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Monitoring annoyance and stress effects of wind turbines on nearby residents: A comparison of U.S. and European samples

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A R T I C L E I N F O

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A B S T R A C T

As wind turbines and the number of wind projects scale throughout the world, a growing number of individuals might be affected by these structures. For some people, wind turbine sounds and their effects on the landscape can be annoying and could even prompt stress reactions. This comparative study analyzed a combined sample of survey respondents from the U.S., Germany and Switzerland. It utilized a newly developed assessment scale (AS-Scale) to reliably characterize these stress-impacted individuals living within populations near turbines. Findings indicate low prevalence of annoyance, stress symptoms and coping strategies. Noise annoyance stress (NAS-Scale) was negatively correlated with the perceptions of a lack of fairness of the wind project's planning and development process, among other subjective variables. Objective indicators, such as the distance from the nearest turbine and sound pressure level modeled for each respondent, were not found to be correlated to noise annoyance. Similar result patterns were found across the European and U.S. samples.

1. Introduction

Wind turbines (WT) change the landscape, generate noise and can cause shadow-flicker. Additionally, most WT also have lighting in the form of aircraft obstruction markings. These emissions have impacts on people living nearby (e.g., Michaud et al., 2016a, 2016b, 2016c; Pedersen et al., 2009; Poulsen et al., 2018a, 2018b; Pohl et al., 1999, 2012, 2018; Rudolph et al., 2017). To analyze and monitor WT impacts, reliable and valid indicators are required. Well-proven stress concepts (Lazarus and Cohen, 1977) provide a framework for understanding the impact of WT on the experiences and behaviors of nearby residents and the opportunity to derive reliable indicators for ambient stressors (Baum et al., 1984; Bell et al., 1990). Based on these stress concepts and the previous studies on WT stress effects the present paper presents a sophisticated monitoring approach which combines the predominant single annoyance ratings with stress symptoms.

The process of developing stress begins with the perception of possible stressors (e.g., WT noise as an ambient stressor), followed by the evaluation of those stressors (e.g., they are annoying), then psychological and physical reactions to or symptoms due to those stressors, and finally ends with cognitive, emotional and behavioral coping strategies to mitigate those stressors (e.g., closing windows to shut out noise). Crucial indicators for higher stress levels are the last two stages: symptoms and coping behavior. Therefore, evaluation of the stressors – as more or less annoying – tackles the possible stress levels only partly. However, to date, the predominant WT impact indicator relied upon has been annoyance, while symptoms have been analyzed separately. Indeed, symptoms of WT noise have been studied. These studies revealed a pattern of stress symptoms due to WT noise including sleep disturbance, irritability, negative mood and a lack of concentration (e.g., Bakker et al., 2012; Hübner and Löffler, 2013; Pedersen and Persson Waye, 2004; Pohl et al., 2018).

The key indicator, however, relied upon was annoyance evaluation. For example, to analyze the impact of WT noise Pedersen and Persson Waye (2007) used a 5-point single item annoyance scale: “do not notice (1)”; “notice but not annoyed (2)”; “slightly (3)”; “rather (4)”; and “very annoyed (5)”, collapsed 1–3 into “not annoyed” and then combine 4–5 into “annoyed”. Similarly, following ISO/TS (International

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Organization for Standardization, 2003), Michaud et al. (2016a) collapse their 6-point single item scale into two groups: being "not highly annoyed" (from "do not hear WT" to "moderately annoyed") and "highly annoyed" ("very" or "extremely annoyed"). Regardless of how the scale is collapsed, it might give a mistaken impression of WT impacts: instead it is symptoms that are most important in order to detect stress levels (e.g., Lazarus and Cohen, 1977), as they provide information on psychological or physical stress reactions and thus the stress level itself. Single annoyance scales do not capture information on the stress reactions but assess a general evaluation of the WT impact, rather comparable to attitude assessments in the sense of liking or disliking the turbines. Therefore, without considering symptoms, a single annoyance scale might not be a sufficient impact indicator. To allow for a more precise WT impact indicator, we introduce the Annoyance Stress-Scale (AS-Scale), which combines the single annoyance scale approach with stress reactions.

Following this approach residents can be classified as "strongly" annoyed if they perceive the WT emission and also:

a) evaluate it at least "somewhat" annoying (based on a 5-level annoyance scale from (1) "not at all"; (2) "slightly"; (3) "somewhat"; (4) "moderately" to (5) "very"),
b) reported at least one physical or psychological symptom that they attributed to WT, and
c) the symptom(s) recurred at least once per month (Hübner and Löffler, 2013; Pohl et al., 2018).

As an example, using the AS-Scale presented in Pohl et al. (2018), this would result in 9.9% "strongly" annoyed residents by WT noise as compared to 16.9% who are considered "annoyed" based on a two-level grouping (moderately and very annoyed), without taking stress reactions into account. The difference in the classification of strongly annoyed residents can lead to uncertainty for decision-makers and the general public. Annoyance does not equal stress reactions but captures only an evaluation of the perceived emission, while the stress level is better indicated by incorporating symptoms.

The present paper focuses on WT noise, as noise problems are the most frequently discussed stress impact on residents. Accordingly, noise has been the most widely studied among all WT impacts to date, with about three dozen field studies published (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, 2018). However, these studies focused mainly on dose response relations. To understand what influences the perceived annoyance and stress reactions due to WT noise, several moderators must be considered: the visibility of WT by residences seems to increase annoyance (e.g., Arezes et al., 2014; Firestone et al., 2015; Pedersen et al., 2009, 2010; Pedersen and Persson Waye, 2007), as well as stress reactions (e.g., Pohl et al., 2018). These decrease, however, when residents have a financial interest in the WT project (e.g., Arezes et al., 2014; Health Canada, 2014; Pedersen et al., 2010; Pohl et al., 1999). Annoyance induced by the planning and construction of wind farms appears related to WT noise annoyance as well as reported stress symptoms (e.g., Hübner and Löffler, 2013; Pohl et al., 2012, 2018). Several studies show that residents with negative attitudes toward wind energy or their local wind farm are more likely to experience WT noise annoyance and vice versa (e.g., Pawlaczyk-Luszczynska et al., 2014; Pedersen and Persson Waye, 2008; Pohl et al., 1999, 2012, 2018). Remarkably, the distance of residences from WT has been inconsistently correlated to WT noise annoyance and stress impact (increased annoyance with decreased distance: e.g., Barry et al., 2018; Pawlaczyk-Luszczynska et al., 2014; Yano et al., 2013; no relation: e.g., Firestone et al., 2015; Pohl et al., 2018). In the present study, several of these moderators are included in order to achieve a deeper understanding of WT noise impacts on residents.

The lack of valid and standardized WT noise impact monitoring and the fact that most research published on WT noise has been conducted in Europe call into question the generalizability of these findings. In this paper, we aim to present the AS-Scale as a valid assessment of WT noise impacts on residents and to improve the generalizability of using data from European samples and the U.S. "National Survey of Attitudes of Wind Power Project Neighbors".[1] The U.S. data were collected using a large, random resident sample from many wind projects. They include annoyance and stress indicators as well as noise annoyance moderators. The same indicators and moderators were used in the previous research of Hübner and Pohl conducted in Switzerland and Germany. Therefore, comparing the two sets of findings – U.S. and European – can provide an opportunity to validate the robustness of the AS-Scale monitoring approach introduced by Hübner and Pohl et al. (2018).

2. Methods

2.1. Survey designs

We use data from the cross-sectional U.S. National Survey of Attitudes of Wind Power Project Neighbors (see, e.g., Firestone et al., 2018) as well as combined data from two European cross-sectional surveys (Hübner and Löffler, 2013; Pohl et al., 2012) and one European longitudinal survey (Pohl et al., 2018). From the longitudinal study, only the data from the first of two surveys are included here, as the second survey occurred after an intervention.

For the U.S. survey, people living near wind farms completed standardized questionnaires via telephone, web or mail. In order to reach a broader portion of the population, which might have different experiences with an online survey and be more or less likely to have a landline telephone, multiple modes were used. The different modes had no significant impact on the results, tested by mean comparisons and a regression analysis. Residents in Europe completed the standardized questionnaires via mail (Pohl et al., 2012) or in a question-answer dialogue with trained interviewers (Hübner and Löffler, 2013; Pohl et al., 2018). All questions in the U.S. survey were designed to facilitate comparison with the European instruments. All data were collected between 2009 and 2016 (Table 1).

The U.S. sample frame included residents living within 8 km of the nearest WT, and yielded 1705 usable data records. Because two of the three European samples did not include respondents living 4.8–8.0 km from the nearest WT, we restricted all samples to participants living within 4.8 km. Of the remaining 1441 U.S. participants, 701 responded via telephone, 434 via paper questionnaire, and 306 via web survey.

U.S. responses were collected near 231 wind farms across 24 states. Each WT had a minimum total height of 111 m and a minimum of 1.5 MW capacity. Wind farms including more than 10 WT were oversampled.

In Europe, special research questions led to the selection of wind farms, such as obstruction marking systems and typical landscapes. Hübner and Löffler (2013) included all existing Swiss wind farms (seven) that had WT with a minimum capacity of 0.6 MW. Pohl et al. (2012) selected 13 wind farms with different aircraft obstruction markings in two different landscapes. Pohl et al. (2018) selected a single wind farm that drew WT noise complaints. Table 1 shows other wind farm characteristics.

2.2. Survey participants

2.2.1. U.S. sample

The U.S. recruitment started with drawing a random sample of 43,041 homes, which was stratified by four distance categories (< 1.6 km, 1.6–3.2 km, 3.2–4.8 km, 4.8–8.0 km; Firestone et al., 2018). After location adjustment with geocoding services (Google, Melissa) and matching with telephone numbers using MSG Data, a random

[1] For the project summary, see https://emp.lbl.gov/projects/wind-neighbor-survey.

Table 1
Summary of studies, samples and wind farms for residents within 4.8 km of the nearest WT.

	U.S. dataset	Combined European dataset	Pohl et al. (2012)	Pohl et al. (2018)	Hübner and Löffler (2013)
Country	USA	Multiple	Germany	Germany	Switzerland
Data collection	2016	2009–2013	2009	2012	2012–2013
$n \leq$ 4.8 km (total shown in paper)	1441	1029	372 (420)	212 (212)	445 (467)
Average age of respondents	57	52	51	55	52
Gender (male; female)	45%; 55%	53%; 47%	59%; 41%	52%; 48%	48%; 52%
Number of wind projects	231	21	13	1	7
WT per project	1–224	1–18	5–18	9	1–16
WT total height (m)[a]	111–150	72–150	118–150	150	72–148
WT capacity (MW)	1.5–3.0	0.6–2.3	0.8–2.3	2.0	0.6–2.0
Distance range to home (km)	0.08–4.80	0.23–4.79	0.44–4.34	1.25–2.89	0.23–4.79
Average distance to home (km)	1.30	1.74	1.35	1.90	1.98

[a] The European samples were collected near some turbines that were smaller in total height than those in the U.S. sample, which was limited to heights of at least 111 m. However, negligible or small effect sizes were found when correlating total height and sound annoyance (0.19), lighting annoyance (0.08), shadow-flicker annoyance (0.06), and landscape-change annoyance (0.38).

sample-drawing procedure was followed for each distance bin. The aim was to recruit 900 participants for the telephone survey. Another sample-drawing approach was carried out for mail and web surveys for residents included both residents who could not be reached by telephone and new contacts. This subsample was recruited using a personal letter with a web address and unique web PIN; a second letter sent with a paper survey, and if necessary a reminder postcard. The approach is generally based on the recommendations of Dillman et al. (2014). The overall response rate of the three survey modes was 22%. Four $500 vouchers were raffled among the participants.

To better analyze the impacts of sound and shadow-flicker, residents within 1.6 km to the nearest WT and to 15 wind farms, which were chosen for sound modeling, were oversampled. Because the population densities near four small wind farms greatly exceeded those near the other small wind farms, and therefore would have been overrepresented in the sample, residents near those projects were undersampled.

2.2.2. European samples

The European participants in two studies were recruited randomly through personal letters and telephone calls using public telephone directories, at a community meeting and via onsite contacts. The overall response rate was 28% (Hübner and Löffler, 2013; Pohl et al., 2018). Participants in the other study were recruited randomly by distributing questionnaires to households, with an overall response rate of 25% (Pohl et al., 2012). As incentives Pohl et al. (2012) offered 15 EUR or participation in a lottery for a 25 EUR Amazon voucher; Hübner and Löffler (2013) offered two balloon rides. Pohl et al. (2018) offered no incentives. After the European sample was limited to those within 4.8 km of WT, the survey totaled 1029 participants.

In addition to demographics, we checked the samples' comparability for central variables such as attitudes toward the local wind farm, emotions, impact on life quality and place attachment. We also checked correlations between attitude toward the local wind farm and a set of variables including visibility, strain during the planning process, setback distance, noise annoyance and impact on landscape. All results showed comparable patterns, which justified sample pooling (see Hübner and Pohl, 2015). Furthermore, in the two studies with interviewers, we could conduct non-response analyses based on four questions. In the Swiss and German samples (Pohl et al., 2018) we did not find relevant differences between responders and non-responders concerning a) attitude toward the local wind farm, b) age, or c) visual impact. Only in the German sample we observed a small difference concerning the mean WT noise annoyance level found: while non-responders were on average slightly annoyed, responders were slightly-to-somewhat annoyed. First, the difference was too small to suggest a relevant self-selection bias of strongly annoyed residents. Second, this rather small difference becomes barely relevant when pooling the samples.

2.3. Sample characteristics and comparison

Table 2 shows demographic statistics from the U.S. and European samples as well as test statistics comparing the two means or frequencies. The U.S. means are weighted to control for sampling methodology (see Section 2.5). Mean age of the U.S. sample (57 years) was slightly higher than the European sample (52 years, small effect size), but the difference is too small to assume any influence on attitudes or stress effects. More women than men participated in the U.S. study, and the opposite is true in the European dataset. However, the different ratios can be neglected because the effect size is not relevant. The U.S. participants had on average more years of education than the European

Table 2
Sample demographic statistics.

	U.S. dataset	Combined European dataset	Effect size (d, w) p-value (*t*-test, Chi[2]-test)
Age (mean, SEM)	56.92 (0.43) n = 1407	52.22 (0.47) n = 1015	Small (0.30) $p < 0.0001$
Gender			Not relevant (0.08) p < 0.0001
Male	45%	53%	
Female	55% n = 1428	47% n = 1018	
Years of education (mean, SEM)	14.78 (0.06) n = 1423	12.23 (0.13) n = 986	Medium (0.77) p < 0.0001
Occupation			Medium (0.31) p < 0.0001
Employed full-time	43.0%	50.2%	
Employed part-time	10.5%	0.0%	
Unemployed and looking for work	2.6%	1.5%	
Unemployed not looking for work	0.5%	6.3%	
Retired	35.9%	27.1%	
Homemaker	3.5%	9.0%	
Other	4.1% n = 1413	5.9% n = 909	
Working partly at home			Not relevant (0.09) p = 0.001
No	67.3%	75.2%	
Yes	32.7% n = 782	24.8% n = 755	
Years lived on property	16.70 (0.40) n = 1426	21.40 (0.51) n = 999	Small (0.30) p < 0.0001
Occupancy status			Not relevant (0.07) p = 0.001 (test without "other")
Owner	83.4%	78.5%	
Renter	16.1%	21.5%	
Other	0.5% n = 1432	0.0% n = 1006	
Financial participation in wind project			Not relevant (0.03) p = 0.196
No	95.6%	96.7%	
Yes	4.4% n = 1420	3.3% n = 1020	

Table 3
Overview of Annoyance Stress-Scale (AS-Scale).

Annoyance scale level	Does not perceive sound or shadow-flicker	Not at all (0)	Slightly (1)	Somewhat, moderately, or very (2–4)	Somewhat, moderately, or very (2–4)
	⇓	⇓	⇓	⇓	⇓
Symptom frequency	Not applicable	No symptoms	No symptoms	No symptoms	Monthly, weekly, or daily
	⇓	⇓	⇓	⇓	⇓
AS-Scale level	Does not perceive sound or shadow-flicker (0)	Not at all (1)	Slightly (2)	Somewhat (3)	Strongly (4)

Note: We assume that landscape change and WT lighting is perceived by all people residing in a distance up to 4.8 km from a wind farm.

participants (medium effect size). In both samples about 50% of the respondents were employed. In the U.S. sample smaller proportions of participants were homemakers or unemployed, and a larger proportion was retired compared to the European sample (medium effect size). Nearly a third of the U.S. sample worked partly at home; a quarter did in Europe (effect size not relevant, by testing frequency differences). The European participants on average lived longer on their property than the U.S. participants (small effect size). The vast majority of participants in both samples owned their property; the small differences between the samples are negligible. Less than 5% of both samples participated financially in the wind farm.

2.4. Stress indicators and moderators

In this report a selection of stress indicators and moderators is presented that were assessed in the U.S. and Europe comparatively.

2.4.1. Indicators

Following the common practice employed in the field of environmental annoyance research, we used a single annoyance item to assess annoyance related to specific WT impacts (noise, shadow-flicker, lighting, landscape change). This item entailed participants rating their experiences on a 5-point annoyance scale for each impact: 0 (“not at all”), 1 (“slightly”), 2 (“somewhat”), 3 (“moderately”) and 4 (“very”). Participants also rated annoyance due to other noise sources such as traffic using the same scale.

We used data on stress symptoms attributed to wind farms via assessments of five symptoms: bad mood, anger, lack of concentration, difficulty falling asleep and otherwise not sleeping well. These represent the most frequent stress symptoms related to WT (Pohl et al., 2018). Respondents rated the frequency of symptoms, which they also attributed to a particular source (such as WT sound, lighting), on a scale ranging from “less than once a month” to “daily”. An alternative approach to recording stress reactions is stress protocols. However, such an approach needs a longitudinal design and highly motivated participants. In our longitudinal study (Pohl et al., 2018) only a few participants agreed to record their experience and even fewer delivered analyzable data. Stress protocols seem applicable to small sample size case studies but rather not for cross-sectional designs and larger samples.

As outlined in the introduction, based on stress psychological models the single annoyance level might be considered a measure of attitude rather than a reliable stress indicator (Pohl et al., 2012, 2018). Therefore, we combined the above indictors in the AS-Scale (Hübner and Löffler, 2013; Pohl et al., 2018). More precisely, the AS-Scale combines the ratings from the annoyance and symptom scales as shown in Table 3. For example, to be rated “strongly annoyed” on the AS-Scale (level 4), a resident must be at least “somewhat annoyed” on the annoyance scale (level 2) and experience at least monthly one physical or psychological symptom related to the WT. Additionally we created the NAS-Scale, which has the same levels as the AS-Scale but applies only to noise.

To picture how residents deal with WT impacts, we assessed cognitive and behavioral coping responses via six items with “no” or “yes” coding: tried to relax, talked with others, ignored it, accepted it, reduced its effect, and avoided it.

2.4.2. Moderators

We explored several possible moderators of AS-Scale levels:

- Attitude—The general attitude toward a local wind farm was assessed by one bipolar scale in the U.S. questionnaire, and a semantic differential with six pairs of bipolar adjectives (for example “bad – good”) in the European version. The average over these items was used as an indicator for attitude. Values ranged from −2 (“very negative “) to +2 (“very positive”).
- Health indicators and noise sensitivity—The assessment of acute health problems (during the past 4 weeks for a short time) and chronic (lasting at least several months) health problems assessed independently of any relationship to the local wind project, and noise sensitivity were indicated on three unipolar rating scales each ranging from 0 (“not at all”) to 4 (“very”).
- Evaluation of the planning process—Participants rated their annoyance based on the fairness of the wind farm planning process on two unipolar rating scales each ranging from 0 (“not at all”) to 4 (“very”).
- Physical features—Measured physical features included the number of WT visible from the resident's property, the number of WT at the nearest wind farm, distance from the nearest wind farm, and the calculated A-weighted Leq-sound pressure level according to ISO 9613 (ISO, 1993).[2]

2.5. Statistical analyses

We weighted the U.S. data using “iterative ranking” or “sample balancing” (e.g., Battaglia et al., 2009; Deming, 1943) to account for over- and under-sampling, different response rates by distance categories, and samples that were not representative of the population. We used USCB/AFF (2014) census tract-level household and demographic data to adjust for gender, age and education, aligning the percentage of homes within each census tract considering the sampling area (< 4.8 km to the nearest WT). A detailed description of the weighting process is contained in Firestone et al. (2018). The European data could not be weighted because population-level demographic data for the studied regions and years in Germany and Switzerland were not readily available.

Following Jöreskog (1990, 1994), we assume an underlying continuous variable for the rating scales applied. Therefore we interpret these scales as interval-scaled, a standard statistical method in psychological research. Additionally, relevant research on WT noise annoyance to which we refer used the same or comparable methods (e.g., Bakker et al., 2012; Michaud et al., 2016a; Pawlaczyk-Luszczynska et al., 2014; Pedersen and Persson Waye, 2004, 2007).

To analyze group differences for interval-scaled variables, we used descriptive statistical values such as the arithmetical mean and standard error of the mean (SEM). For nominal-scaled variables, we report absolute and relative frequencies (%-values). We calculated Pearson-

[2] The A-weighted Leq-sound pressure level is the time-averaged overall sound level adjusted to the approximate frequency sensitivity of human hearing at nominal levels, expressed as “dBA” or “dB(A).”

correlations to identify moderator variables; only coefficients of 0.30 or higher (a medium effect size according to Cohen, 1988) are regarded as relevant. For each sample we ran a multiple regression analysis with unweighted data to predict Noise Annoyance Stress Scale (NAS-Scale; see Section 3.3) values by several variables. Beta weights are understood as effect sizes (Nieminen et al., 2013), and we used a cut-off of > 0.15 to indicate an influential predictor. We used Chi^2-tests for inferential analysis of frequency distributions. We compared means of two groups via *t*-tests. In the case of unequal variances we have used Welch's *t*-tests.

Our data analysis and description follow the principles of Abt's (1987) "Descriptive Data Analysis." Correspondingly, reported *p*-values of the two-tailed significance tests only possess a descriptive function labeling the extent of group differences. Despite the multiplicity of significance tests, we made no alpha-adjustment because our analysis is not a confirmatory data analysis. We describe p-values of 0.05 or less as statistically significant. In addition, we use the effect size parameters d and w to report practical significance (Cohen, 1988). The effect size categories (small, medium, large) mentioned in the results section always refer to statistically significant group differences. Effect sizes d and w were calculated by Excel procedures. The statistical software SPSS was used for other analyses.

3. Results

3.1. WT annoyance

Relatively few participants perceived shadow-flicker on their property, particularly in the U.S. (Table 4). Residents also perceived noise relatively infrequently in the U.S. In Europe a substantially higher percentage of residents perceived noise, perhaps because on average the European respondents lived closer to the WT compared to U.S. respondents; the mean weighted U.S. distance was 2.72 km (SEM = 0.03), and the mean European distance was 1.74 km (SEM = 0.03), giving a large effect size (d = 1.02, $p < 0.0001$). Another reason may be different background sound levels depending on different population densities, for example.

Based on the single annoyance item – without stress symptoms – average annoyance induced by WT lighting was very low, while landscape change was between "not at all" and "slightly"; shadow-flicker and noise were between "slightly" and "somewhat" annoying (Table 5) in the U.S.. The European sample showed WT noise annoyance similar to that in the U.S. sample. Annoyance related to shadow-flicker, lighting and landscape change was higher in Europe than in the U.S., although these effects were still between "slightly" and "somewhat" annoying in Europe.

Average annoyance due to local traffic noise was relatively low in both samples and, more importantly, comparable to WT noise annoyance. Annoyance caused by agricultural machinery noise was clearly stronger in the European sample compared to the U.S., but it was still only "slightly" annoying in Europe.

As shown in Table 6, when the AS-Scale is used to assess annoyance – that is, when stress symptoms are included in addition to reported annoyance level – only a small percentage of residents rate as "strongly annoyed" (at least somewhat annoyed with at least one symptom occurring at least once per month; see Table 3). These results are similar for the U.S. and Europe across WT effects, except for noise, for which the percentage of strongly annoyed residents in Europe is slightly higher. Because all residents who reported symptoms were at least somewhat annoyed, the percentage of strongly annoyed residents equals the percentage of respondents reporting any symptom.

The percentages of "strongly annoyed" residents based on the AS-Scale are smaller than the percentages of "very annoyed" residents based on the single-item annoyance scale, as would be expected. For example only 1.1% of U.S. residents and 4.3% of European residents were "strongly annoyed" by WT noise under the AS-Scale. Combining

Table 4
Perception of shadow-flicker and noise of WT.

	United States	Europe	Effect size (w) *p*-value (Chi^2-test)
Blades cast shadow, outside home	3.3% *n* = 1423	8.8% *n* = 467	Small (0.11) p < 0.0001
Blades cast shadow, inside home	2.3% n = 1434	8.8% *n* = 467	Small (0.15) *p* < 0.0001
Can hear wind farm, outside home	10.9% *n* = 1434	41.0% *n* = 671	Medium (0.35) p < 0.0001

Table 5
Average annoyance induced by WT impacts and other local sources (single item scale).

	United States	Europe	Effect size (d) p-value (*t*-test)
	Mean (SEM)		
Shadow-flicker (limited to those experiencing WT flicker on property)	1.25 (0.07) *n* = 454	1.98 (0.24) n = 46	Small (0.46) *p* = 0.002
Lighting (WT aircraft obstruction markings)	0.47 (0.03) *n* = 1397	1.16 (0.05) *n* = 752	Medium (0.52) p < 0.0001
Landscape change by WT	0.70 (0.03) *n* = 1414	1.35 (0.05) *n* = 1024	Small (0.46) p < 0.0001
WT noise (limited to those hearing sounds on property)	1.44 (0.06) n = 779	1.46 (0.09) n = 264	Not relevant (0.01) *p* = 0.851
Traffic noise	1.26 (0.04) *n* = 1422	1.32 (0.10) *n* = 211	Not relevant (0.04) *p* = 0.515
Agricultural machinery noise	0.33 (0.02) *n* = 1382	1.39 (0.09) *n* = 212	Large (1.02) p < 0.0001

Table 6
Percentages of strongly annoyed residents based on the AS-Scale.

	United States	Europe	Effect size (w) p-value (Chi^2-Test)
	Percentage (number) of strongly annoyed residents		
Noise	1.1% (16) n = 1441	4.3% (28) *n* = 657	Small (0.102) p < 0.0001
Landscape change	1.5% (22) n = 1441	0.0% (0) *n* = 445	Not relevant (0.060) *p* = 0.009
Lighting (aircraft obstruction markings)	1.2% (18) n = 1441	1.2% (10) *n* = 817	Not relevant (0.001) *p* = 0.959
Shadow-flicker	0.2% (3) n = 1441	0.2% (1) n = 445	Test not possible
Total	2.3% (33) n = 1441	3.7% (38) *n* = 1029	Not relevant (0.049) *p* = 0.041

the highest single-item categories of "moderately" and "very" annoyed leads to clearly higher percentages: 18.3% for the U.S. and 9.7% for Europe.

To analyze the general impact of WT noise on all residents, we needed to include the total sample. But even when we drew our intention only to the subsamples of residents who heard the turbines – 11% of the total U.S. sample and in Europe 41% – based on the NAS-Scale we still only find 10% of strongly annoyed residents in both subsamples.

3.2. Symptoms and coping responses

In both samples fewer than 5% of residents reported psychological and physical symptoms at least monthly due to WT impacts (Table 7).

Table 7
Percentages of all residents reporting symptoms at least monthly by WT impact.

	Noise		Landscape change		Lighting		Shadow-flicker	
	United States (n = 1441)	Europe (n = 679)	United States (n = 1441)	Europe (n = 467)	United States (n = 1441)	Europe (n = 887)	United States (n = 1441)	Europe (n = 467)
Bad mood	3.3%	4.1%	2.6%	0.4%	1.8%	0.3%	2.3%	0.0%
Anger	1.1%	4.0%	1.9%	0.4%	1.7%	0.0%	0.6%	0.0%
Lack of concentration	2.4%	3.7%	0.6%	0.0%	0.7%	0.3%	1.3%	0.2%
Difficulty falling asleep	3.2%	4.6%	0.6%	0.0%	1.0%	1.0%	0.6%	0.0%
Otherwise not sleeping well	2.7%	4.7%	0.5%	0.0%	1.1%	0.8%	0.6%	0.0%

The result pattern in the European sample showed slightly higher percentages for noise symptoms than in the U.S. sample, and the opposite for the other WT impacts.

The U.S. sample includes data on coping responses to the WT effects overall. Out of the Swiss and German studies constituting the European sample only one is suitable for comparison – the longitudinal study, in which Pohl et al. (2018) used an equivalent coping response assessment, specifically addressing WT noise. Table 8 shows the percentages of coping responses to WT effects overall in the U.S. sample, as well as the coping responses to WT noise specifically in that European study (Pohl et al., 2018). In the U.S. sample the percentages of residents reporting coping responses to any WT impacts were less than 6%. In contrast the percentages of residents reporting coping responses to WT noise only ranged from 12%–36% in the European case. These percentages are substantially higher than those for noise-related coping in the U.S. sample, which may be explained in part by more frequent perception of WT noise in the Pohl et al. (2018) study.

3.3. Moderators of WT noise annoyance

Table 9 shows moderators of WT noise annoyance; see Section 2.4.2 for the response options corresponding to their −2 to +2 or 0 to 4 ranges. In both samples the average present attitude toward the local wind farm was somewhat positive. However, attitude was marginally more positive in the European sample even though Europeans reported slightly stronger acute and chronic health problems as well as stronger noise sensitivity. Conversely, the planning process was perceived as more fair in the U.S. sample even though residents there were marginally more strongly annoyed by it. Overall, the annoyance by the planning process was low in both samples.

We performed a moderator analysis to clarify the factors influencing WT noise annoyance and to predict it using the NAS-Scale. The European NAS-Scale mean of 0.89 (SEM = 0.05, n = 647) was higher than the U.S. mean of 0.28 (SEM = 0.02, n = 1316; $p < 0.0001$, d = 0.58, medium effect size). We used the NAS-Scale to calculate Pearson correlations and multiple linear regressions.

For both samples, we found the same pattern of four relevant correlations (criterion: $r \geq |0.30|$, at least a medium effect size, Table 10). Attitudes toward the wind farm and the perceived fairness of the planning process correlated negatively with NAS-Scale. That is, the more residents held a positive attitude toward the wind farm or perceived the planning process as fair, the less they were annoyed by WT noise, and vice versa. Conversely, planning process annoyance/stress correlated positively with NAS-Scale. Among the physical features, the number of WT visible from the property (only in Europe) and the number of WT at the nearest wind farm correlated positively with NAS-Scale, though not with the distance to the nearest WT or sound pressure level.

Table 9
Comparison of subjective moderator variables.

	United States	Europe	Effect size (d) p-value (t-test)
	Mean (SEM)		
Present attitude toward wind farm	0.72 (0.03) n = 1416	1.00 (0.05) n = 987	Small (0.22) $p < 0.0001$
Perceived planning process fairness	2.31 (0.06) n = 692	1.62 (0.05) n = 906	Small (0.48) $p < 0.0001$
Annoyed by planning process	0.90 (0.05) n = 769	0.56 (0.04) n = 1000	Small (0.26) $p < 0.0001$
Acute health problems in past 4 weeks, not wind	0.64 (0.03) n = 1388	1.20 (0.03) n = 1010	Medium (0.50) $p < 0.0001$
Chronic health problems, not wind	0.70 (0.03) n = 1384	1.08 (0.04) n = 1007	Small (0.33) $p < 0.0001$
Noise sensitivity	1.66 (0.03) n = 1431	2.01 (0.05) n = 710	Small (0.28) $p < 0.0001$

For each sample we performed a multiple regression analysis on all residents who heard the WT in order to predict NAS-Scale. We found two relevant variables in the U.S. sample and four in the European sample (Table 11). Here, relevance is based on beta weights and p-values; a beta weight $> |0.15|$ is considered relevant for any coefficient with $p < 0.05$. In both samples "present attitude toward wind farm" showed the strongest relation, indicating that a more positive attitude is correlated with less annoyance. Another relevant factor in the U.S. sample was "planning process annoyance/stress." In the European sample the other relevant factors were "planning process fairness," "sensitivity to noise" and "education level." In both samples the physical features of the wind farm were negligible factors. Overall, the included variables substantially predicted noise annoyance (defined by the NAS-Scale), capturing about 60% of the variance in noise annoyance in the U.S. sample and about 50% in the European sample.

Explicitly we controlled the direct impact of weighting variables (age, gender, education levels as well as two variables for under- and over-sampling) in the regression analysis. We did not find any

Table 8
Percentages of residents' coping responses to WT impacts overall (United States) and WT noise effects specifically (Europe, from Pohl et al., 2018).

	Overall effects, United States	Noise effects, Europe (Pohl et al., 2018)
Talked with others	5.7%	29.7%
Tried to relax	4.1%	26.4%
Accepted it	3.8%	35.8%
Ignored it	3.6%	No item
Reduced its effects (e.g., sound dampening, shutting windows, closing blinds)	3.1%	25.9%
Avoided it	3.0%	11.8%

Table 10
Pearson correlations with NAS-Scale.

	United States	Europe
	r (effect size, *p*-value)	
Present attitude toward wind farm	−0.362 (medium, p < 0.0001) *n* = 1294	−0.620 (large, p < 0.0001) *n* = 644
Planning process fairness	−0.395 (medium, p < 0.0001) *n* = 639	−0.397 (medium, p < 0.0001) *n* = 565
Planning process annoyance/stress	0.490 (medium, p < 0.0001) *n* = 709	0.467 (medium, p < 0.0001) *n* = 620
Acute health problems	0.204 (small, p < 0.0001) *n* = 970	0.010 (not relevant, *p* = 0.796) *n* = 632
Chronic health problems	0.065 (not relevant, *p* = 0.043) *n* = 966	0.106 (small, *p* = 0.008) *n* = 629
Sensitivity to noise	0.106 (small, p = 0.001) *n* = 1004	0.209 (small, p < 0.0001) *n* = 336
Number of WT visible from the property	0.282 (small, *p* = 0.001) *n* = 965	0.423 (medium, p < 0.0001) *n* = 517
Number of WT in the nearest wind farm	0.365 (medium, p < 0.0001) *n* = 1316	0.398 (medium, p < 0.0001) *n* = 648
Distance to nearest WT (excluding those that cannot be heard)	0.197 (small, p < 0.0001) *n* = 779	0.057 (not relevant, *p* = 0.357) *n* = 261
Sound pressure level, day (excluding those that cannot be heard)	0.116 (small, *p* = 0.060) *n* = 264	0.204 (small, *p* = 0.016) *n* = 139

Table 11
Multiple regression prediction of noise annoyance stress (NAS-Scale) for all residents who experienced WT noise (relevant variables in bold).

	United States R^2 adjusted = 0.615 *n* = 393, all VIF < 2.8		Europe R^2 adjusted = 0.510 *n* = 187, all VIF < 1.9	
	Beta	p-Value	Beta	p-Value
Present attitude toward wind farm	**−0.459**	< 0.0001	**−0.432**	< 0.0001
Planning process fairness	−0.088	0.059	**−0.165**	0.008
Planning process annoyance/stress	**0.254**	< 0.0001	0.068	0.259
Acute health problems	0.029	0.465	−0.082	0.246
Chronic health problems	−0.049	0.213	0.100	0.146
Sensitivity to noise	0.110	0.002	**0.246**	< 0.0001
Number of WT visible from the property	0.022	0.522	0.139	0.010
Number of WT in the nearest wind farm	0.069	0.057	0.034	0.580
WT total height	0.042	0.208	−0.059	0.397
Distance to nearest WT	−0.009	0.786	−0.033	0.584
Housing duration	−0.029	0.469	−0.144	0.026
Age	0.001	0.988	0.081	0.199
Gender	−0.042	0.190	−0.038	0.484
Education level	−0.032	0.325	**0.164**	0.004
Modeled-sound wind farms[b]	−0.028	0.414	[a]	[a]
Under-sampled small wind farms[b]	0.010	0.770	[a]	[a]

Note: A VIF below 5 is considered an indication of low collinearity between independent variables.
[a] No variable available.
[b] See Section 2.2.

significant impact of the weighting variables in the U.S. Consequently, as the weighting variables did not have an impact on our main dependent variable (NAS-Scale), the international comparison of the results patterns is valid.

4. Discussion and conclusion

Wind energy is an important pillar of the worldwide energy transformation from fossil and nuclear to sustainable energy sources. However, the growing number and increasing height of WT affects landscapes and the lives of nearby residents, and these impacts influence local and public acceptance of WT. Thus, reliable and valid information about the magnitude and consequences of WT impacts is of high social relevance. Several studies have analyzed the impact of WT noise on annoyance and stress reactions, but the different assessment methods used hinder comparisons of the findings and, consequently, hinder valid cross-study annoyance monitoring. Moreover, these studies did not sufficiently combine annoyance evaluation with stress indicators such as symptoms and/or coping strategies, with few exceptions (Hübner and Löffler, 2013; Pohl et al., 2018). Our study helps bridge these gaps, providing a study of WT stress impacts on nearby residents in Europe and the U.S. The present study is the first comparison between individual residing on different continents and validation of WT annoyance monitoring utilizing the AS-Scale, based on the European sample and a U.S. survey of wind power perception.

The comparison of results from the NAS-Scale and single item annoyance scale shows that assessing annoyance alone is imprecise as it does not accurately reflect the small subset of residents who experience psychological and physical symptoms. First, the single item noise annoyance averages were similar between the U.S. and European samples. But the percentages of strongly annoyed residents measured using the AS-Scale, which accounts for stress symptoms, differed statistically across the samples. Second, strong correlations between the single annoyance scale and the attitude toward the local WT (U.S.: r = −0.73, Europe: r = −0.68) underline the stress concept's (Lazarus and Cohen, 1977) definition of annoyance as an evaluation. Embedded in a larger stress concept, the AS-Scale combines annoyance and stress symptoms. By doing so, it complements the previous, rather on single annoyance scales focused research on this subject (e.g., Pawlaczyk-Luszczynska et al., 2014; Pedersen et al., 2009; Pedersen and Persson Waye, 2004, 2007).

Information about the magnitude of WT impacts on residents resulting in symptoms are of high social relevance. This is true for two reasons: 1) this segment of the population would need to be protected; and 2) only by accurately studying them, which is preceded by first identifying them, can methods to mitigate stress reactions to WT emissions be tested and provide empirical foundations for political and planning decisions. Our findings provide evidence that WT annoyance and related stress effects are not a widespread problem. Average annoyance levels of residents near wind farms in Europe and the U.S. were low, with the levels for noise similar across both samples, with European levels slightly higher for shadow-flicker, lighting and landscape change. In all cases the annoyance levels were comparable to the levels associated with traffic noise.[3] Fewer than 5% of residents were strongly annoyed (based on the AS-Scale's combination of annoyance ratings and stress symptoms) in Europe and the U.S.; in the subgroup of residents who could hear the turbines it was still only about 10%. Although the relatively low frequency of strongly annoyed residents indicates that negative impacts with symptoms are not common when the immission control regulations are applied correctly, individual cases of wind farms with strongly annoyed residents do exist. Long-term monitoring of a sample of WT neighbors – including analyses of sound parameters, amplitude modulation, stress indicators and situational conditions – can clarify sources of annoyance and symptoms.

A slightly higher percentage of European residents than U.S. residents was strongly annoyed by WT noise, even though European attitudes were more positive toward the wind farms compared to U.S. attitudes. This result might stem from Europeans' higher sensitivity to noise and their perception that the planning process was less fair, because both those factors predicted noise annoyance stress in our regression analysis. The difference in the perceived process fairness possibly could be explained by differences in planning laws: the WT permitting process is strictly regulated in the U.S. as well as in Europe. Still, legal rulings in the U.S. might allow for more local decisions compared to regulations in Germany and Switzerland. However, this speculation requires further investigation. While the planning process was an influential factor in the U.S. (process stress) and Europe (process fairness), in both samples the present attitude toward wind farms was most strongly connected to noise annoyance stress (based on the NAS-Scale) for residents who experienced WT noise. Overall, the observed relation between the NAS-Scale and the subjective variables – while the objective factors such as sound level pressure and distance were correlated negligibly – underlines that factors other than hearing the turbines influence strong annoyance, including stress effects. In sum, the included variables explained the assessed stress level substantially. Additionally, the impact of the subjective factors corroborates findings of qualitative research that the impact of WT noise is socially mediated by factors such as the perceived fairness and participative approach of planning processes (e.g., Fast et al., 2016; Haggett, 2012).

Despite the strong evidence for the AS-Scale, the cross sectional design can be interpreted as a weakness – in most available international studies on WT impacts, including this study. To allow for better monitoring, longitudinal studies are recommended to investigate changes over time, including qualitative approaches to better understanding process over time. Additionally, pre-post research designs should investigate whether the WT impact changes due to new technical WT developments, such as height, power and noise mitigations measurements (e.g., serrations, noise quality of rotor blade shapes related to noise quality). Another weakness might be the different sampling techniques applied in the U.S. and Europe. However, despite the different sampling methods and other methodological differences between the U.S. and European studies, both samples exhibited similar result patterns of correlation. Also, independent of the continents, we find similarities in the proportion of strongly annoyed residents as well as in the factors related to noise annoyance. If the different sampling approach would have had a substantial impact, we would not have found these comparable result patterns. This finding speaks for the robustness of the results. Additionally, regarding disturbed sleep, a comparable percentage (4–6%) was found in the large Dutch study by Bakker and colleagues (Bakker et al., 2012). Again, these similar results are suggestive that the results can be generalized.

Our results have practical implications for wind farm development and monitoring. For example, the strong links between residents' experiences with wind farm planning processes and their levels of experienced stress impacts suggest that improving planning processes – such as by engaging residents actively from the beginning (Firestone et al., 2018; Pohl et al., 2018) – might reduce annoyance and related symptoms. There are positive experiences with early and informal resident participation (Devine-Wright, 2011; Rand and Hoen, 2017; Rau et al., 2012). Although participation cannot guarantee positive perceptions of the planning process, additional problems are more likely in the absence of substantive resident engagement.

Finally, the reliability and validity of the AS-Scale, which seems to be well-suited to identify both annoyance perceptions and symptoms, should be tested through further research. Moreover, because of the simplicity of its application, it easily could be adopted to case studies and epidemiological surveys. More importantly, regular monitoring of residents near wind farms with such an instrument will lead to a better understanding of long-term WT stress and annoyance impacts, and possible mitigation strategies. Because the AS-Scale accounts for stress symptoms, it allows us to examine this important cohort of the population in a way that the single-item scale does not. In addition, as demonstrated by the large disparity in U.S. noise annoyance ratings between the two scales, the single-item scale cannot be used as a proxy for the AS-Scale.

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Declaration of competing interests

All authors report no conflict of interest.

Authors' contributions

BH led the U.S. National Survey of Attitudes of Wind Power Project Neighbors effort. All authors contributed to study conception and design, including developing the survey instrument to allow international comparisons. RH provided the estimate of sound pressure level for the U.S. sample. JP, GH, and BH analyzed the data. JP and GH drafted the manuscript with editing from BH and a technical editor at LBNL. All authors participated in interpreting results, revising the manuscript, and approving the final submitted version of the manuscript.

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[3] The noise annoyance level seems comparable to that engendered by traffic noise. For example, Pohl et al. (2018) found a larger proportion of the residents was strongly annoyed by traffic (16%) than by WT noise (7%).

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