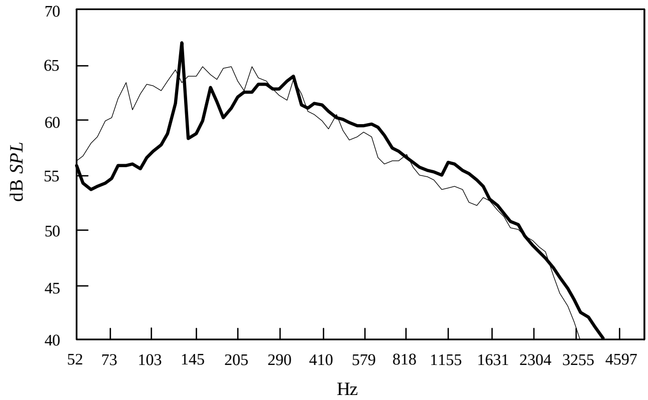

Figure 1. Equivalent 1/12-octave band sound pressure levels from Bonus and Vestas. —, bonus; —, Vestas.

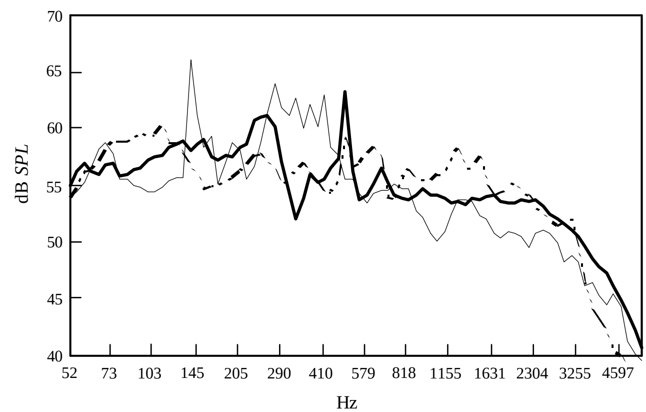

Figure 2. Equivalent 1/12-octave band sound pressure levels from Wind World (WW), Nordic Wind Power (NWP) and Zephyr. ——, WW; ——, NWP; –··–-, Zephyr.

2.3. PSYCHO-ACOUSTIC ANALYSIS

The analysis of the psycho-acoustic parameters of loudness, sharpness, roughness, fluctuation strength and modulation [3] were carried out at by Professor Weber and colleagues at the working group of acoustics/psychoacoustics at the University of Oldenburg. The parameters were analyzed from 30 s long sequences from DAT recordings taken in the exposure room, using a microphone B&K 4165 placed in the position of a subject's head. The calculations were carried out using Binaural Analysis System 4.3 software (Head Acoustics). Loudness was calculated according to the standardized method described in reference [4] while roughness, sharpness, tonality and fluctuation strength were calculated using models provided by Aures [5, 6], Terhardt *et al.* [7] and Zwicker and Fastl [3]. Modulation was calculated from the specific modulation degrees, i.e., from the modulation spectra of the selected frequency bands in relation to the intensity of the DC-part of the signal. The degree of modulation was the sum of the specific modulation degrees over all the modulation frequencies between 0 and k Hz. The following percentiles were computed, L_{max}, 1, 4, 5, 10, 50% and L_{eq}. In this paper, the L_{eq} and L_{max} values are reported.

2.4. EXPOSURE ROOM

The exposure room was a semi-reverberant 4×5 m large, sound-insulated room. The background noise level from the ventilation was less than 22 dB(A) and the sound pressure levels for the frequencies below 160 Hz were below the threshold of normal hearing [8]. As disturbance from wind turbine noise is normally experienced outdoors, the room was furnished as an outdoor environment with garden chairs and a sun umbrella. To further resemble an outdoor situation, recordings of bird song were played when the subjects entered the room and in the pauses between noises. The recordings from the wind turbine noises were emitted from two loudspeakers hidden behind thin curtains. As we wanted to achieve a sense of direction of the sound, the loudspeakers were placed in the two corners in the far end of the room when entering the room.

2.5. SUBJECTS

For the study, 25 students, 13 women and 12 men, at Göteborg University were recruited. Each person underwent a hearing test (SA 201 II Audiometer, Entomed, Malmö, Sweden) and only persons with normal hearing, <20 dB HL, were allowed to participate.

2.6. QUESTIONNAIRES

Four sets of questionnaires were used. Questionnaire A was answered sitting in the exposure room, before the noise exposure began. The first part evaluated attitude towards wind turbine noise, and was a Swedish translation of a questionnaire previously used by Wolsink [9, 10]. It contained four questions on possible wind turbine developments on which the subjects were asked to give their opinion, using a five-graded scale from 1 "very bad" to 5 "very good". It also included 14 statements on positive and negative consequences of wind turbine developments. These statements were answered on a five-graded scale from 1 "remote chance" to 5 "considerable chance". Section 2 of the questionnaire evaluated sensitivity to noise using the questionnaire developed by Weinstein [11], and with a direct question phrased: "Are you sensitive to noise," which was answered on a four-graded scale (1 "not at all sensitive" to 4 "very sensitive").

Questionnaire B evaluated annoyance and awareness of the wind turbine noises. Annoyance was rated on a 10 cm long scale with the endpoints 0 "not at all" to 10 "very much". Awareness was evaluated with the question: How long time did you pay attention to the wind turbine noise? The question was answered on a five-graded scale with the following alternatives, 1 "not/nearly not/aware of it at all" 2 "only for a short time", 3 "often", 4 "nearly the whole time" to 5 "the whole time".

In questionnaire C, subjects were asked to rate perception and annoyance of 14 psycho-acoustic descriptors on a six-graded scale with the alternatives: 0 "do not notice", 1 "notice but not at all annoying", 2 "barely annoying", 3 "somewhat annoying", 4 "rather annoying" and 5 "very annoying". The descriptors were obtained in a previous pilot study where subjects were asked to describe the wind turbine noises in their own words. Finally, in Questionnaire D, subjects rated the relative annoyance of the five noises, from 1 "least" to 5 "most annoying".

2.7. EXPERIMENTAL DESIGN

Subjects were exposed in groups of five persons to five different wind turbine noises at 40 dB L_{Aeq}. The order of the noises was randomized between the groups. The design for the

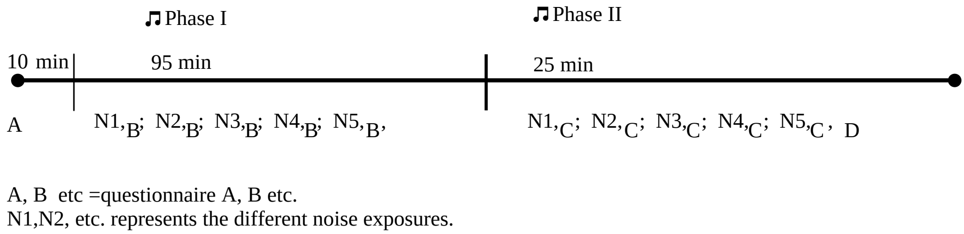

Figure 3. The experimental design.

TABLE 2

Average values and (standard deviations) of annoyance, awareness and relative annoyance for the wind turbine noises

	Bonus	Vestas	NWP	Zephyr	WW
Annoyance	26·6 (21·9)	28·6 (22·4)	32·3 (26·5)	33·4 (21·5)	37·0 (32·3)
Awareness	2·0 (0·79)	2·2 (0·64)	2·3 (0·80)	2·3 (0·69)	2·6 (1·04)
Relative annoyance	2·6	2·0	3·2	3·4	4·1

study is shown in Figure 3. In phase I of the experiment, subjects were relaxed reading books of their own choice during the noise exposures, which each lasted 10 min. Questionnaire B was answered after each noise exposure. In phase II, subjects listened to the exposure noises during 3 min periods. During this time they filled in questionnaire C. At the end of phase II, subjects filled in questionnaire D.

During phase I, subjects were allowed to have a short break of 3 min between the exposures, and a longer break of 5 min after three exposure noises. In total, the experiment took 2 h and 10 min.

2.8. STATISTICAL ANALYSIS

The differences between the subjective ratings of the noises were evaluated using analysis of variance of dependent data (ANOVA). Tests of significance for separate noises were carried out with Duncan new multiple-range test. Analyses of relationships between variables were done using Pearson's correlation coefficient. All tests were two-tailed and a p-value of $<0{\cdot}05$ was considered as statistically significant.

3. RESULTS

The average value of annoyance, awareness and relative annoyance for the different wind turbine noises are shown in Table 2.

The ratings of annoyance were significantly different between noises ($F(4,23) = 2{\cdot}63$, $p < 0{\cdot}05$). A separate analysis showed that the noise from WW was significantly more annoying compared to Vestas and Bonus ($p < 0{\cdot}001$, $p < 0{\cdot}05$ respectively).

The ratings of relative annoyance were in agreement with the ratings of annoyance.

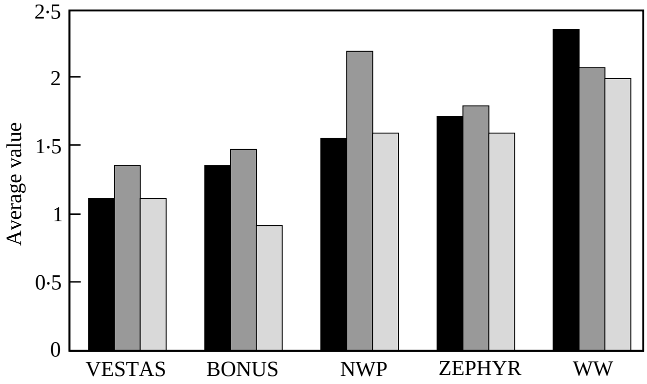

Figure 4. Average values of lapping, swishing and whistling for the different wind turbine noises. ■, lapping; ▒, swishing; □, whistling.

A significant difference in the rating of awareness was found between noises ($F(4,23) = 4{\cdot}34$, $p < 0{\cdot}01$). A separate analysis showed that Zephyr, NWP and WW were given a higher rating of awareness compared to Bonus ($p < 0{\cdot}05$) and WW was given a higher value compared to Vestas ($p < 0{\cdot}05$). The percentage of subjects that was aware of the noises "often", "nearly the whole time" and "the whole time", was 28% for Bonus, 32% for Vestas, 36% for NWP and Zephyr, and 40% for WW.

The psycho-acoustic descriptors given an average value of two or higher were "lapping", "swishing", "whistling", "uneven", "low frequency" and "grinding". These descriptors were analyzed more in detail. Only one noise (WW) was perceived as "tonal", but the average value of this rating was only 1·8.

The rating of "lapping" was significantly different between the noises ($F(4,23) = 5{\cdot}72$, $p < 0{\cdot}001$). Analysis of separate noises showed that WW was given a significantly higher value compared to the other noises ($p < 0{\cdot}05$) and Zephyr was rated significantly higher compared to Vestas ($p < 0{\cdot}05$). "Swishing" was rated significantly different between the noises ($F(4,23) = 4{\cdot}18$ $p < 0{\cdot}01$). A separate analysis showed that NWP and WW were perceived as significantly more "swishing" than Vestas and Bonus ($p < 0{\cdot}05$). "Whistling" was also rated significantly different between noises ($F(4,23) = 4{\cdot}74$, $p < 0{\cdot}01$). The noise from WW was perceived as significantly more "whistling" than Vestas and Bonus ($p < 0{\cdot}01$). "Uneven" was rated differently between noises ($F(4,23) = 5{\cdot}44$, $p < 0{\cdot}001$). A separate analysis showed that NWP, WW, Zephyr and Bonus were given a higher rating for "uneven" compared to Vestas ($p < 0{\cdot}05$). The rating of "low frequency" and "grinding" were not significantly different between noises.

When these descriptors were related to the annoyance ratings for the five noises a pattern was seen, where the most annoying noises were predominantly described as "swishing", "lapping" and "whistling" and where the least annoying noises were predominantly described as "grinding" and "low frequency". "Uneven", on the other hand, was found both among the most annoying and the least annoying noises. Figures 4–6 show the average values of these descriptors for the different noises.

An analysis of relationships between annoyance, awareness and the different psycho-acoustic descriptors showed that annoyance was significantly correlated to "lapping", $r = 0{\cdot}39$, $p < 0{\cdot}05$, and "whistling", $r = 0{\cdot}38$, $p < 0{\cdot}05$, while the correlation to "swishing", $r = 0{\cdot}32$, did not reach significance. Awareness was significantly correlated only to "lapping", $r = 0{\cdot}48$, $p < 0{\cdot}01$.

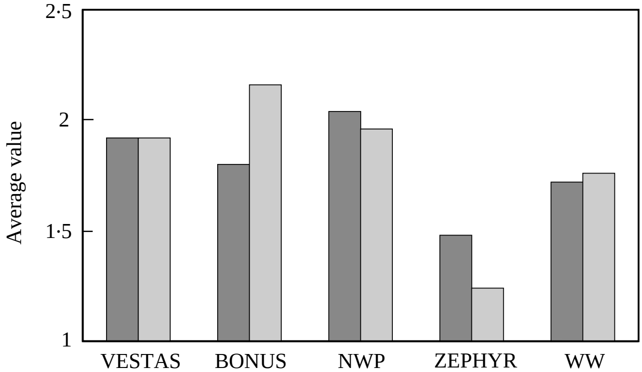

Figure 5. Average values of grinding and low frequency for the different wind turbine noises. ■, grinding; □, low frequency.

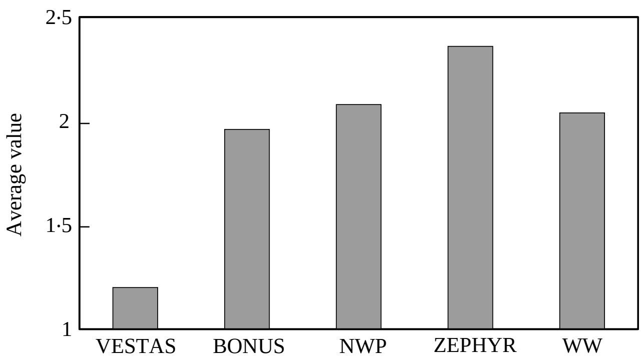

Figure 6. Average values of uneven for the different wind turbine noises.

The L_{max} and L_{eq} values of the psycho-acoustic parameters are shown in Table 3. The differences in values between the five noises were rather small, and no variable could alone explain the difference in the annoyance ratings given during the experimental session. When the ratings of annoyance, awareness and the six psycho-acoustic descriptors attributed an average value of two or higher, were related to the equivalent or the maximum levels of the psycho-acoustic parameters, none of the correlations reached significance.

There were no significant relationships between the subjects' attitude to, or opinion of wind turbines and experimentally evaluated annoyance to wind turbine noise. A relationship was found between estimated annoyance and sensitivity to noise measured with the direct question ($r = 0{\cdot}38$, $p < 0{\cdot}05$) as well as with Weinstein's questionnaire ($r = 0{\cdot}47$, $p < 0{\cdot}05$).

4. COMMENTS

The results were obtained in an experimental situation and it would be presumptuous to assume that annoyance measured in the laboratory situation would directly reflect the degree of annoyance perceived in a real life situation. In this study, the main interest was to

TABLE 3

Equivalent and (maximum) levels of the psycho-acoustical parameters for the five noises

	Bonus	Vestas	NWP	Zephyr	WW
Loudness sone GD	35·68(44·30)	36·75(42·65)	38·35(47·45)	43·80(55·20)	35·85(45·06)
Sharpness acum	1·94(2·29)	2·08(2·51)	2·61(3·18)	2·82(3·25)	1·91(2·21)
Tonality tu	0·03(0·21)	0·04(0·21)	0·05(0·20)	0·04(0·17)	0·03(0·21)
Roughness asper	2·84(3·78)	2·93(3·74)	3·00(3·61)	3·35(4·18)	2·82(3·60)
Fluctuation strength vacil	3·32(3·73)	3·14(3·56)	3·38(3·74)	3·56(4·10)	3·38(3·78)
Modulation %	68·72(101·60)	68·95(111·82)	68·45(102·50)	67·95(101·40)	68·90(104·0)

evaluate the relative annoyance between the noises and it is plausible that this relationship would reflect differences between different wind turbines in a real life situation and hence useful to evaluate differences between various technical solutions. Annoyance to wind turbine noise is mainly an outdoor problem (e.g., [1]) and efforts were therefore invested in order to make the laboratory resemble an outdoor area. The exposure level of 40 dB L_{Aeq} was selected as this corresponds to the Swedish recommendations for noise level from wind turbines that should not be exceeded at the nearest house [12].

The psycho-acoustical metrics were analyzed using a Binaural Analysis System, Head Acoustics. With the exception of loudness [4], calculations of these parameters are not standardized, and calculations using different commercial systems may, therefore, differ somewhat. In this study, it was not possible to evaluate as to whether the different methods for calculation would have improved the relationships with annoyance, although it is probable that any effect would have been small.

It has previously been shown that opinion and attitude to wind turbines have been of relevance for reported annoyance [9, 10]. We used the same questions as used by Wolsink, but could not find such a relationship. A major difference between the studies was that most of the subjects in our study had very little own experience of wind turbines, while the subjects participating in the study by Wolsink were living near wind turbines. The different results were, therefore, probably due to differences in previous experience among the participating subjects.

The results showed that the test subjects rated annoyance of the noises differently although the L_{Aeq} level was the same. The results are supported by the similar pattern seen among the rating of annoyance, awareness and the relative ranking of the noises. A large percentage of the subjects paid attention to the noise “often”, “nearly the whole time” or “the whole time” during the session. The observation that the more annoying noises were also paid attention to for a longer time, support the hypothesis that the content of intruding acoustical characters were of importance for whether or not the subject became aware of the noise and also possibly for the degree of annoyance. The psycho-acoustic profiles obtained gave some information on characteristics in the noise that were important for perception and annoyance, while none of the psycho-acoustical metrics developed by Zwicker and Fastl [3], alone could explain the variation in annoyance response.

Based on the psycho-acoustic profiles and the results of the annoyance ratings, two major groups of psycho-acoustic descriptors could be distinguished, where “lapping”, “swishing” and “whistling” can be hypothesized to be related to easily noticed and potentially annoying sounds, while “low frequency” and “grinding” can be hypothesized to be related to less intrusive and potentially less annoying sounds. These descriptors should be identified in acoustical terms and further analyzed in interactive studies.

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