Auditory masking of wind turbine noise with ambient sounds

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The expansion of wind energy production creates an increase in wind turbine (WT) noise. The purpose of this paper is to examine if a possible reduction of WT noise might be achieved by adding natural ambient sounds, so called auditory masking. A loudness experiment was conducted to explore this possibility, using four ambient sounds of trees, birds and water as maskers. Sixteen listeners assessed the loudness of WT noise heard alone or in the presence of 40 dB masking sounds, using the method of magnitude estimation. Partial masking of WT noise was found in the presence of all ambient sounds. The masking effect corresponded to a dB-reduction of the WT noise from a few dB for signal-to-noise ratios (S/N) close to 0 dB up to around 10 dB at -15 dB S/N. These results indicate that addition of ambient sounds may be a useful method for masking unwanted noise from wind turbines.

Wind turbine (WT) noise is increasing as the use of this renewable energy source is rapidly expanding. Sweden plans to tenfold the production of wind power before 2020, from 2 TWh a year to 20 TWh (Energimyndigheten, 2007). This will lead us closer to fulfilling the Koyoto agreement but it will also increase the exposure to WT noise and thereby have an impact on peoples well-being and health (Gjestland, 2008; WHO, 2000). Conventional noise mitigation may not be technically or economically feasible for wind turbine noise. As a complement, auditory masking may be used. That is, adding sounds to improve the sound environment (Bolin, Khan, & Nilsson, 2010; Brown & Muhar, 2004). The purpose of the present listening experiment was to explore the possibility of reducing wind turbine loudness by adding positive sounds from bird song, vegetation and water structures.

Auditory masking takes place both in the auditory periphery (energetic masking) and in the auditory cortex (informational masking). Energetic masking occurs when both sounds contain energy in the same critical bands at the same time and portions of one or both of the signals are inaudible. Informational masking occurs when the signal and masker are both audible but the listener is unable to disentangle the elements of the target signal from a similar-sounding distracter (Brungart, 2006; Oh & Lutfi, 1999). The overall masking of a sound may therefore be seen as the sum of energetic and informational masking (Watson, 2005).

Fégeant (1999) predicted that the sound induced by the wind in vegetation would be an ideal masker of WT noise as high wind speeds increasing wind turbine noise emission will coincide with the increasing sound levels from vegetation and therefore provide energetic masking. The noise produced by both wind turbines and vegetation are of steady and broadband character which increases the potential of both energetic masking and informational masking. Bolin (2009) showed that the sounds of coniferous and deciduous trees had masking effect on WT noise as it affected the absolute threshold of hearing.
The guidelines for WT noise differs from country to country, where some has a fixed level, like Sweden with 40 dB ($L_{Aeq}$) (Naturvårdsverket, 2001) and some, like Great Britain, allows WT levels 5 dB ($L_{Aeq}$) above the 90 percentile background noise level ($L_{A90}$) (Working Group on Wind Turbine Noise, 1996). Increasing WT noise, differing guidelines and the findings that WT noise has been shown to evoke annoyance even at sound pressure levels below 45 dB ($L_{Aeq}$) (Pedersen & Persson-Waye, 2004) raises the question how WT noise is perceived in the presence of natural background sounds. The purpose of this experiment was to investigate and quantify how the perceived loudness of wind turbine noise is affected by the addition of ambient sounds in an experimental setting.

![Figure 1. Photo of recording equipment during field measurements of the old windturbine (left) and new windturbine (right).](image)

**Method**

**Participants**

16 university students participated in the experiment (10 women and 6 men; mean age = 24 years). All participants had hearing threshold levels below 25 dB in their best ear in all tested frequencies (0.5, 1, 2, 3, 4, 5, and 6 kHz, Interacoustics Diagnostic Audiometer, model AD226). The participants received course credit for their participation.

**Recordings**

The recorded sounds consisted of two types of WT noise, an older model, 850 kW, and a modern model, 2 MW containing three WTs spaced approximately 200 m apart. They were recorded by Dr. Karl Bolin and the author at a distance of approximately 200 m from the closest WT using a binaural head (see Fig. 1). All WTs were of relatively modern standard and therefore the noise contained only aero-acoustic components from the blades and no mechanical noise from the hub.
Experimental sounds
The experimental sounds consisted of the two recorded sounds and four types of natural ambient sounds, deciduous trees, deciduous trees with birds singing and two types of water sounds. All ambient sounds were taken from a BBC collection of sounds (BBC, 1991), except the birds singing which was taken from a database of soundscape recordings at the Gösta Ekman Laboratory, Stockholm University. The ambient sounds were presented at 40 dB $L_{Aeq,5s}$, which is a realistic level of these type of sounds as heard outdoor for instance in a garden or forest.

The WT noise was either presented alone or combined with an ambient sound of constant level of 40 dB $L_{Aeq,5s}$. When alone, WT noise ranged from 19 to 52 dB in 3 dB steps. When combined with an ambient masking sound, the WT noise ranged from 26 to 46 dB $L_{Aeq,5s}$ in 2 dB steps. In addition, “blanks” were included, that is the masker sound presented alone at 40 dB $L_{Aeq,5s}$. All experimental sounds were 5 seconds long and the WT noise was gated on 1 s after the start of the sound to facilitate higher detect ability.

The ambient sound samples were chosen because the types of sounds are distinctively different and of broadband character. The spectra of the WT sounds (right panel) and the background sounds (left panel) are shown in Figure 2.

![Figure 2. 1/3-octave-band spectra of the background sounds and WT sounds.](image)

Scaling method
Perceived loudness was assessed with the method of free number magnitude estimation (Stevens, 1975). In this method, the listener is instructed to use any number he or she likes as long as they are proportional to perceived intensity. This method was chosen for two reasons, first to obtain direct measurements of perceived loudness and second, to obtain indirect matches of loudness of masked and unmasked WT noise. Compared to direct matching, indirect matching is a cost effective method which allows matching of large numbers of sound combinations (Marks, 1974). Note that indirect matching using ratio-scaling methods do not assume that listeners are able to produce magnitude estimates with ratio-scale properties. The only assumption is that, on average, equal numbers (magnitude estimates) means equal loudness (cf. Marks, 1974; Nilsson, 2007).

Procedure
The listener was seated in a soundproof room in front of a computer screen connected to a computer in another room. The experimental sounds were binaurally presented using
ear phones. The experiment consisted of ten listening sessions, in which only one type of sound was included. Thus, there was one session with only new-WT noise, one session with only old-WT noise, four sessions with new-WT combined with one of the four ambient sounds including one blank, and four corresponding sessions with old-WT combined with ambient sound. Each session contained six repetitions of each unique sound level of the WT noise. The experimental sounds were presented in random orders, which were different for each session and participant. Listening session duration was approximately 7 min. The sessions were separated from one another with 1 min pauses, except for the pause between sessions 5 and 6, which was 10 min. A training session with six sounds was conducted prior to the first session. The participants entered their magnitude estimates on a computer keyboard.

Equipment
Sounds were recorded using a head and torso simulator (Brüel & Kjaer type 4100, with microphone type 4190 and preamplifier type 2669), conditioning amplifier (NEXUS Brüel & Kjaer type 2690 A 054) and a calibrator (Brüel & Kjaer type 4231 plus adapter model 0887). Sounds were recorded on a portable computer (DELL) with a six channel soundcard (LynxTwo) using a software for sound recording with 24 bit resolution and 44.1 kHz sampling frequency (Audacity). The recordings were edited on a personal computer (DELL Precision 220) using the SOUND FORGE 7.0 software. 2 samples of wind turbine sounds and 4 samples of ambient sounds were used to create 72 samples using a script written in MATLAB. Frequency analyses of the sounds were conducted using the ArtemiS software.

Experimental sounds were stored on a personal computer (DELL Precision 220 with a LynxTwo soundcard). The digital signal was fed into a digital filter and digital/analog converter (Rane RPM 26z) and was then presented through ear phones (Sennheiser HD 600). The whole listening system was calibrated using a pink-noise signal, which was measured at the point of the listener’s ear. The frequency response of the whole listening system was flat within 2 dB (1/3-octave-band levels, 25-16000 Hz).

Results
Each listener assessed each experimental sound 6 times. For each set of 6 responses, magnitude estimates that were more than three times greater than the next largest estimate or less than one third of the next smallest estimate of the same sound were excluded as outliers (cf. Nilsson, Andéhn & Lesna, 2008). In total, 76 estimates (less than 1%) were excluded.

The intra-individual reliability was high, as determined by Pearson’s coefficients of correlation between magnitude estimates of sounds in the first three and last three sessions. Coefficients ranged between 0.56 and 0.98 (median = 0.94). As expected, the intra-individual reliability was higher than the inter-individual agreement. Still, the latter was fairly high as determined by the Pearson’s coefficient of correlation between individual scales of loudness ranging from 0.46 to 0.90 (median = 0.73). It was therefore justified to include data from all participants in the group analyses reported below.
Individual free number magnitude estimates were first brought to a common mean by dividing each listener’s estimates with the listener’s arithmetic mean estimate, after which all listeners had the same mean estimate (= 1.0). This transformation is allowed since it keeps the ratio scale properties of the values, unlike for instance the standard z-transformation (cf. Stevens, 1946). The estimates were then logarithmically transformed and averaged arithmetically to obtain a group scale of loudness (cf. Gescheider, 1997). This procedure excluded all magnitude estimates equal to zero, since log(0) is not defined. However, if more than half of the estimates of a given sound were zero, then the group value was set to zero (cf. Nilsson et al., 2009). In the present experiment, this was true only for the sounds with no wind turbine noise (blanks), for which 71% of the responses were zero (that is, the false-alarm rate was 29%). For the sounds containing WT noise, the percentage non-zero responses of WT loudness ranged from 53% to 100%. In the following, group scales of WT loudness are presented on a logarithmic scale as magnitude estimation is a ratio scaling method (e.g., Gescheider, 1997).

Figure 3 shows WT-loudness as a function of WT sound pressure level, separately for WT noise presented alone (filled circles) and WT noise heard together with a 40 dB masking sound (open symbols). Steven’s law postulates a linear relationship between perceived and physical intensity in log coordinates (Stevens, 1975). However, it is well known that the loudness function is not linear, but negatively accelerating at levels below approximately 40 dB (Stevens, 1975). Furthermore, there was a slight tendency for a curvature of the data at the highest levels, possibly due to a kind of ceiling effect. For these reasons, a second-order polynomial was fitted to the WT alone sounds (least square). This function was used to derive indirect matches of WT loudness (see below Eqs. 1-3).

As suggested by Figure 3, the reduction in loudness was least for the bird masker (upside down triangles), followed by the brook masker (diamonds). The masking effect of the brook masker was slightly less than for the leaves (triangles) and the wave sounds...
(squares), which were similar in their masking effect. A 4 (masking sound, averaged over levels) x 2 (old vs. new WT) within subject ANOVA revealed a significant effect of masking sound ($F_{3,45} = 3.7, p = .031$, partial $\eta^2 = 0.20$). The differences between the masker sounds were slightly more pronounced for the old (left) than for the new WT (right diagram). And, in general, there was a tendency for the ambient sounds to mask the old WT noise more than the new WT noise (horizontal distance between the symbols and the curve is slightly larger in the left than in the right diagram). However, both the main effect of WT ($F_{1,15} = 0.55, p = .471$, partial $\eta^2 = 0.04$) and the masker by WT interaction ($F_{3,45} = 1.28, p = .348$, partial $\eta^2 = 0.07$) were non significant.

For both the old WT noise (Fig 3., left diagram) and the new WT noise (right diagram) there was a reduction in loudness below 40 dB corresponding to a signal-to-noise ratio of 0 dB or less. In order to quantify this masking effect, we calculated the level difference between WT noise heard alone and an equally loud WT noise heard together with the 40 dB masking ambient sound. The main advantages of expressing the masking effect in decibels are that this is a meaningful unit and that it only assumes ordinal-scale properties of the magnitude estimates. The masking effect was calculated using the second-order polynomial fitted to the WT alone noises (curve in Fig. 3):

$$\log(R_{WT\text{-alone}}) = a + bL_{WT} + cL_{WT}^2,$$  \hfill{1}

where $\log(R_{WT\text{-alone}})$ is the perceived loudness of the WT alone noise (group scale in log-units) and $L_{WT}$ is the sound pressure level of the WT alone noise ($L_{Aeq,5s}$). Equation 1 was used to calculate levels of WT noise heard alone that was equally loud as WT noise heard in combination of ambient sound. Equally loudness means that $\log(R_{WT\text{-alone}}) = \log(R_{WT+ambient})$, and, from Eq. (1),

$$\log(R_{WT+ambient}) = a + bL_{WT} + cL_{WT}^2,$$  \hfill{2}

where $\log(R_{WT+ambient})$ is the perceived loudness of the WT heard in combination with the ambient sound. Solving for $L_{WT}$ in Eq. (2) gives two values, one which corresponds to the increasing section of the function. This value is the “effective” level of WT noise in ambient sound, that is, the level of WT noise alone that is equally loud as WT noise heard in combination with ambient sound, denoted $WT_{eff}$. Partial masking level is then defined as

$$\text{Partial masking level} = L_{WT} - WT_{eff},$$  \hfill{3}

which corresponds to the horizontal distance between an open symbol (masked sound) and the fitted curve representing the loudness of the target alone sound in Figure 3.

Figure 4 shows partial masking levels (Eq. 3) as a function of S/N ratio of WT-masking sound, separately for the old WT (left panel) and the new WT (right panel), and separately for the four masking sounds. Positive numbers indicate masking and negative numbers indicate the opposite (“facilitation”). For the old WT, the masking level ranged from around -2 dB at 6 dB S/N-ratio to around 10 dB at -15 dB S/N-ratio. For the new WT the partial masking levels were slightly lower.
Discussion

The results showed a masking effect for all the ambient sounds. The birdsong showed the least masking effect on both WTs and the leaves and water sounds masked the most. A probable explanation is that leaves and water sounds cover more of the frequency spectra of both WTs than the sounds of birds. This suggests that energetic masking is occurring in these stimuli. Furthermore, the temporal aspect of birdsong, a highly time varying sound, can have deteriorated the possibility of masking.

The results showed a reduction of perceived loudness of WT noise for S/N-ratios up to 0 dB, with an anticipated increase in masking with decreasing S/N-ratio. The masking effect corresponded to a dB-reduction of the WT noise of a few dB for S/N-ratios close to 0 and up to around 10 dB at -15 dB S/N-ratios. This suggest that addition of ambient sound may be a useful tool for reducing WT noise, given that the sound level of the ambient sound is equal or higher than the level of the WT noise. This opens up for possibilities to improve the soundscape for groups of people that find even low levels of WT noise disturbing (Pedersen & Persson-Waye, 2004).

A slight tendency for a “facilitation” effect was found for both WT above 40 dB (S/N-ratio > 0 dB). That is, the target sound was assessed as louder when heard with a masker than when heard alone. This is possibly explained by that the target and masker sounds are confused and the masking sound is incorrectly perceived as the target sound, i.e. informational masking due to target-masker similarity (cf. Watson, 2005; Nilsson et al., 2009). However, replications of this finding is necessary to rule out alternative explanations related to the methodology used, for instance using direct rather than indirect matching of WT noise alone and heard in combination of ambient sound.

The present result were reached in an experiment conducted in laboratory settings with earphones. In real life, binaural cues and head movements for detecting different sound sources would have been used. Therefore the results may show an overestimation of the masking of WT noise by background sounds. However, in typical situations the WT
sound and background sound, like an offshore wind park and the sound of the waves, would be localized in the same direction and therefore not significantly affect audibility of WT noise. This would also be the case for land based WT, were, for example, masking trees would be planted between the WT noise source and nearest settlement.

The reduction in loudness shown when WT noise and ambient sounds were presented at the same level, 40 dB, supports Fégeant’s (1999) prediction of vegetation sounds as ideal maskers as the increase in sound emission from WT and ambient sounds will coincide. The results also indicate that the noise guidelines for WT noise should be defined in relative levels instead of fixed levels, since the masking effect increased systematically with the S/N ratio.

In summary, this study shows that presentation of natural ambient sounds to WT noise should be taken into serious consideration as a soundscaping tool when designing future wind turbine parks. The potential of masking opens up for possibilities to use locations that are naturally free from community noise i.e. rural areas with low population density (Gjestland, 2008), where WT noise otherwise could be a disturbance. Further experiments could use the ambient sounds as maskers but instead measuring perceived annoyance or pleasantness to investigate effects on evaluative aspects of the sound environment. Further experiments will give us glimpses of the sound of tomorrow, in a world powered by clean renewable wind energy, hopefully masked by pleasant ambient sounds.

References

BBC (1991). Sound FX Library 01-20, Ontario, Canada: BBC Enterprises LTD


