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# Self-reported and measured stress related responses associated with exposure to wind turbine noise

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The current study was the first to assess stress reactions associated with wind turbine noise (WTN) exposure using self-reported and objective measures. Randomly selected participants, aged 18–79 yr (606 males; 632 females), living between 0.25 and 11.22 km from wind turbines, were exposed to outdoor calculated WTN levels up to 46 dBA (response rate 78.9%). Multiple regression modeling left the great majority (77%–89%) of the variance in perceived stress scale (PSS) scores, hair cortisol concentrations, resting blood pressure, and heart rate unaccounted for, and WTN exposure had no apparent influence on any of these endpoints. PSS scores were positively, but weakly, related to cortisol concentrations and resting heart rate (Pearson $r = 0.13$ and $r = 0.08$, respectively). Across WTN categories, modeled mean PSS scores ranged from 13.15 to 13.84 ($p = 0.8614$). Modeled geometric means for hair cortisol concentrations, resting mean systolic, diastolic blood pressure, and heart rate were 150.54–191.12 ng/g ($p = 0.5416$), 113.38–116.82 mmHg ($p = 0.4990$), 67.98–70.34 mmHg ($p = 0.5006$), and 68.24–70.71 bpm ($p = 0.5223$), respectively. Irrespective of WTN levels, diastolic blood pressure appeared to be slightly (2.90 mmHg 95% CI: 0.75,5.05) higher among participants highly annoyed by blinking lights on turbines ($p = 0.0081$). Collectively, the findings do not support an association between exposure to WTN up to 46 dBA and elevated self-reported and objectively defined measures of stress.

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## I. INTRODUCTION

Noise exposure has the potential to act as a stressor and can directly or indirectly impact one's health [World Health Organization (WHO), 1999, 2011; Guski, 2001; Vallet, 2001]. Susceptibility or resistance to indirect stressor-induced health effects depends on a complex interaction between a stressor and coping strategies developed through previous experience, psychological, biological, and social factors, in addition to competing stressors and personality type (Job, 1988, 1996; Institute of Medicine, 2001; Stansfeld and Marmot, 2002). At the dwelling, wind turbine noise

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(WTN) levels are well below levels expected to cause direct health effects (McCunney *et al*., 2014). Potential effects are more likely to be mediated through a complex interaction as described above, wherein the perception of wind turbines becomes the acting stressor. Other factors such as noise sensitivity and the magnitude of annoyance or perceived stress engendered by a noise exposure could very likely contribute to the overall response. A theoretical representation for such an indirect pathway is presented in the Appendix.

Social surveys, which have been relied on to measure annoyance, perceptions of stress, and/or health effects, provide only partial support for potential WTN-mediated health effects because they are based on unverified self-reporting. An additional level of insight is provided from the current study, which includes objective measures of stress to characterize the associations between WTN exposure and stress.

Stress-induced cortisol changes have traditionally been measured using blood and saliva samples, which can be difficult to interpret (Legler *et al*., 1982; Hennig *et al*., 2000; Edwards *et al*., 2001; Broderick *et al*., 2004). Many of the limits associated with short-term sampling can be eliminated by using a measure of cortisol that is integrated over time (Russell *et al*., 2012; Stalder and Kirschbaum, 2012). Cortisol integrates and remains in hair over time as it grows further from the scalp. As human scalp hair have a predictable average growth rate of ∼1 cm/month (Wennig, 2000), cortisol in hair can be measured and used to retrospectively characterize cortisol levels over several months. For this reason, hair cortisol analysis has become an increasingly utilized methodology for examining chronic stress and its effects on human health (Van Uum *et al*., 2008; Pereg *et al*., 2011; Gerber *et al*., 2013; Grunau *et al*., 2013; Hinkelmann *et al*., 2013; Manenschijn *et al*., 2013; Pereg *et al.*, 2013; Stalder *et al*., 2013; Walton *et al*., 2013; Veldhorst *et al.*, 2014; Wells *et al*., 2014; Wester *et al*., 2014) making hair cortisol analysis a particularly useful methodology in evaluating the impact that long-term exposure to WTN may have on the human stress response. Hair cortisol analysis, when considered together with validated questionnaires such as the perceived stress scale (PSS) (Cohen *et al*., 1983; Al kalaldeh and Shosha, 2012), as well as blood pressure measures, provides a more comprehensive assessment of WTN exposure and stress reactions.

The purpose of the current study was to investigate the possibility that living in the vicinity of wind turbines increases stress. To this end, multiple measures of stress reported by and objectively measured in participants exposed to WTN were assessed. In addition, multiple regression analysis was used to identify the variables that best predicted the modeled stress-related endpoints.

## II. METHODS

### A. Sample design

#### *1. Target population, sample size, and sampling frame strategy*

Michaud *et al*. (2013) and Michaud *et al*. (2016a) have described the study design, target population, final sample size, allocation of participants, as well as the sampling strategy. Briefly, the study locations were drawn from areas in southwestern Ontario (ON) and Prince Edward Island (PEI) where there were a sufficient number of dwellings within the vicinity of wind turbine installations. There were 2004 potential dwellings identified from the ON and PEI sampling regions, which included 315 and 84 wind turbines, respectively. All turbines had three pitch controlled rotor blades (∼80 m diameter) upwind of the tower. The wind turbine electrical power outputs ranged between 660 kW and 3 MW [average 2.0, standard deviation (SD) = 0.4 MW]. Turbine hub heights were predominantly 80 m. All identified dwellings within ∼600 m from a wind turbine and a random selection of dwellings between 600 m and 11.22 km were selected from which one person per household between the ages of 18 and 79 years was randomly chosen to participate.

This study was approved by the Health Canada and Public Health Agency of Canada Review Ethics Board (Protocol Nos. 2012-0065 and 2012-0072).

### B. Wind turbine sound pressure levels

Keith *et al*. (2016a) have provided a detailed description of the approach applied to sound pressure level modeling. Briefly, sound pressure levels were estimated at each dwelling using both ISO 9613-1 (ISO, 1993) and ISO 9613-2 (ISO, 1996) as incorporated in the commercial software CadnaA version 4.4 (Datakustik®, 2014). The calculations included all wind turbines within a radius of 10 km, and were based on manufacturers' octave band sound power spectra at 10 m height, 8 m/s wind speed for favourable propagation conditions. The few dwellings beyond this distance were assigned the same calculated WTN value as dwellings at 10 km. The manufacturers' data were verified for consistency using on-site measurements of wind turbine sound power (Keith *et al*., 2016b). Unless otherwise indicated, all references to decibels (dB) are A-weighted values.

In the current study, low-frequency noise was estimated by calculating C-weighted sound pressure levels. The correlation between C-weighted and A-weighted levels ranged from $r = 0.81$ to 0.97 (Keith *et al*., 2016b) and, therefore, no additional benefit would be gained by assessing outcomes in relation to dBC.

### C. Data collection

#### *1. Questionnaire content and administration*

A detailed description of the questionnaire content has been presented by Michaud *et al*. (2013), Michaud *et al*. (2016a), and Feder *et al*. (2015). Briefly, the questionnaire instrument includes modules on basic demographic variables, annoyance, health effects, quality of life, sleep quality, perceived stress, lifestyle behaviours, and prevalent chronic diseases, including diagnosed high blood pressure. Long-term high annoyance toward several wind turbine features was assessed with separate questions that targeted specific wind turbine features (i.e., noise, blinking lights, vibrations, visual, and shadow flicker). As per ISO (2003), high annoyance was defined by combining the top two response categories of the following five-point adjectival scale: *not at all*, *slightly*, *moderately*, *very*, and *extremely*. The time reference period for annoyance was intended to capture the participants' integrated annoyance toward wind turbine features over the previous year while at home (see Michaud *et al.*, 2016b, for more details). Self-reported stress was assessed using the PSS (Cohen *et al.*, 1983), which is a widely used questionnaire with established, acceptable psychometric properties, designed to measure an individual's perception of stress. The questionnaire evaluates the degree to which respondents believe their life is unpredictable, uncontrollable, and overloaded during the previous month. In addition, the scale includes a number of direct questions about current levels of experienced stress. According to Cohen *et al.* (1983), this instrument was designed for use in community samples that have at least a junior high school education, and contains questions that are of a general nature and free of content specific to any subpopulation. Body mass index (BMI) was calculated based on self-reported height and weight, whereby weight in kilograms was divided by height in meters squared.

Consistent with many epidemiological studies that aim to reduce possible survey bias, an attempt was made to mask the primary subject of interest in this study, which was to investigate the community response to wind turbines. To this end, the study was introduced to participants as the *Community Noise and Health Study* and the questionnaire included several items unrelated to wind turbines. A total of 16 trained interviewers collected data through in-person interviews between May, 2013, and September, 2013, in southwestern ON and PEI. Once a roster of adults living in the dwelling was compiled, a computerized method of random selection was used with no substitution permitted.

### D. Blood pressure and heart rate evaluation

Measures of blood pressure and heart rate followed the standardized procedures used by the Canadian Health Measures Survey (Bryan *et al.*, 2010) with the following two exceptions: (1) the interviewer remained in the room, seated behind the respondent during testing as it was neither practical nor appropriate for the interviewer to leave the room during in-home testing; and (2) there was no imposed 5 min rest period prior to testing. This was considered to be unnecessary because the participant had already been seated for the previous 40–45 min while completing the questionnaire.

Systolic and diastolic blood pressure and resting heart rate were measured electronically in a quiet room with a firm chair and table using an automated oscillometric device (BpTRU$^{TM}$BPM-100, Medical Devices Ltd., Coquitlam, British Columbia). A series of six consecutive measurements were taken at one minute intervals. Interviewers ensured proper functioning of the BpTRU$^{TM}$ and the respondent did not talk or move during the test. The last five measurements of the series were used to determine the average resting heart rate and blood pressure.

### E. Hair cortisol analysis

#### *1. Hair sample collection*

Hair samples were obtained from the vertex posterior of the head using scissors and cutting as close to the scalp as possible. The diameter of the grouping of hair strands removed was 5–10 mm. The hair sample was then taped to a section of bar-coded paper that identified the scalp end of the hair. The sample was stored in an envelope at room temperature for later analysis. The average time lapse between storage and analysis was ∼60 days, which would not degrade cortisol concentrations (Webb *et al.*, 2010).

#### *2. Hair treatment and enzyme-linked immunosorbent assay (ELISA)*

In subjects from whom a length of 3 cm or more of hair was collected, the 3 cm portion most proximal to the scalp was analyzed. Hair sample collection and cortisol analysis were conducted in accordance with a previously established protocol described by Pereg *et al.* (2013). A hair mass of 10–15 mg was required for each analysis. Each hair sample was washed twice in isopropanol for 3 min to remove contaminants coating the hair. Following washing, hair samples were allowed to dry for a minimum of 5 h in a fume hood. A methanol extraction was then used to remove the cortisol from the hair. Hair samples were immersed in 1 ml of methanol, minced finely with surgical scissors and then incubated for 16 h at 50 °C while shaking at 100 rpm. The methanol solution was then removed and evaporated under nitrogen gas. The remaining residue was reconstituted with 250 $\mu$l of phosphate buffered saline and analyzed using a salivary cortisol immunoassay (Alpco Diagnostics, Salem, NH). The value determined was subsequently corrected to the hair mass used to yield a hair cortisol concentration in nanograms of cortisol per gram (ng/g) of hair. The lower quantification limit was 25 ng/g for hair mass of 10 mg and 16.67 ng/g for hair mass of 15 mg. The upper limit of detection was 20 000 ng/g and 13 333 ng/g, respectively. The assay detection limit was 0.063 ng/g and 0.042 ng/g for 10 mg and 15 mg hair mass samples, respectively. The intra- and inter-assay variations were 5.87% and 7.05%, respectively.

### F. Statistical methods

The main objective of the analysis was to assess the exposure-response relationship between WTN levels and hair cortisol concentrations, scores on the PSS, blood pressure/heart rate, and to evaluate the sample characteristics that may influence these relationships. All of these health outcomes were measured on a continuous scale. The analysis for continuous outcomes closely follows the description outlined in Michaud *et al.* (2013), which gives a summary of the planned study design and objectives, as well as proposed data analysis. A-weighted WTN categories were defined based on final data collection and are as follows: {<25 dB; [25–30) dB; [30–35) dB; [35–40) dB; [40–46] dB}. Identification of variables that best explain the variability in self-reported and objectively measured stress-related endpoints was done using multiple linear regression. As a first step to develop the best predictive model for each outcome, univariate regression models only adjusting for WTN exposure groups and province were fitted. Explanatory variables significant at the 20% level for univariate analysis were considered in the multiple linear regression models. It should be emphasized that variables considered in the univariate analysis have been previously demonstrated to be related to the modeled endpoint and/or considered by the authors to conceptually have a potential association with the modeled endpoint. Province was initially assessed as an effect modifier. Since the interaction was never statistically significant, province was treated as a confounder in all of the regression models.

Multiple linear regression models describing the relationship between a stress endpoint (PSS, hair cortisol concentrations, blood pressure, and resting heart rate measurements) and predictors were developed using stepwise regression with a 20% significance entry criterion for predictors and a 10% significance criterion to remain in the model. The stepwise regression was carried out in three different ways wherein the base model included exposure to (1) WTN category and province; (2) WTN category, province, and an adjustment for individuals who reported receiving personal benefit from wind turbines in the area; and (3) WTN category and province, stratified for those who received no personal benefit. When developing the model for PSS, hair cortisol was not used as an explanatory variable as this would reduce the sample size substantially from 1231 observations to 675. When developing the model for hair cortisol, PSS was used as a potential explanatory variable in the model. Since time of day was shown to significantly influence heart rate, it was included in the multiple regression model to adjust for it.

Hair cortisol, blood pressure, and resting heart rate endpoints were log-normally distributed (by the Anderson-Darling test for normality), therefore, the geometric mean and corresponding 95% confidence interval (CI) were reported for these endpoints. When the assumptions for the various models for these endpoints were still not satisfied for the logged data, non-parametric approaches were used, in which case the geometric mean and CI were still reported, but the test results were based on non-parametric methods.

Statistical analysis was performed using SAS (Statistical Analysis System) version 9.2 (2014). A 5% statistical significance level was implemented throughout unless otherwise stated. In addition, Tukey corrections were made to account for all pairwise comparisons to ensure that the overall Type I (false positive) error rate was $<0.05$.

## III. RESULTS

### A. Wind turbine sound pressure levels at dwellings

Modeled sound pressure levels and the measurements used to support the calculations are presented in detail by Keith *et al.* (2016a,b). Calculated immission levels as determined by the ISO 9613-1 (ISO, 1993) and ISO 9613-2 (ISO, 1996) reached levels as high as 46 dB under conditions of 8 m/s wind speeds at 10 m heights for favourable propagation conditions. Calculations are representative of typical worst case long-term (1 yr) average WTN levels.

### B. Response rates and sample characteristics

A detailed breakdown of the response rates, along with sample characteristics variables by WTN category is presented by Michaud *et al.* (2016a). Of the 2004 potential dwellings, 1570 were valid and 1238 agreed to participate in the study. This yielded a final response rate of 78.9%. For blood pressure measurements, a total of 1077 respondents participated providing a response rate of 87.0%. A total of 195 respondents were not able to participate in the hair cortisol portion of the physical measures, therefore, a potential 1043 respondents remained. A subsample of 917 of these 1043 respondents consented to the hair sampling for cortisol analysis (response rate, 87.9%).

Factors that could potentially exert an influence on stress responses, including self-reported prevalence of diagnosed chronic diseases and health conditions, quality of life, satisfaction with health, noise sensitivity, and self-reported high sleep disturbance (in general) were all found to be equally distributed across WTN categories (Michaud *et al.*, 2016a).

### C. Hair cortisol, perceived stress, blood pressure, and heart rate

Table I presents the summary statistics for hair cortisol, PSS, blood pressure, and resting heart rate endpoints along with Cronbach's alpha ($\alpha$) for the PSS. Cronbach's $\alpha$ is a measure of the internal consistency or reliability of test scores. Cronbach's $\alpha$ was substantially over the recommended acceptable range of 70% for PSS (Cronbach's $\alpha = 0.86$).

Of the 917 participants who consented to take part in the hair cortisol sampling, 214 samples were found to be of insufficient mass (i.e., $<10$ mg). Of the remaining 703 samples, 9 exceeded the ELISA upper limit of quantification for which no value was given, and the computed results from 19 observations were found to be above the assay detection limit but below the lower limit of quantification. These were removed because 14 of the 19 participants in this subgroup reported using a chemical hair treatment within the previous 3 months, indicating that the results were not reliable. A total of 675 observations remained for hair cortisol analysis. The majority of the hair samples collected were from females ($n = 431$, 63.9%), and individuals aged between 45 and 64 years

TABLE I. Descriptive statistics for stress-related outcomes.

| | *n* | GM (95% CI)[a] | (Min, Max) | Cronbach's $\alpha$ |
|---|---|---|---|---|
| Hair cortisol (ng/g) | 675 | 146.09 (135.46,157.56) | (18.12,7139.34) | |
| Perceived stress scale | 1231 | 11.87 (11.49,12.24)[b] | (0,37) | 0.86 |
| Systolic blood pressure (mmHg) | 1077 | 119.23 (118.27,120.19) | (83,186) | |
| Diastolic blood pressure (mmHg) | 1077 | 75.15 (74.55,75.75) | (50,114) | |
| Heart rate (bpm) | 1077 | 72.50 (71.79,73.21) | (41,125) | |

[a]GM is the geometric mean and corresponding 95% confidence interval (CI) unless otherwise indicated.
[b]Arithmetic mean and corresponding 95% CI.

($n = 311$, 46.1%). The age group least represented were individuals in the ≤25 yr age group ($n = 35$, 5.2%). Hair cortisol levels ranged from 18.12 to 7139.34 ng/g with a geometric mean of 146.09 ng/g and 95% CI: (135.46,157.56).

Blood pressure measurements were fairly equally distributed between men and women (males = 527, 48.9%), although the majority of the measures were from individuals aged between 45 and 64 years ($n = 467$, 43.4%). Similar to hair sampling, those least represented were individuals in the ≤25 yr age-group ($n = 62$, 5.8%). The time of day that blood pressure and heart rate measures were taken had no impact on blood pressure, but did significantly influence resting heart rate ($p = 0.0008$). Average resting heart rate was lower during the morning hours (06:00–11:59 h; 69.19, 95%CI: 67.50,70.92) compared to afternoon (12:00–17:59 h; 72.66, 95% CI: 71.47,73.87) and evening (18:00–22:00 h; 72.65, 95% CI: 71.01,74.32) (data not shown).

#### *1. Association between self-reported and measured blood pressure*

The consistency between self-reported diagnosed high blood pressure and measured blood pressure was assessed by the two-sample *t*-test. In the self-reported high blood pressure group, the geometric mean for systolic blood pressure was 127.51 (95% CI: 125.78,129.27) compared to 115.83 (95% CI: 114.77,116.90) for those who did not report high blood pressure ($p < 0.0001$). Similarly, the corresponding geometric means for diastolic blood pressure were 76.62 (95% CI: 75.51,77.75) and 74.54 (95% CI: 73.83,75.25) ($p = 0.0019$).

### D. Effects of personal and situational variables on hair cortisol concentrations, blood pressure, resting heart rate, and scores on the PSS

An exploratory univariate analysis of self-reported personal and situational variables in relation to hair cortisol concentrations, measured blood pressure, resting heart rate, and scores on the PSS only adjusting for WTN levels and province is presented in the supplementary material attached to the online version of this article.[1] The list of variables considered was extensive and includes, but is not limited to, demographics, illnesses/chronic diseases, quality of life, sleep disturbance, caffeine consumption, and variables related to the perception of wind turbines.

### E. Association between PSS scores, hair cortisol concentrations, blood pressure and resting heart rate

The consistency between self-reported stress and an objective measure of stress was assessed by examining the association between PSS scores and hair cortisol concentrations. Hair cortisol was positively correlated with the PSS scores (Pearson $r = 0.13$, $p = 0.0007$) regardless of WTN exposure. When examining each of the WTN categories, a positive correlation between PSS and hair cortisol is significant only in the following WTN categories: [25–30) dB ($r = 0.35$, $p = 0.0137$) and [40–46] dB ($r = 0.20$, $p = 0.0270$). Nevertheless, in fitting a regression line relating hair cortisol to PSS and accounting for WTN exposure and province, the slope is positive and significant [slope = 0.02, standard error (SE) = 0.01, $p = 0.0008$]. This indicates that higher levels of PSS are correlated with higher levels of hair cortisol.

The association between measured blood pressure and resting heart rate with hair cortisol and PSS was also investigated. Hair cortisol levels were not correlated with blood pressure values (regardless of WTN exposure levels; $r < 0.04$, $p > 0.30$, in all cases). Furthermore, it was observed that none of the blood pressure measures were associated with hair cortisol levels even after adjusting for WTN exposure levels in the regression models. PSS was positively associated only with resting heart rate ($r = 0.08$, $p = 0.0076$), but not with blood pressure. After accounting for WTN in a regression model the association remained (i.e., increased PSS scores were related to increased resting heart rate).

### F. Multiple regression modeling for PSS scores, hair cortisol concentrations, blood pressure, and resting heart rate

The final models for the three approaches to stepwise regression listed in the statistical methods section produced nearly identical results. Therefore, only the regression model whereby the variables WTN, province, and personal benefit were forced into the model is presented. Table II provides a summary of the variables retained in the final multiple linear regression models for the self-reported and objectively measured stress-related outcomes.

#### *1. PSS scores and hair cortisol concentrations*

Tables III(a) and III(b) present the detailed results for the multiple linear regression models for PSS and hair cortisol, respectively. Exposure to WTN was not found to be significantly associated with these endpoints. Some of the variables that increased PSS scores at the 5% level of significance included age (i.e., being <65 years of age), income (i.e., making <$60000 per year), smoking status (i.e., being a smoker), and the presence of self-reported health conditions including migraines/headaches, dizziness, chronic pain, and a diagnosed sleep disorder. PSS scores were not related to receiving personal benefit from having wind turbines in the area ($p = 0.1579$). The final multiple linear regression model explained 21% of the variability in PSS scores.

Being male, having high school or trade/certificate/college education, being obese, and having tinnitus significantly increased the hair cortisol concentrations at the 10% level. Cortisol was reduced among those who cosmetically treated their hair and among those who washed their hair more than eight times per week compared to those who washed it less than once per week. Hair cortisol concentrations were not associated with receiving personal benefit ($p = 0.1084$). Finally, as PSS scores increased so did hair cortisol concentrations ($p = 0.0037$). The final multiple linear regression model accounted for 14% of the variability observed in hair cortisol concentrations.

#### *2. Blood pressure and resting heart rate*

Tables IV(a)–IV(c) present the multiple linear regression models for systolic and diastolic blood pressure, as well as resting heart rate. In all three models exposure to WTN

TABLE II. A summary of significant variables retained in multiple linear regression models for self-reported and measured stress endpoints. The specific direction of change, level of statistical significance, and pairwise comparisons between variable groups are provided in Tables III(a), III(b), and IV(a)–IV(c).

| | Perceived stress scale[a] | Hair cortisol[a] | Systolic blood pressure[a] | Diastolic blood pressure[a] | Heart rate[a] |
|---|---|---|---|---|---|
| Base model | | | | | |
| WTN levels | | | | | |
| Province | | | ++ | ++ | ++ |
| Demographic variables | | | | | |
| Sex | | ++ | ++ | ++ | |
| BMI group | | ++ | ++ | ++ | ++ |
| Age group | ++ | | ++ | ++ | |
| Income | ++ | | | | |
| Smoking status | ++ | | | + | ++ |
| Caffeine consumption | | | + | ++ | ++ |
| Education | + | + | | | |
| Situational variables | | | | | |
| Audible road traffic | ++ | | | | |
| Audible rail noise | ++ | | ++ | + | |
| Time of day | | | | | ++ |
| Wind turbine related variables | | | | | |
| Personal benefits | | | | | ++ |
| Annoyance with blinking lights | | | | ++ | |
| Personal and health related variables | | | | | |
| Cosmetic hair treatment | | ++ | | | |
| Hair washing frequency | | + | | | |
| Health compared to one year ago | ++ | | | | |
| Migraines | ++ | | | | |
| Dizziness | ++ | | | | |
| Tinnitus | | + | + | | |
| Chronic pain | ++ | | | | |
| Asthma | | | | | + |
| High blood pressure | | | ++ | | |
| History of high blood pressure in family | | | ++ | ++ | |
| Chronic bronchitis/emphysema/COPD[b] | | | | ++ | |
| Diabetes | | | + | ++ | ++ |
| Heart disease | | | | ++ | ++ |
| Diagnosed sleep disorder | ++ | | | | |
| Perceived stress scale | N/A | ++ | | | |

[a]+, ++ denote statistically significant, $p < 0.10$, $p < 0.05$, respectively.
[b]COPD, chronic obstructive pulmonary disease.

was not found to be a significant factor in explaining the variability in these measures. Overall, the ON sample had higher systolic and diastolic blood pressures and heart rate (regardless of WTN exposure).

*a. Resting systolic and diastolic blood pressure.* Increased systolic blood pressure was associated with being male, 45 years of age or more, and having a BMI $\geq$25. The participants who self-identified as having high blood pressure or a history of high blood pressure in the family did, in fact, have significantly higher measured systolic blood pressure. In the multiple linear regression model, diastolic blood pressure was not only affected by the same factors as systolic blood pressure, but was also elevated among smokers, those who consumed caffeinated beverages within 2 h of measurements being taken and 2.90 mmHg (95% CI: 0.75,5.05) higher among those who were annoyed by the blinking lights atop wind turbines. The multiple linear regression models for systolic and diastolic blood pressures explained, respectively, ~23% and 19% of the variability in the outcomes.

*b. Resting heart rate.* Being a current smoker, being obese, and having diabetes were significantly associated with increased resting heart rate. Those who self-identified as having heart disease ($p < 0.0001$) and those who received personal benefit ($p = 0.0254$) had significantly lower heart rates. Similarly, time of day was found to have a significant effect on resting heart rate, with lower values in the morning compared to the afternoon or evening. The multiple linear regression model for resting heart rate explained ~11% of the variability in the endpoint.

## IV. DISCUSSION

Taken together, the study results do not support an association between WTN exposure and increased stress either

TABLE III. (a) Multiple linear regression model for perceived stress. (b) Multiple linear regression model for hair cortisol concentrations.

| | | Perceived stress scale ($R^2 = 0.21$, $n = 987$) | | |
|---|---|---|---|---|
| (a) Variable | Groups in variable | LSM (95% CI)[a] | PWC[b] | $p$-value[c] |
| WTN levels (dB) | <25 | 13.67 (11.88,15.46) | | 0.8614 |
| | [25–30) | 13.84 (11.92,15.75) | | |
| | [30–35) | 13.18 (11.69,14.67) | | |
| | [35–40) | 13.15 (11.75,14.55) | | |
| | [40–46] | 13.48 (12.03,14.92) | | |
| Province | PEI | 13.14 (11.57,14.71) | | 0.2254 |
| | ON | 13.79 (12.58,14.99) | | |
| Age group | ≤24 | 14.22 (12.08,16.36) | A | <0.0001 |
| | [25–45) | 14.67 (13.26,16.07) | A | |
| | [45–65) | 13.48 (12.21,14.75) | A | |
| | ≥65 | 11.49 (10.05,12.93) | B | |
| Education | ≤High school | 14.00 (12.69,15.32) | | 0.0794 |
| | Trade/certificate/college | 14.06 (12.69,15.43) | | |
| | University | 12.33 (10.52,14.13) | | |
| Income | <60 K | 14.08 (12.70,15.45) | A | 0.0493 |
| | [60–100) K | 13.55 (12.11, 15.00) | AB | |
| | ≥100 K | 12.76 (11.30,14.21) | B | |
| Smoking status | Current | 14.16 (12.69,15.62) | A | 0.0328 |
| | Former | 13.42 (11.98,14.86) | AB | |
| | Never | 12.81 (11.48,14.15) | B | |
| Audible road traffic | Yes | 13.96 (12.71,15.22) | A | 0.0455 |
| | No | 12.96 (11.45,14.47) | B | |
| Audible rail noise | Yes | 12.90 (11.36,14.43) | A | 0.0296 |
| | No | 14.03 (12.80,15.26) | B | |
| Personal benefit | Yes | 12.96 (11.21,14.71) | | 0.1579 |
| | No | 13.97 (12.83,15.10) | | |
| Health compared to one year ago | Worse | 14.93 (13.45,16.42) | A | <0.0001 |
| | Better | 11.99 (10.68,13.30) | B | |
| Migraines | Yes | 14.13 (12.69,15.57) | A | 0.0097 |
| | No | 12.79 (11.45,14.14) | B | |
| Dizziness | Yes | 14.47 (13.02,15.92) | A | 0.0001 |
| | No | 12.46 (11.12,13.79) | B | |
| Chronic pain | Yes | 14.34 (12.91,15.77) | A | 0.0003 |
| | No | 12.59 (11.26,13.92) | B | |
| Diagnosed sleep disorder | Yes | 14.41 (12.77,16.04) | A | 0.0050 |
| | No | 12.52 (11.27,13.77) | B | |
| | | Hair cortisol (ng/g) ($R^2 = 0.14$, $n = 528$) | | |
| (b) Variable | Groups in variable | LSGM (95% CI)[d] | PWC[b] | $p$-value[c] |
| WTN levels (dB) | <25 | 150.54 (96.94,233.77) | | 0.5416 |
| | [25–30) | 182.20 (118.52,280.10) | | |
| | [30–35) | 191.12 (135.63,269.33) | | |
| | [35–40) | 181.63 (132.24,249.48) | | |
| | [40–46] | 160.25 (115.70,221.96) | | |
| Province | PEI | 163.11 (111.09,239.48) | | 0.4189 |
| | ON | 182.36 (136.61,243.44) | | |
| Sex | Male | 191.88 (136.66,269.40) | A | 0.0442 |
| | Female | 155.02 (112.87,212.90) | B | |
| Education | ≤High school | 197.89 (144.59,270.83) | | 0.0681 |
| | Trade/certificate/college | 191.39 (139.55,262.48) | | |
| | University | 135.45 (89.41,205.19) | | |
| BMI group | <25 underweight-normal | 157.56 (112.79,220.09) | A | 0.0045 |
| | [25–30) overweight | 155.65 (111.10,218.06) | A | |
| | ≥30 obese | 209.19 (151.00,289.80) | B | |
| Cosmetic hair treatment | Yes | 144.32 (103.03,202.15) | A | 0.0005 |
| | No | 206.10 (150.13,282.95) | B | |
| Hair washing frequency | <1 per week | 387.22 (173.34,864.98) | | 0.0551 |
| | [1–3] times per wk | 138.79 (107.35,179.44) | | |

TABLE III. (*Continued*)

| (b) Variable | Groups in variable | Hair cortisol (ng/g) ($R^2 = 0.14$, $n = 528$) LSGM (95% CI)[d] | PWC[b] | $p$-value[c] |
|---|---|---|---|---|
| | [4–7] times per wk | 141.66 (112.33,178.65) | | |
| | ≥8 times per wk | 116.21 (72.84,185.41) | | |
| Personal benefit | Yes | 194.65 (130.59,290.14) | | 0.1084 |
| | No | 152.81 (115.44,202.27) | | |
| Tinnitus | Yes | 188.21 (133.20,265.93) | | 0.0843 |
| | No | 158.04 (116.23,214.89) | | |
| Perceived stress scale[e] | | 0.02 (0.01) | | 0.0037 |

[a]LSM, least squares mean, and 95% confidence interval (CI) as determined by the multiple linear regression model.
[b]PWC, pairwise comparisons. Where overall $p$-value < 0.05, pairwise comparisons were conducted. After adjusting for multiple comparisons, groups with the same letter are statistically similar, whereas groups with different letters are statistically different.
[c]$p$-value for the variable in the model after adjusting for all other variables in the multiple linear regression model.
[d]LSGM, least square geometric mean and 95% CI.
[e]Parameter estimate (b) or slope and standard error (SE) based on the multiple linear regression model.

reported by, or objectively measured among participants exposed to WTN levels up to 46 dB. In the final multiple linear regression models, the level of WTN was not found to be related to any of the stress-related endpoints. Furthermore, the finding that the WTN annoyance variable was absent in any of these models is notable because potential health effects associated with WTN would presumably be indirect and mediated, at least in part, through noise annoyance (Niemann *et al.*, 2006; Bakker *et al.*, 2012). The audibility of wind turbines, and reported annoyance with WTN, were only related to some of the stress outcomes when the analysis did not adjust for other contributing variables (e.g., age, BMI, smoking status, sex, and education) (supplementary material[1]).

After adjusting for other variables, the only wind turbine-related variable that was found to have an influence on any of the stress endpoints was high annoyance with the blinking aircraft warning lights atop wind turbines. Irrespective of WTN levels, annoyance with blinking lights appeared to be statistically associated with a slight elevation in diastolic blood pressure. Although this finding could be a statistical anomaly, the association may be related to the apparent impact that annoyance with the blinking lights was found to have on sleep. Indeed, reported and measured sleep quality has been associated with elevated blood pressure (Fiorentini *et al.*, 2007; Knutson *et al.*, 2009) and in the current study sample high annoyance with the blinking lights on wind turbines was found to be related to objectively measured sleep disturbance (Michaud *et al.*, 2016c). Until this finding is replicated in future research, the increase in diastolic blood pressure should be interpreted cautiously.

Michaud *et al.* (2016a) reported that the prevalence of hypertension and the use of blood pressure medication in the *Community Noise and Health Study* were unrelated to WTN levels. The later finding indicates that the absent association between blood pressure and WTN exposure reported in the current analysis was not related to a disproportionate use of blood pressure medication among the most exposed participants.

Multiple regression modeling left the great majority (77%–89%) of the variance in hair cortisol, systolic blood pressure, diastolic blood pressure, heart rate, and perceived stress unaccounted for. These study results may be complemented or strengthened by additional research that considers factors known to influence the response to community noise in general beyond exposure to wind turbines themselves (see Fig. 1 in the Appendix). Some of these factors include perceived control over the exposure, which could relate to the level of consultation between a developer and the community; maintaining the belief that action could have been taken to reduce WTN exposure, but was not; attitude toward wind turbines as an alternate source of renewable energy; and personality type (Borsky, 1979; Stansfeld and Matheson, 2003). Exposure to multiple stressors or other sources of annoyance, such as transportation noise, may influence the response to WTN exposure.

Transportation noise levels at participants' dwellings were not quantified, which may be a limitation considering the evidence linking exposure to transportation noise with stress-related health effects. However, it is important to keep in mind that this evidence pertains to sound pressure levels that are typically associated with higher levels of annoyance than reported in the current study (Babisch, 1998; Miedema and Vos, 1998; Babisch *et al.*, 2001; Haralabidis *et al.*, 2008). The percentage highly annoyed by aircraft, rail, and road traffic noise across all WTN categories never exceeded 5%. In our view, it is therefore unlikely that exposure to transportation noise had any significant influence on the reported stress reactions.

Another limitation in the current study is the difficulty in providing a precise timeframe for WTN exposure for each participant. Even a wind farm's operational date may not represent the true time of WTN exposure onset as wind farms are often installed over time so that exposure to WTN may vary from person to person. Future research could include specific questions to more precisely identify the individual's history of exposure. The proxy for exposure history included in the current study was derived from asking participants how long they have been hearing noise coming from wind turbines. Michaud *et al.* (2016b) reported that the odds of reporting to be highly annoyed by WTN were almost four times higher among participants who heard the wind turbines for one year or more, compared to those who heard it for less than one year. However, in the final multiple regression

TABLE IV. (a) Multiple linear regression models for resting systolic blood pressure. (b) Multiple linear regression models for resting diastolic blood pressure. (c) Multiple linear regression models for resting heart rate.

| | | Systolic blood pressure (mmHg) ($R^2 = 0.23$, $n = 810$) | | |
|---|---|---|---|---|
| (a) Variable | Groups in variable | LSGM (95% CI)[a] | PWC[b] | *p*-value[c] |
| WTN levels (dB) | <25 | 113.38 (109.17,117.76) | | 0.4990 |
| | [25–30) | 116.82 (112.36,121.45) | | |
| | [30–35) | 116.53 (113.13,120.03) | | |
| | [35–40) | 115.30 (112.17,118.52) | | |
| | [40–46] | 116.25 (112.83,119.77) | | |
| Province | PEI | 114.23 (110.68,117.89) | A | 0.0338 |
| | ON | 117.09 (114.22,120.04) | B | |
| Sex | Male | 117.43 (114.34,120.60) | A | 0.0003 |
| | Female | 113.90 (110.76,117.12) | B | |
| Age group | ≤24 | 109.01 (103.84,114.43) | A | <0.0001 |
| | [25–45) | 112.55 (109.30,115.89) | A | |
| | [45–65) | 118.96 (116.05,121.95) | B | |
| | ≥65 | 122.58 (119.34,125.90) | C | |
| BMI group | <25 underweight–normal | 111.69 (108.51,114.96) | A | <0.0001 |
| | [25–30) overweight | 116.01 (112.66,119.45) | B | |
| | ≥30 obese | 119.39 (116.16,122.70) | C | |
| Caffeine consumption | Yes | 116.51 (113.28,119.84) | | 0.0937 |
| | No | 114.79 (111.77,117.90) | | |
| Audible rail noise | Yes | 114.36 (110.89,117.94) | A | 0.0345 |
| | No | 116.95 (114.08,119.90) | B | |
| Personal benefit | Yes | 115.53 (111.36,119.85) | | 0.8924 |
| | No | 115.77 (113.30,118.30) | | |
| Tinnitus | Yes | 116.65 (113.21,120.19) | | 0.0756 |
| | No | 114.66 (111.80,117.59) | | |
| High blood pressure | Yes | 117.89 (114.45,121.42) | A | 0.0004 |
| | No | 113.46 (110.49,116.50) | B | |
| History of high blood pressure in family | Yes | 116.78 (113.66,119.98) | A | 0.0262 |
| | No | 114.53 (111.40,117.74) | B | |
| Diabetes | Yes | 114.04 (110.17,118.05) | | 0.0567 |
| | No | 117.28 (114.50,120.12) | | |

| | | Diastolic blood pressure (mmHg) ($R^2 = 0.19$, $n = 815$) | | |
|---|---|---|---|---|
| (b) Variable | Groups in variable | LSGM (95% CI)[a] | PWC[b] | *p*-value[c] |
| WTN levels (dB) | <25 | 67.98 (64.90,71.21) | | 0.5006 |
| | [25–30) | 70.20 (67.01,73.55) | | |
| | [30–35) | 69.92 (67.26,72.70) | | |
| | [35–40) | 69.66 (67.11,72.30) | | |
| | [40–46] | 70.34 (67.71,73.06) | | |
| Province | PEI | 68.23 (65.50,71.08) | A | 0.0011 |
| | ON | 71.03 (68.66,73.48) | B | |
| Sex | Male | 71.37 (68.82,74.01) | A | <0.0001 |
| | Female | 67.91 (65.44,70.46) | B | |
| Age group | ≤24 | 67.22 (63.50,71.15) | A | 0.0002 |
| | [25–45) | 69.95 (67.33,72.66) | A | |
| | [45–65) | 72.07 (69.68,74.55) | B | |
| | ≥65 | 69.32 (66.89,71.84) | A | |
| Smoking status | Current | 70.80 (68.12,73.59) | | 0.0586 |
| | Former | 68.85 (66.28,71.51) | | |
| | Never | 69.22 (66.71,71.81) | | |
| BMI group | <25 underweight–normal | 67.00 (64.50,69.60) | A | <0.0001 |
| | [25–30) overweight | 69.96 (67.34,72.69) | B | |
| | ≥30 obese | 71.97 (69.39,74.65) | C | |
| Caffeine consumption | Yes | 70.59 (68.00,73.28) | A | 0.0035 |
| | No | 68.65 (66.21,71.18) | B | |
| Annoyed with blinking lights | Yes | 70.95 (67.95,74.09) | A | 0.0081 |
| | No | 68.31 (66.12,70.56) | B | |
| Audible rail noise | Yes | 68.87 (66.20,71.64) | | 0.0539 |

TABLE IV. (*Continued*)

| (b) Variable | Groups in variable | Diastolic blood pressure (mmHg) ($R^2 = 0.19$, $n = 815$) LSGM (95% CI)[a] | PWC[b] | *p*-value[c] |
|---|---|---|---|---|
| | No | 70.37 (67.96,72.87) | | |
| Personal benefit | Yes | 69.38 (66.30,72.61) | | 0.6844 |
| | No | 69.85 (67.69,72.08) | | |
| History of high blood pressure in family | Yes | 70.55 (68.02,73.17) | A | 0.0023 |
| | No | 68.69 (66.21,71.26) | B | |
| Chronic bronchitis/ emphysema/ COPD | Yes | 67.86 (64.80,71.06) | A | 0.0059 |
| | No | 71.42 (69.12,73.79) | B | |
| Diabetes | Yes | 67.98 (65.16,70.92) | A | 0.0020 |
| | No | 71.29 (68.87,73.80) | B | |
| Heart disease | Yes | 67.79 (64.91,70.80) | A | 0.0019 |
| | No | 71.49 (69.05,74.02) | B | |

| (c) Variable | Groups in variable | Heart rate (bpm) ($R^2 = 0.11$, $n = 990$) LSGM (95% CI)[a] | PWC[b] | *p*-value[c] |
|---|---|---|---|---|
| WTN levels (dB) | <25 | 68.24 (64.98,71.66) | | 0.5223 |
| | [25–30) | 70.59 (67.38,73.95) | | |
| | [30–35) | 69.72 (67.17,72.37) | | |
| | [35–40) | 69.56 (67.21,71.99) | | |
| | [40–46] | 70.71 (68.20,73.32) | | |
| Province | PEI | 68.64 (66.07,71.31) | A | 0.0161 |
| | ON | 70.89 (68.65,73.21) | B | |
| Smoking status | Current | 72.21 (69.54,74.99) | A | <0.0001 |
| | Former | 67.62 (65.30,70.03) | B | |
| | Never | 69.52 (67.15,71.97) | C | |
| BMI group | <25 underweight-normal | 68.90 (66.41,71.47) | A | 0.0475 |
| | [25–30) overweight | 69.42 (66.98,71.95) | AB | |
| | ≥30 obese | 70.97 (68.59,73.44) | B | |
| Caffeine consumption | Yes | 70.91 (68.45,73.45) | A | 0.0036 |
| | No | 68.63 (66.34,70.99) | B | |
| Time of blood pressure measurement | Morning | 67.43 (64.90,70.06) | A | 0.0004 |
| | Afternoon | 71.09 (68.73,73.53) | B | |
| | Evening | 70.82 (68.26,73.47) | B | |
| Personal benefit | Yes | 68.37 (65.44,71.44) | A | 0.0254 |
| | No | 71.17 (69.14,73.27) | B | |
| Asthma | Yes | 70.98 (67.92,74.18) | | 0.0592 |
| | No | 68.56 (66.59,70.59) | | |
| Diabetes | Yes | 71.49 (68.53,74.57) | A | 0.0062 |
| | No | 68.07 (65.98,70.23) | B | |
| Heart disease | Yes | 66.10 (63.29,69.03) | A | <0.0001 |
| | No | 73.62 (71.40,75.91) | B | |

[a]LSGM least square geometric mean and 95% CI.
[b]PWC, pairwise comparisons. Where overall *p*-value < 0.05, PWC were conducted. After adjusting for multiple comparisons, groups with the same letter are statistically similar, whereas groups with different letters are statistically different.
[c]*p*-value for the variable in the model after adjusting for all other variables in the multiple linear regression model.

models, self-reported history of hearing WTN was not related to any of the stress outcomes assessed in this study.

## V. CONCLUDING REMARKS

The results provide no evidence that self-reported or objectively measured stress reactions are significantly influenced by exposure to increasing levels of WTN up to 46 dB. There is an added level of confidence in the findings as this is the first study to date to investigate the potential stress impacts associated with WTN exposure using a combination of self-reported and objectively measured endpoints. Specifically, cortisol concentrations in hair, blood pressure, resting heart rate, and perceived stress using the PSS were measured in relation to WTN exposure. Although the positive correlation found between PSS scores and hair cortisol concentrations was statistically weak, the fact that they move in the same direction provides confidence regarding the validity of the study results and selected endpoints. The weak correlation could be owing to the fact that each endpoint has a different time reference period associated with its outcome. Hair cortisol concentrations and perceived stress scores reflect the previous 90 and 30 days, respectively.

The association between perceived stress and hair cortisol concentrations was similarly found between reported high blood pressure and measured blood pressure. Specifically, participants that indicated they had been diagnosed with high blood pressure from a health care professional had higher resting systolic and diastolic blood pressure.

The observation that the WTN annoyance variable was not retained in the final multiple linear regressions should not be interpreted to mean that this variable has no influence on the modeled endpoints. Rather, in the presence of the other variables in the model, WTN annoyance was not found to contribute further to the overall variance in the measured endpoint(s). In theory, one could arrive at different conclusions if the variables considered in the modeling are not universally incorporated across different study designs.

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## APPENDIX

Figure 1 presents a theoretical model of the complex processes that may be involved in the development of indirect stress-related health effects from exposure to wind turbines. The model assumes the origin of an indirect pathway

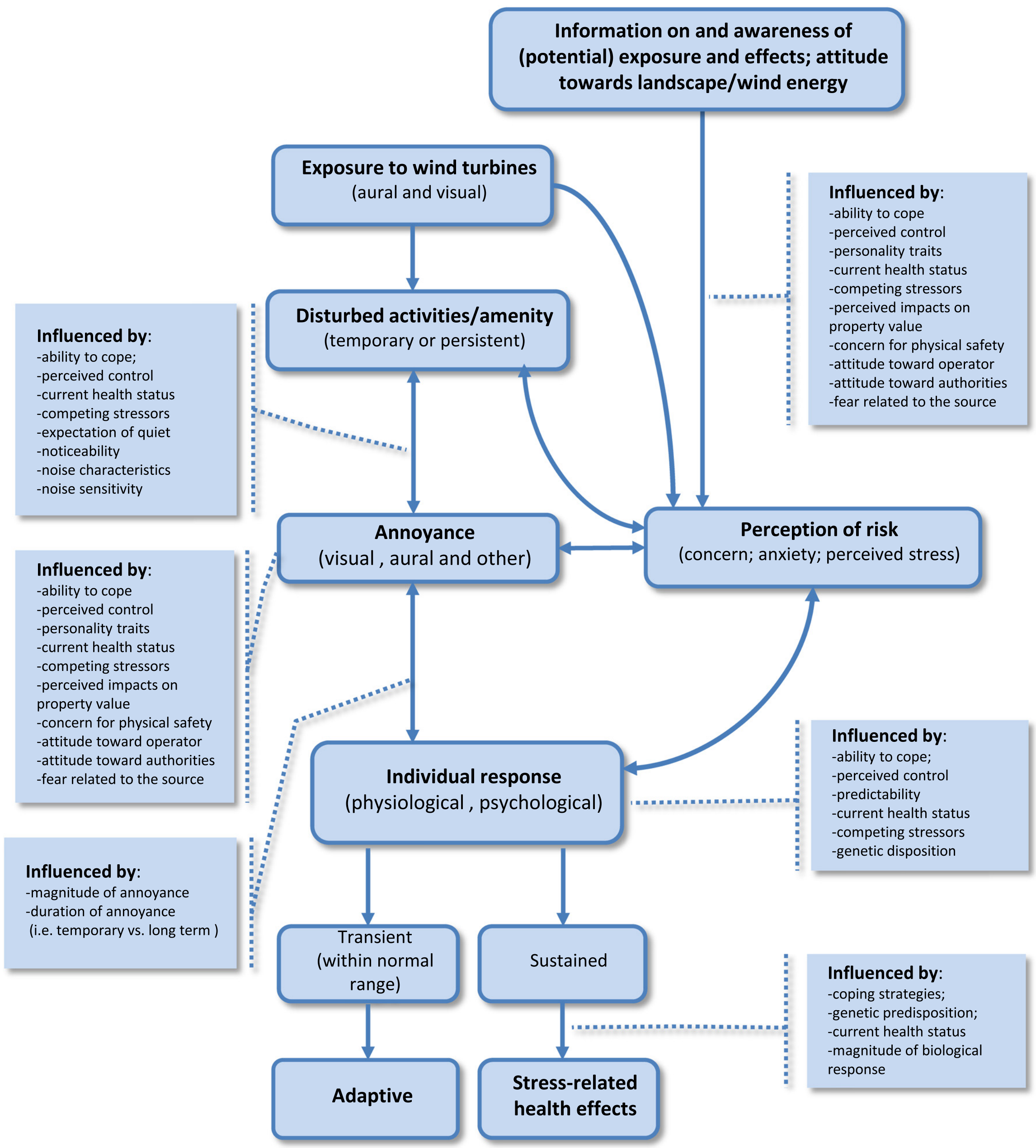


FIG. 1. (Color online) A theoretical model demonstrating the complex processes that may be involved in the potential progression towards indirect health effects from community noise exposure.

beginning with exposure, which can lead to an individualized perception of risk, which itself may be based on information about and attitude toward wind turbines. Perceived risk, and/or other factors that increase annoyance, may then lead to the development of stress-related health effects. Solid arrows represent the proposed direction of interaction. Broken lines represent some of the factors that would be expected to exert an influence at each level in the pathway, or the progression from one level to the next. The proposed model is not limited to WTN and could be applicable for other environmental exposures that are associated with annoyance.

[1]See supplementary material at http://dx.doi.org/10.1121/1.4942402 for the univariate analysis results.


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