The visual effect combined with audible noise of wind turbine and its related EEG reaction

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Summary
The visual effect combined with audible noise of wind turbine (WT) was investigated in this paper. Eight signals contained the same wind turbine noise (WTN) combined with different visual contents of wind turbine were presented to 16 subjects, and their brain reaction were observed simultaneously with EEG equipment. The significant correlation between the subjective annoying feelings and the relative power spectral density (RPSD) of EEG bands were found at the emotional function area of the brain. The different variation of the RPSD at different brain areas and its relationship with the subjective annoying value (SAV) of the signals indicated that under the same WTN subjects' annoyance could be changed due to the visual stimulus of WT with different landscapes. Questionnaires related to hearing problem, noise sensitivity, mental performance, self-report emotion and attitude to WT were answered by the subjects, and the results showed different brain reactions and annoyance evaluations among the different groups.

1. Introduction

Wind power is a relatively new form of electricity generation, and it has a low impact on the environment compared with other power sources. However, due to the typical size of wind turbines (WTs) and their airspace configuration, they have also bring adversely effects such as noise emission, vibrations, non-ionizing radiation, emergency situations, the shadow flicker effect, and permanent shade conditions [1].
Besides the negative annoying feeling caused by WTN, the visual aspect also showed an important effect on the overall impression and evaluation to the WTs. People who felt that the WTs would have a negative visual effect on the landscape and thought that the turbines would decrease it recreational value, were more likely to oppose WTs [2]. Seeing one or more WTs increased not just the possibility of perceiving the sound, but also the possibility of being annoyed. This result showed a multimodal effect of the audible and visual exposure from the same source, which could lead to an enhancement of the negative evaluation of the noise by the visual stimuli [3]. However, most of the investigations were field questionnaire surveys, which didn't show precisely relationship between visual aspect and subjective annoyance due to WTs. For the other noise situations, the visual attitude towards the noise source was studied more [4]. Still, the effect of the sound source being visible is not always clear. Loudness of the noise transmitted through barriers of different solidity was compared, and loudness was judged to be lower with a barrier partially obscuring the sound source than without barrier, but greater when the sound source was totally obscured [5]. When a visually attractive street was presented together with traffic noise, the evaluated annoyance was lower than the same noise level but with a visually unattractive street [6]. The same tendency was found in an experimental study where subjects evaluated the stimuli combined with five visual settings of varying degrees of urbanization and eight urban sounds [7]. For both traffic noise and natural sound like bird song, the more urbanized the visual stimulus, the more negative were the sound ratings.
Several individual factors were found having a clear influence on annoyance from a noise source, for example noise sensitivity and mental performance. The difference in annoyance between people with lowest and highest noise sensitivity was equivalent to difference in sound level of approximately 11 dB [8]. Psychological distress was assessed with the General Health Questionnaire - 12 items in a WTN study. Although the direct relation between noise level and psychological distress was not significant, the result indicated that the annoyance and sleep disturbance caused by the WTN rather than the noise itself may lead to the distress [9].

EEG was found useful to observe the brain reaction caused by noise [10] [11]. Kasprzak tried to find the influence of infrasound from WTs on EEG signal patterns [1]. He calculated the power spectral density of Delta, Theta, Alpha, SMR, Beta1 and Beta2 in different stages, the Alpha wave amplitude was found to decrease during the infrasound exposure, but it was not statistically significant. One theory was that upwind wind turbines of a standard design do not emit audible infrasound, which was supported with some other field measurement, for example the infrasound level from upwind wind turbines at a distance of 100m was found below the normal hearing threshold [12]. Therefore, the WTN in this paper was in the audible range.

The purpose of this study is to investigate the subjective annoying variation caused by the same WTN combined with different visual contents of WT and observe the simultaneous brain reaction under the laboratory environment. The discussions are focus on the following aspects: 1) how people's annoyance change due to the additional visual stimulus of WT; 2) whether surrounded with nature landscapes could improve the negative effect caused by WT; 3) the relationship between subjective feelings and brain reaction, whether there are different EEG patterns among subjects with different noise sensitivity, mental performance or other individual factors.

2. Experimental material and methods

Six-teen students (8 male and 8 females) from University of Wuppertal were recruited as subjects in the experiment. The experiment was taken in a chamber with a low background noise level (17 dBA). According to the measurement result of 29 WTs in Japan [13], all WTs have similar spectral characteristics, which can be approximated by a -4 dB/octave slope in band spectrum. Therefore, the WTN used in the test was generated with the same form, which was White Noise through low pass filter (cut frequency 20 Hz and order 1). The level of the WTN was set to 40 dBA, which was used in several national standards [14]. The visual signals were field recordings in Zetel of Lower Saxony in Germany. The types of the WTs were Vestas 110 and Enercon E-66. There were three baseline signals and eight test signals contained the same WTN and different visual stimuli in the test (Table I). Considering the types of the WTs and the limitation of the visual recordings, the high blade rotating speed was set to 15 rpm (rpm= revolutions per minute), normal speed as 10 rpm, and low speed as 7.5 rpm. The distance between the recording location and the WT was around 300m. Different blade rotating speeds of WT (Signal 1, 3, 5) and WT in still (Signal 8) were renamed as Signal Group1 (SG1) and WT with different landscapes (Signal 2, 4, 6) and Signal with several WTs (Signal 7) were renamed as Signal Group2 (SG2). There was only one WT in the signals except Signal 7.

Table I. The signals in the test. (N = normal blade rotating speed, A = Audio, V= Video).

B1	*B2*	*B3*
no V, no A	only A	only V (N)
Signal 1	*Signal 2*	*Signal 3*
Slow speed	hidden by trees	Fast speed
Signal 4	*Signal 5*	*Signal 6*
with several cows	Normal speed	90° side
Signal 7	*Signal 8*	
several WTs	Still	

Firstly, the subjects were asked to answer some questionnaires before the test, which included the Basic Hearing Problems Questions (HP), the Edinburgh inventory for L/R hands [15], General Health Questionnaire-28 (GHQ-28) [16], Noise Sensitivity Questionnaire (NS) [17], the Positive and Negative Affect Schedule (PANAS) [18]. And they also gave their attitude opinions to WT, which included the overall opinion and whether they felt WT environmental friendly or impacting, pretty or ugly, necessary or unnecessary, natural or unnatural, safe or dangerous. Then the subjects were sitting in front of a monitor and two loudspeakers with a 1.5 m distance. The order of the signals was from B1 to B3 then followed by Signal 1 to 8. The duration for Baseline and each test signal was 1 min, and between each stage there was a 30 seconds pause. In the pause the subjects were asked to evaluate the annoying level to the previous segment (except B1) in a five evaluation criterion ("1" for not annoying at all and "5" for very annoying). The brain reaction was observed with EEG equipment, the Neuro-Spectrum-5. The electrode positions chosen in this test were AF3, AF4, T3, T4, O1 and O2 according to the "10-10" system, with CZ as the reference position, EOG at left and right sides were also recorded.

3. Data analysis

Firstly, 16 subjects were classified into different groups depended on the results of the different questionnaires. For the Hearing Problem Question, the higher the score, the worse the subject's hearing ability, so HP-G1 was the subjects who got the score more than 3 and considered as subjects with slightly hearing problem, HP-G2 was with score lower than 3. The subjects were classified into three groups according to the noise sensitivity result, followed by NS-G1 (≥70); NS-G2 (35-70); NS-G3 (≤35), and also the higher the score the more sensitive to the general noise. GHQ-28 groups were divided with 23 points, and GHQ-G1 was subjects with score higher than 23, which meant they might have poor mental performance. There were 10 positive and 10 negative questions in the PANAS, and the scores of PA and NA were collected separately. The range for each question of the attitude to WT was from 1 to 5 with "1" for positive and "5" for negative.

Because the subject 10 gave the same subjective annoyance value (SAV) to all the signals, his result was removed from the further analysis. And considering the possible effect of the handedness on the EEG result, the subject 15 with L handedness was also eliminated. The modified SAV result was collected under subjects (Figure 1) and different signal groups (Figure 2), questionnaire groups (Figure 3), and also the SAV comparison of two signal groups for different questionnaire groups (Figure 4). The mean value (black dots) and Standard Deviation (SD) value were calculated, the significant results according to the ANOVA (Analysis of Variance) obtained from SPSS were also given in the figures.

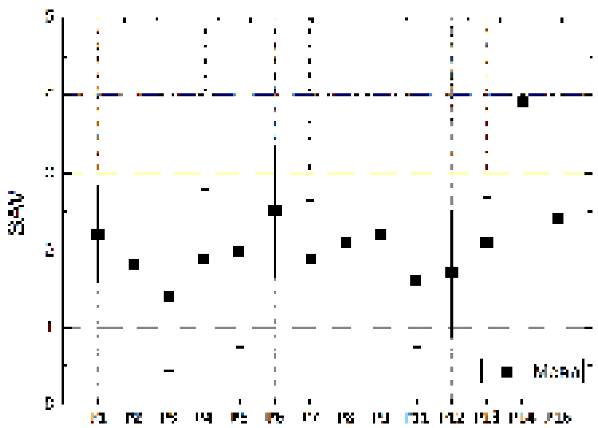

Figure 1. The SAV result of 14 subjects.

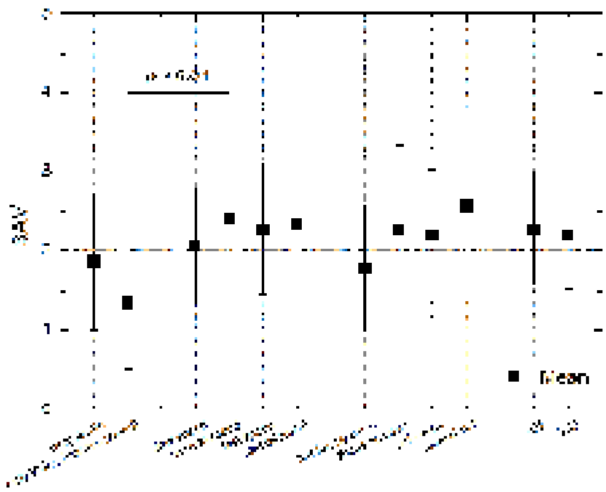

Figure 2. The SAV results of all signals.

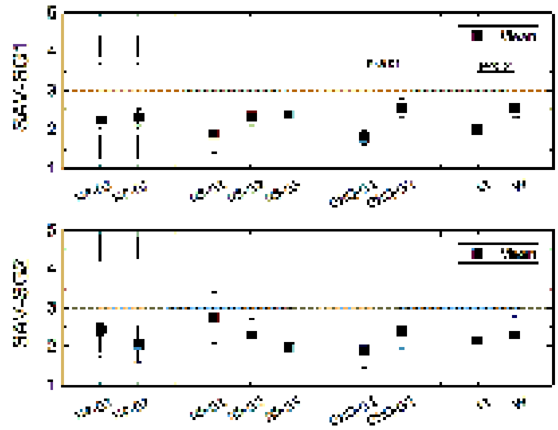

Figure 3. The SAV results of two signal groups.

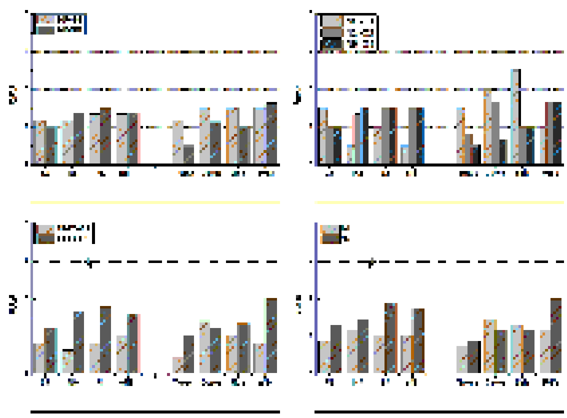

Figure 4. The SAV results of SG1 and SG2 for different questionnaire groups.

The remaining subjects gave different annoyance evaluation for different signals, which meant that the same WTN combined with different WT visual contents could cause them different subjective annoyance. The SAV of B2 was lower than all eight signals, which indicated that the employed visual stimuli of WT could increase the subjects' annoyance, and supported the previous conclusion that people would feel more annoyed when they could not only hear WTN but also see WT. To check the annoyance variation among different WT blade rotating speeds, the SAV among SG1 were compared. The result was only with little disparity and the significant difference appeared only between GHQ groups or between the genders. According to the feedback after the experiment, a lot of subjects said that they did not notice the different blade rotating speeds, which could be the reason for the low variation among the SAV of SG1. In Figure 4 it showed that the SAV of S2, 4, 6 were lower than the SAV of S5, and special for subjects with normal hearing capability (HP-2), with normal sensitive or insensitive to noise (NS-2, NS-3) or with normal mental performance (GHQ-2), but for subjects who were sensitive to noise (NS-G1) the result was opposite. This tendency indicated that for most subjects their annoying feelings could decrease when WT was partly unseen or not directly faced to them or surrounded with other more natural landscapes. However, for subjects who were more sensitive to noise they might feel more annoyed due to these additional landscapes. The SAV of S7, in which there were several WTs in the video, the annoyance level for most subjects was the highest. It showed that when there were several WTs subjects would feel more annoy even they were exposed to the same WTN. The comparison between B3 and S5, which contained the same video stimulus, the SAV of signal with both visual content of WT and WTN was higher than the SAV of only visual stimulus. This result also supported the theory that the combination of visual and auditory contents of WT would enhance the overall negative feelings towards the situation with only one sensory stimulus.

The EEG data was cut into the same length as each segment (1min), and removed the eye artefacts with EEGLAB. The absolute power spectral density (PSD) values of 10 different EEG bands were obtained with the software (Neuro-Spectrum-5). Considering the individual difference of the EEG level, relative PSD (RPSD) was calculated as the index which was the ratio of PSD and the baseline PSD (B1). Table II is the details of the 10 EEG bands [19, 20].

Table II. The frequency range of EEG bands.

EEG band	Frequency range
Theta ( )	4 – 8 Hz
Theta1 (1)	3.5 – 5.4 Hz
Theta2 (2)	5.4 – 7.4 Hz
Alpha ( )	8 – 13 Hz
Alpha1 (1)	7.4 – 9.9 Hz
Alpha2 (2)	9.9 – 12.4 Hz
Beta ( )	13 – 30 Hz
Beta1 (1)	12.5 – 17.9 Hz
Beta2 (2)	18 – 23.9 Hz
Beta3 (3)	24 – 30 Hz

The correlation between SAV and the RPSD of EEG bands were calculated (Table III). Beta band especially over temporal area has been implicated in emotional phenomena [21], and the result here showed its negative correlation with SAV, which was in agreement with the conclusion that more Beta activity was present in the temporal area during positive than during negative emotional tasks [21]. The eye blink number in each stage was also been counted, but there was no significant correlation between this parameter and SAV or the RPSD of EEG bands.

Table III. The correlation between SAV and the RPSD of EEG bands (* means significant positive correlation, and -* means significant negative correlation)

		AF3	AF4	O1	O2	T3	T4	All
All		*						
						-*		
HP-G1						*		
					*			*
HP-G2		*						
		*						
						-*		
GHQ-G1								
							*	
GHQ-G2								
						-*		
NS-G1			-*					
			-*					
NS-G2								
		*			*			*
NS-G3								

The SD value of 10 EEG bands for each subject was also compared with SAV. The result showed that the SD of RPSD for Beta1 band has a significant negative correlation with SAV. So subject who got larger RPSD variation for Beta1 band, he or she got lower average SAV for all signals. As mentioned above, the subject 10 gave the same and very low SAV to all signals, and his SD result for Beta1 band was also the highest among all subjects, which was agreed with the obtained relationship result.

The comparisons among the different groups of the questionnaires showed that subjects with slight hearing problem gave higher annoyance level than the subjects with normal hearing ability, and the visual stimuli caused them more frequently eye blink. The SAV for most subjects was lower when there were other landscapes with WT in the field compared with only WT was existent, but for subjects with higher noise sensitivity score the SAV could be higher. The SAV of female subjects were higher than the male subjects. There was no significant different SAV results between two GHQ groups, but the RPSD results at Frontal and Temporal lobe were found statistically significant differences.

Most of the subjects gave positive or neutral overall opinion to WT. The negative attitude to WT appeared mainly at question B and D that a part of the subjects thought WT ugly or unnatural。 The subjects were classified into two different groups with the average result of the five specific questions, AT-G1 was the subjects with neutral attitude to WT (the result higher than 2) and AT-G2 was with more positive attitude to WT (score lower than 2). The SAV of SG2 for AT-G1 was higher than that of AT-G2, but there was no obvious regularity for SG1. The subject who gave the highest SAV also had the most negative option for WT. The influence of attitude to WT on the subjective annoyance for WTN combined with different WT videos was not significant, but there was still an evaluation trend that subjects with more positive attitude to WT would give less annoyance judgment.

The PA or NA result didn't show significant correlation with SAV, but for subjects who gave more negative self-reported personality stats and traits, there was a high possibility that they might also have slightly hearing problem or poor mental situation or either very sensitive to noise or insensitive to noise.

4. Conclusions

The visual impact of WTs combined with WTN perception was investigated and the brain reaction was observed simultaneously. There were eight signals used in the test, which contained the same WTN and visual stimuli related with WT (WT in different blade rotating speeds and WT with different landscapes). Before the test, the subjects asked several questionnaires related with hearing situation, noise sensitivity, mental performance, self-report emotion and attitude to WT. Then they gave their subjective annoyance evaluation to the signals and their brain waves were monitored with EEG equipment during the test.

The results of questionnaires, subjective annoyance evaluation and EEG were summarized and analyzed, the interactions among these three aspects were considered. The obvious SAV changes among the signals indicated that people's annoyance could increase when there were auditory and visual sensory stimuli of WT together, and it was also possible for a decrease of the annoying feelings with a diversion due to natural landscapes. The annoyance level was found a rise when there were more WTs in the field. Due to the limitation of the field video recordings of WT, the distinction of the WT blade rotating speeds in the test was not significant. Many subjects didn't perceive the different speed, which might lead to the similar SAV results of these signals. It is necessary to investigate this part with more sufficient experimental materials in the future.

The relationship between subjective annoying feelings caused by WTN combined with different WT views and the brain reaction was calculated and analyzed. The significant correlation between SAV and RPSD was found at temporal lobe for Beta band, which was agreed with previous findings that Beta power was related with emotional phenomena.

The emotional activation was found that it could produce measureable effects on the EEG, therefore, it was hypothesized that personality traits would interact with the strength [22]. The obvious different SAV and RPSD results for subjects with different hearing capability, mental performance, noise sensitivity, self-reported personality traits or gender confirmed it. In addition, subjects with more positive attitude to WT was found with lower SAV result than the others.

The noise emitted from WT has been considered as the main problem to impact people's healthy and normal life, but from the results of this test the visual aspects are found also important for the overall feelings for WT. Therefore, it should be paid more attention to the effect of the visual environments around WT to decrease its negative influence on people's normal life.

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