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Understanding stress effects of wind turbine noise – The integrated approach

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ABSTRACT

To better understand causes and effects of wind turbine (WT) noise, this study combined the methodology of stress psychology with noise measurement to an integrated approach. In this longitudinal study, residents of a wind farm in Lower Saxony were interviewed on two occasions (2012, 2014) and given the opportunity to use audio equipment to record annoying noise. On average, both the wind farm and road traffic were somewhat annoying. More residents complained about physical and psychological symptoms due to traffic noise (16%) than to WT noise (10%, two years later 7%). Noise annoyance was minimally correlated with distance to the closest WT and sound pressure level, but moderately correlated with fair planning. The acoustic analysis identified amplitude-modulated noise as a major cause of the complaints. The planning and construction process has proven to be central – it is recommended to make this process as positive as possible. It is promising to develop the research approach in order to study the psychological and acoustic causes of WT noise annoyance even more closely. To further analysis of amplitude modulation we recommend longitudinal measurements in several wind farms to increase the data base — in the sense of “Homo sapiens monitoring”.

1. Introduction

Noise problems are one of the most frequently discussed impacts of wind turbines (WT) on residents. Indeed, several studies provide empirical evidence for WT noise to be a potential source of annoyance. However, while about three dozen field studies on the noise effects of large WT (e.g., Health Canada, 2014; Michaud et al., 2016a, 2016b, 2016c, Pawlaczyk-Luszczynska et al., 2014; Pedersen et al., 2009; Pedersen and Persson-Waye, 2004, 2007; Pohl et al., 1999, 2012) and small WT (Taylor et al., 2013) indicate noise annoyance, the reported prevalence of annoyed residents is inconsistent and varies between 4.1% (Pedersen and Persson Waye, 2007) and 21.8% (Pohl and Hübner, 2012). One possible explanation for these different findings is that annoyance is not influenced solely by noise. For example, significant relations between noise levels from < 28 dB(A) to > 45 dB(A) – estimated by diffusion models – and annoyance repeatedly were found. However, the sound level explained only 12–26% of the annoyance variance (Pedersen and Persson-Waye, 2004, 2007; Pedersen et al., 2009), leaving more than 70% to be explained. Consequently, annoyance is influenced by further factors, so-called moderator variables such as visibility and financial participation. However, despite some knowledge on the moderating factors, it remains an open question under what conditions WT noise can lead to strong annoyance. Most of the mentioned studies calculated sound levels and used not local sound measurement at recipient locations, which may contribute to unexplained variance because in diffusion models local acoustical specificities were not considered.

Former studies provided valuable insight into the relation between WT noise and annoyance (e.g., Health Canada, 2014; Pawlaczyk-Luszczynska et al., 2014; Pedersen et al., 2009; Pedersen and Persson-Waye, 2004, 2007). However, they relied on a smaller range of stress indicators and moderators. Additionally, these studies remain descriptive and the indicators are not embedded in a larger stress concept. The benefit of a stress concept is to derive specific strategies for stress reduction on different stages of the stress process. Therefore, we rely on the well-established model of Lazarus (e.g., Lazarus and Cohen, 1977) enlarged by Baum et al. (1984) and Bell et al. (1990). This approach starts with the perception of a possible stressor (e.g., WT noise), followed by evaluation of the stressor (e.g., threatening), psychological and physical reactions (e.g., symptoms) and cognitive, emotional and behavioral coping (e.g., closing the window). Acoustic (e.g., sound pressure level), psychological (e.g., experiences during the planning process) and situational (e.g., distance to the nearest WT) moderators of the stress reaction were also considered.

The present study provides an interdisciplinary approach for a differentiated analysis of WT noise. This approach integrates noise

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measurement, weather and operational information connected with the WT and psychological concepts on social acceptance as well as stress psychology. To develop this integrated approach a field study was conducted involving 212 residents living in the vicinity of a wind farm in Lower Saxony, Germany. Finally, this approach offers a systematic background for recommendations regarding noise mitigation and on how to deal with WT noise.

2. Factors influencing noise annoyance by WT and stress effects

2.1. Influencing factors

Citizens and wind project operators refer to several influencing factors to explain noise annoyance. Some of these lay explanations are not mirrored by empirical evidence such as noise sensitivity, which has a rather weak impact on annoyance (e.g., Hübner and Löffler, 2013; Pedersen and Persson-Waye, 2004; Pohl et al., 2012). Socio-demographic variables such as age, gender and emotional lability, have not been proven to show significant impact (e.g., Pedersen and Larsman, 2008; Pedersen et al., 2010; Pohl et al., 2012).

A well-known moderator of noise annoyance due to WT is the visibility of WT from the property or homes of residents living nearby: on average, residents are significantly more annoyed when the WT are visible from their dwellings (e.g., Arezes et al., 2014; Pedersen et al., 2009, 2010; Pedersen and Persson Waye, 2007). This effect can be explained by the higher salience of the WT in case of visibility. In line with the explanation seems to be the finding that residents in rural and flatland regions reported higher noise annoyance than residents living in a more urban and hilly region (Pedersen and Larsman, 2008; Pedersen and Persson-Waye, 2007, 2008; Pedersen et al., 2009).

Additional relevant moderating variables that have the ability to decrease annoyance are financial participation in the wind farm (e.g., Arezes et al., 2014; Health Canada, 2014; Pohl et al., 1999; Pedersen et al., 2010), positive attitudes towards wind energy (e.g., Pawlaczyk-Luszczynska et al., 2014; Pedersen and Persson Waye, 2008; Pohl et al., 1999, 2012), and positive attitudes towards the local wind farm (e.g., Pohl et al., 1999, 2012). On the other hand, annoyance during planning and construction (e.g., Hübner and Löffler, 2013; Pohl et al., 2012) and a negative visual impact of WT on the landscape (e.g., Health Canada, 2014; Pawlaczyk-Luszczynska et al., 2014; Pedersen and Larsman, 2008; Pedersen et al., 2009) increase annoyance.

Additionally, noise annoyance is influenced by situational factors, such as weather conditions and time of day (e.g., Health Canada, 2014; Hübner and Löffler, 2013; Pawlaczyk-Luszczynska et al., 2014; Pedersen and Persson-Waye, 2004; Pedersen et al., 2009). The strongest noise annoyance occurs in the evening and night hours, especially when wind blows constantly from WT towards the dwellings or during periods of strong wind. Furthermore, residents experience higher noise annoyance outside rather than inside the home. Overall, however, the source directivity of wind turbines is still an under-researched topic especially in situations with strong amplitude modulation (AM).

In summary, moderator variables seem to better predict the annoyance caused by WT than, e.g., sound pressure level or distance to the nearest WT (e.g., Pawlaczyk-Luszczynska et al., 2014; Pedersen et al., 2009). Additionally, WT are rated more annoying than other noise sources with a similar sound level (Janssen et al., 2011; Pedersen and Persson-Waye, 2004; Pedersen et al., 2009). This finding also indicates that other factors contribute to the annoyance, such as some factors mentioned so far in combination with e.g., specific noise patterns and qualities. For example, residents felt most strongly annoyed by a noise pattern described as "swishing" (Pedersen and Persson-Waye, 2004, 2008).

2.2. Stress effects of WT noise

Sleep disturbance due to WT noise was reported in some studies (e.g., Bakker et al., 2012; Hübner and Löffler, 2013; Pedersen and Persson-Waye, 2004; Pohl et al., 1999). The proportion ranged from 6% (Bakker et al., 2012) to 11% of the residents (Pohl et al., 1999). Further symptoms caused by WT noise, such as negative mood, nervousness and irritability, occurred only to a small extent (up to 5.8% affected residents) and so far have been demonstrated in two earlier studies (Pohl et al., 1999; Wolsink et al., 1993). Further, there are only a few studies − and with heterogeneous findings − on the relationship between WT noise annoyance and disturbed work, leisure activities and alternating whereabouts (e.g., Hübner and Löffler, 2013; Pohl et al., 1999, 2012). Likewise, cognitive and behavioral coping strategies of annoyed residents have been subject only to a few studies (e.g., Hübner and Löffler, 2013; Pedersen and Persson Waye, 2007; Pohl et al., 1999, 2012). Typical reported measures include closing the windows and turning up the volume of the TV/radio.

While the aforementioned research refers to the health impacts of WT noise, other studies compare residents living near WT (≤ 2 km) with those living further away (≥ 3.3 km) in general (e. g., Nissenbaum et al., 2012; Sheperd et al., 2011). Although deteriorating health characteristics were reported for nearby residents, these studies are to be strongly criticized for their methods. They exclude the impacts of specific emissions, moderator variables or possible previous illness, and they do not control for the possible impact of additional noise sources (Nissenbaum et al., 2012; Sheperd et al., 2011).

2.3. Present research

The present research aims to provide a deeper understanding of the causes and consequences of WT noise stress effects. This knowledge is the base to derive recommendations for noise mitigation.

While existing research provides a basic understanding of the WT noise phenomenon, at least three open questions remain:

First, is there a greater proportion of residents living in the vicinity of a wind farm that is not only annoyed by noise but that also suffers from stress effects or even adverse health effects related to WT noise? To answer this question it is useful to assess possible stress effects by several indicators based on stress psychology concepts (Baum et al., 1984; Bell et al., 1990; Lazarus and Cohen, 1977). Further, it is unclear whether the proportion is stable over the time, since longitudinal studies thus far are missing.

Second, due to the chosen assessment methods, it is still uncertain whether the reported symptoms are directly attributed to WT noise or confounded by others stressors. The link is lacking in most studies. A first attempt to assess and directly link to WT noise was made in the late 1990s (Pohl et al., 1999). This study was mainly directed to analyse the stress impact of periodical shadow-casting but also included several items concerning noise.

Third, we need a deeper understanding of the conditions contributing to substantial annoyance.

Previous research results, illustrated above, suggest that physical factors (e.g., sound pressure level, sound quality, visibility of the wind farm) and psychological factors (e.g., stress during the planning phase, attitude toward wind energy) contribute to this.

Due to our aim to disentangle the responsible factors for WT noise annoyance, we used a case study approach with several psychological stress indicators and physical parameters.

3. Methods

3.1. Design

A longitudinal study design was chosen to test if WT noise annoyance is a stable phenomenon over time or can annoyance be influenced by information about causes and effects of WT noise. The design was based on the methodology of environmental and stress psychology in combination with noise measurement and audio recordings (Baum et al., 1984; Bell et al., 1990; Lazarus and Cohen, 1977). Using a standardized questionnaire, residents of one wind farm were interviewed face-to-face twice over a two-year period (March through April 2012, February through March 2014). Interviewers were trained students who visited the participants in their homes. Furthermore, they were able to submit complaint sheets over several months and audiotape any disturbing noises. In order to assess the generalizability of the results, the central findings were compared to findings of a nationwide sample, including more than 400 residents living in the vicinity of 13 wind farms (Pohl et al., 2012).

The wind farm was located in a rural, flat area in the German state of Lower Saxony. There were nine WT with a power of 2 MW and a total height of 150 m each (Enercon E-82). At the time of the first survey (2012), the time in operation was 37 months.

3.2. Participants

3.2.1. Recruitment

After information about the project was disseminated via radio and press releases, the participants were recruited through letters and phone calls, and at a community meeting. Based on address lists of authorities and public phone directories, letters were sent to 590 people. About the same number lived in an area with predicted sound pressure level of 25–30 dB(A) and in an area with 30–35 dB(A). There are no residents living in an area with levels > 35 dB(A). A few days later, those who received letters were called and asked to participate. Additionally, 45 persons were contacted on-site during the interview days, of whom 14 were partners of previously recruited single persons.

In the study, therefore, both randomly selected persons and persons who had directly contacted us were included. The latter was done to increase the acceptance of the study in the community. To proof possible self-selection bias we have assessed in the Wilstedt and the nationwide study possible moderators and tested their influence on WT noise annoyance, e.g., age, gender, health state, noise sensitivity, distance.

A total of 212 persons participated in the first survey; nearly two-thirds (133 persons) remained in the second one. Accordingly, one-third dropped out (“drop-outs”; 79 participants). It was controlled whether these dropouts represented extreme opinions, indicating a self-selection bias. Indeed, the dropouts differed statistically from the other participants only in terms of education level and household size. The remaining participants had a relatively higher education level and slightly larger household, compared to the dropouts (small effect size each). These socio-demographic variables had no significant influence on the central stress and attitude indicators; significant differences in the central attitude and annoyance assessments did not appear. Accordingly, analysing longitudinal effects with the remaining sample size of the second measurement time is reliable and does not lead to misinterpretation.

3.2.2. Sample characteristics

The respondents’ age ranged from 19 to 88 years, averaging 55 years (SD = 13.19). Slightly more men than women participated (47.6% women, 52.4% men). A completed junior high school qualification was held by 34.3%, 42.9% held university entrance qualifications. The majority owned property, and was married and had children. On average, the participants lived in a three-person household and lived in their community for about two decades. More than half were pensioners or had been exempted from work, one-fifth each being public servant or self-employed. Two-fifths of respondents worked at home. Only a minority of 3.8% benefited financially from the local WT, and no participant was employed by the WT industry. Participants lived an average of 1.90 km to the closest WT (SD = .37, range 1.25—2.89 km). From their homes they saw an average of nearly four WT (M = 3.93, SD = 3.35).

3.2.3. Non-response analysis

104 residents contacted via phone call refused to participate in the survey but answered four short items. More of the non-respondents were women (60.6%) than men (39.4%), and less of them had a view of the WT compared to respondents (61.5% vs. 81.6%). Both groups rather strongly approved of wind farms in general (M > 3 each) but differed in their judgment of the local wind farm: On average, respondents approved of the local WT less (M = .98, SD = 2.14) than the non-respondents (M = 1.51, SD = 1.78, small effect size). Additionally, respondents felt more annoyed by WT noise than non-respondents (M = 1.57, SD = 1.28 versus M = .43, SD = .83, large effect size). This result indicates that residents were more likely to participate when they felt more negatively affected by the local wind farm.

3.3. Questionnaires, stress indicators and moderators

The survey questionnaire included 450 items adopted from previous studies on stress effects of WT emissions (Pohl et al., 1999, 2012). Four residents – two annoyed and two not – gave feedback on a draft version concerning whether it covered their experiences and concerns properly. Based to their statements we revised the questionnaire. The complaint sheet included 25 items self-rating to describe actual noise annoyance. Complaint sheets were offered to each respondent.

3.3.1. Several stress indicators were assessed

a) The general impact of the wind farm was assessed by five items (e.g., "I feel disturbed by the wind farm" or "I experience physical complaints due to the wind farm") on a 5-point scale ranging from “not at all (0)” to “very (4)”.
b) For a general evaluation of WT noise, a semantic differential with four pairs of adjectives was used. The scale ranged from −3 (e.g., „very unpleasant“) to +3 (e.g., „very pleasant“).
c) To assess the overall noise annoyance, participants were asked to rate their noise experience on a unipolar rating scale ranging from 0 ("not at all") to 4 ("very"). In addition, the ICBEN-scale Q. V. ranging from 0 ("not at all") to 4 ("extremely") as well as the ICBEN-scale Q. N. for noise annoyance in the past 12 months (ranging from 0 to 10) were used (Felscher-Suhr et al., 2000; Fields et al., 2001).
d) To indicate temporal changes of the experienced noise annoyance since the wind farm construction a 3-point bipolar scale ranging from −1 („decreasing “) to +1 („increasing “) was applied.
e) To analyse typical situations with WT noise annoyance, participants were asked to provide a description of the noise pattern (nine items; e.g., "rush" or “swishing”), their frequency, the extent of noise annoyance, the day time, weather conditions, impaired activity, arisen emotions, etc.
f) In addition to WT noise, respondents were asked to evaluate other wind farm emissions (12 items; e.g., periodical shadow-casting, aircraft obstruction markings, landscape change) and other local annoyance sources (14 items; e.g., traffic noise, noise from maize choppers), each on a unipolar rating scale ranging from 0 ("not at all") to 4 ("very").
g) A number of 39 psychological and somatic symptoms as well as distractions linked to WT noise were assessed. Symptoms belonged to the domains (a) general performance, e.g., fatigue, concentration, (b) emotions and mood, (c) somatic complaints, e.g., dizziness, nausea, (d) pain, (e) cardiovascular system, and (f) sleep. Additionally, the frequency of the respective complaints was rated, ranging from 0 ("never") to 4 ("about every day"). In the follow-up survey, the same symptoms due to traffic noise were assessed in order to compare the impact of both noise sources.
h) As indicators for low frequency noise, participants were asked to report annoyance due to feelings of pressure and vibrations related to the WT on a unipolar rating scale ranging from 0 ("not at all") to 4 ("very").

i) Cognitive and behavioral coping responses were assessed. Five items indicated four cognitive strategies (unipolar rating scale, from 0 ("not at all") to 4 ("very")), such as trivializing or accepting. Based on 24 items, participants reported if and which behavioral strategies they applied to reduce the annoyance impact, e.g., changing rooms, closing windows or complaints to authorities.

3.3.2. In addition to the stress indicators, several moderators were assessed

a) Physical features: number of visible WT, distance to the nearest wind farm, calculated A-weighted Leq-sound pressure level according to ISO 9613 (1993). The distance was determined using the WT's geographical coordinates, residents' mailing addresses, and Google Earth™.
b) Past passivity or activities either in favor or against the wind farm.
c) Evaluation of the planning and construction phase: Participants were asked about stress and fairness of these processes on eight unipolar rating scales ranging from 0 ("not at all") to 4 ("very").
d) General attitude towards the local wind farm and WT were assessed by two semantic differentials with six pairs of adjectives; each on a bipolar scale ranging from −3 (e.g., „very bad“) to +3 (e.g., „very good“). The two means over the items were used as attitude indicators (Cronbach's alpha .95 and .88). Additionally, residents were asked if they financially participated in the local wind farm and if they are working in the wind energy business.
e) Health indicators: The general health state was rated on a unipolar scale ranging from 0 ("bad“) to 4 ("excellent"). For the assessment of noise sensitivity the mean of six items inspired by Zimmer and Ellermeier (1997, 1998) were used. Emotional lability was evaluated by a six item test of Trautwein (2004).

3.3.3. Complaint sheet, audio recordings, emission and immission measures

Participants were instructed to fill out the complaint sheet in case of WT noise annoyance (25 items), including items to measure annoyance, noise pattern, disturbed activities, symptoms and weather conditions. Residents also could borrow an audio recorder in order to record annoying noises induced by WT. The audio recordings were evaluated by experienced specialists from DEWI and correlated with operating data from the wind farms (e.g., wind direction, wind speed at hub height and at 10 m height, rotor speed). In the period from March 2012 to January 2013 a total of 98 complaint sheets were filled in by 11 participants, two of whom made a total of 28 evaluable audio recordings. In addition, DEWI performed emission measurements according to IEC 61400-11 Ed. 2.1 and immission measurement on the property of a strongly annoyed resident.

3.4. Statistical analyses

To analyse group differences in the case of interval-scaled variables, descriptive statistical values were used such as the arithmetical mean (M), empirical standard deviation (SD), and standard error of mean (SEM). In the case of nominal-scaled variables, absolute and relative frequencies (%-values) were reported. Pearson-correlations were calculated to identify moderator variables – only coefficients equal to or greater than .30 were regarded as relevant (medium effect size according to Cohen (1988)).

Chi^2-tests were used for inferential analysis of frequency distributions. To analyse mean group differences, analysis of variance (ANOVA) with repeated measurement was conducted. Least significant difference *t*-tests (LSD) were used for post hoc comparisons for ANOVA's means. A priori planned mean comparisons of two groups were analysed by *t*-tests.

Data analysis and description followed the principles of Abt's (1987) “Descriptive Data Analysis.” Correspondingly, reported p-values (p) of the two-tailed significance tests only possess a descriptive function labelling the extent of group differences. Despite the multiplicity of significance tests, no alpha-adjustment was conducted, since the present analysis was not a confirmatory data analysis. P-values ≤ .05 were described as significant; p-values greater than .05 and less than .10 described as a trend. Additionally, the effect size parameters, d, and w were used to report practical significance (Cohen, 1988). The effect size categories (small, medium, large) mentioned in the results section always refer to significant group differences. Effect sizes d and w were calculated by Excel procedures. The statistical software SPSS was used for any other analysis.

4. Results

4.1. WT noise annoyance

Of all participants 69.3% perceived WT noise and 30.7% did not; 18.4% of total sample were not annoyed at all by WT noise (scale-point 0), 16.0% were slightly annoyed (scale-point 1), 17.9% were somewhat annoyed (scale-point 2), 10.9% were moderately annoyed (scale-point 3) and 6.1% very annoyed (scale-point 4). According to the scale criteria of Miedema and Vos (1998), 34.9% of all participants were annoyed (scale-points 2–4). However, from a stress psychological perspective, the possible appearance of symptoms should be considered as an additional criterion for strong annoyance. Therefore, we define participants with no symptoms and scale values 2–4 as “somewhat annoyed” (25.0%). If additionally, at least one symptom linked to WT noise occurred the participant was indicated as “strongly annoyed” (9.9%).

For the total sample in 2012, the average WT noise annoyance was between the levels “slightly” and “somewhat” (M = 1.58, SD = 1.28), mean score on the ICBEN-scale Q. V. was at the level “slightly” (M = 1.23, SD = 1.14) and on the ICBEN-scale Q. N. at the lower end at 3.26 (SD = 2.67). The group of strongly annoyed participants had slightly higher mean values than those of the somewhat annoyed (medium and large effect size). Since the three annoyance scales were strongly correlated (.84 to .91), only the values of the WT noise annoyance scale will be reported in the following. Until 2012, the participants on average had not observed any change of annoyance over the years of operation of the wind farm (M = .02, SD = .41). Between 2012 and 2014 there was a marginal perceived change. Only the somewhat annoyed participants experienced a slight decrease in annoyance (large effect size, Fig. 1).

4.2. WT noise annoyance in comparison to other local noise sources

For participants perceiving WT noise the wind farm was as annoying as local road traffic noise, maize choppers, and sand trucks, but marginally less annoying than balloon-wheel trucks (small effect size, Fig. 2). The annoyance caused by WT and sand trucks decreased marginally from 2012 to 2014 (small effect sizes) but not for road traffic noise and other sources.

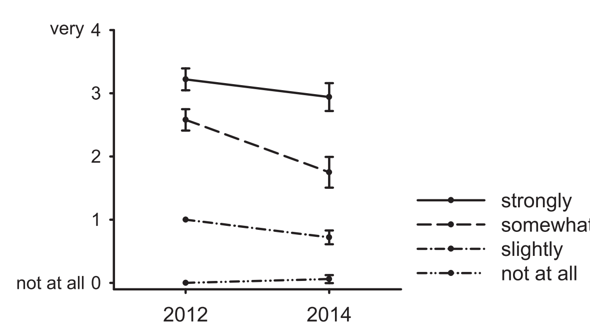

Fig. 1. Change of WT noise annoyance decrease for somewhat group only (M ± SEM, scale range: 0–4).

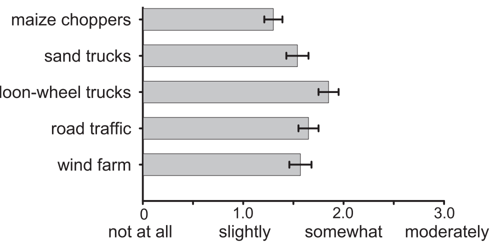

Fig. 2. WT noise annoyance lower compared to balloon-wheel trucks (2012, M ± SEM, scale range: 0–4).

4.3. Typical WT noise situation

About half of all participants (51.9%) reported in 2012 at least one typical annoying situation caused by WT noise. About half (53.6%) of this sub-sample experienced annoying noise about once a week, one-fifth (20.9%) about once a month, and 13.6% almost daily. Annoying noise occurred most frequently in the evening (33.6%) and at night (18.2%). This sub-sample felt most frequently disturbed while sleeping (30.0%), relaxation (24.5%) and leisure activities (19.1%). Most frequent emotional reactions were irritability or anger (39.1%). More than 10% of the sub-sample described WT noise as swooshing (76.4%), rumbling (72.7%), buzzing (23.6%) or grumbling (18.2%). Most frequently, the annoyance occurred during westerly winds (68.2%) – the local main wind direction – as well as during humid weather (30.9%) and frost (13.6%). The number of participants who reported a typical WT noise situation decreased clearly from 2012 to 2014 by about 22–29.3%. The pattern of noise effects remained comparable.

4.4. General impact of WT noise

In 2012, the somewhat and strongly annoyed residents assessed WT noise clearly to be more negative than the other groups (Fig. 3, medium or large effect sizes). Furthermore, the strongly annoyed participants rated WT noise more "threatening", "harmful" and "intolerable" than the somewhat annoyed residents (medium effect sizes). Significant changes over time were only detected for the group without annoyance, which rated WT noise in 2014 slightly less peaceful and harmless than in 2012 (medium effect sizes).

4.5. Psychological and somatic symptoms

As mentioned above, only a few participants reported (9.9%) psychological or physical symptoms that they attributed to WT noise and which they experienced at least once a month (Table 1). In 2014, this

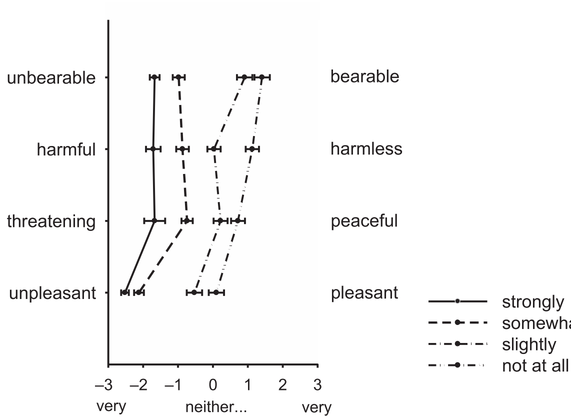

Fig. 3. WT noise impact most negative for strongly annoyed group (2012, M ± SEM, scale range: −3 – +3).

Table 1
Percentage of symptoms caused by WT noise or traffic noise at least once a month.

Symptoms	WT noise 2012	WT noise 2014	traffic noise 2014
general mental indisposition	5.7%	0%	6.0%
reduced performance and work capacity	5.2%	0%	3.0%
fatigue	5.2%	0%	4.5%
lack of concentration, reduced sustained attention	4.7%	0%	3.8%
nervousness	4.2%	0%	4.5%
tenseness	5.3%	2.3%	6.8%
negative mood	6.6%	0%	7.5%
helplessness	4.2%	3.8%	6.0%
irritability, anger, hostility	5.7%	3.0%	7.5%
general somatic indisposition	5.3%	0%	.8%
hindered falling asleep	6.7%	3.0%	3.8%
multiple awakening	4.7%	1.5%	5.3%
reduced sleep quality	6.1%	2.3%	6.0%
reduced depth of sleep	5.7%	1.5%	4.5%
overall symptom carriers	9.9%	6.8%	15.8%

proportion decreased to 6.8%. With an average of 12 symptoms, these participants clearly reported more symptoms in 2012 (M = 12.33, SD = 8.03) than in 2014 (M = 3.00, SD = 1.94, large effect size). Furthermore, strongly annoyed participants rated their general health slightly better in 2014 (2012: M = 2.00, SD = .71; 2014: M = 2.59, SD = 1.06; medium effect size). The symptoms were related to general performance, emotion, mood and sleep. From 2012 to 2014, sleep disturbance decreased, and symptoms of impaired performance did not recur. Strongly annoyed participants were not affected more by acute or chronic diseases than the other groups.

Distraction due to noise can lead to stress experience. The strongly annoyed residents in 2012 felt somewhat distracted by WT noise (M = 1.88, SD = 1.01), clearly stronger than any other group (large effect sizes). For this group the distraction decreased slightly from 2012 to 2014 (medium effect size, Fig. 4), while it remained relatively low and unchanged in the other groups.

Only a few participants showed evidence for low-frequency WT noise effects (< 100 Hz): in 2012, 8.5% reported wind farm-related feelings of pressure and 6.1% experienced vibrations in the body. Over time, these proportions decreased to 6.8% and 3.8%, respectively. The experienced annoyance induced by pressure feelings or vibrations was somewhat (2012: M = 2.17, SD = .86; M = 1.85, SD = 1.07 respectively; 2014: M = 2.00, SD = 1.12; M = 2.40, SD = 1.52 respectively). The symptom "dizziness" was not observed. Therefore, no indicator for a negative vegetative effect of low-frequency noise could be detected (Krahé et al., 2014).

In order to evaluate stress effects appropriately, WT noise was compared with traffic noise. More participants experienced symptoms induced by traffic noise (15.8% of total sample) than WT noise; in 2014 only three participants reported complaints induced by both sources. In

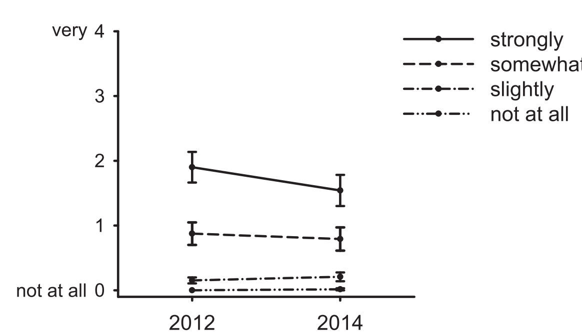

Fig. 4. Decrease of distraction induced by WT noise in the strongly annoyed group (M ± SEM, scale range: 0–4).

Fig. 5. Inefficient coping strategies in the strongly annoyed group (2012, M ± SEM, scale range: 0–4).

2014 about one-third (34.9%) of all participants was somewhat annoyed by traffic noise and 21.2% by WT noise. The pattern of symptoms for WT noise (2012) and traffic noise (2014) is very similar (Table 1).

4.6. Coping responses

Somewhat and strongly annoyed residents reported only little acceptance ("made peace", "all that bad") of WT noise in 2012 and observed it more critically than the other groups (Fig. 5, small to large effect sizes). Compared to the other groups, the somewhat annoyed participants showed a stronger emotional reassurance (i.e., had "stopped getting excited"; small to large effect sizes), which slightly increased from 2012 to 2014 (small or medium effect sizes). In contrast, cognitive coping for the strongly annoyed participants remained relatively stable. Thoughts of moving due to WT noise were only weak, even among the strongly annoyed residents (M = .81, SD = 1.25).

The most commonly used measures to reduce noise effects in 2012 were conversations with family members, friends and neighbors (32.1% of all participants), closing windows (25.9%), place leaving inside and outside the house(11.8%, 7.1%), and turning up the volume of the radio/TV (7.5%). In the groups of the somewhat and strongly annoyed participants, relatively more residents participated in conversations and closed their windows relatively more often (large effect sizes). Other measures taken were collecting signatures (13.7%) and demonstrating (9.4%), gathering information on WT noise (9.9%), and engaging in an environmental group/citizens' action committee (6.1%).

4.7. Analysis of complaint sheets and audio recordings

Ninety-five complaint sheets from 11 residents were included in the analysis, as well as 28 evaluable sound recordings from two participants. Almost all the records were made at night. WT operating data and measurements of wind speed and wind direction at hub height as well as at 10 m above ground level were included in the analysis. For the full report of this part of the project, see DEWI RS14-00017-01 (Gabriel and Vogl, 2014). Most of the complaints occurred during a southwesterly wind, which is the main wind direction, and at wind speeds at hub height of 6–9 m/s. There was a slight tendency to annoyance when the wind blew from the direction of the wind farm (downwind). The complaints occurred mainly during the night and early morning hours (83%), accumulating in the period from midnight to 3 a.m. The large number of nocturnal complaints can be explained by low background noise at nighttime, because Wilstedt is located far from any main road. Therefore, there is almost no nighttime traffic noise masking the relatively low level of sound from the WT.

Regarding the performed sound analyses, neither loudness of the broadband acoustic noise from the WT nor tonality or impulsivity is responsible for the documented complaints. Annoying WT noise has been characterized as predominantly irregular and fluctuating in loudness (71.6% pulsating swooshing). Thus – as opposed to national noise immission control regulation – it is not an absolute value of loudness, but the variation of loudness with the frequency of the rotating rotor blades, that primarily causes complaints. The perceived changes of sound are directly associated with the rotating blades. This noise characteristic is called amplitude modulation (AM). Special algorithms developed by DEWI (Vogl, 2013) were used to quantify AM in the sound recordings of perceived annoying WT noise. Examples are shown in Figs. 6 and 7 with AM for minutes or sporadic AM lasting a few seconds (typically < 10 s). This method of analysis is described in detail in report DEWI RS14-00017-01 (Gabriel and Vogl, 2014). The first algorithm calculated the physical modulation depth ΔL in dB after A-filtering. This measure is defined as the difference between the maximum and the following minimum of the sound pressure level (lower line). The second algorithm calculates the level of the pure psychoacoustic loudness variation F* (upper line) which is very similar to the fluctuation strength F developed by Zwicker and Fastl (1999).

The highest modulation depth ΔL was found in the frequency range 160–200 Hz, at wind speeds at hub height between 6 to 9.5 m/s, and WT rotational speed in the range of 14–18 U/min (average 16.2 U/min). Therefore, it can be concluded that maximum modulation occurred just below nominal rotational speed of the WT. A significant correlation of AM and wind direction could not be detected. The highest ΔL and F* values were found during nighttime.

AM can be used to explain the annoyance of WT noise (Fig. 7). We get used to regular stimuli and do not pay attention to them. New, unexpected and irregular stimuli attract attention. They trigger an orientation reaction and an alarm reaction in the case of a danger signal. The attention is directed unconsciously to such signals. This process can lead to a distraction of actions that are taking place.

4.8. General attitude towards WT and the local wind farm

In 2012 respondents reported on average a positive general attitude towards WT (M = 1.51, SD = 1.02) which remained positive with increasing annoyance level. The somewhat (M = 1.00, SD = 1.02) and strongly annoyed participants (M = .44, SD = .94) differed clearly from each other and the other three groups (medium and large effect sizes). For the somewhat annoyed residents, the attitude was marginally more positive in 2014 compared to 2012 (small effect size). No significant change was detected for the other groups. Participants reported strong involvement for the topic of wind energy (M = 3.09, SD = .78) – without significant differences between strongly annoyed (M = 3.22, SD = .76) and non-annoyed residents (M = 3.34, SD = .66).

Also regarding the local wind farm, participants reported on average a positive general attitude in 2012 (M = .73, SD = 1.64). Accordingly, attitudes towards wind energy and the local wind farm were highly

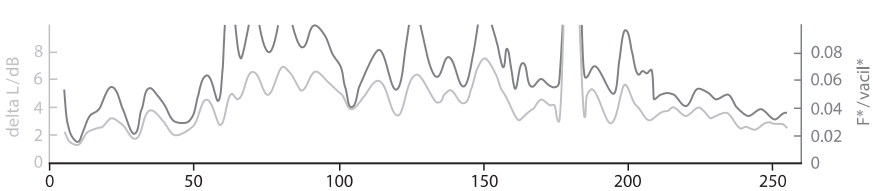

Fig. 6. Example for AM with strong modulation for minutes.

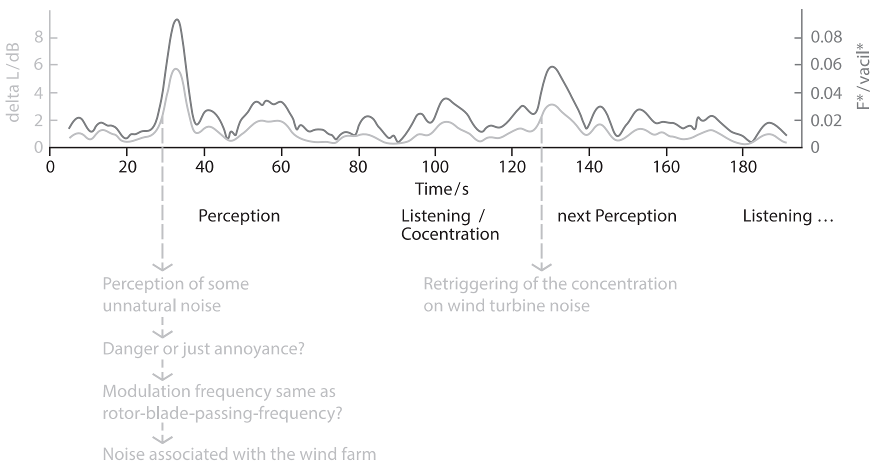

Fig. 7. Example for AM with short time perceptible modulation (upper part) and a description of the perception process of WT AM (lower part).

correlated (r = .83). In contrast, the somewhat and strongly annoyed residents showed a slightly negative attitude towards the local wind farm (M = −.60, SD = 1.42; M = −1.12, SD = 1.13 respectively) and differed clearly from each other and from the other three groups (small or large effect sizes).

Additionally, the participants were explicitly asked whether they had been wind farm opponents or proponents. Proponents (40.2%) were slightly more often represented than opponents (35.8%). Only a minority of 16.7% was ambivalent; 7.4% had no opinion on the wind farm. A further subdivision by active versus passive showed that opponents were more often active than the proponents: 30.4% of respondents indeed had been in favor of the wind farm but remained passive, and only a small proportion turned to be active (9.8%). Conversely, 26.5% had been active opponents and only 9.3% remained passive. It is noticeable that the majority of strongly annoyed residents (75.0%) had been passively or actively against the wind farm, whereas only 34.2% of the other participants showed active or passive behavior against the wind farm (small effect size).

4.9. Moderators

The analysis of relations between physical features and WT noise annoyance showed only small correlations for “distance to the closest WT“ (r = –.13) and “calculated A-weighted sound pressure level (SPL)” according to ISO 9613-2 (1993, r = .27). The SPL was on average 29.29 dB(A) (SD = 2.58, minimum = 10.23, maximum = 36.40). The correlation with “number of visible WT” was slightly stronger (r = .40).

There was a moderately negative relation between general attitude towards the local wind farm and WT noise annoyance (r = –.71). Further relevant correlations were found between “strain during the planning phase” (r = .37), “strain during the construction phase” (r = .34), “planning has been fair concerning one's own interests“ (r = –.52), “planning has been fair concerning community's interests” (r = –.52) and WT noise annoyance.

There were only small correlations between health indicators and WT noise annoyance (general health state, r = –.12; noise sensitivity, r = .26; emotional lability, r = .05), age (r = .20), and occupancy (r = .08). Women reported slightly stronger WT noise annoyance than men (M = 1.80, SD = 1.27 versus M = 1.36, SD = 1.25, small effect size).

4.10. Wilstedt sample in comparison with nationwide sample of residents of 13 wind farms

Overall, both groups rated the level of annoyance of the different WT emissions as very low to somewhat (Fig. 8). Concerning WT noise annoyance, the two groups did not differ significantly. Compared to the nationwide sample (Pohl et al., 2012), the Wilstedt sample reported

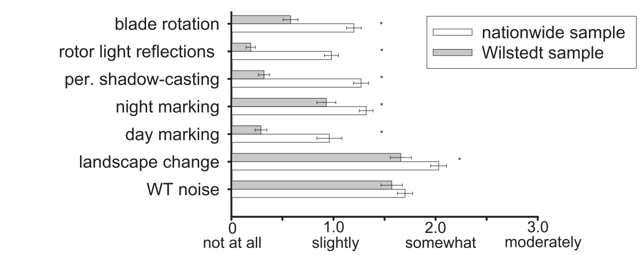

Fig. 8. Annoyance due to WT emissions comparing a nationwide and case sample (M ± SEM, scale range: 0–4, * $p < .05$).

significantly less annoyance due to landscape change, day and night obstruction marking, periodical shadow- casting, rotor light reflections and blade rotation (small and medium effect sizes). For both samples no statistically significant correlations were found between annoyance induced by different emissions and the distance to the nearest WT (all r < absolute value .25).

The general attitude towards the local wind farm was rated slightly positive in both groups without significant difference (Wilstedt sample: M = .43, SD = 1.67; nationwide sample: M= .30, SD = 1.92).

The general attitude towards WT was clearly positive in both groups. In the Wilstedt sample (M = 1.95, SD = .95) the attitude was slightly more positive than the comparison group (M = 1.43, SD = 1.61, small effect size). For the nationwide sample there was a strong correlation between the general attitude towards wind energy and the local wind farm (r = .78).

The gender distribution was comparable in both surveys. On average, respondents of the comparison group were four years younger than respondents of the Wilstedt sample. This difference, however, is too small to invalidate the interpretation of group differences in the mentioned features.

In conclusion, the comparison between both samples indicates Wilstedt to be a typical sample regarding WT noise annoyance. Therefore, the results regarding WT noise annoyance can be generalized. The other WT emission sources were rated more positively in the Wilstedt sample than in the nationwide sample. Therefore, the Wilstedt results for those other sources should not be generalized.

5. Discussion and recommendations

The present study is the first to extensively and differentially analyse the impact of WT noise on the experience and behavior of wind farm residents using an inter- and transdisciplinary approach. We have included a systematic approach to analyse stress effects in combination with noise audio recordings by residents and calculated sound pressure levels. It is also the first study to explore possible stress effects due to WT noise over the course of two years.

Only for a small percentage of all residents could strong WT noise annoyance be observed, which even decreased over time: in 2012 one-tenth (9.9%) was strongly annoyed, and two years later, this was true for only 6.8% of the residents. However, the WT were by no means the most potent local noise source – local traffic noise was strongly annoying for 15.8% of all participants. Residents belonging to one of the groups of strongly annoyed participants not only felt at least somewhat annoyed but also reported stress symptoms. Both noise sources – WT and traffic – led to a similar pattern of symptoms that is typical of noise effects (reduction in performance, concentration, and the incidence of irritability/anger, negative mood and disturbed sleep; Stansfeld and Matheson, 2003; Stansfeld et al., 2012). A similar pattern has already been shown in a previous study (Pohl et al., 1999). Regarding disturbed sleep, a comparable percentage (4–6%) was found in the large Dutch study by Bakker and colleagues – in this study they also found a very similar percentage of symptom-carriers due to traffic and engine noise (15%; Bakker et al., 2012). The similar results give a hint that the results could be generalize. Furthermore, the percentage of strongly WT noise-annoyed participants in Wilstedt is between the percentage of strongly annoyed residents in Switzerland (4.5%; Hübner and Löffler, 2013) and in the German state Schleswig-Holstein (15.7%; Pohl et al., 1999). The higher percentage of the Schleswig-Holstein sample is likely due to the older design of the WT and the differences regarding official directives – here the directives regarding the limitation of periodically shadow-casting of WT which was put into effect, taking into account the results of the study. The present results not being a special case is additionally proven by the comparison the Wilstedt-sample with a nationwide German sample of residents of 13 wind farms (Pohl et al., 2012). Thus, the present results suggest a generalization. The results of both studies were not distorted by extreme opinions (e.g., the general attitude towards the local wind farm or annoyance ratings). WT noise annoyance was not significantly correlated to age, general health state, emotional lability, and noise sensitivity. Overall, we concluded that our results are not influenced by a strong self-selection bias.

To better understand why some residents feel more annoyed by emissions of WT than others, we divided the participants into subgroups regarding noise perception and the level of annoyance. Compared to other groups, the strongly annoyed residents showed the strongest stress effects due to WT noise and an overall more negative evaluation of the wind farm. It can be assumed that stress began during the planning phase of the wind farm and was maintained throughout. This assumption is supported by the findings that this group had perceived a stronger annoyance due to the planning, approval and construction phase of the wind farm. Furthermore, 75% of the strongly annoyed residents reported to be actively or passively against the wind farm in the past. They showed comparatively less positive cognitive coping in terms of WT noise. As part of a stress management training, positive cognitive coping could be supported, as existing approaches show (Leventhall et al., 2008, 2012). However, the affected residents in our study responded with limited interest to such a remedial offer. Rather, a positive implementation of the planning and construction phase is more urgently recommended. There are positive experiences with early and informal resident participation (Devine-Wright, 2011; Rand and Hoen, 2017; Rau et al., 2012).

Even informal participation cannot guarantee that residents will experienced the planning process positively. Without serious resident participation, however, additional problems are more likely. For, as proven by the present results, the majority of the residents showed a positive attitude towards WT on the condition that their concerns are taken seriously. An often recurring concern by residents is the noise impact of WT. The present study was a response to the residents' complaints in Wilstedt. Their implementation and results are likely to have contributed to a decline in annoyance. Only little change in the evaluation of the wind farm was observed from 2012 to 2014. For the somewhat annoyed residents, noise annoyance decreased slightly and cognitive coping improved. For the strongly annoyed participants there was a reduction in WT noise-related distraction. The reduction of residents with noise related symptoms from 10% to 7%, and the decrease in the average number of symptoms from 12 to 3, can be interpreted as a significant change. We attribute the positive change – even after talking to some complainants – to the residents' positive evaluation of the study and the chosen approach and to the residents' active support and involvement.

For instance, the disturbing noises were independently recorded by residents and later analysed by us. Residents were informed about preliminary results (community meeting, letter with presentation of results). Additionally, plausible explanations for WT noise annoyance were offered and discussed in the plenum (e.g., AM). The aforementioned participation regarding the research process may have contributed to the positive changes. For the reported results reduced uncertainties and possible alternating interpretations of the findings and thus somewhat indirectly decreased WT noise annoyance. To our knowledge it is the first known field experiment showing that empirical information helps residents to reduce stress induced by WT noise.

This study does not provide any empirical evidence for the repeatedly asserted relationship between annoyance or acceptance of WT and distance to the residence. There is no numerically strong relationship between noise annoyance and the distance to the nearest WT or the estimated sound pressure level. Additionally, studies by Pohl et al., (1999, 2012) and Hübner and Löffler (2013) proved WT noise annoyance to be independent from the distance ($r = .03$; $-.07$; $-.10$), suggesting the existing emission protection laws are effective in general. For example, the German emission protection law determines the limits for permissible sound levels, which, among other features, determines the minimum distance.

However, an important indicator regarding the analysis of the causes was provided by the acoustic analysis of the disturbing WT noise, which has been recorded by the residents. A cause for the WT noise annoyance might be the amplitude modulation (AM), which explains the origin of certain annoying noise patterns. One explanation why AM cause annoyance is, that short-term amplitude changes may attract the residents' attention and thus disturbs current behavior. Research should be deepened in order to better understand the mechanism of action and develop technical solutions.

It became clear that there is detectable disturbing noise associated with the AM (from an acoustic point of view), but not with infrasound. Today, the data base of freely available AM data is very small (e.g., Cand et al., 2013). Further studies on AM of WT noise should broaden the database. For this, a long-term monitoring station needs to be developed that continuously records WT noise and residents' complaints.

Parallel to the sound detection, wind farm operating data and the wind speed profile (LIDAR) should be recorded in high solution, in order to improve understanding of the mechanisms of AM and check for possible dependency of the AM from the wind profile. Another interesting aspect is the overall interaction of WT in a wind farm with sporadic short modulation periods. For instance it is unknown whether AM is supported by the turbulent wake or the interaction of several WT. From the synopsis of meteorology data and WT operating data as well as sound data, knowledge regarding the causes of AM and their possible mitigation strategies can be derived.

For the development of noise mitigation strategies, the measurability of AM with an appropriate assessment tool is a necessary condition. The used algorithm must be improved because e.g., currently only the sinusoidal modulation is considered (for other methods proposed see e.g., Amplitude Modulation Working Group, 2016; Fukushima et al., 2013; Tachibana et al., 2014). To validate the evaluation of non-sinusoidal modulations and other tool modifications (in order to provide an AM-evaluation standard), hearing tests should be performed.

Overall, it appears promising to further develop the research approach used to understand in a more differentiated manner the psychological and acoustic causes and their interaction in the development and maintenance of WT noise annoyance. The present study provides insight into the mechanisms causing noise annoyance. However, replication studies are needed to further explore why some residents are strongly annoyed by WT noise and others are not, especially in comparison to traffic noise. Furthermore, the long-term effects are to be probed, e.g., whether or not and under what conditions habituation or sensitization occurs. To explore the influence of WT noise on sleep the method of ambulatory sleep monitoring would be useful. In this respect, first steps were made in the Health Canada study (2014) and in a study by Jalali et al. (2016). Both field studies did not find any relation between objective sleep parameters and WT noise exposure. Additionally it would be possible to supplement the research by including seismological studies in order to explore the transmission of low-frequency noise (< 100 Hz) through soil layers. Although no evidence of symptoms that would indicate low-frequency noise were reported by the participants, in order to address the concerns of WT opponents, low-frequency noise measurements are recommended for further studies. Overall the installation of a long-term monitoring station for WT noise as well as further studies on the effects on local residents (in the meaning of "Homo sapiens monitoring") seem to be advisable. Homo sapiens monitoring is not recommended by the authors only but encouraged by the local residents.

Finally, it should be noted that strongly annoyed residents and explanations for the causes of their annoyance could be identified by means of the presented research paradigm. This approach complements the previous, rather epidemiological research on this subject (e.g., Pedersen and Persson Waye, 2004; Pedersen et al., 2009).

The most important and immediately realizable recommendation is to make the planning and construction process more of a positive experience for the residents. Thereby operators and authorities can preventatively reduce the likelihood of complaints after construction of the wind farm. Creating a more positive planning process includes the early and informal participation of residents and the consideration of their concerns. Although more residents seem to be strongly annoyed by traffic noise than by WT noise, a further improvement of WT technology is desirable. After all, the present study shows that citizens are not only in favor of wind energy in general but also support local installations, as long as they are developed sustainably.

Most important, the present results shows that noise annoyance can be reduced by providing empirical information to the residents.

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