Annoyance potential of wind turbine noise compared to road traffic noise

Beat Schäffer
Empa, Swiss Federal Laboratories for Materials Science and Technology, Dübendorf, Switzerland.
Sabine J. Schlittmeier
Katholische Universität Eichstätt-Ingolstadt, Eichstätt, Germany.
Kurt Heutschi
Empa, Swiss Federal Laboratories for Materials Science and Technology, Dübendorf, Switzerland.
Mark Brink
Federal Office for the Environment, Noise and NIR Division, Bern, Switzerland.
Ralf Graf
Katholische Universität Eichstätt-Ingolstadt, Eichstätt, Germany.
Reto Pieren
Empa, Swiss Federal Laboratories for Materials Science and Technology, Dübendorf, Switzerland.
Jürgen Hellbrück
Katholische Universität Eichstätt-Ingolstadt, Eichstätt, Germany.

Summary
The production of wind energy is becoming increasingly important worldwide, with the result that greater numbers of the population are being exposed to wind turbine noise. There is evidence that wind turbine noise has a high annoyance potential, which might be caused by specific sound characteristics such as amplitude modulation. Compared to road traffic noise, however, knowledge of the annoyance effects of wind turbine noise remains scarce. In this study, the annoyance of wind turbine noise and road traffic noise were investigated and compared. To that aim, listening tests were done in the laboratory, allowing controlled experimental conditions and the exclusion of potential effect modifiers such as the visual appearance of wind turbines in field surveys. For the listening tests, specific sound scenarios were generated, either by sound synthesis (wind turbine noise) or by mixing of single pass-by recordings (road traffic noise). The set of sound scenarios enabled auralisation of variations of three variables potentially influencing annoyance, namely source type (wind turbine, road traffic), sound pressure level, and temporal level variation (without, periodic, or random variation). Subjects were exposed to these different sound scenarios, and their ratings on subjectively perceived annoyance were collected. The factorial design of the experiment allows separating the individual contributions of the above three variables to the annoyance ratings. Here, the setup of the listening tests, the most important results and possible applications in environmental impact assessment are presented.

PACS no. 88.50.G-, 88.50.Xy, 43.50.Rq, 43.50.Qp

1. Introduction

The production of wind energy is becoming increasingly important worldwide [1], with the result that greater numbers of the population are being exposed to wind turbine noise. There is evidence from literature that, at comparable sound levels, wind turbine noise is more annoying than transportation or industrial noise [2], which might be caused by visibility, individual (e.g. noise sensitivity) and situational characteristics (e.g. economic benefit) of the affected persons, or sound characteristics. Here, amplitude modulation might be particularly important [3]. Compared to other sound sources such as road traffic, however, knowledge of the annoyance effects of wind turbines remains scarce. In particular, it is not known to which degree acoustic characteristics alone contribute to the (noise) annoyance. The objective of this study was therefore to investigate and compare the annoyance caused by wind turbine noise (WTN) and road traffic noise (RTN). To that aim, laboratory listening tests were done, allowing controlled experimental conditions and the exclusion of potential effect modifiers such as the visual appearance of wind turbines in field surveys.

2. Methods

In this study, the annoyance of WTN and RTN was studied under laboratory conditions. The ratings correspond to "psychoacoustic annoyance" according to [4], which is inherently different to the annoyance assessed in field surveys (e.g. [5]).

2.1. Listening tests – concept

In the listening tests, the sound stimuli were systematically varied with respect to the three variables: source type (wind turbine, road traffic), sound pressure level (L_{Aeq} from 35–60 dB(A)) and temporal level variation (i.e. amplitude modulation, at three conditions: without, periodic, random) to study their individual contribution to the annoyance ratings (Table I).

Table I. Design of the listening tests with sound stimuli covering six different sound pressure levels (L_{Aeq}), two source types and three amplitude modulations. "x" denotes studied stimuli.

Sound level	Source type					
	Wind turbine			Road traffic		
	Amplitude modulation (AM)					
	without	random	periodic	without	random	periodic
35	x	x	x			
40	x	x	x	x	x	x
45	x	x	x	x	x	x
50	x	x	x	x	x	x
55	x	x	x	x	x	x
60				x	x	x

The above sound pressure levels cover an environmentally relevant range (e.g. [2]). RTN was not studied at an L_{Aeq} of 35 dB(A), as the corresponding annoyance ratings were expected to be negligible. WTN was not presented at an L_{Aeq} of 60 dB(A), as such levels occur only very close to turbines. All amplitude modulations (AM) include atmospheric turbulences. "Without AM" corresponds to constant RTN or WTN. "Periodic AM" represents WTN situations with "thumping" sound. "Random AM" is the typical situation of RTN close to streets with low to intermediate traffic density. To study the contribution of these source-specific AM separately from the source type, hypothetical situations of random WTN and of periodic RTN amplitude modulation were also included in the study to obtain a complete factorial design.

2.2. Sound stimuli

For the listening tests, the stimuli were generated either by sound synthesis (WTN) or by mixing of single pass-by recordings (RTN).

Wind turbine noise (WTN): Sound synthesis was done using the tools of [6, 7]. As a sound source, one single 2 MW Vestas V90 turbine at an operation mode at "strong wind" conditions with a sound power level of 102 dB(A) was chosen. The emission files with periodic AM and without AM were synthetized as described in [7]. Periodic AM was generated with a standard deviation of the level fluctuation of 3 dB and a fluctuation frequency of 0.75 Hz. Random AM was generated as an amplitude modulated version of an emission file without AM. The AM was adjusted for a standard deviation of 3 dB, the fluctuation frequency was set to be comparable to periodic AM (range of 0.3–1.1 Hz). Propagation filtering [6] was performed for flat terrain for distances of 60–600 m, corresponding to an L_{Aeq} of approximately 35–55 dB(A). The resulting synthesized single channel audio signals were converted into 2-channel (stereo) files by channel duplication.

Road traffic noise (RTN): To create the stimuli 2-channel recordings of individual car pass-by events were used. The recordings were taken at a straight interurban road in a rural environment with a speed limit of 80 km/h at distances of 30 m and 100 m. At both distances, two omnidirectional microphones were installed in a Jecklin Disc arrangement. For situations with random and periodic AM, the recordings at 30 m were used. Subsequent mixing of the events was done assuming two traffic lanes with a density of 500 vehicles per hour and lane. The fluctuation frequency of RTN is thus much lower than of WTN, and the sound level varies strongly between individual car pass-by events. For situations without AM, the recordings at 100 m were used. For the mixing, two traffic lanes with a density of 3'000 vehicles per hour and lane were assumed. Propagation filtering was applied for distances of 40–600 m, corresponding to an L_{Aeq} of approximately 40–65 dB(A), by performing an overall spectral shaping due to atmospheric absorption. The resulting audio signals were 2-channel (stereo) files.

In total 30 stimuli, representing the sound situations of Table I, were established. The desired sound level of each file was adjusted to the L_{Aeq} of Table I. Stimuli length was set to 25 s, which in preliminary tests was found to be optimal.

Note that while some of the above sound situations do not occur in reality, preliminary listening tests showed that also these stimuli sounded plausible and realistic. Also, none of the subjects labelled them as being "unrealistic", and the corresponding annoyance ratings fit well to the results of the other stimuli (see below).

2.3. Annoyance ratings and questionnaire

The aim of the listening tests was to assess the annoyance of outdoor WTN and RTN situations during the day (e.g. leisure time), for residents in the vicinity of wind farms or roads. To that aim, annoyance ratings of the stimuli were done on the basis of the ICBEN 11-point scale of ISO/TS 15666 [8], by answering the following question (in German, modified from [8]): "When you imagine that this is the soundscape in your garden, what number from 0 to 10 best shows how much you would be bothered, disturbed or annoyed by it?"

The listening tests were complemented with a questionnaire. The first part contained questions on hearing and well-being, and the second part questions on gender, age, living environment, noise sensitivity, and attitude towards WTN and RTN.

2.4. Subjects

60 subjects (31 males, 29 females), aged from 18–60 years (median of 35 years) and covering a wide range of noise sensitivity and attitudes towards WTN and RTN (not reported here), participated in the listening tests. Their living environment covered all areas from rural to urban and from quiet to loud, but not areas close to wind turbines. Only half of the subjects had heard WTN before.

2.5. Listening tests

Experimental setup: The listening tests were done in a semi-anechoic chamber. The reproduction system was a 3-channel stereo setup (left, centre, right; Figure 1). The loudspeakers (Focal CMS 50) were installed at a similar height as the seated subjects' head, at a distance of 150 cm from the subjects. The centre speaker reproduced the attenuated sum of the left and right channel. This setup allowed the reproduction of the directional information of pass-by events of RTN, while the monaural WTN signal was more robustly localizable from the front even if the subjects' head moved during the listening test. Prior to the tests, the reproduction chain was calibrated with a sound level meter located at the position of the seated subjects' head.

Figure 1. Experimental setup with the software displayed on the computer screen. Details see text.

Experimental procedure: The experiments were done as focused tests, i.e. the subjects had to deliberately listen to the stimuli. All stimuli were played once only, and the subjects rated them during or directly after play-back. The stimuli were played one by one, after complete play-back and rating of the previous one. The subjects did the listening tests individually (one subject at a time). A software developed for this study guided the subjects through the whole test, by automatically choosing and playing the stimuli, and by recording the subjects' ratings. These were entered by the subjects via a graphical user interface to answer the question of section 2.3.

After a short introduction to the listening tests and their task of annoyance rating, the subjects signed a consent form to participate in the study. Thereafter, they answered the questions on hearing and well-being (section 2.3). None of the subjects included in the study wore a hearing aid, and all of them declared to have normal hearing and to feel well (without cold), so that hearing impairment could be excluded.

The subjects were then instructed about the software and subsequently started the actual listening test. After exposure to some short stimuli as an orientation and two (non-recorded) exercise ratings to get used to the 11-point scale, the main experiment was conducted with the 30 experimental stimuli (Table I). At first, the 24 stimuli with sound levels of 40–55 dB(A) were randomly reproduced. Thereafter, the remaining 6 stimuli with sound levels of 35 and 60 dB(A) were reproduced in balanced order. After the experiment, the subjects completed the second part of the questionnaire (section 2.3).

The whole listening test including the introduction and the questionnaire lasted about 1 hour.

2.6. Data set

In the listening tests, a data set of 1'800 annoyance ratings (60 subjects × 30 stimuli) was recorded. Each rating was attributed to the specific levels of the variables in Table I and the subject's characteristics (age, gender, …). In addition, the ratings were transformed into the binary variable "high annoyance (HA)", with a HA value of 1 indicating highly annoyed (ratings of 8–10 [9]) and a HA value of 0 indicating not highly annoyed (ratings 0–7).

2.7. Statistical analysis

Annoyance ratings: The annoyance ratings were analyzed by means of a linear mixed-effects model. Such a model combines fixed effects (cf. Table I) and random effects (randomly chosen from a population with a large set of possible levels; i.e. the subjects). It accounts for multiple (repeated) "measurements" (i.e. annoyance ratings) per subject, which have correlated errors, by using a hierarchy of levels, the upper level being the subjects and the lower level being the repeated ratings per subject. Sound level was treated as a covariate in the analysis. Thus a complete 2 × 3 factorial design was obtained (source type × AM; cf. Table I). Differences in annoyance ratings between groups were analyzed with contrasts.

High annoyance: The dependence of the binary variable HA on the variables of Table I was analyzed by means of logistic regression. To account for the repeated ratings of the subjects, a logistic model with random intercept (for the subjects) was developed, which allows modeling the individual probabilities for high annoyance (HA value of 1). This model yields exposure-response curves for the probability of high annoyance (%HA).

Effects and/or their interactions were considered to be significant if their p-values were below 0.05.

3. Results

3.1. Annoyance ratings – raw data

Figure 2 visualizes the frequency of the individual annoyance ratings in the listening tests. Though the ratings cover a wide range of the 11-point scale at any sound level, there is a clear trend of WTN to cause higher annoyance than RTN, symbolized by mostly larger bubbles for WTN at the upper part and smaller bubbles at the lower part of the ordinate than for RTN. The data set is analyzed in more detail below.

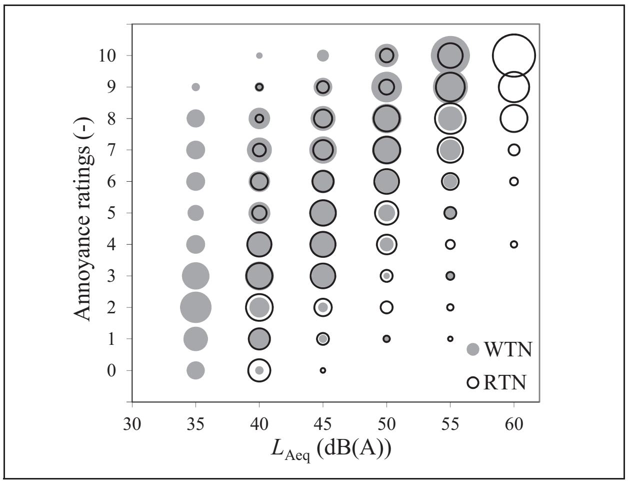

Figure 2. Bubble chart of the individual annoyance ratings as a function of the L_{Aeq} of the stimuli representing wind turbine (WTN) or road traffic noise (RTN). Bubble size is proportional to the number of responses.

3.2. Annoyance ratings

The averaged annoyance ratings of the investigated stimuli are shown in Figure 3. Annoyance increases linearly with the sound level, for any combination of source type and AM. Furthermore, over the studied sound level range, WTN is substantially more annoying than RTN, irrespective of whether AM is present or not.

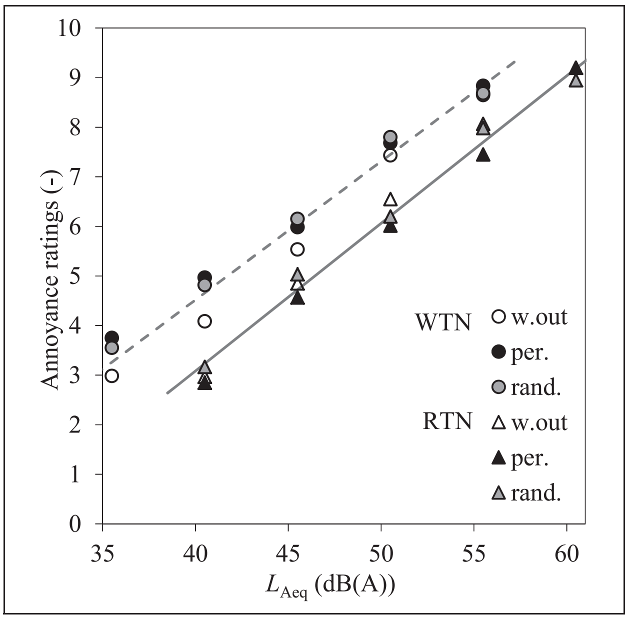

Figure 3. Annoyance ratings (averaged values of the ratings in Figure 2) as a function of the L_{Aeq} of the stimuli representing wind turbine (WTN) or road traffic noise (RTN) without (w.out), or with periodic (per.) or random (rand.) AM. Lines represent the mixed-effects model for the pooled WTN and RTN data.

The effect of AM strongly depends on the source type. Constant WTN is less annoying than varying WTN, while the difference between periodic and random AM is small. For RTN, the effect of AM is less clear, although periodic AM is slightly less annoying than random AM or without AM. The effects of source type and AM are distinct at low sound levels and decrease with increasing levels. This indicates that the ratings progressively adopt values of "high annoyance" (ratings of up to 10) at large sound levels, irrespective of source and AM.
Statistical analysis of the data with a mixed-effects model confirmed statistical significance of the observed effects. Source type, AM and level all significantly affect the annoyance ratings ($p < 0.005$–0.001), and there are interactions between source type and AM ($p < 0.001$), AM and level ($p < 0.01$), and in trend also between source type and level ($p < 0.07$; indicated by the slight convergence of the regression lines in Figure 3). The interactions indicate that the effects of the variables in Table I depend on the levels of the other variables.
The combination of the aforementioned effects resulted in distinctly disparate annoyance ratings of the stimuli at a given sound level. As an example, contrast analysis revealed that at an L_{Aeq} of 50 dB(A), WTN with an annoyance value of 7.4 is significantly more annoying than RTN with a value of 6.2 ($p < 0.001$). Furthermore, WTN with periodic and random AM is equally annoying ($p > 0.25$), but significantly more annoying than without AM (annoyance difference of 0.4, $p < 0.001$). Finally, RTN without AM or with random AM had similar annoyance ratings ($p > 0.45$), while periodic AM was significantly less annoying (annoyance difference of 0.3, $p < 0.001$).

3.3. Probability of high annoyance

Figure 4 shows the probability of high annoyance (%HA) for WTN and RTN. The observed %HA data approximately follow a sigmoid trend, for any combination of source type and AM. As for the absolute annoyance ratings (section 3.2), WTN is substantially more annoying at any sound level, indicated by a higher %HA than RTN (Figure 4). Furthermore, WTN with random and periodic AM has a higher %HA than constant WTN, while the stimuli of RTN with periodic AM tend to have a lower %HA than the stimuli of RTN with random AM or without any AM.
Preliminary results of the logistic regression analysis confirm the statistical significance of the observed effects. Level ($p < 0.001$) and in tendency also source type ($p < 0.07$) affect %HA, while AM affects %HA by a significant interaction with source type ($p < 0.02$), i.e. its effect differs between WTN and RTN (cf. Figure 4). In contrast to the absolute annoyance ratings (section 3.2) there were no significant interactions between sound level and source type or level and AM.

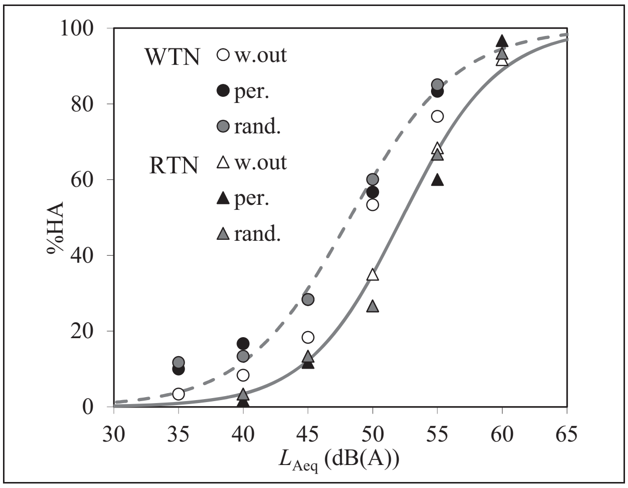

Figure 4. Probability of high annoyance (%HA) (observed averaged values) as a function of the L_{Aeq} of the stimuli representing wind turbine (WTN) or road traffic noise (RTN) without (w.out), or with periodic (per.) or random (rand.) AM. Curves represent the logistic regression model for the pooled WTN and RTN data.

4. Discussion

In this study, laboratory listening tests with a factorial design were done, using stimuli representing specific, fully controlled environmental sound situations, generated by sound synthesis or mixing tools. The experimental design not only allowed separating the individual contributions of level, source type and AM on the annoyance ratings, but could also exclude effect modifiers such as the visibility of wind turbines, that are inherent to field surveys. This enabled to investigate effects which are exclusively caused by acoustic characteristics.
The observed annoyance and resulting %HA are generally high compared to field surveys. As an example, at an L_{Aeq} of 50 dB(A), %HA is ~30% for RTN and ~55% for WTN (Figure 4), while in field studies, %HA was found to be as low as ~5% for RTN and ~15% for WTN at an L_{den} of 50 dB [2]. However, these differences are at least partly due to the fact that in field surveys the subjects are not only outdoors but often also indoors and in these times exposed to substantially lower and thus less annoying sound levels. Also non-focused laboratory listening tests including tasks such as reading yield rather lower ratings [10], while similar ratings were obtained in other focused tests

[11]. Context is highly influential therefore for the absolute ratings, which needs to be accounted for when comparing studies (see also [5]).

The annoyance ratings were strongly dependant on the L_{Aeq}, which confirms recent findings that an A-weighted metric is an appropriate annoyance predictor for WTN [12] as well as RTN [13]. However, other sound characteristics such as source type need to be considered as well. WTN was found to be substantially more annoying than RTN (Figures 3 and 4), causing the same %HA at ~3–5 dB(A) lower L_{Aeq} than RTN in the range of %HA values of 10–90%. Visual factors were excluded in this study; therefore the disparate annoyance is exclusively caused by differences in the acoustic characteristics of the sources such as the spectra. While higher annoyance ratings of (outdoor) WTN compared to RTN is in line with results of field surveys [2], the situation might be different for indoor noise [10]. Also the high annoyance of WTN with periodic AM is in agreement with previous studies [3, 11]. Interestingly, the subjects did not discriminate between periodic and random AM in their rating. However, the latter finding might have been different if the subjects had lived close to wind turbines, thus being accustomed to WTN and potentially recognising random AM not to occur in reality. For RTN, the effect of AM was quite different from WTN, which might indicate that the fluctuation frequency as well as its strength strongly affects annoyance.

The high annoyance of WTN needs to be accounted for when assessing its impact, e.g. by charging it with a certain penalty (addition of a correction term). In defining such penalties, not only average differences between different source types should be considered, but also the prevalence of situations with periodic amplitude modulation and/or visibility of wind turbines, which might additionally increase annoyance in the field.

5. Conclusions

In the present laboratory study, wind turbine noise was found to be substantially more annoying than road traffic noise, particularly in situations with "thumping" amplitude modulation, but also in other situations. Visual factors were excluded from the experiments; therefore the difference in annoyance is caused exclusively by the sound characteristics of wind turbines compared to road traffic. Further investigation of the specific sound characteristics that cause increased annoyance would be recommended. The high annoyance potential of wind turbines should be considered in environmental impact assessment, e.g. by source-specific penalties, to guarantee an adequate protection against the impact of wind turbine noise.

Acknowledgement

This project is funded by the Federal Office for the Environment (BAFU/FOEN) of Switzerland (assignment No. 5211.00723.100.02).

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