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Wind turbine sound pressure level calculations at dwellings

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Wind turbine sound pressure level calculations at dwellings

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This paper provides calculations of outdoor sound pressure levels (SPLs) at dwellings for 10 wind turbine models, to support Health Canada's *Community Noise and Health Study*. Manufacturer supplied and measured wind turbine sound power levels were used to calculate outdoor SPL at 1238 dwellings using ISO [(1996). ISO 9613-2−Acoustics] and a Swedish noise propagation method. Both methods yielded statistically equivalent results. The A- and C-weighted results were highly correlated over the 1238 dwellings (Pearson's linear correlation coefficient $r > 0.8$). Calculated wind turbine SPLs were compared to ambient SPLs from other sources, estimated using guidance documents from the United States and Alberta, Canada.
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I. INTRODUCTION

In Canada, the sound pressure level (SPL) of outdoor community noise at a dwelling is typically predicted with the International Organization for Standardization standards (ISO, 1993, 1996). Wind turbine noise (WTN) can be difficult to distinguish from ambient sound (Pedersen and Halmstad, 2003; Van Renterghem *et al.*, 2013) and varies with weather conditions. As a result, calculations can be more representative of long-term levels than estimates based solely on measurements (ISO, 2007). It is not currently feasible to use more sophisticated methods than ISO (1996) as those methods require data that are usually not available: a sound speed profile, or wind speed and temperature as a function of height (Attenborough *et al.*, 1995). The derivation of such data using cloud cover (Eurasto, 2006; Jonasson, 2007) is also not feasible in rural Canada as this information is typically only available in urban areas or at airports, which often are hundreds of kilometers away, and are not typically near wind turbines.

The ISO (1996) noise propagation standard was not developed for high (>30 m) noise sources such as wind turbines, and its accuracy for distances over 1 km is not specified. As a result, several studies have investigated the agreement between calculated and measured SPL from wind turbines, usually for favorable (downwind) conditions. At distances up to 2 km downwind of the turbines, calculated SPLs were found to underestimate the measured SPLs by 0−5 dB (van den Berg, 2004; Forssén *et al.*, 2010; Plovsing and Søndergaard, 2011; Öhlund and Larsson, 2015).

When modeling wind turbine SPL there are a number of considerations that can increase the modeled values to offset possible underestimates in SPL. In the context of WTN exposure and health, the reference period of time used in the *Community Noise and Health Study* (CNHS) questionnaire

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required an estimate of long-term exposures (Michaud *et al.*, 2016). Ontario (ON) and British Columbia (BC) perform calculations with an assumed temperature of 10 °C and at a relative humidity of 70% (ONMOE, 2008; BC, 2012). These are plausible conditions where the atmospheric absorption is near its minimum (ISO, 1993). In addition, in these provinces, all farm fields are assumed to be mixed ground, 70% absorbing and 30% reflecting, where the reflective part can increase the calculated A-weighted SPL by 1 dB at 4 m receiver height (per ISO, 1996). Higher receiver heights tend to increase SPL due to reduced ground absorption effects, and second or higher storey heights can be used in assessments. The provinces also use the maximum wind turbine sound power for sound level monitoring.

Over a period of a year, changing meteorological conditions can make the long-term average SPL as much as 2 dB lower than the short-term SPL under favorable conditions (ISO, 1996). Research by van den Berg (2008) has shown that for the weather conditions in the Netherlands (for two turbine models), 4.7 dB (standard deviation, SD = ±1.5 dB) must be added to the sound power levels corresponding to 8 m/s wind speed to calculate the long-term average A-weighted DENL (day evening night equivalent SPL). The long-term yearly averaged SPL (van den Berg, 2008) was similar in each of the day, evening and nighttime periods so that the DENL and DNL (day night equivalent SPL; USEPA, 1974) would be approximately equal. For a truly constant SPL, DENL, and DNL are both 6.4 dB higher than the equivalent constant SPL. As such, the yearly average DENL for a wind turbine in the Netherlands would be approximately 1.7 dB (SD = 1.5 dB) lower than the DENL calculated for a constant 8 m/s wind speed. A similar difference applies to DNL or yearly averaged SPL.

There is no current modeling procedure to account for short-term, site-specific variations in sound propagation or sound characteristics (e.g., tonal noise, impulsive noises or amplitude modulation) that could affect an individual's response. This evaluation would require statistical data relevant to the terrain, weather and wind turbine models, as well as a more thorough, quantitative knowledge of the sound characteristics. As such, short-term, site-specific variations are outside the scope of the CNHS and, if present, would be more suited to a case-by-case analysis.

This paper describes the calculation of SPLs and noise propagation modeling carried out for the CNHS. The C-weighted SPLs are estimated and compared to outdoor A-weighted SPLs to evaluate the potential for low frequency noise issues at the selected wind turbine and dwelling locations. Finally, the ambient SPLs in the study areas are estimated for comparison to WTN SPLs.

II. METHODS

A. Study area description

Outdoor SPLs were calculated at 1238 dwellings in the vicinity of 399 wind turbines with rated electrical power output ranging from 660 kW to 3 MW. The distribution of the number of wind turbines is as follows: 16 at 0.66 MW rated electrical power, 52 at 1.5 MW, 24 at 1.65 MW, 82 at 1.8 MW, 30 at 2 MW, 187 at 2.3 MW, and 8 at 3 MW. All turbines were of modern design with tubular towers and 3 pitch-controlled rotor blades upwind of the tower. The average rated electrical power output was 2.0 MW with 0.4 MW SD. There were 315 wind turbines in southwestern Ontario and 84 in Prince Edward Island (PEI). Most wind turbines had a hub height of 80 m, and rotor diameter of approximately 80 m. All dwelling locations were on generally flat agricultural land with crops ranging from soybeans to mature corn stalks. Between many fields there were deciduous, and/or coniferous treed wind breaks as well as scattered small forested sections. In these areas, tree heights range from 10 m to a maximum of 30 m (Gaudet and Profitt, 1958; Sharma and Parton, 2007; Ontario Ministry of Natural Resources, 2014). Roadways varied from gravel to two lane asphalt highways, as well as a single six-lane concrete surface freeway in ON. Most roads were within agricultural zones, averaging less than 1000 vehicles daily (ONMT, 2010). There were 34% of the dwellings associated with built up areas (i.e., in towns, or along roads with population density above 1740 people per square mile) and 38% had a population density below 300 people per square mile (Statistics Canada, 2011).

B. Calculated outdoor A-weighted SPLs at dwellings

Consistent with standard Canadian practice, outdoor WTN SPLs were modeled at dwellings using the ISO 9613 standards (ISO, 1993, 1996). A simpler Swedish method (SEPA, 2012) was also used for comparison. The Swedish method included all turbines in the CNHS, and the ISO (1996) calculations were limited to wind turbines within a radius of 10 km of dwellings. Calculations were based on manufacturer supplied octave band sound power spectra for a wind speed standardized to 8 m/s at 10 m height as per the International Electrotechnical Commission (IEC, 2012) standard. Consistent with common practice in Canada (ONMOE, 2008, 2011; BC, 2012) temperature was set to 10 °C, relative humidity to 70%, mixed ground (i.e., 70% absorbing and 30% reflecting), and a receiver height of 4 m.

Locations of wind turbines and dwellings were estimated using global positioning system (GPS) data. The wind turbine GPS data were obtained from wind turbine operators and were compared with an Aeronautical Obstacle database licensed from Canada's civil air navigation service (NAV Canada). GPS positions of participating dwellings were obtained by Statistics Canada during their in-person survey and these were compared with topographic maps (GeoBase, 2010a). If the comparison of GPS data sources showed positional differences of more than 40 m, the positions were corrected using Google Earth, Google Street View, Bing Maps, and in consultation with the GPS data providers.

Calculations based on the ISO (1996) sound propagation standard were made with CadnaA version 4.4 software (DataKustik GmbH®, 2014). Additional calculations with this software were performed using the Harmonoise module (as implemented by DataKustik GmbH®, 2014). Forested areas, hydrological features and 1 m contour interval elevation data were obtained from GeoBase (2005, 2010a), and were processed using Global Mapper v.14 software (Blue Marble Geographics®, 2014). Buildings were not included in model calculations for two reasons. One reason was that the building heights and locations were only sometimes known. Second, the scale of spatial variations in dwelling SPL, due to building reflection and shielding is less than the 40 m position accuracy for dwellings.

Calculations for SPLs based on the Swedish noise propagation method (SEPA, 2012) used Microsoft Excel software. For the turbines in the study (Keith *et al.*, 2016) the chosen wind speed, 8 m/s, approximated the speed at which the sound power levels were near maximum and independent of wind speed, so the "k" factor from the Swedish method was set equal to zero.

C. Calculated outdoor C-weighted SPLs at dwellings

C-weighted levels were calculated by extending ISO (1993, 1996) to lower frequencies. The propagation calculations at 16 and 31.5 Hz were assumed to have the same change with distance as at 63 Hz. At these low frequencies farm fields are acoustically reflecting with negligible atmospheric attenuation (Sutherland and Bass, 2004, 2006). The CNHS locations also had negligible barriers to sound, and no intervening large bodies of water. At and above 63 Hz, both the A- and C-weighted SPL modeling used the same octave band data from manufacturers. As manufacturers did not provide 16 and 31.5 Hz octave band sound power levels, measured data (Keith *et al.*, 2016) were used in these octave bands for the modeling. At all frequencies the measured 1/3 octave band data were also used to identify, and correct for, significant discrete frequency components that could affect the conversion from the A- to C-weighted data.

D. Calculated yearly averaged SPL at dwellings using wind turbine operational data

Using an analysis similar to van den Berg (2008), the difference between the SPL calculated at 8 m/s wind speed and the yearly averaged daytime, evening and nighttime SPL was also calculated. This was based on the wind turbine nacelle anemometer data obtained in the 12 months before May 2013 (immediately preceding the CNHS). The data were averaged in 10 min intervals and combined with the manufacturers' sound power levels as a function of wind speed. Wind speed and sufficient sound power data were available for four of 10 wind turbine models, in eight of 14 wind turbine facilities. Using the corrections found for this data, an averaged correction was applied to all wind turbines.

E. Estimation of ambient noise SPL in the absence of WTN

The A-weighted ambient SPLs at dwellings, based on population density and transportation, were estimated using the noise guidance from Alberta, Canada (DeGagne, 1999; AUC, 2013) shown in Table I. This table provides estimates of ambient noise including all natural and manmade sources, with the exception of those produced by the energy industry. At some locations it is possible to have a very low ambient SPL and the AUC (2013) guidance provides for adjustments of up to ±10 dB when unusually low (or unusually high) SPLs are documented by measurements.

The AUC (2013) guidance is based on distance to roads that have more than 90 vehicles per night in any month. This value, assuming 10% of the traffic volume occurs at night, approximates the threshold for reported data from ON and PEI (ONMT, 2010, 2013; PEIMT, 2012). Geospatial data for road and rail (GeoBase, 2010a,b, 2012) was processed with the Global Mapper v. 14 software and the dwelling density was adjusted (typically increased by 10%) to conform to the most recent Statistics Canada census (Statistics Canada, 2012).

For ON dwellings near the 6 lane freeway, nighttime SPLs were estimated using the US Traffic Noise Model (FHWA, 1998) and CadnaA software (DataKustik GmbH®, 2014). A speed of 105 km per hour was used for heavy trucks as this value is controlled by a speed limiter (Ontario Highway Traffic Act, 2011). For cars, not a dominant noise source, a speed of 120 km per hour was used as a reasonable worst case. A concrete road surface was used with 78% of the traffic volume during the day, and 10% of that daytime traffic made up of heavy trucks. The evening was assumed to have 10.8% of the traffic volume of which 15% was assumed to be heavy trucks. Heavy trucks were assumed to make up one quarter of the nighttime traffic volume. As actual values were not known, Austrian values were used as implemented by DataKustik GmbH® (2014).

The AUC (2013) predictions were compared to the available short-term measurements at eight dwellings in the CNHS area, where dwelling wall transmission loss was evaluated. These homes did not participate in the survey portion of the CNHS. Attended ambient noise measurements were available from measurements according to ISO (1998), and made 2 m from the dwelling facade at a height of 1.5 m above the bedroom floor. With the possible (unavoidable)

TABLE I. AUC (2013) estimates of average overall A-weighted nighttime ambient SPL. Population density in persons per square kilometer (km) was derived from the specified dwelling density per quarter section (where quarter section is interpreted as an area with 454 m radius) assuming 2.9 persons per Canadian farm dwelling (Statistics Canada, 2011). To convert to either DNL or daytime SPL add 10 dB to the levels in the table.

		Population density, persons per square km		
		<40	40 to 720	>720
Distance to transportation, (road or rail)	<30 m	45 dB	48 dB	51 dB
	30 to 500 m	40 dB	43 dB	46 dB
	>500 m	35 dB	38 dB	41 dB
		Number of dwellings in CNHS (% of total in brackets)		
		100 (8%)	1106 (89%)	32 (2.6%)

exception of distances to building edges, these measurements were consistent with the ISO (2007) procedures for a +3 dB microphone position in front of a facade. The measurements were only made when there were no passing cars and no activity from nearby noise sources. At each location, the measurement was corrected by (i) subtracting, (arithmetically), 3 dB for the facade reflection (ISO, 2007) and (ii) subtracting (on an energy basis), the calculated WTN SPL. This yielded a lower bound on the ambient noise level at the time of the measurement.

F. Accuracy of modeling results

Uncertainties in the ISO (1996) and Swedish (SEPA, 2012) calculation methods are expected to have a SD of approximately 4 dB for distances less than 1 km. This is based on the 3 dB SD given in the ISO (1996) method, the SD for the wind turbine sound power level of 2 dB (Keith *et al.*, 2016) and the comparatively small additional uncertainty from GPS position data (SD $\leq$1 dB).

At the greatest distance of 10 km in the CNHS the standard deviation may approach 10 dB. This is due to the range of values that can occur at larger distances. The ISO (1996) standard assumes spherical propagation with 6 dB reduction per doubling of distance. At distances beyond 10 times the source height weather conditions have a stronger influence (ISO, 2007) and an acoustic shadow can occur. Conversely, beyond approximately 1 km under favorable propagation conditions, up to a frequency of 70 Hz (MG Acoustics, 2014), WTN can propagate cylindrically at 3 dB per doubling of distance (Willshire and Zorumski, 1987; Hubbard and Shepherd, 1991; MG Acoustics, 2014).

The C-weighted results were assumed to have a slightly larger uncertainty than the A-weighted results due to additional uncertainties in the measurements below 63 Hz (Keith *et al.*, 2016). As such the C-weighted values were assumed have a 5 dB SD within 1 km of the wind turbines, rising to 12 dB at distances of 10 km.

The Alberta predictions (AUC, 2013) are estimated to have an uncertainty of 6 dB SD. This is based on Schomer *et al.* (2011) who estimated a SD ranging from 4.5 to 5.2 dB for similar data at a predominantly higher population density and noted that there is more scatter to the data at a lower population density.

G. Measured outdoor SPL at a dwelling

In one case, propagation modeling was compared to measurements at a dwelling located 290 m from the closest wind turbine in a wind turbine facility. Based on weather data from wind turbine anemometers and a local ground based weather station (Keith *et al.*, 2016), 10 s SPL measurements were collected at a microphone flush with the ground (per IEC, 2012) when the wind speed at the turbine nacelle was 7.5−8.5 m/s. At 63 Hz the ISO (1996) propagation standard treats the ground as hard and always adds 3 dB to the modeled levels. Above 63 Hz, assuming mixed ground (30% hard and 70% soft), ISO (1996) adds up to 1.1 dB to the modeled levels due to ground reflection (this value may be lower depending on receiver height or distance from the wind turbine). As a result, to account for reflection in the ground level measurements, they were corrected by subtracting 3 dB at 63 Hz and below, and by subtracting 6 dB at higher frequencies so as to compare to the modeled levels at 4 m height (which approximates a free field).

III. RESULTS AND DISCUSSION

A. Swedish method versus ISO standard at 8 m/s wind speed

The ISO (1996) noise propagation method and the simpler Swedish method (SEPA, 2012) have a similar theoretical basis, so comparison of the results was not made to validate the propagation model. Rather, comparison of the results acts primarily as a check on the consistency of the calculation procedures. Statistically there was little difference between the results obtained with either method. For A-weighted SPLs greater than 25 dB, the Swedish method yielded slightly higher values, with differences ranging from −0.2 to 2.7 dB, and an average difference of 1.1 dB (Pearson's linear correlation coefficient $r > 0.99$). Differences became more pronounced beyond 1 km distance as compared to the ISO (1996) propagation standard because the Swedish method uses slightly lower air absorption and omits ground absorption, and (as calculated for the CNHS) included wind turbines at distances larger than 10 km. These findings provide an independent check of the ISO (1996) calculations. The consistency in the results within their respective SDs also suggests that, using the ISO (1996) model, there is little effect of ignoring turbines beyond 10 km. The agreement between the two methods also shows that over flat farmland, SEPA (2012) can be a useful alternative to ISO (1996). Furthermore, these results show that the CNHS SPL estimates were calculated in a manner that is similar to, or consistent with, a range of previous studies (Pedersen and Persson Waye, 2004; Pedersen, 2007; Pedersen *et al.*, 2009; Pawlaczyk-Łuszczyńska *et al.*, 2014). Note, however, that Pedersen and Persson Waye (2004) and Pedersen (2007) used an older version of the Swedish method (SEPA, 2001) which underestimates SPL beyond 1 km (below about 35 dB A-weighted, depending on the wind turbine characteristics).

B. Comparison of calculated and measured outdoor SPL at a dwelling

Figure 1 shows a comparison of modeling with 2.5 h of measured data (at 0 m, i.e., ground level) obtained near one dwelling when the wind was 8 m/s from the direction of the nearest wind turbine. The ISO (1996) modeling was done at both 0 m receptor height and at the 4 m receptor height used for the CNHS. While agreement between all curves is good below 125 Hz, the measurements and calculations clearly separate at 2 and 4 kHz where measured levels were influenced by audible wind-induced noise from a dry corn field and some trees within 30 m of the microphone position.

At 500 Hz, there appears to be a point of inflection in the measured curve where the ISO (1996) sound propagation standard would predict a notch due to ground absorption. Close to a wind turbine ISO (1996) may overestimate ground

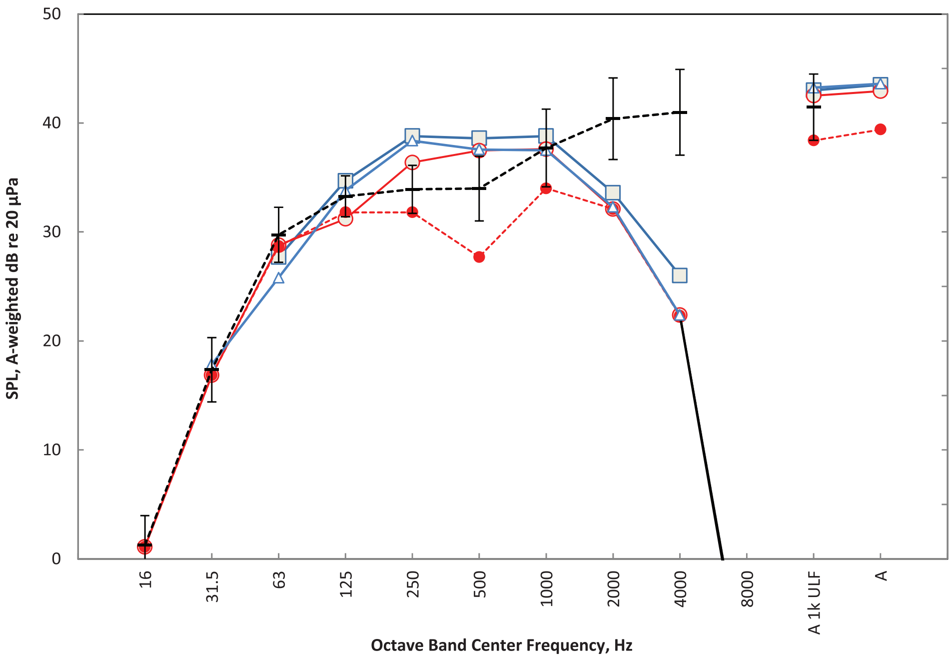

FIG. 1. Comparison of measured and modeled A-weighted SPL at a position 290 m from a wind turbine in a wind turbine facility. On the right hand side are shown the A weighted overall SPL and A-weighted overall SPL with an upper limiting frequency (ULF) of 1 kHz. Black bars and dashed black line: measured energy average SPL at 0 m receptor height with 1 SD error bars; open squares: Swedish method; open triangles: Harmonoise SPL at 4 m height; open red circles and red dashed line: ISO (1996) at 4 m height; filled red circles: ISO (1996) at 0 m height.

attenuation when the receptor height is close to the ground. In such a case, the ISO (1996) standard assumes similar ground absorption for all sources more than 3.5 m high. Conversely, for a receptor height above 3.5 m, the ISO (1996) standard predicts little ground absorption. Wind turbines are high sources, and these measurements were located within 2 km of a large body of water. Therefore, the simple models used may not adequately reflect short term measurement results.

For comparison, the Harmonoise model closely matched the Swedish method and ISO (1996) results at 4 m height. Notably, the A-weighted results from the Harmonoise model varied within a 0.3 dB range for all possible combinations of measurement height (0 or 4 m), wind direction, time of day and atmospheric stability.

C. Calculated outdoor A-weighted SPLs at dwellings using wind turbine operational data

Calculated sound power levels using wind speed from the wind turbine nacelle anemometers and the manufacturers' sound power levels showed that for wind turbines in the CNHS areas, the yearly average sound power level, is approximately 4.5 dB lower compared to continuous wind turbine operation at 8 m/s wind speed. Day, evening, and nighttime yearly average sound power levels were similar so the corresponding correction to obtain yearly averaged DNL and DENL is 1.9 dB (SD = 0.9 dB) higher than the modeled SPL in the CNHS.

The change from modeled levels to yearly average levels is 2.7 dB smaller than the correction found by van den Berg (2008) for two turbine models in the Netherlands. This means that for example, a modeled A-weighted level of 40 dB would be associated with a 41.9 dB long-term average DNL in the CNHS but a 44.7 dB long-term average DNL in the Netherlands. The calculations were repeated using the CNHS hub height wind speed data and the two wind turbine models used by van den Berg. The results showed that the main determinant of the 2.7 dB difference between the two studies was not the change in annual variation of wind speeds. Rather, the effect was largely determined by the difference in wind turbine sound power levels, as functions of wind speed.

D. Estimated C-weighted SPL based on extrapolation of manufacturer data using measurements

Overall, in the CNHS, for 8 m/s wind speed, the C-weighted WTN SPL, L_{eqC} can be related to the A-weighted SPL, L_{eqA} (for $L_{\mathrm{eqA}} > 25$ dB), using the formula

$$L_{\mathrm{eqC}} = 0.514 L_{\mathrm{eqA}} + 34.4, \tag{1}$$

where the SD is approximately 1.5 dB for $L_{\mathrm{eqA}} > 30$ dB. The linear correlation coefficient for this equation (Pearson's r) is 0.81. Given this one-to-one relationship between A and C weighted values there is no statistical advantage to using one metric over the other. Similar results have been obtained in other studies (Søndergaard, 2013; Pawlaczyk-Łuszczyńska *et al.*, 2014; Tachibana *et al.*, 2014). Nevertheless, this finding should not be interpreted to mean that reduction of A-weighted SPL can automatically be used as the only basis for noise mitigation measures aimed at reducing community reaction. If investigations show that this reaction can be reasonably demonstrated as being due to low frequency noise, mitigation measures should target noise metrics that most accurately reflect the frequencies of interest.

E. Ambient SPL in the absence of wind turbines

The AUC (2013) ambient noise predictions were broadly consistent with the available measurements. At 8 dwellings where the wall transmission loss was measured in the CNHS area, the corrected outdoor ambient noise measurements were lower than predicted values by 3.2 dB (SD = 4.5 dB). This difference is minor for a number of reasons: (i) 3 dB was subtracted from measurements to account for the facade reflection; (ii) the microphone was shielded from noise sources behind the dwelling; and (iii) measurements were not used in the analysis when there were local vehicle pass-bys, or other nearby noise sources present.

Figure 1 shows that ambient noise levels can exceed the wind turbine noise. In this figure most data were from nighttime, when AUC (2013) predicted noise levels were 40 dB A-weighted. In the 4 kHz band alone, the ambient noise in Fig. 1 was over 40 dB. As noted in Sec. III A, this is likely due to vegetation noise from trees and crops, which were common in the CNHS areas.

The ambient noise results suggest that, in the CNHS, the WTN was highest away from more densely populated areas and roads. The calculated ambient SPL in the CNHS spanned the range of AUC (2013) predictions. In addition to the 1232 dwellings where ambient noise was calculated using AUC (2013), there were six dwellings near the freeway where the calculated ambient SPL values were found to be up to 61 dB A-weighted (FHWA, 1998). Overall, beyond approximately 1 km from the wind turbines a typical average nighttime A-weighted ambient SPL of 44.9 dB was found, independent of the calculated WTN SPL (corresponding to 8 m/s wind speed). An exception occurred within approximately 1 km of the wind turbines for the 743 dwellings where calculated WTN SPL was above 35 dB A-weighted. At these locations the average calculated ambient SPL dropped 0.6 dB for every dB increase in calculated WTN SPL.

Of the 1238 dwellings in the CNHS, 471 dwellings (38.0%) were in areas below 300 persons per square mile. Comparison to the USEPA estimates based on population density (USEPA, 1974; Schomer *et al.*, 2011) shows that Table I extends the results to lower population densities and gives values consistent with the available measurements (Schomer *et al.*, 2011).

IV. CONCLUSIONS

The findings of this study provide the sound pressure levels needed for the determination of exposure response relationships from the CNHS.

The simplified Swedish noise propagation method was found to give results similar to that obtained using the ISO (1996) method. Although topographical corrections do not appear in the Swedish model, they were not important due to the flat topography in the CNHS areas. The similarity of results provides an added level of confidence in the findings reported in the CNHS.

Over distances less than 1 km, the SD for predicted outdoor SPL outside dwellings was 4 dB, but at 10 km this uncertainty was estimated to rise to at least 10 dB SD.

C-weighted levels were found to be approximately linearly related to the A-weighted levels. Given this one-to-one relationship between A- and C-weighted values there is no statistical advantage to using one metric over the other for WTN in the CNHS.

In comparing calculated long-term average exposure levels in different studies, it was found that it was important to consider the wind turbine sound power curves as a function of wind speed as well as the variation in the wind speed itself. For a long-term average SPL, the SPL based on 8 m/s wind speed should be reduced by 4.5 dB.

Background noise estimated from a Canadian model was consistent with the limited available measured data from the study and it showed that the wind turbines in the CNHS tended to be sited away from existing roads and densely populated areas.

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Attenborough, K., Taherzadeh, S., Bass, H. E., Di, X., Raspet, R., Becker, G. R., Güdesen, A., Chrestman, A., Daigle, G. A., L'Espérance, A., Gabillet, Y., Gilbert, K. E., Li, Y. L., White, M. J., Naz, P., Noble, J. M., and van Hoof, H. A. J. M. (**1995**). "Benchmark cases for outdoor sound propagation models," J. Acoust. Soc. Am. **97**(1), 173–191.

AUC (**2013**). Rule 012-Noise Control, Alberta Utilities Commission, available at http://www.auc.ab.ca/acts-regulations-and-auc-rules/rules/Pages/Rule012.aspx (Last accessed on 5/29/2014).

BC. (**2012**). Best practice for wind power project acoustic assessment British Columbia 2012, British Columbia Ministry of Forests, Lands and Natural Resource Operations, Ministry of Energy, Mines and Natural Gas Environmental Assessment Office, available at http://www2.gov.bc.ca/assets/gov/business/land-water-use/crown-land/bmp_wind_acoustic.pdf (Last accessed on 5/29/2014).

Blue Marble Geographics (**2014**). Global Mapper version 14, available at http://www.bluemarblegeo.com/products/global-mapper.php (Last accessed on 5/29/2014).

DataKustik GmbH® (**2014**). Cadna A version 4.4 Software for Immission Protection, available at www.datakustik.com (Last accessed on 5/29/2014).

DeGagne, D. C. (**1999**). "The evolution of environmental noise legislation for Alberta's energy industry over three decades," Can. Acoust. **27**(3), 76–77.

Eurasto, R. (**2006**). "Nord2000 for road traffic noise prediction. Weather classes and statistics," Research Report VTT-R-02530-06, VTT Technical Research Centre of Finland. http://vejdirektoratet.dk/DA/vejsektor/forskning-og-udvikling/Miljovenlige%20veje/Stoj/NORD2000/Documents/PDF%20til%20st%C3%B8jtema/image.pdf (Last accessed on 12/17/2014).

FHWA (**1998**). FHWA Traffic Noise Model®, technical manual (United States Department of Transportation, Federal Highway Administration, Washington, DC).

Forssén, J., Schiff, M., Pedersen, E., and Persson Waye, K. P. (**2010**). "Wind turbine noise propagation over flat ground: Measurements and predictions," Acta Acust. Acust. **96**(4), 753–760.

Gaudet, J. F., and Profitt, W. M. (**1958**). *Native Trees of Prince Edward Island* (Department of Agriculture, Charlottetown, Prince Edward Island).

GeoBase–Canadian Digital Elevation Data–1945–2010 (**2010a**). Ministry of Natural Resources, Ottawa, ON, http://www.geobase.ca/geobase/en/browse.do?produit=cded&decoupage=50k&map=040J (Last accessed on 1/30/2014).

GeoBase–Land Cover, Circa 2000. 1996–2005 (**2005**). Ministry of Natural Resources, Ottawa, ON, http://www.geobase.ca/geobase/en/browse.do?produit=csc2000v&decoupage=250k&map=040 (Last accessed on 2/19/2014).

GeoBase–National Railway Network (**2012**). Ministry of Natural Resources, Ottawa, ON, http://www.geobase.ca/geobase/en/search.do?produit=nrwn&language=en (Last accessed on 1/20/2014).

GeoBase–National Road Network (**2010b**). Ministry of Natural Resources, Ottawa, ON, http://www.geobase.ca/geobase/en/search.do?produit=nrn&language=en (Last accessed on 12/23/2013).

Hubbard, H. H., and Shepherd, K. P. (**1991**). "Aeroacoustics of large wind turbines," J. Acoust. Soc. Am. **89**(6), 2495–2508.

IEC (**2012**). IEC 61400-11 Ed. 3.0. "Wind turbine generator systems−Part II: Acoustic noise measurement techniques" (International Electrotechnical Commission, Geneva, Switzerland).

ISO (**1993**). ISO 9613-1−Acoustics. "Attenuation of sound during propagation outdoors. Part I: Calculation of the absorption of sound by the atmosphere" (International Organization for Standardization, Geneva, Switzerland).

ISO (**1996**). ISO 9613-2−Acoustics. "Attenuation of sound during propagation outdoors. Part 2: General method of calculation" (International Organization for Standardization, Geneva, Switzerland).

ISO (**1998**). ISO 140-5−Acoustics. "Measurement of sound insulation in buildings and of building elements-Part 5: Field measurements of airborne sound insulation of facade elements and façades" (International Organization for Standardization, Geneva, Switzerland).

ISO (**2007**). ISO 1996-2−Acoustics. "Description, assessment and measurement of environmental noise. Part 2: Determination of environmental noise levels" (International Organization for Standardization, Geneva, Switzerland).

Jonasson, H. (**2007**). "Determination of Lden and Lnight using measurements," SP Technical Research Institute of Sweden, report IMA32-040510 delivered to IMAGINE project.

Keith, S. E., Feder, K., Voicescu, S. A., Soukhovtsev, V., Denning, A., Tsang, J., Broner, N., Richarz, W., and van den Berg, F. (**2016**). "Wind turbine sound power measurements," J. Acoust. Soc. Am. **139**(3), 1431–1435.

MG Acoustics. (**2014**). Analysis, modeling, and prediction of infrasound and low frequency noise from wind turbine installation, phase 1: PEI site, final report, MG Acoustics report for Health Canada, 81 pp.

Michaud, D. S., Feder, K., Keith, S. E., Voicescu, S. A., Marro, L., Than, J., Denning, A., McGuire, D., Bower, T., Lavigne, E., Murray, B. J., Weiss, S. K., and van den Berg, F. (**2016**). "Exposure to wind turbine noise: Perceptual responses and reported health effects," J. Acoust. Soc. Am. **139**(3), 1443–1454.

Öhlund, O., and Larsson, C. (**2015**). "Meteorological effects on wind turbine sound propagation," Appl. Acoust. **89**, 34−41.

ONMOE (**2008**). Noise guidelines for wind farms—interpretation for applying MOE NPC publications to wind power generating facilities—October, PIBS 4709e, Ontario Ministry of the Environment.

ONMOE (**2011**). Compliance protocol for wind turbine noise—guideline for acoustic assessment and measurement, PIBS 8540e, Ontario Ministry of the Environment.

ONMT (**2010**). Provincial Highways Traffic Volumes 2010, Highway Standards Branch, Traffic Office, Ontario Ministry of Transportation.

ONMT. (**2013**). icorridor Ontario Ministry of Transportation http://www.mto.gov.on.ca/iCorridor/map.shtml?accepted=true#tab_4 (Last accessed on 12/23/2013).

Ontario Highway Traffic Act (**2011**). Revised Statutes of Ontario 1990, Revised Regulations of Ontario 1990, Regulation 587: Equipment https://www.ontario.ca/laws/regulation/900587 (Last accessed on 2/19/2016).

Ontario Ministry of Natural Resources (**2014**). The Tree Atlas. http://www.ontario.ca/environment-and-energy/tree-atlas (Last accessed on 11/12/14).

Pawlaczyk-Łuszczyńska, M., Dudarewicz, A., Zaborowski, K., Zamojska-Daniszewska, M., and Waszkowska, M. (**2014**). "Evaluation of annoyance from the wind turbine noise: A pilot study," Int. J. Occup. Environ. Health **27**, 364−388.

Pedersen, E. (**2007**). "Human response to wind turbine noise—perception, annoyance and moderating factors," Doctoral thesis, Göteborg University, Sweden.

Pedersen, E., and Halmstad, H. I. (**2003**). "Noise annoyance from wind turbines: A review," Report 5308, Naturvårdsverket, Swedish Environmental Protection Agency pp. 1−26.

Pedersen, E., and Persson Waye, K. (**2004**). "Perception and annoyance due to wind turbine noise−A dose-response relationship," J. Acoust. Soc. Am. **116**(6), 3460−3470.

Pedersen, E., van den Berg, F., Bakker, R., and Bouma, J. (**2009**). "Response to noise from modern wind farms in The Netherlands," J. Acoust. Soc. Am. **126**(2),634−643.

PEIMT (**2012**). Traffic volume for Prince Edward Island 2012, Capital Projects, Engineering Services, Prince Edward Island Ministry of Transportation and Infrastructure Renewal, available upon request at http://www.gov.pe.ca/tir/index.php3?number=1001593.

Plovsing, B., and Søndergaard, B. (**2011**). "Wind turbine noise propagation: Comparison of measurements and predictions by a method based on geometrical ray theory," Noise Control Eng. J. **59**(1), 10−22.

Schomer, P., Freytag, J., Machesky, A., Luo, C., Dossin, C., Nookala, N., and Pamdighantamc, A. (**2011**). "A re-analysis of Day-Night Sound Level (DNL) as a function of population density in the United States," Noise Control Eng. J. **59**(3), 290−301.

SEPA (**2001**). "Ljud från vindkraftverk" ("Noise from wind turbines"), Report 6241 (in Swedish), Swedish Environmental Protection Agency, Stockholm.

SEPA (**2012**). "Ljud från vindkraftverk" ("Noise from wind turbines"), Report 6241 version 3.0 (in Swedish), Swedish Environmental Protection Agency, Stockholm.

Sharma, M., and Parton, J. (**2007**). "Height-diameter equations for boreal tree species in Ontario using a mixed effects modeling approach," For. Ecol. Manage. **249**, 187−198.

Søndergaard, B. (**2013**). "Low frequency noise from wind turbines: Do the Danish regulations have any impact?," *Wind Turbine Noise 2013*, 28−30 August 2013, Denver, CO.

Statistics Canada (**2011**). Highlights and analysis, 2011 Census of Agriculture, available at http://www.statcan.gc.ca/eng/ca2011/ha (Last accessed on 10/7/2015).

Statistics Canada (**2012**). Census Profile, 2011 Census of Population, Statistics Canada Catalogue no. 98-316-XWE, Ottawa, released October 24, 2012, http://www12.statcan.gc.ca/census-recensement/2011/dp-pd/prof/index.cfm?Lang=E.

Sutherland, L. C., and Bass, H. E. (**2004**). "Atmospheric absorption in the atmosphere up to 160 km," J. Acoust. Soc. Am. **115**(3), 1012−1032.

Sutherland, L. C., and Bass, H. E. (**2006**). "Erratum: Atmospheric absorption in the atmosphere up to 160 km," J. Acoust. Soc. Am. **120**(5), 2985.

Tachibana, H., Yano, H., Fukushima, A., and Shinichi, S. (**2014**). "Nationwide field measurement of wind turbine noise in Japan," Noise Control Eng. J. **62**(2), 90−101.

USEPA (**1974**). "Population Distribution of the United States as a Function of Outdoor Noise Level," Report EPA 550/9-74-009 (U.S. Environmental Protection Agency, Office of Noise Abatement and Control, Washington, DC).

van den Berg, F. (**2008**). "Criteria for wind farm noise: Lmax and Lden," *EURONOISE 2008*, June 29−July 4, Paris, pp. 4043−4048.

van den Berg, G. P. (**2004**). "Effects of the wind profile at night on wind turbine sound," J. Sound Vib. **277**(4-5), 955−970.

Van Renterghem, T., Bockstael, A., De Weirt, V., and Botteldooren, D. (**2013**). "Annoyance, detection and recognition of wind turbine noise," Sci. Total Environ. **456−457**, 333−345.

Willshire, W. L., and Zorumski, W. E. (**1987**). "Low-frequency acoustic propagation in high winds," in *Noise-Con87, Proceedings of the National Conference on Noise Control*, Engineering, State College, PA, June 8−10, pp. 275−280.

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S.I. : WIND TURBINE NOISE

Clarifications on the Design and Interpretation of Conclusions from Health Canada's Study on Wind Turbine Noise and Health

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Abstract

It has been extensively communicated that Health Canada's Community Noise and Health Study (CNHS) did not find positive associations between wind turbine noise (WTN) levels and any of the evaluated health outcomes, beyond an increase in the prevalence of high annoyance toward several wind turbine features. The authors emphasize that this general conclusion remains bound by the study strengths and limitations. Following the publication of the CNHS findings, there has been interest among some individuals to present alternative interpretations of the results originally reported by Michaud et al. (J Acoust Soc Am 139(3):1443–1454, 2016. https://doi.org/10.1121/1.4942391). While recognizing the importance of independent scientific re-evaluation and/or reinterpretation, this commentary serves to clarify and, where necessary, correct some of the information put forward by others. One factor that has been re-evaluated by external stakeholders is the subsample of participants that comprise the lowest WTN category. In their reanalysis, they have eliminated this category, or introduced alternative comparative data. This paper identifies substantial issues associated with the re-evaluation put forth. To thoroughly address these issues and to avoid further confusion or misinterpretation, the authors of the CNHS provide a comparison between the CNHS health condition prevalence data and nationally representative health-based surveys conducted in Canada during the same calendar year. In addition, this paper responds to comments received to date on the CNHS, including the study's age range, the generalization of findings, the provision of raw data, and conclusions on the association between WTN level and health.

Keywords Canada · Community Noise and Health Study · Wind turbine · Noise · Health effects · Cross-sectional study

1 Background

From 2012–2014, Health Canada, in collaboration with Statistics Canada and other external experts conducted a cross-sectional study to investigate the relationship between exposure to sound levels produced from wind turbines and the extent of health effects reported by, and objectively measured in individuals living near wind turbines. In March 2016, the study findings from Health Canada's Community Noise and Health Study (CNHS) were published in the *Journal of the Acoustical Society of America* as a special section on wind turbine noise (WTN) [1–6]. These papers followed the

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CNHS's publications related to quality of life [7] and sleep [8].

The study design was subjected to a rigorous peer review process, which included a 60-day public consultation, a Research Ethics Board review, a review by Health Canada's Science Advisory Board, a review by external experts selected by the World Health Organization (WHO), and the publication of the final planned study design [9]. Publications also reflect the assessment conducted as part of the independent journal review process. Discussions during the study design phase included the selection of a "control group" (i.e., individuals who would have no meaningful exposure to WTN). In any epidemiological study, a control group is always a challenge to establish because it is exceedingly difficult to ensure that the only distinction between the control and exposed group is the exposure of interest; in this case, WTN. In the CNHS, it was determined before the study was conducted that an exposure–response design would be implemented. Inherent to the exposure–response design is that participants are primarily distinguished by the magnitude of their exposure to WTN. Random sampling across different WTN categories strengthens the validity of the exposure–response insofar as it minimizes the likelihood that participant differences will bias the response to WTN at any given exposure level. With this study design participants in the lowest WTN exposure group (i.e., $<$ 25 dBA) can be viewed as a control or comparison group, even though a true control group is more readily established under structured laboratory conditions.

The entire sample was drawn from areas in Prince Edward Island (PEI) and Ontario with similar topography, trees, hills, bodies of water, climate and socioeconomic characteristics. Exposure to WTN levels ranged from $<$ 25 to 46 dBA and the distance between dwellings and turbines was between 0.25 and 11.22 km. The study design included over-sampling in areas where WTN levels were highest to increase the statistical power for detecting potential WTN-associated effects on sleep quality. This over-sampling was also intended to better characterize the exposure–response relationship between WTN levels and various self-reported and objectively measured outcomes in areas where potential health impacts were more likely to be observed. As shown in Michaud et al. [1], reproduced as Table 1, participants in the lowest WTN exposure category had similar demographics compared to participants in other WTN categories. Demographically, some minor differences were found with respect to age, employment, type of dwelling and dwelling ownership; however, with the possible exception of employment, these factors showed no obvious pattern with WTN levels and none were strong enough to exert an influence on the overall results. The primary distinction across the study sample, based on the data collected, was the participants' exposure to WTN.

2 Study Strengths and Limitations

The strengths of the CNHS are as follows: (1) large randomly selected sample of participants ($n = 1238$), (2) high response rate (78.9%) that did not vary by proximity to wind turbines in either province, (3) broadly scoped questionnaire, (4) inclusion of objectively measured endpoints of stress, blood pressure, heart rate and sleep, (5) calculated WTN levels validated with representative field measures, and (6) an exposure–response analysis that encompassed a greater than 21 dB range of exposure to WTN. Despite these strengths, no single cross-sectional study should be viewed as conclusive, and all studies have some limitations. As part of the external peer review of the current publication, it has been noted that the objectively measured outcomes included are not without their own shortcomings. This comment has merit insofar as no single observation should be interpreted in isolation, whether self-reported or objectively measured. Although each objective measure can be criticized in isolation as imperfect, there is added assurance of their validity insofar as they were found to be consistently related to their corresponding self-reported measures. Self-reported high blood pressure was related to higher measured blood pressure, higher perceived stress scores were related to higher hair cortisol concentrations and a lack of an association between WTN levels and reported sleep disturbance (for any reason) was consistent with sleep actigraphy findings.

Cross-sectional studies are a useful and powerful epidemiological tool used to evaluate issues related to public health. However, they are observational studies that collect data at a specific point in time and as such they are typically limited for making causal inferences. Furthermore, they rarely have the statistical power to characterize associations between exposures under study and health conditions that may have very low prevalence rates. Conclusions from the CNHS do not necessarily extrapolate beyond the study sample because the communities in the study may have important differences when compared to others in Canada, or elsewhere. Similarly, the findings are representative only of areas where long-term outdoor WTN levels do not exceed 46 dBA (or 63 dBC) [4,5] and for individuals between the ages of 18 and 79 years. It should be acknowledged that long-term WTN calculations do not investigate specific noise characteristics, such as amplitude modulation and/or the presence of tones and are insensitive to very brief changes in WTN levels. Despite the fact that participants in the study were randomly selected, the locations were not and for this reason the level of confidence for generalizing the results to other areas can only be based on a scientific judgment regarding the level of exposure, terrain, climate, meteorology, and the similarity between the current study sample and others. These study limitations have been identified previously [10]. Thus, similar to epidemiological studies conducted in other areas, this study should be viewed

Table 1 Study sample characteristics reported in Health Canada's Community Noise and Health Study

Variable	WTN (dBA)						
	< 25	[25–30)	[30–35)	[35–40)	[40–46]	Overall	CMH *p* value[a]
n	84[b]	95[b]	304[b]	521[b]	234[b]	1238[b]	
Range of closest turbine (km)	2.32–11.22	1.29–4.47	0.73–2.69	0.44–1.56	0.25–1.05		
Range of BNTS (dBA)	35–51	35–51	35–56	35–57	35–61		
BNTS (dBA) mean (SD)	43.88 (3.43)	44.68 (2.91)	45.21 (3.60)	43.29 (4.11)	41.43 (4.21)		
ON	44.98 (2.88)	44.86 (2.78)	45.54 (3.31)	44.06 (3.86)	42.70 (4.25)		< 0.0001[c]
PEI	41.13 (3.18)	43.00 (3.67)	43.81 (4.38)	38.44 (1.59)	38.05 (1.00)		< 0.0001[c]
Sex *n* (% male)	37 (44.0)	48 (50.5)	150 (49.3)	251 (48.2)	120 (51.3)	606 (49.0)	0.4554
Age mean (SE)	49.75 (1.78)	56.38 (1.37)	52.25 (0.93)	51.26 (0.68)	50.28 (1.03)	51.61 (0.44)	0.0243[d]
Marital status *n* (%)							0.2844
Married/common-law	54 (64.3)	69 (73.4)	199 (65.7)	367 (70.6)	159 (67.9)	848 (68.7)	
Widowed/separated/divorced	16 (19.0)	18 (19.1)	61 (20.1)	85 (16.3)	35 (15.0)	215 (17.4)	
Single, never been married	14 (16.7)	7 (7.4)	43 (14.2)	68 (13.1)	40 (17.1)	172 (13.9)	
Employed *n* (%)	43 (51.8)	47 (49.5)	161 (53.0)	323 (62.0)	148 (63.2)	722 (58.4)	0.0012
Level of education *n* (%)							0.7221
≤ High school	45 (53.6)	52 (54.7)	167 (55.1)	280 (53.7)	134 (57.3)	678 (54.8)	
Trade/certificate/college	34 (40.5)	37 (38.9)	110 (36.3)	203 (39.0)	85 (36.3)	469 (37.9)	
University	5 (6.0)	6 (6.3)	26 (8.6)	38 (7.3)	15 (6.4)	90 (7.3)	
Income (x$1000) *n* (%)							0.8031
< 60	39 (51.3)	40 (54.8)	138 (52.5)	214 (49.1)	100 (49.3)	531 (50.5)	
60–100	18 (23.7)	17 (23.3)	72 (27.4)	134 (30.7)	59 (29.1)	300 (28.5)	
≥ 100	19 (25.0)	16 (21.9)	53 (20.2)	88 (20.2)	44 (21.7)	220 (20.9)	
Detached dwelling *n* (%)[e]	59 (70.2)	84 (88.4)	267 (87.8)	506 (97.1)	216 (92.3)	1132 (91.4)	
ON[e]	46 (76.7)	77 (89.5)	228 (93.1)	437 (97.1)	154 (90.6)	942 (93.2)	< 0.0001[f]
PEI[e]	13 (54.2)	7 (77.8)	39 (66.1)	69 (97.2)	62 (96.9)	190 (83.7)	< 0.0001[f]
Property ownership *n* (%)	60 (71.4)	85 (89.5)	250 (82.2)	466 (89.4)	215 (91.9)	1076 (86.9)	
ON	45 (75.0)	78 (90.7)	215 (87.8)	399 (88.7)	157 (92.4)	894 (88.4)	0.0085[f]
PEI	15 (62.5)	7 (77.8)	35 (59.3)	67 (94.4)	58 (90.6)	182 (80.2)	< 0.0001[f]
Façade type *n* (%)							0.0137
Fully bricked	20 (23.8)	30 (31.6)	85 (28.0)	138 (26.5)	67 (28.6)	340 (27.5)	
Partially bricked	24 (28.6)	29 (30.5)	62 (20.4)	88 (16.9)	15 (6.4)	218 (17.6)	
No brick/other	40 (47.6)	36 (37.9)	157 (51.6)	295 (56.6)	152 (65.0)	680 (54.9)	

Originally presented as Table III in reference [1]

BNTS Background nighttime sound level; *dBA* A-weighted decibel; *km* kilometer; *ON* Ontario, *PEI* Prince Edward Island; *SD* standard deviation; *SE* standard error; *WTN* wind turbine noise

[a] The Cochran–Mantel–Haenszel (CMH) chi-square test is used to adjust for province unless otherwise indicated, *p* values < 0.05 are considered to be statistically significant

[b] Totals may differ due to missing data

[c] Analysis of variance (ANOVA) model

[d] Non-parametric two-way ANOVA model adjusted for province

[e] Non-detached dwellings included semi/duplex/apartment

[f] Chi-square test of independence

with its numerous strengths and limitations in mind, in context of other similarly well conducted studies as well as what is known with respect to biologically plausible mechanisms.

Bearing in mind the stated strengths and limitations of the CNHS, the CNHS data support the general conclusion that beyond an increase in the prevalence of long-term high annoyance toward several wind turbine features [1], there was no evidence to support an association between WTN levels up to 46 dBA and any of the other self-reported or objectively measured health outcomes. Reported and measured health outcomes included, but were not limited to, migraines, dizziness, tinnitus, blood pressure, heart disease, stress, quality of life and multiple measures of sleep [1,3,7,8]. Conclusions based on objectively measured outcomes for measures of stress, blood pressure/heart rate and sleep have additional credibility insofar as they are not influenced by participant awareness bias, which is always something that researchers need to consider when relying solely on self-reported measures of health.

3 Clarifications in Response to CNHS Criticisms and Misinterpretations

Constructive criticism of scientific research is encouraged because it often stimulates improvements in future studies. Some of the points of criticism put forward to challenge the conclusions of the CNHS relate to issues already documented by Health Canada as part of the acknowledged study strengths and limitations (see above). Other misinterpretations of the CNHS findings have resulted from selective reanalysis of some of the self-reported health data by external stakeholders. The issues discussed below have been noted either through discussions between individuals and the CNHS principal investigator (DSM) at scientific conferences and/or in feedback submitted directly to Health Canada. The CNHS authors' response to each of these criticisms (summarized in bold) is presented below.

3.1 The CNHS is Flawed Because of Age Exclusions

A primary objective of the study was to assess the potential impacts that WTN had on measured sleep. For this reason, the study design aimed to maximize the number of participants that fell within the age range studied most frequently by other researchers in this area, and in other community noise and sleep studies published to date. This approach would be expected to increase the statistical power of the CNHS to detect changes in sleep, should they exist. Sleep patterns among children and the elderly are sufficiently different from the study sample age group that their inclusion may have diluted the ability to detect subtle impacts on sleep from WTN exposure [11]. Furthermore, the questionnaire in the study included questions that would not be suitable for minors. Participants above the age of 79 years were also excluded, in part, because age-related hearing loss may influence their perception of WTN, and they are more likely to have other comorbid conditions that impact sleep. Ultimately, the study sample was limited to the age categories investigated by other researchers in this area in order to maximize the possibility of identifying impacts on sleep and other health outcomes, should they exist.

3.2 Data from the CNHS Have Not Been Provided to the Public

In support of transparency and scientific integrity, data originating from the study are available to Canadians, other jurisdictions and interested parties through a number of sources that include the Statistics Canada Research Data Centres [12], and by request through the Health Canada Wind Turbine Noise webpage (additional information) [13]. All publications are freely available as open access in scientific journals, and as plain language summaries on Health Canada's Web site [13]. All data that would be required to reproduce the CNHS findings are available through the means identified above. Data that contain information that could either be used to reveal the identity of a study participant or considered to be confidential business information is not provided, consistent with requirements/exclusions under Canada's *Statistics Act* and *Privacy Act*. Acoustical field recordings made to support WTN calculations are not provided to the public as they contain personal conversations which due to the length of the recordings (over 4000 hours) cannot be redacted.

3.3 The CNHS Did Not Adequately Investigate People Who Have Abandoned Their Homes Due to Health Effects Suffered Following the Installation of Wind Turbines

This is one of the more common assertions by external stakeholders, which is, at least in part, due to the imprecise terminology originally used to describe addresses that were not valid dwellings and therefore considered out-of-scope. The number of addresses considered out-of-scope for the sample was consistent with numbers predicted by Statistics Canada for a rural environment in Canada. Of the 434 out-of-scope addresses, 132 of these were identified as unoccupied for unknown reasons and were found to be randomly distributed across all distances studied in both provinces. Health Canada has no way of knowing the reasons for such vacancies. As specified in Michaud et al. [1] locations coded as out-of-scope were originally [14] assigned the following categories: Demolished for unknown reasons, vacant for unknown reasons, unoccupied, seasonal, > 79 years of age, and other. In an effort to address feedback and provide further clarification, the categories used to define these addresses have been more precisely defined in [1]. Specifically, locations that were originally defined broadly as "unoccupied for unknown reasons" are now more precisely defined as 1) inhabitable dwelling not occupied at time of survey, 2) newly constructed dwelling, but not yet inhabited, or 3) unoccupied trailer in vacant trailer park. Furthermore, it was confirmed that 6 addresses originally identified as unoccupied were in fact GPS coordinates listed in error [1]. There was no evidence in the study to support the suggestion that the unoccupied dwellings have been abandoned by homeowners suffering adverse health effects from WTN exposure.

3.4 Despite an Increase in Annoyance, the CNHS Concluded No Adverse Health Effects

No evidence was found that would reject the null hypothesis; in essence, there was no association between exposure to WTN and the self-reported or objectively measured health endpoints examined. However, the study did demonstrate a relationship between increasing levels of WTN and annoyance toward several features (including noise, perceived indoor vibration during operations,[1] visual impacts, shadow flicker, and the aircraft warning lights on top of the turbines) associated with wind turbines. The WHO Community Noise Guidelines list annoyance as one of the adverse health effects of community noise exposure and include guidelines for annoyance that vary in level based on location and time of day [15]. In their estimation of the burden of disease from environmental noise exposure, the WHO regional office for Europe has assigned a "conservative" disability weight of 0.02 to long-term high (transportation) noise annoyance, where 0 is equivalent to ideal health and 1 is equivalent to death [16]. Although a statistical association was found between high WTN annoyance and several reported and measured health endpoints in the CNHS, these were unrelated to the level of WTN exposure, and there is no way of determining if these conditions may have either pre-dated, and/or were possibly exacerbated by, exposure to wind turbines [1–3,7]. The extent to which long-term high noise annoyance may impact one's health is uncertain. To illustrate, a national Canadian survey on road traffic noise annoyance where 2565 respondents rated their level of annoyance toward road traffic noise over the previous year is highlighted. In the latter study, respondents assessed on an 11-point numerical scale, where 0 was equivalent to "no effect" and 10 was equivalent to "very strong effect," the extent to which their annoyance toward road traffic noise was perceived to have a negative impact on their health. Among respondents who rated their annoyance toward road traffic noise as *high*, 39% perceived the impact of their annoyance on their health to be equivalent to 7 and above. On the other hand, only 6% of respondents who reported lower magnitudes of annoyance (i.e., moderate or lower), perceived the impact on their health as 7 and above. These observations imply a greater importance of "high" noise annoyance in comparison with lower magnitudes and appear to suggest that approximately 2 in 5 Canadians highly annoyed by road traffic noise perceive their annoyance to have a rather strong impact on their health. However, the same survey also demonstrated that annoyance magnitude was not correlated with self-reported health status, that is, many who reported to be highly annoyed by road traffic noise also reported to be in good health [17]. Thus there are inconsistent findings between long-term noise annoyance and potential impacts on health. Considering the comparatively low magnitude of the aforementioned disability weight while noting the observations that high noise annoyance has been reported to be associated with other health conditions [16,18,19] support an interpretation of high noise annoyance as a *potential,* but not a necessary or distinct indicator of adverse health. Collectively, these observations may support decisions by jurisdictions to consider changes in the prevalence of community annoyance when evaluating wind turbine installation projects.

3.5 The Prevalence of Health Effects in the Lowest WTN Category Were Inflated

Following publication of CNHS findings, there has been interest among some individuals not involved in the original CNHS, to reassess a sub-selection of the reported health effects. The CNHS authors recognize the importance of independent scientific re-evaluation and/or reinterpretation however, emphasize caution when reinterpreting results that have been derived through selective removal of data and statistically questionable methodologies. One such reanalysis involved the removal of participants from areas where WTN levels were below 25 dBA based on a concern that the prevalence rates for certain health outcomes (i.e., tinnitus, migraines, dizziness and relative health status compared to last year) were inflated and non-representative [20,21].

An alternative comparison group was comprised for one such reanalysis that included multiple data sources from the USA[2] in addition to sources from a study conducted in a city within the province of Ontario (n=671). The Ontario data were collected in 2001 and 2003 with the purpose of assessing how self-reported health changed over time when the same individuals were evaluated in both surveys [22]. Collectively, these multiple data sources have been mistakenly interpreted and presented to reflect "*General Population Prevalence*" data. The scientific rationale for removing the

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[1] Vibrations/rattles during wind turbine operations were not directly measured or modeled in the CNHS. Michaud et al [1] reported that 4.7% of participants perceived vibrations/rattles during operations, and 1.5% reported to be highly annoyed by vibrations/rattles. Both the perception of and annoyance toward vibration/rattle were found to be statistically related to WTN level.

[2] USA data sources included Migraine Research Foundation, which reports 12% of the population suffers from migraine; however, this statistic appears to include children, who were excluded from the CNHS. The same Web site indicated that 1 in 4 (or 25%) of U.S. households included an individual with migraine. Other cited USA sources include Dizziness-and-balance.com, and Hearing Health Foundation, where the latter source reports that 10% of the USA adult population experienced tinnitus over the last 3 months.

prevalence data observed in the lowest WTN exposure category and then re-evaluating the recompiled data is tenuous given, in part, that they were derived at different time periods for different years (almost a decade earlier) and/or nations. Furthermore, the selective reanalysis of only *tinnitus*, *dizziness*, *migraines* and *relative health status compared to 1 year earlier* is inconsistent with assertions that WTN exposure adversely impacts a wide range of outcomes including, but not limited to sleep, stress and anxiety, cardiovascular responses and quality of life; all of which were among the 20 health conditions evaluated in the CNHS, reproduced in Table 2.

Several factors can reduce scientific validity when making comparisons with historical data from different studies. There may be little scientific support for comparisons between self-reported data that are collected in different study populations especially when the collection periods are separated by several years. A more serious deterrent to such comparisons arises where there are important differences between study methodologies (e.g., data collection, questionnaire content), which can lead to erroneous comparisons, even when the endpoints assessed are similar. For example, there is a clear distinction between a question that evaluates the *current* status of migraines or tinnitus and one that seeks to determine if these conditions were *ever* experienced in one's lifetime. Similarly, the prevalence of a self-reported health condition is not equivalent to the prevalence of consulting with a health-care professional for the same condition. Table 3 illustrates this difference for migraines, dizziness and tinnitus, as reported in the CNHS. Studies like the CNHS, that investigate the potential association between an environmental exposure and health, are especially sensitive to the possibility that publicity regarding health impacts may influence participant response (i.e., awareness bias). Strategies to mitigate this bias in the CNHS included masking the study objective during recruitment, random sampling, a high response rate and supplementing self-report with objective measures. Nevertheless, awareness bias can never be fully eliminated and is another factor to consider when comparing study findings that may be distorted by this bias to varying degrees. No attempt was made to ensure the CNHS was representative of a larger population as doing so is not necessary to ensure a reliable cross-sectional study. Therefore, one must avoid potential "apples to oranges" comparisons as the sample population in the CNHS is not generalizable. This has been identified by the CNHS authors as one of the limitations (i.e., caution on extrapolation beyond the study sample because the communities in the study may have important differences when compared to others in Canada, or elsewhere). With these considerations in mind, this paper presents an opportunity to make some careful comparisons between the CNHS and larger population-based studies that were conducted in Canada during the same calendar year as the CNHS. These comparisons may be of interest to persons reviewing the prevalence data published as part of the CNHS [1].

The Canadian Community Health Survey (CCHS)[3] and the Canadian Health Measures Survey (CHMS)[4] [23,24] are two large-scale population-based surveys routinely conducted by Statistics Canada to collect nationally representative health data on Canadians. These studies are weighted to account for the distribution of Canadians by sex and age. These surveys do not claim to be representative of any particular sub-community. Individual communities may have important differences in the sample characteristics (e.g., health status, socioeconomic variables), which can influence the reported prevalence rates. Response rates for the CCHS and CHMS tend to be lower than that observed in the CNHS (i.e., 78.9%) and therefore caution should be exercised in comparing these larger surveys with the CNHS, which is more appropriately referred to as a community *study* and not a national survey. Table 3 provides comparisons between these larger studies and the CNHS on self-reported measures of health. Potentially important differences were noted between questionnaire content (Table 4), which should be factored into the interpretation of study differences. To our knowledge, the prevalence of dizziness has not been assessed in any nationally representative Canadian survey. Reported prevalence rates vary considerably depending on the type of dizziness evaluated, participant sex and age [25]. Indeed, several health effects are known to increase in prevalence with age. Since the average age in the CNHS was higher than the CCHS and CHMS, differences in overall prevalence rates could potentially reflect age differences. For this reason, results are stratified by age category in Table 3.

Finally, it should be underscored that the comparison of prevalence rates across exposure categories within any given study should consider the sample size for each exposure category. The Cochran–Mantel–Haenszel (CMH) test used in Michaud et al. [1] is a test used in the analysis of stratified categorical data. It allows an investigator to test the association between a categorical predictor or treatment and a binary outcome such as case or control status while taking into account the stratification of the study [26]. The test accounts for the variability or variance associated with each

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[3] The Canadian Community Health Survey (CCHS) is a cross-sectional survey conducted by Statistics Canada to gather health-related data at the sub-provincial levels of geography. The CCHS relies on a large sample (65,000) to provide reliable health-related data every 2 years. The CCHS produces an annual microdata file and a file combining two years of data [23].

[4] The Canadian Health Measures Survey (CHMS) is a survey conducted by Statistics Canada with the objective of collecting information on Canadians' health. The CHMS includes an in-home interview and a collection of physical measures on a wide range of outcomes, including blood pressure, height, weight, bone density, hearing, and vision. The sample size of each cycle of the CHMS is approximately 5700 [24].

Table 2 Distribution of health conditions reported in Health Canada's Community Noise and Health Study

Variable *n* (%)	WTN (dBA)						
	< 25	[25–30)	[30–35)	[35–40)	[40–46]	Overall	CMH[a] *p* value
n	84[b]	95[b]	304[b]	521[b]	234[b]	1238[b]	
Health worse versus last year [c]	17 (20.2)	12 (12.6)	46 (15.1)	90 (17.3)	51 (21.8)	216 (17.5)	0.1724
Migraines	18 (21.4)	24 (25.3)	56 (18.4)	134 (25.8)	57(24.4)	289 (23.4)	0.2308
Dizziness	19 (22.6)	16 (16.8)	65 (21.4)	114 (21.9)	59 (25.2)	273 (22.1)	0.2575
Tinnitus	21 (25.0)	18 (18.9)	71 (23.4)	129 (24.8)	54 (23.2)	293 (23.7)	0.7352
Chronic pain	20 (23.8)	23 (24.2)	75 (24.8)	118 (22.6)	57 (24.5)	293 (23.7)	0.8999
Asthma	8 (9.5)	12 (12.6)	22 (7.2)	43 (8.3)	16 (6.8)	101 (8.2)	0.2436
Arthritis	23 (27.4)	38 (40.0)	98 (32.2)	175 (33.7)	68 (29.1)	402 (32.5)	0.6397
High blood pressure (BP)	24 (28.6)	36 (37.9)	81 (26.8)	166 (32.0)	65 (27.8)	372 (30.2)	0.7385
Medication for high BP	26 (31.3)	34 (35.8)	84 (27.6)	163 (31.3)	63 (27.0)	370 (29.9)	0.4250
Family history of high BP	44 (52.4)	49 (53.8)	132 (45.5)	254 (50.6)	121 (53.8)	600 (50.3)	0.6015
Chronic bronchitis/emphysema/COPD	3 (3.6)	10 (10.8)	17 (5.6)	27 (5.2)	14 (6.0)	71 (5.7)	0.7676
Diabetes	7 (8.3)	8 (8.4)	33 (10.9)	46 (8.8)	19 (8.2)	113 (9.1)	0.6890
Heart disease	8 (9.5)	7 (7.4)	31 (10.2)	32 (6.1)	17 (7.3)	95 (7.7)	0.2110
Highly sleep disturbed[d]	13 (15.7)	11 (11.6)	41 (13.5)	75 (14.5)	24 (10.3)	164 (13.3)	0.4300
Diagnosed sleep disorder	13 (15.5)	10 (10.5)	27 (8.9)	44 (8.4)	25 (10.7)	119 (9.6)	0.3102
Sleep medication	16 (19.0)	18 (18.9)	39 (12.8)	46 (8.8)	29 (12.4)	148 (12.0)	0.0083
Restless leg syndrome	7 (8.3)	16 (16.8)	37 (12.2)	81 (15.5)	33 (14.1)	174 (14.1)	
Restless leg syndrome (ON)	4 (6.7)	15 (17.4)	27 (11.0)	78 (17.3)	28 (16.5)	152 (15.0)	0.0629[e]
Restless leg syndrome (PEI)	3 (12.5)	1 (11.1)	10 (16.9)	3 (4.2)	5 (7.8)	22 (9.7)	0.1628[e]
Medication anxiety or depression	11 (13.1)	14 (14.7)	35 (11.5)	59 (11.3)	23 (9.8)	142 (11.5)	0.2470
QoL past month[f]							
Poor	9 (10.8)	3 (3.2)	21 (6.9)	29 (5.6)	20 (8.6)	82 (6.6)	0.9814
Good	74 (89.2)	92 (96.8)	283 (93.1)	492 (94.4)	213 (91.4)	1154 (93.4)	
Satisfaction with health[f]							
Dissatisfied	13 (15.5)	13 (13.7)	49 (16.1)	66 (12.7)	36 (15.4)	177 (14.3)	0.7262
Satisfied	71 (84.5)	82 (86.3)	255 (83.9)	455 (87.3)	198 (84.6)	1061 (85.7)	

Originally presented as Table V in reference [1]

dBA A-weighted decibel; *COPD* chronic obstructive pulmonary disease; *ON* Ontario, *PEI* Prince Edward Island, *WTN* wind turbine noise

[a] The Cochran–Mantel–Haenszel (CMH) chi-square test is used to adjust for provinces unless otherwise indicated, p values < 0.05 are considered to be statistically significant

[b] Columns may not add to total due to missing data

[c] Worse consists of the two ratings: "*Somewhat worse now*" and "*Much worse now*"

[d] High sleep disturbance consists of the two ratings: "*very*" and "*extremely*" sleep disturbed

[e] Chi-square test of independence

[f] Quality of Life (QoL) and Satisfaction with Health were assessed with the two stand-alone questions on the WHOQOL-BREF. Reporting "*poor*" overall QoL reflects a response of "*poor*" or "*very poor*", and "*good*" reflects a response of "*neither poor nor good*", "*good*" or "*very good*". Reporting "*dissatisfied*" overall Satisfaction with Health reflects a response of "*very dissatisfied*" or "*dissatisfied*", and "*satisfied*" reflects a response of "*neither satisfied nor dissatisfied*", "*satisfied*" or "*very satisfied*". A detailed presentation of the results related to QoL is presented by reference [7]

data point due to sample size within each WTN level category. Claims of a detectable trend in the data based solely on a linear regression line drawn through 4 data points are not supported as they do not reflect the variability (or precision) associated with each of these data points. This variability is related to the sample size in each of the WTN exposure categories and is a necessary statistical consideration when interpreting the CNHS data. Scientifically, the linear regression model used in [20] does not take into account sample sizes and the error is compounded by the elimination of participants from the lowest WTN exposure category. Furthermore, a simple regression line does not adjust for any confounding factors, an important consideration from an epidemiological point of view. For the reasons mentioned above, the CNHS authors agree with the State of Wisconsin's conclusion [27] that the analysis of the CNHS presented as part of the expert testimony in [20] was inappropriate and misleading.

Table 3 Age-adjusted health conditions reported in the Canadian Health Measures Survey, Canadian Community Health Survey and Health Canada's Community Noise and Health Study

	CHMS[a] (2012–2013)			CCHS[a] (2013)			CNHS[a] (2013)		
	18–39 $n = 1258$ % (95% CI)	40–59 $n = 1082$ % (95% CI)	60–79 $n = 1049$ % (95% CI)	18–39 $n = 15{,}746$ % (95% CI)	40–59 $n = 17{,}093$ %(95% CI)	60–79 $n = 18{,}809$ % (95% CI)	18–39 $n = 302$ % (95% CI)	40–59 $n = 496$ % (95% CI)	60–79 $n = 440$ % (95% CI)
Health worse versus last year[b,c]	12.4 (8.8, 17.2)	15.6 (13.1, 18.5)	14.7 (11.2, 19.0)	8.4 (7.8, 9.1)	11.3 (10.4, 12.3)	14.6 (13.7, 15.4)	11.6 (8.5, 15.7)	17.4^{+} (14.3, 21.0)	21.6^{*+} (18.0, 25.7)
Asthma[b]	13.5^{E} (7.7, 22.5)	6.0^{E} (3.9, 9.1)	7.9^{E} (4.3, 14.1)	8.6 (7.9, 9.3)	7.2 (6.6, 7.9)	7.5 (6.8, 8.2)	10.3 (7.3, 14.2)	7.3 (5.3, 9.9)	7.7 (5.6, 10.6)
Arthritis[b]	F	17.4 (13.2, 22.7)	38.1 (32.4, 44.2)	3.0 (2.6, 3.4)	15.8 (14.9, 16.8)	35.1 (34.0, 36.2)	7.3^{+} (4.9, 10.8)	31.3^{*+} (27.4, 35.5)	51.1^{*+} (46.5, 55.8)
Hypertension[b]	F	20.8 (16.8, 25.5)	46.0 (41.4, 50.6)	2.8 (2.4, 3.2)	17.7 (16.6, 18.8)	43.0 (41.7, 44.3)	4.0 (2.3, 6.9)	24.6^{+} (21.1, 28.6)	54.1^{*+} (49.4, 58.7)
Medication for hypertension[b]	F	17.1 (13.5, 21.3)	46.4 (41.2, 51.6)	1.5 (1.3, 1.8)	15.4 (14.4, 16.5)	44.0 (42.7, 45.3)	2.6 (1.3, 5.1)	22.6^{*+} (19.1, 26.5)	57.1^{*+} (52.4, 61.6)
Familial hypertension[b]	48.4 (40.1, 56.8)	60.8 (53.8,67.4)	53.5 (49.3, 57.6)				45.2 (39.5, 50.9)	48.7*(44.3, 53.2)	55.7 (50.9, 60.3)
Chronic bronchitis/ emphysema/ COPD[b,d]	F	2.3^{E}(1.3, 4.0)	6.0^{E} (3.6, 10.0)	0.2^{E} (0.1, 0.3)	3.0 (2.6, 3.5)	6.6 (6.0, 7.2)	2.3^{+} (1.1, 4.7)	4.0 (2.6, 6.2)	10.0^{*+} (7.5, 13.2)
Diabetes[b]	F	6.3^{E} (3.6, 10.6)	15.5 (12.0, 19.7)	1.2 (1.0, 1.5)	6.6 (5.9, 7.3)	16.2 (15.3, 17.1)	1.7 (0.7, 3.8)	7.1 (5.1, 9.7)	16.6 (13.4, 20.4)
Heart disease[b]	F	F	11.2 (8.4, 14.8)	0.8 (0.6, 1.0)	3.1 (2.6, 3.6)	12.5 (11.8, 13.3)	1.0 (0.3, 2.9)	5.6^{+} (3.9, 8.0)	14.6 (11.6, 18.2)
Self-rated quality of life[b,e,f]									
Poor	3.9^{E} (2.0, 7.6)	10.4^{E} (7.1, 15.1)	5.4^{E}(3.6, 8.1)				2.3 (1.1, 4.7)	7.9 (5.8, 10.6)	8.2 (6.0, 11.1)
Good	96.1 (92.4, 98.0)	89.6 (84.9, 92.9)	94.6 (91.9, 96.4)				97.7 (95.3, 98.9)	92.1 (89.4, 94.2)	91.8 (88.9, 94.0)
Health in general[b,f,g]									
Poor/dissatisfied	8.6 (6.1, 12.0)	12.4 (9.1, 16.7)	16.1 (12.8, 20.1)	5.7 (5.1, 6.2)	12.0 (11.1, 13.0)	18.0 (17.1, 19.0)	8.6 (5.9, 12.3)	16.7^{+} (13.7, 20.3)	15.5 (12.4, 19.1)
Good/satisfied	91.4 (88.0, 93.9)	87.6 (83.3, 90.9)	83.9 (79.9, 87.2)	94.3 (93.8, 94.9)	88.0 (87.0, 88.9)	82.0 (81.0, 82.9)	91.4 (87.7, 94.1)	83.3^{+} (79.7, 86.3)	84.5 (80.9, 87.6)
Migraine headaches[b]							30.6 (25.6, 36.0)	25.2 (21.6, 29.2)	16.4 (13.2, 20.1)
Consulted for migraine headaches[b]				11.7 (10.8, 12.5)	12.4 (11.5, 13.4)	6.3 (5.7, 6.9)	17.6^{+} (13.7, 22.3)	12.1 (9.5, 15.3)	9.3^{+} (6.9, 12.4)

Table 3 continued

	CHMS[a] (2012–2013)			CCHS[a] (2013)			CNHS[a] (2013)		
	18–39 $n = 1258$ % (95% CI)	40–59 $n = 1082$ % (95% CI)	60–79 $n = 1049$ % (95% CI)	18–39 $n = 15{,}746$ % (95% CI)	40–59 $n = 17{,}093$ %(95% CI)	60–79 $n = 18{,}809$ % (95% CI)	18–39 $n = 302$ % (95% CI)	40–59 $n = 496$ % (95% CI)	60–79 $n = 440$ % (95% CI)
Tinnitus[b]	37.8 (31.4, 44.7)	32.5 (25.2, 40.7)	33.9 (29.4, 38.7)				17.9* (14.0, 22.6)	25.0 (21.4, 29.0)	26.2* (22.3, 30.5)
Consulted for tinnitus[b]							5.3 (3.3, 8.4)	8.1 (6.0, 10.8)	13.7 (10.8, 17.2)
Dizziness[b]							21.2 (17.0, 26.1)	22.8 (19.3, 26.7)	21.8 (18.2, 25.9)
Consulted for dizziness[b]							11.6 (8.5, 15.7)	14.3 (11.5, 17.7)	14.5 (11.6, 18.1)

CI confidence interval; *CNHS* Community Noise and Health Study; *CCHS* Canadian Community Health Survey; *CHMS* Canadian Health Measures Survey, *COPD* Chronic obstructive pulmonary disease

[E] High sampling variability; use with caution

[F] Suppressed due to extreme sampling variability

[a] Mean age is 45.4, 45.6 and 51.6 years old for CHMS, CCHS and CNHS, respectively

[b] Health endpoint unrelated to WTN exposure in the CNHS

[c] Worse consists of the two ratings: “Somewhat worse now” and “Much worse now”

[d] Reflects a "yes" to any of the three conditions in CHMS

[e] "Poor" includes categories "poor" and "fair"; "Good" includes categories "good", "very good" and "excellent"

[f] "Poor" includes categories "very poor" and "poor"; "Good" includes categories "neither poor nor good", "good" and "very good"

[g] Reporting “dissatisfied” overall Satisfaction with Health reflects a response of “very dissatisfied” or “dissatisfied”, and “satisfied” reflects a response of “neither satisfied nor dissatisfied”, “satisfied” or “very satisfied"

* significantly different from CHMS at the 5% level

[+] significantly different from CCHS at the 5% level

Note, important differences in the questions used to evaluate each health condition in the three studies are shown in Table 4

Table 4 Disparity between questions used to assess the same health conditions in the Canadian Health Measures Survey, Canadian Community Health Survey and Health Canada's Community Noise and Health Study

Health condition	CNHS question	CHMS question	CCHS question
Health worse versus last year	Compared to one year ago, how would you say your health is now? Is it…? Much better now, Somewhat better now, About the same, Somewhat worse now, Much worse now	Same question as CNHS	Same question as CNHS
Asthma[a]	Do you have asthma?	Same question as CNHS	Same question as CNHS
Arthritis[a]	Do you have arthritis?	Same question as CNHS	Do you have arthritis, excluding fibromyalgia?
Hypertension[a]	Do you have high blood pressure?	Same question as CNHS	Same question as CNHS
Medication for hypertension[b]	In the past month, have you taken any medicine for high blood pressure?	Same question as CNHS	Same question as CNHS
Familial hypertension (risk factor)	Is there a history of high blood pressure in your family?	Has anyone in your immediate family ever had high blood pressure, excluding during pregnancy?	Not evaluated
Chronic bronchitis/ emphysema/COPD[ac]	Do you have chronic bronchitis, emphysema or chronic obstructive pulmonary disease?	Do you have chronic bronchitis? Do you have emphysema? Do you have chronic obstructive pulmonary disease?	Same question as CNHS
Diabetes[a]	Do you have diabetes?	Same question as CNHS	Same question as CNHS
Heart disease[a]	Do you have heart disease?	Same question as CNHS	Same question as CNHS
Self-rated quality of life	In the past month, how would you rate your quality of life? Very poor, Poor, Neither poor nor good, Good, Very good	Would you rate your quality of life as…? Poor, Fair, Good, Very good, Excellent	Not evaluated
Health in general	In the past month, how satisfied were you with your health? Very dissatisfied, Dissatisfied, Neither satisfied nor dissatisfied, Satisfied, Very Satisfied	In general, would you say your health is…? Poor, Fair, Good, Very good, Excellent	In general, would you say your health is…? Poor, Fair, Good, Very good, Excellent
Migraine headaches[d,e]	In the last 12 months, have you experienced frequent migraines or headaches (includes nausea, vomiting, sensitivity to light and sound)?	Not evaluated	Do you have migraine headaches?
Tinnitus[d,f]	In the last 12 months, have you experienced ringing, buzzing or whistling sounds in your ears for no reason?	Now I'd like to ask you about tinnitus. Tinnitus is the presence of hissing, buzzing, ringing, rushing or roaring sounds in your ears when there is no other sound around you. Have you ever experienced tinnitus?	Not evaluated
Dizziness[d]	In the last 12 months, have you experienced dizziness?	Not evaluated	Not evaluated

CNHS Community Noise and Health Study; *CCHS* Canadian Community Health Survey; *CHMS* Canadian Health Measures Survey, *COPD* Chronic obstructive pulmonary disease

[a] In CNHS, CHMS and CCHS these questions are preceeded by : "We are interested in "long-term conditions" which are expected to last or have already lasted 6 months or more and that have been diagnosed by a health professional"

[b] In CCHS, this question is skipped if the answer to high blood pressure is "no"

[c] Question asked only if age $\geq$ 35 in CCHS, and questions on emphysema and COPD if age $\geq$ 30 in CHMS

[d] In CNHS, if participants reported the condition, a follow-up question asked if they consulted with a health-care professional regarding the condition. Results originally reported by Michaud et al. [1] were for self-reported prevalence as only a subsample would be expected to consult with a health-care professional about the condition

[e] In CCHS, response to question on migraines was preceeded with the following reminder by the interviewer: "Remember, we're interested in conditions diagnosed by a health professional and that are expected to last or have already lasted 6 months or more"

[f] Tinnitus was evaluated in CHMS with response categories that permitted comparison to CNHS, i.e., experienced within the last year

4 Concluding Remarks

No single study, regardless how comprehensive, can be expected to provide all of the answers to the many questions that exist in any given area of research and any study should be considered in the context of the broader evidence base. Knowledge gained through science is incremental, advanced through replication and consistency in observed outcomes from studies that employ different study designs and methods of exposure assessment. The CNHS results support an association between increasing WTN levels and an increase in the prevalence of annoyance toward various wind turbine features. As noted in the discussion of limitations, cross-sectional studies are not sufficient to establish causality, yet they do have the strength of assessing multiple outcomes and exposures at the same time in large populations over short periods of time. For this reason, they often serve as the basis for hypothesis testing in follow-up case–control and cohort studies. The correlations that were observed between reported high WTN annoyance and some of the self-reported and measured health outcomes are not sufficient, in isolation, to suggest that high degrees of WTN annoyance cause these outcomes (or vice versa). These associations may be influenced by other risk factors that are unaccounted for in a single cross-sectional study, or by design biases (e.g., uses of self-reported data, participation bias). Should an association between high WTN annoyance and adverse health outcomes be established in the future, efforts to minimize annoyance be it from acoustical, or non-acoustical features (e.g., blinking light, shadow flicker mitigation) may be supported on those grounds.

The motivation behind the current commentary was to provide a formal response to feedback that has been received now that more than a year has passed since the primary research findings from the CNHS have been published. It also serves to identify several issues of concern around the reanalysis of the CNHS data presented as part of the expert testimony in [20]. Publishing in a special issue dedicated to WTN should broaden the reach of this response within the scientific community, highlighting important epidemiological principles that need to be considered when evaluating health studies. Our intention is that this commentary may serve as an acknowledgement of, and a collective response to, a range of issues that will undoubtedly remain relevant so long as the CNHS continues to inform discussions that surround the growing science base related to WTN exposure and human health.

References

1. Michaud, D.S., Feder, K., Keith, S.E., Voicescu, S.A., Marro, L., Than, J., Guay, M., Denning, A., McGuire, D., Bower, T., Lavigne, E., Murray, B.J., Weiss, S.K., van den Berg, F.: Exposure to wind turbine noise: Perceptual responses and reported health effects. J. Acoust. Soc. Am. **139**(3), 1443–1454 (2016). https://doi.org/10.1121/1.4942391
2. Michaud, D.S., Feder, K., Keith, S.E., Voicescu, S.A., Marro, L., Than, J., Guay, M., Bower, T., Denning, A., Lavigne, E., Whelan, C., Janssen, S.A., van den Berg, F.: Personal and situational variables associated with wind turbine noise annoyance. J. Acoust. Soc. Am. **139**(3), 1455–1466 (2016). https://doi.org/10.1121/1.4942390
3. Michaud, D.S., Feder, K., Keith, S.E., Voicescu, S.A., Marro, L., Than, J., Guay, M., Denning, A., Bower, T., Villeneuve, P., Russell, E., Koren, G., van den Berg, F.: Self-reported and measured stress related responses associated with exposure to wind turbine noise. J. Acoust. Soc. Am. **139**(3), 1467–1497 (2016). https://doi.org/10.1121/1.4942402
4. Keith, S.E., Feder, K., Voicescu, S., Soukhovtsev, V., Denning, A., Tsang, J., Broner, N., Richarz, W., van den Berg, F.: Wind turbine sound power measurements. J. Acoust. Soc. Am. **139**(3), 1431–1435 (2016). https://doi.org/10.1121/1.4942405
5. Keith, S.E., Feder, K., Voicescu, S., Soukhovtsev, V., Denning, A., Tsang, J., Broner, N., Richarz, W., van den Berg, F.: Wind turbine sound pressure level calculations at dwellings. J. Acoust. Soc. Am. **139**(3), 1436–1442 (2016). https://doi.org/10.1121/1.4942404
6. Voicescu, S., Michaud, D.S., Feder, K., Marro, L., Than, J., Guay, M., Denning, A., Bower, T., van den Berg, F., Broner, N., Lavigne, E.: Estimating annoyance to calculated wind turbine shadow flicker is improved when variables associated with wind turbine noise exposure are considered. J. Acoust. Soc. Am. **139**(3), 1480–1492 (2016). https://doi.org/10.1121/1.4942403
7. Feder, K., Michaud, D.S., Keith, S.E., Voicescu, S.A., Marro, L., Than, J., Guay, M., Denning, A., Bower, T.J., Lavigne, E., Whelan, C., van den Berg, F.: An assessment of quality of life using the WHOQOL-BREF among participants living in the vicinity of wind turbines. Environ. Res. **142**, 227–238 (2015). https://doi.org/10.1016/j.envres.2015.06.043
8. Michaud, D.S., Feder, K., Keith, S.E., Voicescu, S.A., Marro, L., Than, J., Guay, M., Denning, A., Murray, B.J., Weiss, S.K., Villeneuve, P.J., van den Berg, F., Bower, T.: Effects of wind turbine noise on self-reported and objective measures of sleep. SLEEP **39**(1), 97–109 (2016). https://doi.org/10.5665/sleep.5326
9. Michaud, D.S., Keith, S.E., Feder, K., Soukhovtsev, V., Marro, L., Denning, A., McGuire, D., Broner, N., Richarz, W., Tsang, J., Legault, S., Poulin, D., Bryan, S., Duddeck, C., Lavigne, E., Villeneuve, P.J., Leroux, T., Weiss, S.K., Murray, B.J., Bower, T.: Self-reported and objectively measured health indicators among a sample of Canadians living within the vicinity of industrial wind turbines: Social survey and sound level modeling methodology. Noise News Int. **21**, 14–27 (2013)
10. Health Canada: Health Impacts and Exposure to Sound From Wind Turbines: Updated Research Design and Sound Exposure Assessment. https://www.canada.ca/en/health-canada/services/environmental-workplace-health/consultations/health-impacts-exposure-sound-wind-turbines-updated-research-design-sound-exposure-assessment.html (2014). Accessed 14 Nov 2017
11. Ohayon, M.M., Carskadon, M.A., Guilleminault, C., Vitiello, M.W.: Meta-analysis of quantitative sleep parameters from child-

hood to old age in healthy individuals: developing normative sleep values across the human lifespan. SLEEP **27**(7), 1255–1273 (2004). https://doi.org/10.1093/sleep/27.7.1255

12. Statistics Canada Research Data Centre reference. The Research Data Centres (RDC) Program. http://www.statcan.gc.ca/eng/rdc/index (2017). Accessed 14 Nov 2017
13. Health Canada: Wind turbine noise. https://www.canada.ca/en/health-canada/services/environmental-workplace-health/noise/wind-turbine-noise.html (2014). Accessed 14 Nov 2017
14. Health Canada: Wind turbine Noise and Health Study: Summary of Results. https://www.canada.ca/en/health-canada/services/environmental-workplace-health/noise/wind-turbine-noise/wind-turbine-noise-health-study-summary-results.html (2014). Accessed 14 Nov 2017
15. World Health Organization: Guidelines for Community Noise. WHO, Geneva (1999)
16. World Health Organization (WHO): Burden of disease from environmental noise. Quantification of healthy life years lost in Europe. Fritschi, L., Brown, A.L., Kim, R., Schwela, D., Kephalopolous, S. (eds.). Bonn: World Health Organization, Regional Office for Europe (2011)
17. Michaud, D.S., Keith, S.E., McMurchy, D.: Annoyance and disturbance of daily activities from road traffic noise in Canada. J. Acoust. Soc. Am. **123**(2), 784–792 (2008). https://doi.org/10.1121/1.2821984
18. Basner, M., Babisch, W., Davis, A., Brink, M., Clark, C., Janssen, S., Stansfeld, S.: Auditory and non-auditory effects of noise on health. Lancet **383**(9925), 1325–1332 (2014). https://doi.org/10.1016/S0140-6736(13)61613-X
19. Niemann, H., Bonnefoy, X., Braubach, M., Hecht, K., Maschke, C., Rodrigues, C., Röbbel, N.: Noise-induced annoyance and morbidity results from the pan-European LARES study. Noise Health **8**(31), 63–79 (2006). http://www.noiseandhealth.org/text.asp?2006/8/31/63/33537
20. Public Service Commission of Wisconsin (PSCW): Application of Highland Wind Farm, LLC, for a certificate of public convenience and necessity to construct a 102.5 MW wind electric generation facility and associated electric facilities, to be located in the towns of Forest and Cylon, St. Croix County, Wisconsin. Expert statement of Richard James. Docket No.: 2525-CE-100. http://apps.psc.wi.gov/vs2015/ERF_view/viewdoc.aspx?docid=284895. Accessed 14 Nov 2017
21. Nissenbaum, M.A.: Industrial wind turbines and adverse health effects: where we are, where we need to go, and the need for regulations and predictive models to recognize human physiology. J. Acoust. Soc. Am. **139**, 2149 (2016). https://doi.org/10.1121/1.4950348
22. Wilson, K., Elliott, S.J., Eyles, J.D., Keller-Olaman, S.J.: Factors affecting change over time in self-reported health. Can. J. Public Health **98**(2) 154–158 (2007). https://www.ncbi.nlm.nih.gov/pubmed/17441542
23. Statistics Canada: Canadian Community Health Survey - Annual Component (CCHS). https://www.statcan.gc.ca/eng/survey/household/3226 (2015). Accessed 15 Jan 2018
24. Statistics Canada: Ongoing. Canadian Health Measures Survey. http://www.statcan.gc.ca/eng/survey/household/5071 (Ongoing). Accessed 14 Nov 2017
25. Bittar, R.S.M., Oiticia, J., Bottino, M.A., Ganança, F.F., Dimitrov, R.: Population epidemiological study on the prevalence of dizziness in the city of São Paulo. Braz. J. Otorhinolaryngol. **79**(6), 688–698 (2013). https://doi.org/10.5935/1808-8694.20130127
26. Agresti, A.: Categorical Data Analysis (PDF), pp. 231–232. Wiley, Hooken (2002). ISBN 0-471-36093-7
27. Public Service Commission of Wisconsin (PSCW): Application of Highland Wind Farm, LLC, for a certificate of public convenience and necessity to construct a 102.5 MW wind electric generation facility and associated electric facilities, to be located in the towns of Forest and Cylon, St. Croix County, Wisconsin. Final Decision on Remand. http://apps.psc.wi.gov/vs2015/ERF_view/viewdoc.aspx?docid=290039 (2016). Accessed 14 Nov 2017

Exposure to wind turbine noise: Perceptual responses and reported health effects

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Exposure to wind turbine noise: Perceptual responses and reported health effects

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Health Canada, in collaboration with Statistics Canada, and other external experts, conducted the Community Noise and Health Study to better understand the impacts of wind turbine noise (WTN) on health and well-being. A cross-sectional epidemiological study was carried out between May and September 2013 in southwestern Ontario and Prince Edward Island on 1238 randomly selected participants (606 males, 632 females) aged 18–79 years, living between 0.25 and 11.22 km from operational wind turbines. Calculated outdoor WTN levels at the dwelling reached 46 dBA. Response rate was 78.9% and did not significantly differ across sample strata. Self-reported health effects (e.g., migraines, tinnitus, dizziness, etc.), sleep disturbance, sleep disorders, quality of life, and perceived stress were not related to WTN levels. Visual and auditory perception of wind turbines as reported by respondents increased significantly with increasing WTN levels as did high annoyance toward several wind turbine features, including the following: noise, blinking lights, shadow flicker, visual impacts, and vibrations. Concern for physical safety and closing bedroom windows to reduce WTN during sleep also increased with increasing WTN levels. Other sample characteristics are discussed in relation to WTN levels. Beyond annoyance, results do not support an association between exposure to WTN up to 46 dBA and the evaluated health-related endpoints.

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[SF] Pages: 1443–1454

I. INTRODUCTION

Jurisdiction for the regulation of noise is shared across many levels of government in Canada. As the federal department of health, Health Canada's mandate with respect to wind power includes providing science-based advice, upon request, to federal departments, provinces, territories and other stakeholders regarding the potential impacts of wind turbine noise (WTN) on community health and well-being. Provinces and territories, through the legislation they have enacted, make decisions in relation to areas including installation, placement, sound levels, and mitigation measures for wind turbines. In July 2012, Health Canada announced its

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intention to undertake a large scale epidemiological study in collaboration with Statistics Canada entitled Community Noise and Health Study (CNHS). Statistics Canada is the federal government department responsible for producing statistics relevant to Canadians.

In comparison to the scientific literature that exists for other sources of environmental noise, there are few original peer-reviewed field studies that have investigated the community response to modern wind turbines. The studies that have been conducted to date differ substantially in terms of their design and evaluated endpoints (Krogh *et al.*, 2011; Mroczek *et al.*, 2012; Mroczek *et al.*, 2015; Nissenbaum *et al.*, 2012; Pawlaczyk-Łuszczyńska *et al.*, 2014; Pedersen and Persson Waye, 2004, 2007; Pedersen *et al.*, 2009; Shepherd *et al.*, 2011; Tachibana *et al.*, 2012; Tachibana *et al.*, 2014; Kuwano *et al.*, 2014). Common features among these studies include reliance upon self-reported endpoints, modeled WTN exposure and/or proximity to wind turbines as the explanatory variable for the observed community response.

There are numerous health symptoms attributed to WTN exposure including, but not limited to, cardiovascular effects, vertigo, tinnitus, anxiety, depression, migraines, sleep disturbance, and annoyance. Health effects and exposure to WTN have been subjected to several reviews and the general consensus to emerge to date is that the most robust evidence is for an association between exposure to WTN and community annoyance with inconsistent support observed for subjective sleep disturbance (Bakker *et al.*, 2012; Council of Canadian Academies, 2015; Knopper *et al.*, 2014; MassDEP MDPH, 2012; McCunney *et al.*, 2014; Merlin *et al.*, 2014; Pedersen, 2011).

The current analysis provides an account of the sample demographics, response rates, and observed prevalence rates for the various self-reported measures as a function of the outdoor WTN levels calculated in the CNHS.

II. METHOD

A. Sample design

Factors considered in the determination of the study sample size, including statistical power, have been described by Michaud *et al.* (2013), Michaud *et al.* (2016b), and Feder *et al.* (2015). The target population consisted of adults, aged 18 to 79 years, living in communities within approximately 10 km of a wind turbine in southwestern Ontario (ON) and Prince Edward Island (PEI). Selected areas in both provinces were characterized by flat lands with rural/semi-rural type environments. Prior to field work, a list of addresses (i.e., potential dwellings) was developed by Statistics Canada. The list consists mostly of dwellings, but it can include industrial facilities, churches, demolished/vacant dwellings, etc. (i.e., non-dwellings), that would be classified as out-of-scope for the purposes of the CNHS. The ON and PEI sampling areas included 315 and 84 wind turbines, respectively. Wind turbine electrical power output ranged between 660 kW to 3 MW (average 2.0 ± 0.4 MW). All turbines were modern design with 3 pitch controlled rotor blades (∼80 m diameter) upwind of the tower, and predominantly 80 m hub heights. This study was approved by the Health Canada and Public Health Agency of Canada Research Ethics Board (Protocols #2012–0065 and #2012–0072).

B. Wind turbine sound pressure levels at dwellings

A detailed description of the approach applied to sound pressure level modeling [including background nighttime sound pressure (BNTS) levels] is presented separately (Keith *et al.*, 2016b). Briefly, sound pressure levels were estimated at each dwelling using both ISO (1993) and ISO (1996) as incorporated in the commercial software CadnaA version 4.4 (Datakustik, 2014). The calculations were based on manufacturers' octave band sound power spectra at 10 m height, 8 m/s wind speed for favorable propagation conditions (Keith *et al.*, 2016a). As described in detail by Keith *et al.* (2016b), BNTS levels were calculated following provincial noise regulations for Alberta, Canada (Alberta Utilities Commission, 2013). With this approach BNTS levels can range between 35 dBA to 51 dBA. The possibility that BNTS levels due to highway road traffic noise exposure may exceed the level estimated by Alberta regulations was considered. Where the upper limits of this approach were exceeded (i.e., 51 dB), nighttime levels were derived using the US Traffic Noise Model (United States Department of Transportation, 1998) module in the CadnaA software.

Low frequency noise was estimated in the CNHS by calculating outdoor C-weighted sound pressure levels at all dwellings. There was no additional gain by analysing the data using C-weighted levels because the statistical correlation between C-weighted and A-weighted levels was very high (i.e., $r = 0.81$–0.97) (Keith *et al.*, 2016a).

C. Data collection

1. Questionnaire content and collection

The final questionnaire, available on the Statistics Canada website (Statistics Canada, 2014) and in the supplementary materials,[1] consisted of basic socio-demographics, modules on community noise and annoyance, health effects, lifestyle behaviors and prevalent chronic illnesses. In addition to these modules, validated psychometric scales were incorporated, without modification, to assess perceived stress (Cohen *et al.*, 1983), quality of life (WHOQOL Group, 1998; Skevington *et al.*, 2004) and sleep disturbance (Buysse *et al.*, 1989).

Questionnaire data were collected through in-person home interviews by 16 Statistics Canada trained interviewers between May and September 2013. The study was introduced as the "Community Noise and Health Study" as a means of masking the true intent of the study, which was to investigate the association between health and WTN exposure. All identified dwellings within ∼600 m from a wind turbine were selected. Between 600 m and 11.22 km, dwellings were randomly selected. Once a roster of adults (between the ages of 18 and 79 years) living in the dwelling was compiled, one individual from each household was randomly invited to participate. No substitutions were permitted under any circumstances. Participants were not compensated for their participation.

2. Long-term high annoyance

To evaluate the prevalence of annoyance, participants were initially asked to spontaneously identify sources of noise they hear originating from outdoors while they are either inside or outside their home. The interviewer grouped the responses as road traffic, aircraft, railway/trains, wind turbine, and "*other*." Follow-up questions were designed to confirm the initial response where the participant may not have spontaneously identified wind turbines, rail, road and aircraft as one of the audible sources. For each audible noise source participants were asked to respond to the following question from ISO/TS (2003a): "*Thinking about the last year or so, when you are at home, how much does noise from [SOURCE] bother, disturb or annoy you?*" Response categories included the following: "*not at all*," "*slightly*," "*moderately*," "*very*," or "*extremely*." Participants who reported they did not hear a particular source of noise, were classified into a "*do not hear*" group and retained in analysis (to ensure that the correct sample size was accounted for in the modeling). The analysis of annoyance was performed after collapsing the response categories into two groups (i.e., "*highly annoyed*" and "*not highly annoyed*"). As per ISO/TS (2003a), participants reporting to be either "*very*" or "*extremely*" annoyed were treated as "*highly annoyed*" in the analysis. The "*not highly annoyed*" group was composed of participants from the remaining response categories in addition to those who did not hear wind turbines. Similarly, an analysis of the percentage highly subjectively sleep disturbed, highly noise sensitive, and highly concerned about physical safety from having wind turbines in the area was carried out applying the same classification approach used for annoyance.

The use of filter questions and an assessment of annoyance using only an adjectival scale are approaches not recommended by ISO/TS (2003a). The procedures followed in the current study were chosen to minimize the possibility of participant confusion (i.e., by asking how annoyed they are toward the noise from a source that may not be audible). Although there is value in confirming the response on the adjectival scale with a numerical scale, this approach would have added length to the questionnaire, or led to the removal of other questions. Collectively, the deviations from ISO/TS (2003a) conformed to the recommendations by Statistics Canada and to the approach adopted in a large-scale study conducted by Pedersen *et al.* (2009).

D. Statistical methodology

The analysis for categorical outcomes closely follows the description outlined in Michaud *et al.* (2013), which provides a summary of the pre-data collection study design and objectives, as well as the proposed data analysis. Final wind turbine distance and WTN categories were defined as follows: distance categories in km $\{\leq 0.550; (0.550\text{–}1]; (1\text{–}2]; (2\text{–}5]; \text{and} > 5\}$, WTN exposure categories in dBA $\{<25; [25\text{–}30); [30\text{–}35); [35\text{–}40); \text{and } [40\text{–}46]\}$. The top category included 46 dB as only six cases were observed at $\geq$45 dBA. All models were adjusted for provincial differences. Province was initially assessed as an effect modifier. When the interaction between WTN and province was significant, separate models were reported for each province. This included reporting separate chi-square tests of independence or logistic regression models for each province. When the interaction was not statistically significant, province was treated as a confounder in the model. This included using the Cochran-Mantel-Haenszel (CMH) chi-square tests for contingency tables (which adjusts for confounders), as well as adjusting the logistic regression models for the confounder of province.

The questionnaire assessed participant's long-term ($\sim$1 year) annoyance to WTN in general (i.e., location not specified), and specifically with respect to location (outdoors, indoors), time of day (morning, afternoon, evening, nighttime) and season (spring, summer, fall, winter). In addition, participants' long-term annoyance in general, to road, aircraft and rail noise was assessed. These evaluations of annoyance are considered to be clustered because they are derived from the same individuals (i.e., they are repeated measures). Therefore, in order to compare the prevalence of annoyance as a function of location, time of day, season, or noise source, generalized estimating equations for repeated measures were used to account for the clustered responses (Liang and Zeger, 1986; Stokes *et al.*, 2000).

Statistical analysis was performed using SAS version 9.2 (SAS Institute Inc., 2014). A 5% statistical significance level is implemented throughout unless otherwise stated. In addition, Bonferroni corrections are made to account for all pairwise comparisons to ensure that the overall type I (false positive) error rate is less than 0.05. In cases where cell frequencies were small (i.e., <5) in the contingency tables or logistic regression models, exact tests were used as described in Agresti (2002) and Stokes *et al.* (2000).

III. RESULTS

A. Wind turbine sound pressure levels at dwellings

Modeled sound pressure levels, and the field measurements used to support the models are presented in detail by Keith *et al.* (2016a,b). Calculated outdoor sound pressure levels at the dwellings reached levels as high as 46 dB. Unless otherwise stated, all decibel references are A-weighted. Calculations are likely to yield typical worst case long-term (1 years) average WTN levels (Keith *et al.*, 2016b).

B. Response rate

Of the 2004 addresses (i.e., potential dwellings) on the sample roster, 434 dwellings were coded as out-of-scope by Statistics Canada during data collection (Table I). This was consistent with previous surveys conducted in rural areas in Canada (Statistics Canada, 2008). In the current study, 26.7% and 20.4% of addresses were deemed out-of-scope in PEI and ON, respectively. No significant difference in the distribution of out-of-scope locations by distance to the nearest wind turbine was observed in PEI ($\chi^2 = 3.19$, $p = 0.5263$). In ON, a higher proportion of out-of-scope addresses was observed in the closest distance group ($\leq$0.55 km) compared to other distance groups ($p < 0.05$, in all cases). After adjusting for province, there was a

TABLE I. Locations coded out-of-scope.

	Distance to nearest wind turbine (km)						
	≤0.55	(0.55–1]	(1–2]	(2–5]	>5	Overall	CMH p-value[a]
Range of WTN (dB)	37.4–46.1	31.8–43.6	26.3–40.4	14.6–30.9	0–18.2		
Total potential dwellings	143	887	781	95	98	2004	
ON	76	718	669	60	80	1603	
PEI	67	169	112	35	18	401	
Total number of potential dwellings out-of-scope n(%)[b]	48 (33.6)	158 (17.8)	189 (24.2)	19 (20.0)	20 (20.4)	434 (21.7)	0.9755
ON	29 (38.2)	109 (15.2)	166 (24.8)	9 (15.0)	14 (17.5)	327 (20.4)	<0.0001[c]
PEI	19 (28.4)	49 (29.0)	23 (20.5)	10 (28.6)	6 (33.3)	107 (26.7)	0.5263[c]
Code A	28 (19.6)	23 (2.6)	18 (2.3)	5 (5.3)	8 (8.2)	82 (4.1)	0.0068
Code B	12 (8.4)	54 (6.1)	55 (7.0)	5 (5.3)	6 (6.1)	132 (6.6)	0.8299
Code C	2 (1.4)	36 (4.1)	61 (7.8)	7 (7.4)	1 (1.0)	107 (5.3)	
Code D	4 (2.8)	35 (3.9)	50 (6.4)	2 (2.1)	5 (5.1)	96 (4.8)	
Code E	0 (0.0)	7 (0.8)	4 (0.5)	0 (0.0)	0 (0.0)	11 (0.6)	
Code F	2(1.4)	3(0.3)	1(0.1)	0(0.0)	0(0.0)	6(0.3)	

[a] The Cochran Mantel-Haenszel chi-square test is used to adjust for province, p-values <0.05 are considered to be statistically significant.

[b] Total number of potential dwellings out of scope (given as a percentage of total potential dwellings) is broken down by province, as well it is equal to the sum of Code A-F. The percentages of dwellings that are coded as out-of-scope are based on the total number of potential dwellings in the area. Code A—address was a business/duplicate/other (17%), address listed in error (83%). Code B—an inhabitable dwelling unoccupied at the time of the survey, newly constructed dwelling not yet inhabited, a vacant trailer in a commercial trailer park. Code C—summer cottage, ski chalet, or hunting camps. Code D—all participants in the dwelling were >79 years of age. Code E—under construction, institution, or unavailable to participate. Code F—demolished for unknown reasons.

[c] Chi-square test of independence.

significant association between distance groups and the proportion of locations assigned a *Code A* ($p = 0.0068$) (Table I). A post-collection screening of interviewer notes by Statistics Canada has confirmed that of the total number of *Code A* locations, the vast majority (i.e., 83%) were locations listed in error. In rural areas, there is more uncertainty in developing the address list frame and this can contribute to a higher prevalence of addresses listed in error within 0.55 km of a wind turbine where the population density is lower compared to areas at greater setbacks.[2]

The remaining 1570 addresses were considered to be valid dwellings, from which 1238 residents agreed to participate in the study (606 males, 632 females). This resulted in a final response rate of 78.9%, which was not statistically different between ON and PEI or by proximity to wind turbines (Table II).

C. Sample characteristics

Table III outlines demographic information for study populations in each 5 dB WTN category. The prevalence of employment was the only variable that appeared to consistently increase within increasing WTN levels. Household income and education were unrelated to WTN levels. There was no obvious pattern to the changes observed in the other variables that were found to be statistically related to WTN level categories (i.e., age, type of dwelling, property ownership and facade type).

D. Perception of community noise and related variables as a function of WTN level

The prevalence of reporting to be very or extremely (i.e., highly) noise sensitive was statistically similar across all WTN categories ($p = 0.8175$). As expected and as shown in Fig. 1, visibility and audibility of wind turbines increased with increasing WTN levels.

The overall audibility of other noise sources is shown in Table IV. Not shown in Table IV is how often the noise source was spontaneously reported as opposed to being identified following a prompt by the interviewer (see Sec. II).

TABLE II. Sample response rate.

	Distance to nearest wind turbine (km)						
	≤0.55	(0.55–1]	(1–2]	(2–5]	>5	Overall	p-value
Final number of potential participants[a]	95	729	592	76	78	1570	
ON	47	609	503	51	66	1276	
PEI	48	120	89	25	12	294	
Participants n (%)	71 (74.7)	583 (80.0)	463 (78.2)	58 (76.3)	63 (80.8)	1238 (78.9)	0.9971[b]
ON	34 (72.3)	488 (80.1)	396 (78.7)	42 (82.4)	51 (77.3)	1011 (79.2)	0.7009[c]
PEI	37 (77.1)	95 (79.2)	67 (75.3)	16 (64.0)	12 (100.0)	227 (77.2)	0.1666[c]

[a] Potential participants from locations established to be valid dwellings (equal to the difference between "Total potential dwellings" and "total number of potential dwellings out-of-scope"; see Table I) used in the derivation of participation rates.

[b] The CMH chi-square test is used to adjust for province, p-values <0.05 are considered to be statistically significant.

[c] Chi-square test of independence.

TABLE III. Sample characteristics.

Variable	WTN (dB) <25	[25–30)	[30–35)	[35–40)	[40–46]	Overall	CMH *p*-value[a]
n	84[b]	95[b]	304[b]	521[b]	234[b]	1238[b]	
Range of closest turbine (km)	2.32–11.22	1.29–4.47	0.73–2.69	0.44–1.56	0.25–1.05		
Range of BNTS (dB)	35–51	35–51	35–56	35–57	35–61		
BNTS (dB) mean (SD)	43.88(3.43)	44.68 (2.91)	45.21 (3.60)	43.29 (4.11)	41.43 (4.21)		
ON	44.98 (2.88)	44.86 (2.78)	45.54 (3.31)	44.06 (3.86)	42.70 (4.25)		<0.0001[c]
PEI	41.13 (3.18)	43.00 (3.67)	43.81 (4.38)	38.44 (1.59)	38.05 (1.00)		<0.0001[c]
Sex *n* (% male)	37 (44.0)	48 (50.5)	150 (49.3)	251 (48.2)	120 (51.3)	606 (49.0)	0.4554
Age mean (SE)	49.75 (1.78)	56.38 (1.37)	52.25 (0.93)	51.26 (0.68)	50.28 (1.03)	51.61 (0.44)	0.0243[d]
Marital status *n* (%)							0.2844
Married/Common-law	54 (64.3)	69 (73.4)	199 (65.7)	367 (70.6)	159 (67.9)	848 (68.7)	
Widowed/Separated/Divorced	16 (19.0)	18 (19.1)	61 (20.1)	85 (16.3)	35 (15.0)	215 (17.4)	
Single, never been married	14 (16.7)	7 (7.4)	43 (14.2)	68 (13.1)	40 (17.1)	172 (13.9)	
Employed *n* (%)	43 (51.8)	47 (49.5)	161 (53.0)	323 (62.0)	148 (63.2)	722 (58.4)	0.0012
Level of education *n* (%)							0.7221
≤High school	45 (53.6)	52 (54.7)	167 (55.1)	280 (53.7)	134 (57.3)	678 (54.8)	
Trade/Certificate/College	34 (40.5)	37 (38.9)	110 (36.3)	203 (39.0)	85 (36.3)	469 (37.9)	
University	5 (6.0)	6 (6.3)	26 (8.6)	38 (7.3)	15 (6.4)	90 (7.3)	
Income (×$1000) *n* (%)							0.8031
<60	39 (51.3)	40 (54.8)	138 (52.5)	214 (49.1)	100 (49.3)	531 (50.5)	
60-100	18 (23.7)	17 (23.3)	72 (27.4)	134 (30.7)	59 (29.1)	300 (28.5)	
≥100	19 (25.0)	16 (21.9)	53 (20.2)	88 (20.2)	44 (21.7)	220 (20.9)	
Detached dwelling *n* (%)[e]	59 (70.2)	84 (88.4)	267 (87.8)	506 (97.1)	216 (92.3)	1132 (91.4)	
ON[e]	46 (76.7)	77 (89.5)	228 (93.1)	437 (97.1)	154 (90.6)	942 (93.2)	<0.0001[f]
PEI[e]	13 (54.2)	7 (77.8)	39 (66.1)	69 (97.2)	62 (96.9)	190 (83.7)	<0.0001[f]
Property ownership *n* (%)	60 (71.4)	85 (89.5)	250 (82.2)	466 (89.4)	215 (91.9)	1076 (86.9)	
ON	45 (75.0)	78 (90.7)	215 (87.8)	399 (88.7)	157 (92.4)	894 (88.4)	0.0085[f]
PEI	15 (62.5)	7 (77.8)	35 (59.3)	67 (94.4)	58 (90.6)	182 (80.2)	<0.0001[f]
Facade type *n* (%)							0.0137
Fully bricked	20 (23.8)	30 (31.6)	85 (28.0)	138 (26.5)	67 (28.6)	340 (27.5)	
Partially bricked	24 (28.6)	29 (30.5)	62 (20.4)	88 (16.9)	15 (6.4)	218 (17.6)	
No brick/other	40 (47.6)	36 (37.9)	157 (51.6)	295 (56.6)	152 (65.0)	680 (54.9)	

[a] The Cochran Mantel-Haenszel chi-square test is used to adjust for province unless otherwise indicated, *p*-values <0.05 are considered to be statistically significant.

[b] Totals may differ due to missing data.

[c] Analysis of variance (ANOVA) model.

[d] Non-parametric two-way ANOVA model adjusted for province.

[e] Non-detached dwellings included semi/duplex/apartment.

[f] Chi-square test of independence.

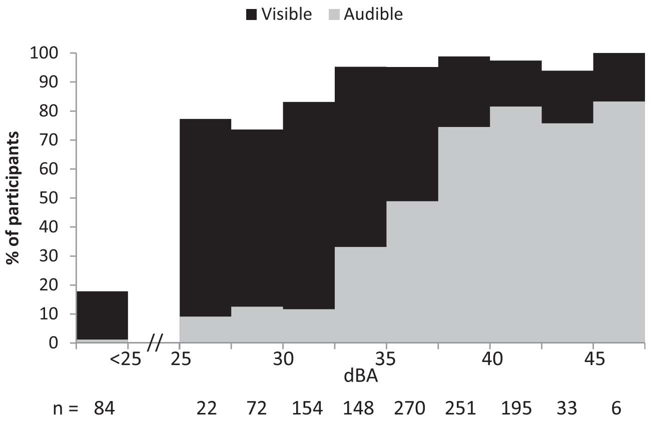

FIG. 1. Proportion of participants as a function of calculated outdoor A-weighted WTN levels. The figure plots the proportion of participants that reported wind turbines were visible from anywhere on their property or audible from inside or outside their homes from the total number of participants with valid responses living in each WTN level category.

Among the participants who reported hearing each specific noise source, the prevalence of spontaneously reporting road traffic, wind turbines, rail and aircraft was 84%, 71%, 66%, and 30%, respectively. A total of 102 participants (8.2%) indicated that there were no audible noise sources around their home. These participants lived in areas where the average WTN levels were 32.4 dB [standard deviation (SD) = 8.3] and the mean distance to the nearest turbine was 1.7 km (SD = 2.0) (data not shown).

Table IV also provides the observed prevalence rates for high (i.e., very or extreme) annoyance toward wind turbine features. The results suggest that there was a tendency for the prevalence of annoyance to increase with increasing WTN levels, with the rise in annoyance becoming evident when WTN levels exceeded 35 dB. The pattern was slightly different for visual annoyance among participants drawn from the ON sample, where there was a noticeable rise in annoyance among participants living in areas where WTN

TABLE IV. Perception of community noise and related variables.

	Wind Turbine Noise (dB)						
Variable	<25	[25–30)	[30–35)	[35–40)	[40–46]	Overall	CMH *p*-value[a]
n	84[b]	95[b]	304[b]	521[b]	234[b]	1238[b]	
Sensitivity to noise[c]	14 (16.7)	14 (14.7)	35 (11.6)	77 (14.8)	35 (15.1)	175 (14.2)	0.8175
Audible perception of transportation noise sources *n* (%)							
Road traffic	62 (73.8)	60 (63.2)	259 (85.2)	443 (85.0)	192 (82.1)	1016 (82.1)	0.0013
Aircraft	43 (51.2)	33 (34.7)	146 (48.0)	263 (50.5)	124 (53.0)	609 (49.2)	
Aircraft (ON)	32 (53.3)	31 (36.0)	120 (49.0)	220 (48.9)	82 (48.2)	485 (48.0)	0.2114[d]
Aircraft (PEI)	11 (45.8)	2 (22.2)	26 (44.1)	43 (60.6)	42 (65.6)	124 (54.6)	0.0214[d]
Rail [e]	30 (50.0)	27 (31.4)	73 (29.8)	90 (20.0)	7 (4.1)	227 (22.5)	<0.0001[d]
Perception of wind turbines *n* (%)							
See wind turbines	15 (17.9)	70 (74.5)	269 (89.1)	505 (96.9)	227 (97.0)	1086 (87.9)	<0.0001
Hear wind turbines	1 (1.2)	11 (11.6)	67 (22.0)	319 (61.2)	189 (80.8)	587 (47.4)	<0.0001
Number of years hearing the WT *n* (%)							<0.0001
Do not hear	83 (98.8)	84 (88.4)	237 (78.0)	202 (39.0)	45 (19.3)	651 (52.8)	
<1 year	1 (1.2)	2 (2.1)	15 (4.9)	31 (6.0)	12 (5.2)	61 (4.9)	
≥1 year	0 (0.0)	9 (9.5)	52 (17.1)	285 (55.0)	176 (75.5)	522 (42.3)	
Notice vibrations/rattles indoors during WTN operations	0 (0.0)	3 (3.2)	8 (2.6)	28 (5.4)	19 (8.2)	58 (4.7)	0.0004
Highly concerned about physical safety	1 (1.2)	3 (3.2)	5 (1.6)	46 (8.9)	22 (9.6)	77 (6.3)	<0.0001
Formal complaint[f]	2 (2.4)	2 (2.1)	3 (1.0)	22 (4.2)	6 (2.6)	35 (2.8)	0.2578
Reporting a high (very or extreme) level of annoyance to wind turbine features, *n* (%)							
Noise	0 (0.0)	2 (2.1)	3 (1.0)	52 (10.0)	32 (13.7)	89 (7.2)	<0.0001
Visual	2 (2.4)	15 (16.0)	17 (5.6)	81 (15.5)	44 (18.9)	159 (12.9)	
Visual (ON)	2 (3.3)	15 (17.6)	17 (7.0)	76 (16.9)	36 (21.2)	146 (14.5)	<0.0001[d]
Visual (PEI)	0 (0.0)	0 (0.0)	0 (0.0)	5 (7.0)	8 (12.7)	13 (5.8)	0.0268[d]
Blinking lights	2 (2.4)	8 (8.5)	17 (5.6)	61 (11.7)	34 (14.6)	122 (9.9)	<0.0001
Shadow flicker	0 (0.0)	3 (3.2)	6 (2.0)	51 (9.8)	36 (15.5)	96 (7.8)	<0.0001
Vibrations/rattles	0 (0.0)	1 (1.1)	2 (0.7)	9 (1.7)	7 (3.0)	19 (1.5)	0.0198
Reporting a high (very or extreme) level of WTN annoyance by time of day, *n* (%)							
Morning	0 (0.0)	0 (0.0)	1 (0.3)	28 (5.4)	10 (4.3)	39 (3.2)	
Afternoon	0 (0.0)	0 (0.0)	1 (0.3)	26 (5.0)	14 (6.1)	41 (3.3)	
Evening	0 (0.0)	1 (1.1)	2 (0.7)	48 (9.2)	26 (11.3)	77 (6.3)	
Nighttime	0 (0.0)	1 (1.1)	2 (0.7)	48 (9.2)	26 (11.3)	77 (6.3)	
Reporting a high (very or extreme) level of WTN annoyance by season, *n* (%)							
Spring	0 (0.0)	1 (1.1)	1 (0.3)	45 (8.6)	22 (9.6)	69 (5.6)	
Fall	0 (0.0)	1 (1.1)	2 (0.7)	42 (8.1)	22 (9.6)	67 (5.5)	
Summer	0 (0.0)	2 (2.1)	4 (1.3)	50 (9.6)	31 (13.7)	87 (7.1)	
Winter	0 (0.0)	1 (1.1)	1 (0.3)	38 (7.3)	21 (9.2)	61 (5.0)	
Closing bedroom window to block outside noise during sleep *n* (%)							
	26 (31.3)	30 (31.6)	87 (28.7)	178 (34.3)	68 (29.2)	389 (31.6)	0.8106
Source identified as cause for closing window[g] *n* (%)							
Road traffic	15 (18.1)	13 (13.7)	47 (15.5)	77 (14.8)	24 (10.3)	176 (14.3)	0.1161
Rail	6 (10.2)	1 (1.2)	7 (2.9)	10 (2.2)	0 (0.0)	24 (2.4)	0.0013
Wind turbines	0 (0.0)	2 (2.1)	6 (2.0)	79 (15.2)	50 (21.6)	137 (11.1)	<0.0001
Other	12 (14.5)	20 (21.1)	54 (17.8)	65 (12.5)	14 (6.0)	165 (13.4)	0.0002
Perceived benefit from having wind turbines in the area *n* (%)							
Personal	3 (3.9)	2 (2.2)	11 (4.0)	47 (9.2)	47 (20.3)	110 (9.3)	
ON	0 (0.0)	1 (1.2)	6 (2.7)	44 (10.0)	36 (21.4)	87 (9.0)	<0.0001[d]
PEI	3 (15.8)	1 (11.1)	5 (9.8)	3 (4.3)	11 (17.2)	23 (10.8)	0.1700[d]
Community	20 (29.0)	14 (20.9)	62 (36.0)	136 (35.1)	79 (40.7)	311 (35.0)	0.0135

[a] The Cochran Mantel-Haenszel chi-square test is used to adjust for provinces unless otherwise indicated, *p*-values <0.05 are considered to be statistically significant.

[b] Columns may not add to total due to missing data.

[c] Sensitivity to noise reflects the prevalence of participants that reported to be either very or extremely (i.e., highly) noise sensitive in general.

[d] Chi-square test of independence.

[e] Nobody reported hearing rail noise in PEI as there is no rail activity in PEI, therefore the percent is given as a percentage of ON participants only.

[f] Refers to anyone in the participant's household ever lodging a formal complaint (including signing a petition) regarding noise from wind turbines.

[g] Reasons for closing bedroom windows due to aircraft noise was suppressed due to low cell counts (i.e., n <5 overall).

levels were between [25 and 30) dB. The prevalence of *household* complaints concerning wind turbines, which could include signing a petition regarding noise from wind turbines, was 2.8% overall and unrelated to WTN levels ($p = 0.2578$). However, complaints were found to be greater among the PEI sample ($13/224 = 5.8\%$), compared to ON ($22/1010 = 2.2\%$) ($p = 0.0050$).

Other notable observations from Table IV include the finding that the number of participants who self-reported to personally benefit in any way (e.g., rent, payments or indirect benefits such as community improvements) from having turbines in their area, was not equally distributed among provinces. In ON, reporting such benefits was significantly related to WTN categories ($p < 0.0001$) and there was a gradual increase from the lowest WTN category (<25 dB: 0.0%) to the loudest WTN category ([40–46] dB: 21.4%), whereas in PEI benefits were statistically evenly distributed across the sample ($p = 0.1700$).

Closing bedroom windows to block outside noise during sleep was equally prevalent across all WTN categories ($p = 0.8106$); however, identifying WTs as the reason for closing the window was found to be related to WTN levels ($p < 0.0001$). In the two loudest categories, [35–40) dB and [40–46] dB, 15.2% and 21.6% of participants identified WTN as the reason for closing bedroom windows, respectively, compared to ≤2.1% in the other WTN categories (Table IV).

Figure 2 plots the fitted percentage highly annoyed by WTN category overall and for ON and PEI separately. WTN annoyance was observed to significantly increase when WTN levels exceeded ≥35 dB compared with lower exposure categories ($p < 0.009$, in all cases). Overall, observed prevalences of noise annoyance increased from less than 2.1% in the three lowest WTN level categories to 10% in areas where WTN levels were between [35 and 40) dB and 13.7% between [40 and 46] dB. Additionally, annoyance was observed to be significantly higher in the ON sample compared to the PEI sample. Across all WTN categories, the odds of being highly annoyed by WTN were 3.29 times greater in ON compared to PEI [95% confidence interval (CI), 1.47–8.68, $p = 0.0015$]; however, the difference was most pronounced above 35 dB.

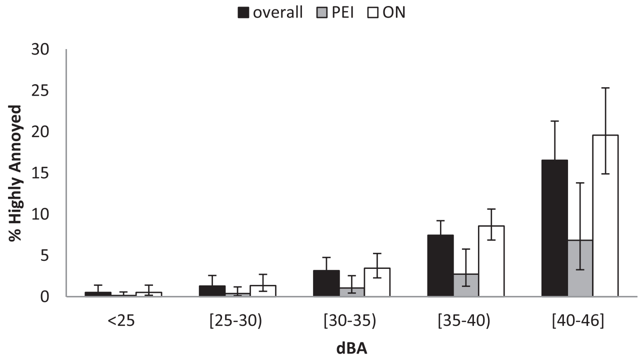

FIG. 2. Prevalence of high annoyance with wind turbine noise overall and by province as a function of calculated outdoor wind turbine noise levels. This illustrates the percentage of participants that reported to be either very or extremely (i.e., highly) bothered, disturbed or annoyed by WTN while at home over the last year. At home refers to either inside or outside the dwelling. Results are shown for participants from southwestern ON, PEI, and as an overall average. Fitted data are plotted along with their 95% confidence intervals. Results are shown as a function of calculated outdoor A-weighted WTN levels at the dwelling (dBA). WTN annoyance was observed to significantly increase when WTN levels exceeded ≥35 dB compared with lower exposure categories ($p < 0.009$, in all cases). Additionally, annoyance was observed to be significantly higher in the southwestern ON sample compared to the PEI sample ($p = 0.0015$), regardless of WTN level.

In addition to asking participants how annoyed they were toward WTN in general (i.e., without reference to their particular location), other questions were designed to assess annoyance as a function of location (i.e., indoors, outdoors). As shown in Fig. 3, the prevalence of high annoyance was significantly higher outdoors.

The prevalence of annoyance by time of day and season is provided in Table IV. For WTN levels below 30 dB, the prevalence of high annoyance was very low (<1.2%) and similar for all times of day. Starting at 30 dB, the percentage highly annoyed during the evening and nighttime were significantly higher than the morning and afternoon; however this difference was most pronounced at WTN levels ≥35 dB. For WTN levels below 30 dB, the prevalence of high annoyance was very low (<2.2%) and similar for all seasons. At WTN levels ≥35 dB, the prevalence of high annoyance during the summer was higher compared to all other seasons.

Noise annoyance toward road, aircraft and rail noise was also assessed in the questionnaire. It was of interest to determine how annoyance to these sources compared to WTN annoyance. In areas where WTN levels were <35 dB the greatest source of noise annoyance was road traffic. In WTN categories ≥35 dB, annoyance toward WTN exceeded all other sources ($p < 0.0003$, in all cases) (see Fig. 4).

E. Self-reported health conditions and use of medication

Table V shows that subjectively reported sleep disturbance from any source while sleeping at home over the last year, in addition to a multitude of health effects, were found

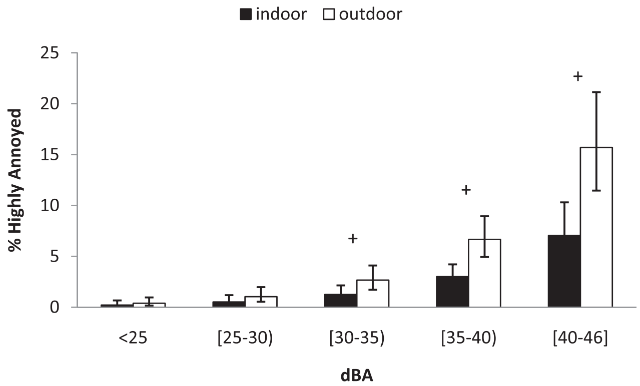

FIG. 3. Prevalence of high annoyance with wind turbine noise by location as a function of calculated outdoor wind turbine noise levels. Participants were asked to think about the last year or so and indicate how bothered, disturbed or annoyed they were by WTN while at home. The percentage of participants reporting to be either very or extremely (i.e., highly) bothered, disturbed or annoyed is shown as a function of calculated outdoor A-weighted WTN levels at the dwelling (dBA). Figure 3 presents the fitted results by location (i.e., indoors and outdoors) along with their 95% confidence intervals. + Indoor significantly different from outdoor ($p < 0.001$).

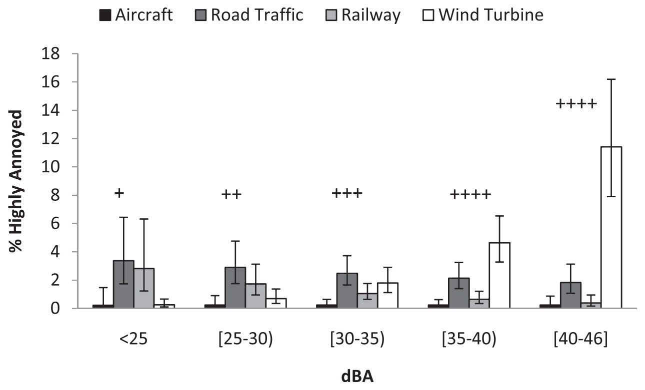

FIG. 4. Prevalence of high annoyance toward different noise sources as a function of calculated outdoor wind turbine noise levels. Illustrates the percentage of participants that reported to be either very or extremely (i.e., highly) bothered, disturbed or annoyed by road traffic, aircraft, rail and wind turbine noise (WTN) while at home over the last year. At home refers to either inside or outside the dwelling. Results represent fitted data along with their 95% confidence intervals and are shown as a function of calculated outdoor A-weighted WTN levels at the dwelling (dBA). $^{+}$WTN significantly different from road traffic and rail noise ($p < 0.001$); $^{++}$WTN significantly different from road traffic ($p < 0.001$); $^{+++}$WTN significantly different from aircraft noise ($p < 0.001$), $^{++++}$WTN significantly different from road traffic, rail, and aircraft noise ($p < 0.0003$).

to be unrelated to WTN levels. Similarly, medication use for high blood pressure, anxiety or depression was also found to be unrelated to WTN levels. Although sleep medication use was significantly related to WTN levels ($p = 0.0083$), the prevalence was *higher* among the two lowest WTN categories {<25 dB and [25–30) dB} (see Table V).

IV. DISCUSSION

The prevalence of self-reporting to be either "*very*" or "*extremely*" (i.e., highly) annoyed with several wind turbine features increased significantly with increasing A-weighted WTN levels. When classified by the prevalence of reported annoyance overall, and in areas where WTN levels exceeded 35 dB, annoyance was highest for visual aspects of wind turbines, followed by blinking lights, shadow flicker, noise and vibrations. Consistent with Pedersen *et al.* (2009), the increase in WTN annoyance was clearly evident when moving from [30–35) dB to [35–40) dB, where the prevalence of WTN annoyance increased from 1% to 10%. This continued to increase to 13.7% for areas where WTN levels were [40–46] dB. The prevalence of WTN annoyance was higher outdoors, during the summer, and during evening and nighttime hours. Pedersen *et al.* (2009) also found that annoyance with WTN was greater outdoors compared to indoors.

Despite a similar pattern of response between the ON and PEI samples, the self-reported WTN annoyance was 3.29 times greater in ON, a difference that was most pronounced at the two highest WTN categories. This difference is in contrast to the prevalence of *household* complaints related to wind turbines. Even though the overall prevalence of such complaints was low (i.e., 2.8%), complaints were more likely in PEI (5.8%) compared to ON (2.2%). The reasons for this difference despite greater reported annoyance in ON are unclear. Research has shown that there are several contingencies that must be met before someone that is highly annoyed will complain (Michaud *et al.*, 2008). Such contingencies include knowing who to complain to, how to file a complaint and holding the belief that the complaint will result in positive change. The fact that the prevalence of complaints regarding wind turbines was unrelated to WTN levels is another indication that complaints do not always correlate well with changes in noise exposure (Fidell *et al.*, 1991). The motives underlying household complaints were not assessed in the present study, but the disparity found with annoyance could also be related to the wording used in the questionnaire. The prevalence of complaints was the one question where the respondent answered on behalf of the entire household.

More participants reported that they were highly annoyed by the visual aspects of wind turbines than by any other feature, even at higher WTN levels. Similar to WTN annoyance, the overall prevalence of annoyance with the visual impact of wind turbines was more than twice as high in the ON sample, and more prevalent across the exposure categories when compared to PEI. In the PEI sample, no participants reported visual annoyance in areas where WTN levels were below 35 dB. This is in contrast to a clear intensification in visual annoyance among the ON sample in areas where WTN levels were [25–30) dB. Exploring the variables that may underscore provincial differences was not within the scope of the current study. The questionnaire was not designed to probe underlying factors that may explain observed provincial differences; however, reported personal benefit from having wind turbines in the area was found to be different between the ON and PEI samples (Table IV).

Shepherd *et al.* (2011) assessed annoyance in response to WTN, but not in a manner that would permit comparisons with the Swedish (Pedersen and Persson Waye, 2004, 2007), Dutch (Janssen *et al.*, 2011; Pedersen *et al.*, 2009) or the current study. Shepherd *et al.* (2011) reported that 59% of participants living within 2 km of a wind turbine installation spontaneously identified wind turbines as an annoying noise source, with a mean annoyance rating of 4.59 (SD, 0.65) when the 5 category adjectival scale was analyzed as a numerical scale from 0 to 5. No exposure-response relationship could be assessed because the authors did not provide an analysis based on precise distance or as a function of WTN levels, which they reported to be between 20 and 50 dB among participants living within 2 km of a wind turbine. This encompasses the entire WTN level range in the CNHS. As such, the only tentative comparison that can be made between the current study and the Shepherd *et al.* (2011) study would be that the observed prevalence of highly annoyed (i.e., "*very*" or "*extremely*") within 2 km of the nearest wind turbine was 7.0%. These data are not shown because the focus of the current study was on WTN levels and an analysis based solely on distance to the nearest turbine does not adequately account for WTN levels at any given dwelling. WTN is a more sensitive measure of exposure level because, in addition to the distance to the turbine, it accounts for topography, presence of large bodies of water, wind turbine characteristics, the layout of the wind farm and the number of wind turbines at any given distance.

TABLE V. Sample profile of health conditions.

	Wind turbine noise (dB)						
Variable *n* (%)	<25	[25–30)	[30–35)	[35–40)	[40–46]	Overall	CMH[a] *p*-value
n	84[b]	95[b]	304[b]	521[b]	234[b]	1238[b]	
Health worse vs last year [c]	17 (20.2)	12 (12.6)	46 (15.1)	90 (17.3)	51 (21.8)	216 (17.5)	0.1724
Migraines	18 (21.4)	24 (25.3)	56 (18.4)	134 (25.8)	57 (24.4)	289 (23.4)	0.2308
Dizziness	19 (22.6)	16 (16.8)	65 (21.4)	114 (21.9)	59 (25.2)	273 (22.1)	0.2575
Tinnitus	21 (25.0)	18 (18.9)	71 (23.4)	129 (24.8)	54 (23.2)	293 (23.7)	0.7352
Chronic pain	20 (23.8)	23 (24.2)	75 (24.8)	118 (22.6)	57 (24.5)	293 (23.7)	0.8999
Asthma	8 (9.5)	12 (12.6)	22 (7.2)	43 (8.3)	16 (6.8)	101 (8.2)	0.2436
Arthritis	23 (27.4)	38 (40.0)	98 (32.2)	175 (33.7)	68 (29.1)	402 (32.5)	0.6397
High blood pressure (BP)	24 (28.6)	36 (37.9)	81 (26.8)	166 (32.0)	65 (27.8)	372 (30.2)	0.7385
Medication for high BP	26 (31.3)	34 (35.8)	84 (27.6)	163 (31.3)	63 (27.0)	370 (29.9)	0.4250
Family history of high BP	44 (52.4)	49 (53.8)	132 (45.5)	254 (50.6)	121 (53.8)	600 (50.3)	0.6015
Chronic bronchitis/emphysema/COPD	3 (3.6)	10 (10.8)	17 (5.6)	27 (5.2)	14 (6.0)	71 (5.7)	0.7676
Diabetes	7 (8.3)	8 (8.4)	33 (10.9)	46 (8.8)	19 (8.2)	113 (9.1)	0.6890
Heart disease	8 (9.5)	7 (7.4)	31 (10.2)	32 (6.1)	17 (7.3)	95 (7.7)	0.2110
Highly sleep disturbed[d]	13 (15.7)	11 (11.6)	41 (13.5)	75 (14.5)	24 (10.3)	164 (13.3)	0.4300
Diagnosed sleep disorder	13 (15.5)	10 (10.5)	27 (8.9)	44 (8.4)	25 (10.7)	119 (9.6)	0.3102
Sleep medication	16 (19.0)	18 (18.9)	39 (12.8)	46 (8.8)	29 (12.4)	148 (12.0)	0.0083
Restless leg syndrome	7 (8.3)	16 (16.8)	37 (12.2)	81 (15.5)	33 (14.1)	174 (14.1)	
Restless leg syndrome (ON)	4 (6.7)	15 (17.4)	27 (11.0)	78 (17.3)	28 (16.5)	152 (15.0)	0.0629[e]
Restless leg syndrome (PEI)	3 (12.5)	1 (11.1)	10 (16.9)	3 (4.2)	5 (7.8)	22 (9.7)	0.1628[e]
Medication anxiety or depression	11 (13.1)	14 (14.7)	35 (11.5)	59 (11.3)	23 (9.8)	142 (11.5)	0.2470
QoL past month[f]							
Poor	9 (10.8)	3 (3.2)	21 (6.9)	29 (5.6)	20 (8.6)	82 (6.6)	0.9814
Good	74 (89.2)	92 (96.8)	283 (93.1)	492 (94.4)	213 (91.4)	1154 (93.4)	
Satisfaction with health[f]							
Dissatisfied	13 (15.5)	13 (13.7)	49 (16.1)	66 (12.7)	36 (15.4)	177 (14.3)	0.7262
Satisfied	71 (84.5)	82 (86.3)	255 (83.9)	455 (87.3)	198 (84.6)	1061 (85.7)	

[a] The Cochran Mantel-Haenszel chi-square test is used to adjust for provinces unless otherwise indicated, *p*-values <0.05 are considered to be statistically significant.

[b] Columns may not add to total due to missing data.

[c] Worse consists of the two ratings: "*Somewhat worse now*" and "*Much worse now*."

[d] High sleep disturbance consists of the two ratings: "*very*" and "*extremely*" sleep disturbed.

[e] Chi-square test of independence.

[f] Quality of Life (QoL) and Satisfaction with Health were assessed with the two stand-alone questions on the WHOQOL-BREF. Reporting "*poor*" overall QoL reflects a response of "*poor*" or "*very poor*," and "*good*" reflects a response of "*neither poor nor good*," "*good*," or "*very good*." Reporting "*dissatisfied*" overall Satisfaction with Health reflects a response of "*very dissatisfied*" or "*dissatisfied*," and "*satisfied*" reflects a response of "*neither satisfied nor dissatisfied*," "*satisfied*," or "*very satisfied*." A detailed presentation of the results related to QoL is presented by Feder *et al.* (2015).

It was important to assess the extent to which the sample was homogenously distributed, with respect to demographics and community noise exposure. The reason for this is that the validity of the exposure-response relationship is strengthened when the primary distinction across the sample is the exposure of interest; in this case, WTN levels. Demographically, some minor differences were found with respect to age, employment, type of dwelling and dwelling ownership; however, with the possible exception of employment, these factors showed no obvious pattern with WTN levels and none were strong enough to exert an influence on the overall results. At the design stage, there was some concern that selecting participants up to 10 km might result in an unequal exposure to community noise sources other than WTN. This may have an influence on the underlying response to WTN. Limited data availability did not permit the modeling of sound pressure levels from other noise sources as originally intended, however it was possible to model BNTS levels. Although Fields (1993) concluded that background sound levels generally do not influence community annoyance, his review did not include wind turbines as a noise source and in the current study BNTS levels were calculated to be lower in areas where WTN levels were higher. Lower BNTS could contribute to a greater expectation of peace and quiet. Therefore, a limitation in the CNHS may be that the expectation of peace and quiet was not explicitly evaluated. This factor may influence the association between long-term sound levels and annoyance by an equivalent of up to 10 dB (ANSI, 1996; ISO, 2003b). The influence this factor may have had on the exposure-response relationship found specifically between WTN levels and the prevalence of reporting high annoyance with WTN in the CHNS is discussed in Michaud *et al.* (2016a).

In the absence of modeling, the audibility of road traffic, aircraft and rail noise provided a crude indication of exposure to these sources. In general, road traffic noise exposure was heard by the vast majority of the sample (82.1%).

Aircraft noise was uniformly audible in ON by about half the sample; in PEI however, hearing aircraft was more common in the higher WTN exposure categories (i.e., above 35 dB) where between 61% and 66% of the respondents indicated that they could hear aircraft. Future research may benefit from assessing the extent to which audible aircraft noise may have influenced the annoyance with WTN in PEI. Only when WTN levels were [40–46] dB was the audibility of wind turbines comparable to road traffic (i.e., both sources were audible by approximately 81% of participants). For these community noise sources, participants were asked how bothered, disturbed, or annoyed they were while at home over the last year or so. The findings are of interest in light of the source comparisons made by Pedersen *et al.* (2009) and Janssen *et al.* (2011), which placed WTN annoyance above all transportation noise sources when comparing them at equal sound levels. In the current study, the overall annoyance toward WTN (7.2%) was found to be higher in comparison to road (3.8%), aircraft (0.4%), and rail in ON (1.9%). Source comparisons need to be made with caution because the observed source differences in annoyance may result from an *actual* difference in sound pressure levels at the dwellings in this study. Modeling the sound levels from transportation noise sources in the current study would allow a more direct comparison between these sources and WTN annoyance at equivalent sound exposures. Another approach is to assess the relative community tolerance level of WTN with that reported for road and aircraft noise studies. This analysis indicates that there is a lower community tolerance level for WTN when compared to both road and aircraft noise at equivalent sound levels (Michaud *et al.*, 2016a).

The list of symptoms that are claimed to be caused by exposure to WTN is considerable (Chapman, 2013), but there is a lack of robust evidence from epidemiological studies to support these associations (Council of Canadian Academies, 2015; Knopper *et al.*, 2014; MassDEP MDPH, 2012; McCunney *et al.*, 2014; Merlin *et al.*, 2014). The results from the current study did not show any statistically significant increase in the self-reported prevalence of chronic pain, asthma, arthritis, high blood pressure, bronchitis, emphysema, chronic obstructive pulmonary disease (COPD), diabetes, heart disease, migraines/headaches, dizziness, or tinnitus in relation to WTN exposure up to 46 dB. In other words, individuals with these conditions were equally distributed among WTN exposure categories. Similarly, the prevalence of reporting to be highly sleep disturbed (for any reason) and being diagnosed with a sleep disorder were unrelated to WTN exposure. These self-reported findings are consistent with the conclusions reached following an analysis of objectively measured sleep among a subsample of the current study participants (Michaud *et al.*, 2016b). Medication use (for anxiety, depression, or high blood pressure) was unrelated to WTN levels. It is notable that the observed prevalence for many of the aforementioned health effects are remarkably consistent with large-scale national population-based studies (Innes *et al.*, 2011; Kroenke and Price, 1993; Morin *et al.*, 2011; O'Brien *et al.*, 1994; Shargorodsky *et al.*, 2010).

V. CONCLUDING REMARKS

Study findings indicate that annoyance toward all features related to wind turbines, including noise, vibrations, shadow flicker, aircraft warning lights and the visual impact, increased as WTN levels increased. The observed increase in annoyance tended to occur when WTN levels exceeded 35 dB and were undiminished between 40 and 46 dB. Beyond annoyance, the current study does not support an association between exposures to WTN up to 46 dB and the evaluated health-related endpoints. In some cases, there were clear differences between the southwestern ON and PEI participants; however, exploring the basis behind these differences fell outside the study scope and objectives. The CNHS supported the development of a model for community annoyance toward WTN, which identifies some of the factors that may influence this response (Michaud *et al.*, 2016a). At the very least, the observed differences reported between ON and PEI in the current study demonstrates that even at comparable WTN levels, the community response to wind turbines is not necessarily uniform across Canada. Future studies designed to intentionally explore the factors that underscore such differences may be beneficial.

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[1] See supplementary material at http://dx.doi.org/10.1121/1.4942391 for the univariate analysis results.

[2] Locations coded as out-of-scope were originally assigned the following categories: *Demolished for unknown reasons*, *vacant for unknown reasons*, *unoccupied*, *seasonal*, *>79 years of age*, and *other* (Michaud, 2015b; Health Canada, 2014). In an effort to address feedback and provide further clarification, the categories used to define out-of-scope locations were further defined elsewhere (Michaud, 2015a) with additional details provided in the current paper. Specifically, locations that were determined to be "demolished for unknown reasons" are presented separately in Table I as Code F. Locations that were originally defined as "unoccupied for unknown reasons" are now more precisely defined under Code B (i.e., inhabitable dwelling not occupied at time of survey, newly constructed dwelling, or unoccupied trailer in vacant trailer park). Furthermore, it was confirmed that 6 dwellings originally listed under Code B (Michaud, 2015a) were in fact GPS coordinates listed in error and have therefore been reassigned to Code A.

Agresti, A. (**2002**). *Categorical Data Analysis*, 2nd ed. (Wiley and Sons, New York).

Alberta Utilities Commission (**2013**). "Rule 012-Noise Control," http://www.auc.ab.ca/acts-regulations-and-auc-rules/rules/Pages/Rule012.aspx (Last viewed 11/24/2014).

ANSI (**1996**). S12.9-1996. *Quantities and Procedures for Description and Measurement of Environmental Sound—Part 4: Noise Assessment and Predication of Long-Term Community Response* (American National Standards Institute, Washington, DC).

Bakker, R. H., Pedersen, E., van den Berg, G. P., Stewart, R. E., Lok, W., and Bouma, J. (**2012**). "Impact of wind turbine sound on annoyance, self-reported sleep disturbance and psychological distress," Sci. Total Environ. **425**, 42–51.

Buysse, D. J., Reynolds, C. F., Monk, T. H., Berman, S. R., and Kupfer, D. J. (**1989**). "The Pittsburgh sleep quality index: A new instrument for psychiatric practice and research," Psychol. Res. **28**, 193–213.

Chapman, S. (**2013**). "Symptoms, diseases and aberrant behaviors attributed to wind turbine exposure," http://ses.library.usyd.edu.au/bitstream/2123/10501/2/Wind_Disease_List.pdf (Last viewed 11/24/2014).

Cohen, S., Kamarck, T., and Mermelstein, R. (**1983**). "A global measure of perceived stress," J. Health Soc. Behav. **24**(4), 385–396.

Council of Canadian Academies (**2015**). *Understanding the Evidence: Wind Turbine Noise. The Expert Panel on Wind Turbine Noise and Human Health* (Council of Canadian Academies, Ottawa, Canada).

DataKustik GmbH (**2014**). "Cadna A, version 4.4, Software for Immission Protection," www.datakustik.com (Last viewed 11/24/2014).

Feder, K., Michaud, D. S., Keith, S. E., Voicescu, S. A., Marro, L., Than, J., Guay, M., Denning, A., Bower, T. J., Lavigne, E., Whelan, C., and van den Berg, F. (**2015**). "An assessment of quality of life using the WHOQOL-BREF among participants living in the vicinity of wind turbines," Env. Res. **142**, 227–238.

Fidell, S., Barber, D., and Schultz, T. J. (**1991**). "Updating a dosage-effect relationship for the prevalence of annoyance due to general transportation noise," J. Acoust. Soc. Am. **89**(1), 221–233.

Fields, J. M. (**1993**). "Effect of personal and situational variables on noise annoyance in residential areas," J. Acoust. Soc. Am. **93**(5), 2753–2763.

Health Canada (**2014**). "Wind turbine noise and health study: Summary of results," http://www.hc-sc.gc.ca/ewh-semt/noise-bruit/turbine-eoliennes/summary-resume-eng.php (Last viewed 9/29/2015).

Innes, K. E., Selfe, T. K., and Agarwal, P. (**2011**). "Prevalence of restless legs syndrome in North American and Western European populations: A systematic review," Sleep Med. **12**(7), 623–634.

ISO (**1993**). 9613-1. *Acoustics. Attenuation of Sound During Propagation Outdoors. Part 1: Calculation of the Absorption of Sound by the Atmosphere* (International Organization for Standardization, Geneva, Switzerland).

ISO (**1996**). 9613-2. *Acoustics. Attenuation of Sound During Propagation Outdoors. Part 2: General Method of Calculation* (International Organization for Standardization, Geneva, Switzerland).

ISO/TS (**2003a**). 15666. *Acoustics—Assessment of Noise Annoyance by Means of Social and Socio-Acoustic Surveys* (International Organization for Standardization, Geneva, Switzerland).

ISO (**2003b**). 1996-1:2003(E). *Acoustics—Description, Measurement and Assessment of Environmental Noise—Part 1: Basic Quantities and Assessment Procedures* (International Organization for Standardization, Geneva, Switzerland).

Janssen, S. A., Vos, H., Eisses, A. R., and Pedersen, E. (**2011**). "A comparison between exposure-response relationships for wind turbine annoyance and annoyance due to other noise sources," J. Acoust. Soc. Am. **130**(6), 3746–3753.

Keith, S. E., Feder, K., Voicescu, S., Soukhovtsev, V., Denning, A., Tsang, J., Broner, N., Richarz, W., and van den Berg, F. (**2016a**). "Wind turbine sound power measurements," J. Acoust. Soc. Am. **139**(3), 1431–1435.

Keith, S. E., Feder, K., Voicescu, S., Soukhovtsev, V., Denning, A., Tsang, J., Broner, N., Richarz, W., and van den Berg, F. (**2016b**). "Wind turbine sound pressure level calculations at dwellings," J. Acoust. Soc. Am. **139**(3), 1436–1442.

Knopper, L. D., Ollson, C. A., McCallum, L. C., Whitfield Aslund, M. L., Berger, R. G., Souweine, K., and McDaniel, M. (**2014**). "Wind turbines and human health," Front. Pub. Health **2**(63), 1–20.

Kroenke, K., and Price, R. K. (**1993**). "Symptoms in the community: Prevalence, classification, and psychiatric comorbidity," Arch. Intern. Med. **153**(21), 2474–2480.

Krogh, C. M. E., Gillis, L., Kouwen, N., and Aramini, J. (**2011**). "WindVOiCe, a self-reporting survey: Adverse health effects, industrial wind turbines, and the need for vigilance monitoring," Bull. Sci. Technol. Soc. **31**(4), 334–345.

Kuwano, S., Yano, T., Kageyama, T., Sueoka, S., and Tachibana, H. (**2014**). "Social survey on wind turbine noise in Japan," Noise Control Eng. J. **62**(6), 503–520.

Liang, K. Y., and Zeger, S. L. (**1986**). "Longitudinal data analysis using generalized linear models," Biometrika **73**(1), 13–22.

Massachusetts Department of Environmental Protection (MassDEP) and Massachusetts Department of Public Health (MDPH) (**2012**). "Wind Turbine Health Impact Study: Report on Independent Expert Panel. Massachusetts: Department of Environmental Protection and Department of Public Health," http://www.mass.gov/eea/docs/dep/energy/wind/turbine-impact-study.pdf (Last viewed 5/15/2015).

McCunney, R. J., Mundt, K. A., Colby, W. D., Dobie, R., Kaliski, K., and Blais, M. (**2014**). "Wind turbines and health: A critical review of the scientific literature," J. Occup. Environ. Med. **56**(11), e108–e130.

Merlin, T., Newton, S., Ellery, B., Milverton, J., and Farah, C. (**2014**). "Systematic review of the human health effects of wind farms" (National Health and Medical Research Council, Canberra, ACT, Australia), https://digital.library.adelaide.edu.au/dspace/handle/2440/87923 (Last viewed 2/29/2016).

Michaud, D. S. (**2015a**). "Self-reported and objectively measured outcomes assessed in the Health Canada wind turbine noise and health study: Results support an increase in community annoyance," in *INTERNOISE, 44th Congress of Noise Control Engineering*, San Francisco, CA, USA (August 9–12, 2015).

Michaud, D. S. (**2015b**). "Wind turbine noise and health study: Summary of results," in *6th International Meeting on Wind Turbine Noise*, Glasgow, Scotland (April 20–23, 2015).

Michaud, D. S., Bly, S. H. P., and Keith, S. E. (**2008**). "Using a change in percent highly annoyed with noise as a potential health effect measure for projects under the *Canadian Environmental Assessment Act*," Can. Acoust. **36**(2), 13–28.

Michaud, D. S., Feder, K., Keith, S. E., Voicescu, S. A., Marro, L., Than, J., Guay, M., Bower, T., Denning, A., Lavigne, E., Whelan, C., Janssen, S. A., and van den Berg, F. (**2016a**). "Personal and situational variables associated with wind turbine noise annoyance," J. Acoust. Soc. Am. **139**(3), 1455–1466.

Michaud, D. S., Feder, K., Keith, S. E., Voicescu, S. A., Marro, L., Than, J., Guay, M., Denning, A., Murray, B. J., Weiss, S. K., Villeneuve, P., van den Berg, F., and Bower, T. (**2016b**). "Effects of wind turbine noise on self-reported and objective measures of sleep," SLEEP **39**, 97–109.

Michaud, D. S., Keith, S. E., Feder, K., Soukhovtsev, V., Marro, L., Denning, A., McGuire, D., Broner, N., Richarz, W., Tsang, J., Legault, S., Poulin, D., Bryan, S., Duddeck, C., Lavigne, E., Villeneuve, P. J., Leroux, T., Weiss, S. K., Murray, B. J., and Bower, T. (**2013**). "Self-reported and objectively measured health indicators among a sample of Canadians living within the vicinity of industrial wind turbines: Social survey and sound level modeling methodology," Noise News Int. **21**,14–27.

Morin, C. M., LeBlanc, M., Bélanger, L., Ivers, H., Mérette, C., and Savard, J. (**2011**). "Prevalence of insomnia and its treatment in Canada," Can. J. Psychiatry **56**(9), 540–548.

Mroczek, B., Banaś, J., Machowska-Szewczyk, M., and Kurpas, D. (**2015**). "Evaluation of quality of life of those living near a wind farm," Int. J. Environ. Res. Public Health. **12**(6), 6066–6083.

Mroczek, B., Kurpas, D., and Karakiewicz, B. (**2012**). "Influence of distances between places of residence and wind farms on the quality of life in nearby areas," Ann. Agr. Environ. Med. **19**(4), 692–696.

Nissenbaum, M. A., Aramini, J. J., and Hanning, C. D. (**2012**). "Effects of industrial wind turbine noise on sleep and health," Noise Health **14**(60), 237–243.

O'Brien, B., Goeree, R., and Streiner, D. (**1994**). "Prevalence of migraine headache in Canada: A population based survey," Int. J. Epidemiol. **23**(5), 1020–1026.

Pawlaczyk-Łuszczyńska, M., Dudarewicz, A., Zaborowski, K., Zamojska-Daniszewska, M., and Waszkowska, M. (**2014**). "Evaluation of annoyance from the wind turbine noise: A pilot study," Int. J. Occup. Med. Environ. Health **27**(3), 364–388.

Pedersen, E. (**2011**). "Health aspects associated with wind turbine noise – Results from 3 field studies," Noise Control Eng. J. **59**(1), 47–53.

Pedersen, E., and Persson Waye, K. (**2004**). "Perception and annoyance due to wind turbine noise—A dose-response relationship," J. Acoust. Soc. Am. **116**(6), 3460–3470.

Pedersen, E., and Persson Waye, K. (**2007**). "Wind turbine noise, annoyance and self-reported health and wellbeing in different living environments," Occup. Environ. Med. **64**(7), 480–486.

Pedersen, E., van den Berg, F., Bakker, R., and Bouma, J. (**2009**). "Response to noise from modern wind farms in The Netherlands," J. Acoust. Soc. Am. **126**(2), 634–643.

SAS Institute Inc. (**2014**). "SAS (Statistical Analysis System) (version 9.2) [software package]" (SAS Institute, Inc., Cary, NC).

Shargorodsky, J., Curhan, G. C., and Farwell, W. R. (**2010**). "Prevalence and characteristics of tinnitus among US adults," Am. J. Med. **123**(8), 711–718.

Shepherd, D., McBride, D., Welch, D., Dirks, K. N., and Hill, E. M. (**2011**). "Evaluating the impact of wind turbine noise on health-related quality of life," Noise Health **13**(54), 333–339.

Skevington, S. M., Lotfy, M., and O'Connell, K. A. (**2004**). "The World Health Organization's WHOQOL-BREF quality of life assessment: Psychometric properties and results of the international field trial—A report from the WHOQOL group," Qual. Life. Res. **13**(2), 299–310.

Statistics Canada (**2008**). "Methodology of the Canadian Labour Force Survey, Catalogue no. 71-526-XIE2007001," http://www.statcan.gc.ca/pub/71-526-x/71-526-x2007001-eng.htm (Last viewed 2/29/2016).

Statistics Canada (**2014**). "Community noise and health study," http://www.statcan.gc.ca/daily-quotidien/141106/dq141106c-eng.htm (Last viewed 11/6/2014).

Stokes, M. E., Davis, C. S., and Koch, G. G. (**2000**). *Categorical Data Analysis Using the SAS System*, 2nd ed. (SAS Institute, Inc. Cary, NC).

Tachibana, H., Yano, H., Fukushima, A., and Shinichi, S. (**2014**). "Nationwide field measurement of wind turbine noise in Japan," Noise Control Eng. J. **62**(2), 90–101.

Tachibana, H., Yano, H., Sakamoto, S., and Sueoka, S. (**2012**). "Synthetic Research Program on Wind Turbine Noise in Japan," in *Proceedings of INTERNOISE, 41st Congress of Noise Control Engineering*, New York, NY (August 19–22, 2012), pp. 8505–8514.

United States Department of Transportation (**1998**). "FHWA TRAFFIC NOISE MODEL," Technical Manual (Federal Highway Administration, Washington, DC).

WHOQOL Group (**1998**). "Development of the World Health Organization WHOQOL-BREF quality of life assessment," Psychol. Med. **28**(3), 551–558.

Personal and situational variables associated with wind turbine noise annoyance

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Personal and situational variables associated with wind turbine noise annoyance

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The possibility that wind turbine noise (WTN) affects human health remains controversial. The current analysis presents results related to WTN annoyance reported by randomly selected participants (606 males, 632 females), aged 18–79, living between 0.25 and 11.22 km from wind turbines. WTN levels reached 46 dB, and for each 5 dB increase in WTN levels, the odds of reporting to be either very or extremely (i.e., highly) annoyed increased by 2.60 [95% confidence interval: (1.92, 3.58), $p < 0.0001$]. Multiple regression models had R^2's up to 58%, with approximately 9% attributed to WTN level. Variables associated with WTN annoyance included, but were not limited to, other wind turbine-related annoyances, personal benefit, noise sensitivity, physical safety concerns, property ownership, and province. Annoyance was related to several reported measures of health and well-being, although these associations were statistically weak ($R^2 < 9\%$), independent of WTN levels, and not retained in multiple regression models. The role of community tolerance level as a complement and/or an alternative to multiple regression in predicting the prevalence of WTN annoyance is also provided. The analysis suggests that communities are between 11 and 26 dB less tolerant of WTN than of other transportation noise sources.

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I. INTRODUCTION

One of the most widely studied responses to environmental noise is community annoyance. There is a large body of social and socio-acoustical research spanning over 50 years which relates to the impact of noise on individuals and communities. Studies using socio-acoustic surveys have consistently shown an association between long-term average noise levels and the prevalence of reporting a high level of noise annoyance. The "*highly annoyed*" classification refers to a social survey question on noise annoyance with a

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response in the top 27%–29% on an anchored numerical scale or in the top two categories on a five point adjectival scale (Schultz, 1978), hereafter referred to as annoyance. The R^2 for models of WTN annoyance as a function of calculated long-term energy equivalent noise level alone varies from study to study, although it is often below 20%, confirming that the expression of annoyance is influenced by more than noise levels alone (Job, 1988). Long-term noise annoyance, and more specifically the change in the percentage of a community reporting to be highly annoyed by noise, has been utilised as a health endpoint in environmental assessments (Michaud *et al.*, 2008a). The support for this is partially based on the possible association between high annoyance and other health effects (Niemann *et al.*, 2006; World Health Organization, 2011). The World Health Organization (WHO) has recently quantified the burden of disease associated with long term high annoyance towards environmental noise (WHO, 2011). Several studies have found statistical associations between high degrees of annoyance toward noise and self-reported health effects that include, but are not limited to, migraines, heart disease, diabetes, and hypertension (Basner *et al.*, 2014; Michaud *et al.*, 2008b; Niemann *et al.*, 2006), with these associations also reported in wind turbine studies (Pawlaczyk-Łuszczyńska *et al.*, 2014; Pedersen *et al.*, 2009). Annoyance need not be part of the causal chain to account for the aforementioned associations with health effects; rather, it may act as an intermediary variable between exposure and health (European Network on Noise and Health, 2013).

In comparison to the scientific literature that exists for other sources of environmental noise, there are few peer-reviewed field studies that have investigated the community response to modern wind turbines (Kuwano *et al.*, 2014; Krogh *et al.*, 2011; Mroczek *et al.*, 2012; Nissenbaum *et al.*, 2012; Pawlaczyk-Łuszczyńska *et al.*, 2014; Pedersen and Persson Waye, 2004, 2007; Pedersen *et al.*, 2009; Shepherd *et al.*, 2011; Tachibana *et al.*, 2012). The studies that have been conducted to date differ in terms of their design and evaluated endpoints. Common features include reliance upon self-reported endpoints, modeled levels of wind turbine noise (WTN), and/or proximity to wind turbines as the explanatory variable for the observed community response. Despite the small number of unique epidemiological studies published in the peer-reviewed wind turbine literature, the association between calculated WTN and self-reported community annoyance has been one of the more robust observations. A general conclusion from these studies is that annoyance increased with increasing WTN levels (or reduced proximity to wind turbines) (Shepherd *et al.*, 2011) and that over and above WTN levels, the exposure-response relationship was influenced by attitudes towards wind turbines, economic incentives and population density (Pedersen and Persson Waye, 2004, 2007; Pedersen *et al.*, 2009).

The present paper provides two multiple regression models for WTN annoyance. In the first *unrestricted* model, the purpose was to assess the variables that, in addition to WTN levels, have the strongest overall association with WTN annoyance. As such, there was no *a priori* exclusion of variables that may be viewed as a response to wind turbine operations (e.g., window closing behaviour, annoyance towards shadow flicker, hearing the wind turbines, etc.). Variables are selected only on the basis of the strength of their statistical association with WTN annoyance. In contrast, a second *restricted* model of community annoyance is also presented wherein, with the exception of WTN exposure, the aforementioned variables, which may be considered to more likely reflect a reaction to wind turbine operations, are not considered in the model, regardless of their statistical association with annoyance. This restricted model may yield information that could serve to identify annoyance mitigation measures, over and above a reduction in WTN levels.

Even with a restricted analysis, complex multiple regression models do not readily afford comparisons to other studies that may not have considered the same variables. The Appendix provides a more parsimonious analysis that permits the prediction of WTN annoyance by calculating community tolerance to WTN. An assessment based on community tolerance readily permits comparisons between *all* field studies. The only requirement is that each study must document the exposure-response relationship between the prevalence of high annoyance and increasing noise levels.

II. METHODS

A. Sample design

1. Target population, sample size and sampling frame strategy

The study design, target population, final sample size, allocation of participants as well as the sampling strategy has been described by Michaud *et al.* (2013) and Michaud *et al.* (2016b). 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 to 3 MW (average 2.0 ± 0.4 MW). Turbine hub heights were predominantly 80 m. All identified dwellings within approximately 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. Several factors influenced the determination of the final sample size, including having adequate statistical power (Michaud *et al.*, 2016b; Michaud *et al.*, 2016c) to assess the study objectives, and the time required for collection of data, as influenced by factors such as the length of the interview and the time needed to collect the physical measures.

This study was approved by the Health Canada and Public Health Agency of Canada Review Ethics Board (Protocols #2012–0065 and #2012–0072).

B. Calculating wind turbine and nighttime background sound pressure levels at dwellings

A detailed description of the approach applied to sound pressure level modeling [including background nighttime sound pressure (BNTS) levels] is presented separately (Keith *et al.*, 2016a,b). 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 8 m/s standardized wind speed and favourable sound 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.*, 2016a). Unless otherwise stated, all decibel references are A-weighted.

The BNTS levels were calculated according to the Alberta noise regulations [Alberta Utilities Commission (AUC), 2013], which estimates ambient noise levels in rural and suburban environments. Estimated levels can range from 35 to 51 dB, based on dwelling density and calculated distance to heavily travelled roads or rail lines. In ON, road noise for the six lane concrete 401 Highway was calculated using the U.S. Traffic Noise Model (United States Department of Transportation, 1998) module in the CadnaA software. This value was used if it exceeded the Alberta noise estimate (Keith *et al.*, 2016b).

C. Data collection

1. Questionnaire

A detailed description of the questionnaire development, including content, pilot testing, administration, and the approaches used to enhance participation, have been described in detail by Michaud *et al.* (2013), Michaud *et al.* (2016b), and Feder *et al.* (2015). The questionnaire included modules on basic demographics, noise annoyance, wind turbine perceptions (including concern for physical safety), health effects, quality of life, sleep quality, perceived stress, lifestyle behaviours, and prevalence of chronic diseases (Statistics Canada, 2014).

The official title of the study, *Community Noise and Health Study* (CNHS), was used throughout all data collection phases as a means of masking the true intent of the study, which was to assess the association between wind turbines and health. This approach is commonly used in epidemiological studies to avoid a disproportionate contribution from any group that may have distinct views towards the study subject, such as wind turbines. At multiple times of the day, 16 Statistics Canada trained interviewers conducted in-person home interviews including physical measures data collection between May 2013 and September 2013, in southwestern ON and PEI. Potential participants were informed that the purpose of the survey was to investigate community noise and the potential impact on health. Once a roster of all adults, 18 to 79 years, living in the dwelling was compiled, a computer algorithm selected one adult per dwelling. No substitution was permitted under any circumstances. Participants were not compensated for their participation.

2. Defining "highly" annoyed

Annoyance toward WTN, road traffic, aircraft and rail noise was assessed using the five-point adjectival scale as per ISO/TS (ISO, 2003a) after it was confirmed that the noise source of interest was audible (Michaud *et al.*, 2016b). For each source of noise heard, participants were then asked to respond to the following question "*Thinking about the last year or so, when you are at home, how much does noise from [SOURCE] bother, disturb or annoy you?*" Participants were asked to select one of the following response categories: "*not at all*," "*slightly*," "*moderately*," "*very*," or "*extremely*." Participants that reported they did not hear a particular source of noise were classified into a "*Do not hear*" group and retained in the analysis. The analysis of annoyance was performed after collapsing the response categories into two groups (i.e., "*highly annoyed*" and "*not highly annoyed*"). As per ISO/TS (ISO, 2003a), participants reporting to be either "*very*" or "*extremely*" annoyed were treated as "*highly annoyed*" in the analysis. Consistent with Pedersen *et al.* (2009), the "*not highly annoyed*" group was comprised of participants who did not hear the source or indicated that they were "*not at all*," "*slightly*," and "*moderately*" annoyed by the source. A similar approach was used for the assessment of highly sleep disturbed and highly concerned for physical safety from having wind turbines in the area.

D. Statistical methodology

The analysis for categorical outcomes closely follows the description as outlined in Michaud *et al.* (2013), which provides a summary of the pre-data collection study design, and objectives, as well as proposed data analysis. Final A-weighted WTN categories were defined as follows: {<25; [25–30); [30–35); [35–40); and [40–46]}. As a first step to develop the best predictive model for WTN annoyance, univariate logistic regression models were carried out with WTN category as the exposure of interest, adjusted for province and a predictor of interest. 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. The analysis of each variable only adjusts for WTN category and province, therefore interpretation of any individual relationship must be made with caution.

Multiple logistic regression models to identify variables associated with WTN annoyance were developed using stepwise regression with a 20% significance entry criterion for predictors (based upon univariate analyses) and a 10% significance criterion to remain in the model. The stepwise regression was carried out in three different ways: (1) the base model included exposure to WTN category and province, (2) the base model included exposure to WTN category, province, and an adjustment for participants who reported receiving personal benefit from having wind turbines in the area, and (3) the base model included exposure to WTN category and province, conditioned on those who reported receiving no personal benefit. In all models, WTN category was treated as a continuous variable. The current model aimed to identify variables that have the strongest overall association with annoyance.

All models were adjusted for provincial differences. Province was initially assessed as an effect modifier. Since the interaction was not statistically significant for any of the regression models, province was treated as a confounder in the models with associated adjustments, as required. In cases when cell frequencies were small (i.e., <5) in logistic regression models, exact tests were used as described in Agresti (2002) and Stokes *et al.* (2000). The Nagelkerke pseudo R^2 and Hosmer-Lemeshow (H-L) p-value were reported for all logistic regression models.

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

III. RESULTS

A. Wind turbine sound pressure levels at dwellings, response rates, and sample characteristics

Calculated outdoor sound pressure levels reached 46 dB. Calculations are representative of typical worst case long term (1 year) average WTN levels. Of the 2004 potential dwellings, 1570 addresses were considered to be valid dwellings, from which 1238 occupants agreed to participate in the study (606 males, 632 females). This produced a final calculated response rate of 78.9%. The 434 dwellings that were found to be out-of-scope was anticipated based on previous surveys carried out in rural Canadian areas and on Census data forecasting a higher out-of-scope dwelling rate in PEI compared to ON. A characterisation of the out-of-scope locations is provided in Michaud *et al.* (2016b).

The study sample was found to be relatively homogenous with some minor differences found with respect to age, employment, type of home and home ownership. Self-reported prevalence of illnesses, chronic diseases, noise sensitivity and reporting to be highly sleep disturbed in any way for any reason were all found to be statistically equivalent across WTN categories (Michaud *et al.*, 2016b).

B. Effects of WTN on annoyance

The analysis of self-reported annoyance towards several features associated with wind turbines (i.e., visual impacts, shadow flicker, vibrations, and blinking lights) in relation to WTN levels has been presented in a separate paper by Michaud *et al.* (2016b). In addition to reporting the prevalence of annoyance toward WTN in general, Michaud *et al.* (2016b) also provided an analysis of the WTN annoyance as a function of location (indoors, outdoors), time of day (morning, afternoon, evening, nighttime), and season (summer, fall, winter, spring). The focus of the current analysis is the characterization of the variables that are related to WTN annoyance in general, hereafter referred to as WTN annoyance.

1. Univariate analysis of variables related to WTN annoyance

The base model included WTN category and province as explanatory variables with regard to WTN annoyance. The Nagelkerke pseudo R^2 for this model was 12% (see supplemental material[1]). The R^2 was less than 10% with only WTN levels in the model.

Variables related to WTN annoyance after accounting for WTN level and province in the logistic regression models are presented in the supplemental material.[1] Some of the notable variables that were related to WTN annoyance in these univariate analyses included property ownership, household complaint regarding WTN, noise sensitivity, perceived stress, self-reported sleep disturbance, annoyance with other wind turbine features (e.g., blinking lights), window closing behaviour, and concern for physical safety from having wind turbines in the area (see supplemental material[1]). Many of the self-reported illnesses (e.g., migraines, tinnitus, dizziness, chronic pain, etc.) were statistically related to WTN annoyance; however, chronic conditions that were reported to have been diagnosed by a health care professional tended to not be related to WTN annoyance (see supplemental material[1]).

The relationship between WTN annoyance and the three validated modules incorporated in the study questionnaire: WHOQOL-BREF (Skevington *et al.*, 2004; WHOQOL Group, 1998), Perceived Stress Scale (PSS) (Cohen *et al.*, 1983), and the Pittsburgh Sleep Quality Index (PSQI) (Buysse *et al.*, 1989) was assessed in the CNHS. Decreased quality of life, higher perceived stress and scores on the PSQI were all associated with higher odds of reporting to be highly annoyed by WTN (see supplemental material[1]).

Modeled BNTS levels ranged between 35 and 61 dB in the sample (Keith *et al.*, 2016b). Average BNTS was highest in the WTN group [30–35) dB and lowest in areas where modeled WTN levels were between 40 and 46 dB. BNTS level was not significantly associated with WTN annoyance and the odds of WTN annoyance did not change as a function of BNTS level. Furthermore, after accounting for BNTS levels, WTN annoyance was still significantly associated with WTN levels ($p < 0.0001$) (see supplemental material[1]).

2. Multiple logistic regression model for WTN annoyance

As noted in Sec. II D, variables considered in the multiple regression model had to be significant at the 20% level and be conceptually related to WTN annoyance. Table I provides a summary of the variables that met these conditions.

The final multiple logistic regression models for the three approaches listed in the statistical methodology section yielded similar results. The predictive strength of the three final models was close to 60%. For these reasons, only the results from the first unrestricted multiple logistic regression model are shown in Table II.

WTN annoyance was strongly related to closing bedroom windows to reduce noise during sleep when WTN was identified as the source. Even after adjusting for the other variables in the final model, those who closed their window

TABLE I. Variables conceptually related to WTN annoyance and statistically significant at the 20% level.

Variable	p-value
Income	0.182
Property ownership[a]	0.007
Personal benefit[a]	<0.0001
At least 1 turbine on property	0.003
Complaint about wind turbine noise	<0.0001
Number of years turbines audible	0.090
Sensitivity to noise[a]	<0.0001
Audible WTN	<0.0001
Audible road traffic[a]	0.150
Ability to see turbines from property[a]	0.153
Visual annoyance to wind turbines	<0.0001
Annoyance with blinking lights	<0.0001
Shadow flicker annoyance	<0.0001
Notice vibrations during turbine operations	<0.0001
Annoyance to vibrations/rattles	<0.0001
Concerned about physical safety[a]	<0.0001
Bedroom window type[a]	0.011
Bedroom on quiet side[a]	0.125
Calculated volume of bedroom (1000 ft^3)[a]	0.049
Closing bedroom window to block outside noise during sleep	<0.0001
Closure of bedroom window due to road traffic	0.123
Closure of bedroom window due to wind turbines	<0.0001
Migraines	<0.0001
Dizziness	<0.0001
Tinnitus	<0.0001
Chronic pain	<0.0001
Medication for high blood pressure	0.191
Diagnosed sleep disorder	0.115
Restless leg syndrome	0.023
Self-reported sleep disturbance	<0.0001
Rated quality of life	0.016
Score on PSQI (categorical and range 0–21)	<0.0001
Physical Health domain (range 4–20)	<0.0001
Psychological domain (range 4–20)	0.049
Environment domain (range 4–20)	<0.0001
Perceived Stress Scale (range 0–37)	0.014

[a] Tested in the restricted multiple regression model.

due to WTN had 8 times higher odds of being annoyed by WTN compared to those who did not need to close their window for this reason. In all three models, this variable was the first factor to enter the multiple logistic regression model and the corresponding Nagelkerke R^2 in the base models increased from approximately 11% to 41%. The variables that added the remaining 17% to the R^2 included, but were not limited to, other wind turbine related annoyances (i.e., blinking lights on the nacelle of the wind turbines, visual impact, and vibrations), noise sensitivity, concern about physical safety from having wind turbines in the area, and self-reported sleep disturbance over the last year.

It was also of interest to develop a model of community annoyance restricted to the variables from Table I that are not likely to reflect a reaction to wind turbine operations. Such a model may yield information that could serve to identify annoyance mitigation measures, which are over and above a reduction in WTN levels. Variables that were considered included, but were not limited to, type of dwelling, facade type, property ownership, type of windows, bedroom location within dwelling, self-reported size of bedroom (e.g., volume), presence of air conditioner in the dwelling, visibility of wind turbines from anywhere on the property, other noise sources that the participant reported hearing (e.g., road traffic, railway, aircraft), receiving personal benefits, concern for physical safety associated with having wind turbines in the area, noise sensitivity, and BNTS levels. Income was not considered for inclusion in the restricted regression model because it would have reduced the sample size from 1129 to 968. Furthermore, income was not statistically significant in the unrestricted multiple regression model. Although the variables considered were different from the unrestricted model, the same stepwise procedure as explained in Sec. II D was carried out to develop the restricted multiple logistic regression model.

Table III presents the results for the final restricted multiple logistic regression model where personal benefits was considered for entry into the model. Variables that entered the final model and were associated with higher odds of being annoyed to WTN included concern for physical safety from having wind turbines in the area, noise sensitivity, personal benefits, window type, dwelling ownership, and audibility of road traffic. Participants with a high concern for their physical safety had 14 times higher odds of being annoyed by WTN [95% confidence interval (CI): (7.71, 26.96)]. Participants who did not receive personal benefits had 12 times higher odds of being annoyed by WTN [95% CI: (1.66, 94.25)]. Participants reporting to have single and double pane windows in their bedroom had statistically similar odds of being highly annoyed to WTN ($p = 0.742$); and both had lower odds of being annoyed to WTN compared to those with triple pane windows ($p < 0.03$, in both cases). Participants who did not hear road traffic ($p = 0.026$) had higher odds of being highly annoyed to WTN. The final model had an R^2 of 40% (Table III).

IV. DISCUSSION

The community response to WTN reported in this study was found to be statistically related to A-weighted WTN levels. In other words, the prevalence of reporting to be very or extremely (i.e., highly) annoyed by WTN increased from 2.1% to 13.7% when sound pressure levels were below 30 dB compared to [40–46] dB, respectively. Although statistically significant, the association between WTN levels and annoyance was found to be rather weak ($R^2 = 9\%$). The R^2 substantially improved after considering annoyance due to other wind turbine related features such as the visual impact of wind turbines, the blinking lights on the nacelle used to alert aircraft, and the perception of vibrations during wind turbine operations. The self-reported high concern about physical safety from having wind turbines in the area was found to be significantly related to WTN annoyance. This finding is reminiscent of the general observation from community noise research that fear of a noise source may be the most important non-acoustic variable related to annoyance (Fields, 1993; Miedema and Vos, 1998). van den Berg *et al.* (2015) also

TABLE II. Multiple logistic regression model (unrestricted) for WTN annoyance.

Variable	Groups in variable[a]	Multiple logistic regression model ($n = 934$, $R^2 = 0.58$,[c] H-L,[d] $p = 0.702$) OR(CI)[b]	p-value	Order of entry into model: R^2 at each step
WTN (dB)[e]	Continuous	2.38 (1.42, 3.99)	0.001	Base: 0.11[f]
Province	ON/PEI	4.98 (1.15, 21.58)	0.032	Base: 0.11[f]
Closure of bedroom window due to wind turbines	Yes/no	8.45 (3.67, 19.46)	<0.0001	Step 1: 0.41
Annoyance with blinking lights	High/low	3.26 (1.40, 7.56)	0.006	Step 2: 0.50
Annoyance with vibrations/rattles	High/low	3.99 (1.22, 13.07)	0.023	Step 3: 0.52
Visual annoyance to wind turbine	High/low	2.77 (1.22, 6.29)	0.015	Step 4: 0.53
Self-reported sleep disturbance[g]	High/low	2.93 (1.27, 6.77)	0.012	Step 5: 0.55
Closure of bedroom window due to road traffic	Yes/no	0.42 (0.17, 1.05)	0.063	Step 6: 0.56
Sensitivity to noise	High/low	2.11 (0.97, 4.59)	0.061	Step 7: 0.57
Concerned about physical safety	High/low	2.56 (1.08, 6.07)	0.033	Step 8: 0.57
Complaint about wind turbines	Yes/no	3.22 (0.85, 12.20)	0.085	Step 9: 0.58

[a] Where a reference group is not specified it was taken to be the last group.

[b] Odds ratio (OR) and 95% confidence interval (CI) based on logistic regression model; an OR > 1 indicates that annoyance levels were higher, relative to the reference group.

[c] The Nagelkerke pseudo R^2 indicates how useful the explanatory variables are in predicting the response variable.

[d] H-L: Hosmer-Lemeshow test, $p > 0.05$ indicates a good fit.

[e] WTN level is treated as a continuous scale in the logistic regression model, giving an overall OR for each unit increase in WTN level, where a unit reflects a 5 dB WTN category.

[f] Note that the results of the base model differ from the supplemental material (see footnote 1) and Table III due to sample size differences.

[g] Evaluates the magnitude of reported sleep disturbance for any reason over the previous year while at home.

reported that self-reported worry about a noise source was strongly correlated to noise annoyance from that source.

Noise sensitivity was found to be a significant predictor of WTN annoyance in the current study—a finding that is consistent with previously published community noise research (Guski, 1999; Miedema and Vos, 2003), including WTN studies (Janssen *et al.*, 2011). Despite the influence that concern for physical safety and noise sensitivity seem to have on WTN annoyance, the variable found to have the strongest association with annoyance was identifying wind turbines as the source of noise that led to window closing because it was disturbing sleep. In fact, the R^2 increased from 11% to 41% when this variable entered the final model. This is an observation that requires careful interpretation because sleep disturbance (of any kind) was not found to be related to WTN exposure in the current study

TABLE III. Multiple logistic regression model (restricted) for WTN annoyance.

Variable	Groups in variable[a]	Multiple logistic regression model ($n = 1129$, $R^2 = 0.40$,[c] H-L,[d] $p = 0.480$) OR(CI)[b]	p-value	Order of entry into model: R^2 at each step
WTN (dB)[e]	Continuous	2.84 (1.96, 4.11)	<0.0001	Base: 0.11[f]
Province	ON/PEI	3.46 (1.32, 9.10)	0.012	Base: 0.11[f]
Concerned about physical safety	High/low	14.42 (7.71, 26.96)	<0.0001	Step 1: 0.28
Sensitivity to noise	High/low	5.54 (3.12, 9.84)	<0.0001	Step 2: 0.34
Personal benefit	No/yes	12.49 (1.66, 94.25)	0.014	Step 3: 0.37
Bedroom window type	Single pane	0.17 (0.04, 0.79)	0.024	Step 4: 0.38
	Double pane	0.21 (0.07, 0.63)	0.006	
	Triple pane	Reference		
Property ownership	Own/rent	5.89 (1.19, 29.06)	0.030	Step 5: 0.40
Audible road traffic	No/yes	2.08 (1.09, 3.95)	0.026	Step 6: 0.40

[a] Where a reference group is not specified it was taken to be the last group.

[b] Odds ratio (OR) and 95% confidence interval (CI) based on logistic regression model; an OR > 1 indicates that annoyance levels were higher, relative to the reference group.

[c] The Nagelkerke pseudo R^2 indicates how useful the explanatory variables are in predicting the response variable.

[d] H-L: Hosmer-Lemeshow test, $p > 0.05$ indicates a good fit.

[e] WTN level is treated as a continuous scale in the logistic regression model, giving an overall OR for each unit increase in WTN level, where a unit reflects a 5 dB WTN category.

[f] Note that the results of the base model are different from the supplemental material (see footnote 1) and Table II due to sample size differences.

sample (Michaud *et al.*, 2016c). It is conceivable that closing the window may be an expression of the annoyance toward WTN and/or a coping strategy that protects against sleep disturbance. When closing the window reduces the indoor WTN level and hence improves sleep, this action may conceivably explain the absent association between WTN levels and sleep disturbance.

In the restricted model, variables not expected to be a direct response to wind turbine operations were considered. The rationale for such a model was that it could identify factors that may serve to diminish the annoyance response, over and above a reduction in levels of WTN exposure. The finding that concern for physical safety due to the presence of wind turbines in the area was a significant predictor of annoyance in both the unrestricted and restricted models is informative. This suggests that actions (e.g., education, community consultation) which aim to address this concern during the planning stages of a wind project may also serve to reduce community annoyance toward WTN. Noise sensitivity as a personality trait has long been known to influence the response to community noise (Job, 1988) and it is therefore not surprising that this variable was found to be associated with WTN annoyance.

In the unrestricted model, personal benefit was not retained, although this was likely due to the small number of participants in this category (i.e., 110). Indeed, in the restricted model, personal benefit was found to be statistically significant, although the increase in R^2 was rather modest (3%). Taken together with Pedersen *et al.* (2009), these findings would support initiatives that facilitate direct or indirect personal benefit among participants living within a community in close proximity to wind power projects. There was a significant effect related to window type in the current study that remained in the final model, but nevertheless appears to be counter-intuitive when considering the reduction in noise annoyance that has been reported as a result of noise insulation programs (Amundsen *et al.*, 2013; Asensio *et al.*, 2014). The odds of reporting to be highly annoyed by WTN were higher among participants who self-reported that they had triple pane windows in their bedroom. A tentative explanation for this finding could be that installing these types of windows may be a coping strategy among those who are more highly annoyed by noise. However, the potential influence this action may have on annoyance over time cannot be accounted for in the current study because no information was gathered about the time they were installed.

The possibility that elevated background noise may influence community annoyance has been reviewed by Fields (1993) with the general conclusion that the vast majority of studies reviewed indicated that ambient noise levels have no impact on community annoyance. However, wind turbines were not among the sources reviewed by Fields (1993). Certainly, there is some evidence that the association between WTN levels and annoyance is stronger in areas that are classified as quiet, compared to those classified as noisy (Bakker *et al.*, 2012; Pedersen *et al.*, 2010a,b). It has been recommended that sound levels are adjusted by up to 10 dB when estimating the prevalence of annoyance in areas where there may be a greater expectation of peace and quiet (ANSI, 1996; ISO, 2003c). In the current study, there was a tendency for BNTS levels to be slightly higher in areas where WTN levels (and therefore the prevalence of annoyance) were lower. For this reason, it is difficult to reconcile what influence, if any, BNTS had on WTN annoyance in the current study. A more appropriate assessment of the potential influence that BNTS levels may have on WTN annoyance requires a sufficient sample size in areas with similar WTN levels in the presence of varying BNTS levels. Future research in this area may clarify the influence of background noise on the overall community response to WTN, which could prove to be an important consideration in an urban planning context where it may inform decisions regarding wind turbine siting.

In the univariate analysis the odds of reporting to be highly annoyed by WTN were almost 4 times higher (95% CI: 1.17, 19.41) among participants who heard the wind turbines for 1 year or more compared to those who heard it for less than 1 year (see supplemental material[1]). Unfortunately, the limited breakdown for the audibility categories was dictated by sample size and there may be added value to having a more refined history of WTN audibility. Nevertheless, if this finding is corroborated in future research it would support sensitisation rather than habituation/adaptation with prolonged exposure to WTN.

Some discussion on the potential link between health effects and WTN annoyance is warranted. Long-term high annoyance, as a measure of community response to noise is considered to be a health effect by the World Health Organization (WHO, 1999, 2011) and has been associated with other health effects (Michaud *et al.*, 2008b; Niemann *et al.*, 2006; Pawlaczyk-Łuszczyńska, 2014; Pedersen *et al.*, 2009). This is consistent with the current findings demonstrating that participants who reported being highly annoyed by WTN were more likely to report migraines, dizziness, tinnitus, chronic pain, and restless leg syndrome (see supplemental material[1]). In addition, self-reporting to be highly sleep disturbed for any reason and rating overall quality of life as either "*very poor*" or "*poor*" were also related to WTN annoyance. Higher scores on the PSS and PSQI were likewise found to be related to WTN annoyance. Finally, hair cortisol concentrations, systolic and diastolic blood pressure were significantly higher among the participants that reported to be highly annoyed by WTN (Michaud *et al.*, 2016a). These associations between annoyance and other health effects/indicators need to be interpreted cautiously for a number of reasons. First, none of these associations were related to calculated WTN levels. Second, the R^2 in any of the reported or measured health effects was very low (i.e., <7%), which demonstrates the dominance of other factors. Finally, WTN annoyance was never retained in the final multiple regression models developed for stress, sleep, or quality of life outcomes (Michaud *et al.*, 2016b; Michaud *et al.*, 2016a; Feder *et al.*, 2015). Rubin *et al.* (2014) recently reviewed studies examining symptoms related to modern technology (including wind turbines) and found that health symptoms were more commonly reported among participants who were more anxious, worried, concerned, or annoyed by a source they perceived to be a health risk. The authors suggested that annoyance may promote changes in physiology, behaviour, self-monitoring or enhance recall bias (Rubin *et al.*, 2014). Despite an incomplete understanding of the mechanisms through which annoyance may impact health, or vice versa, it is nevertheless relevant that there were observed associations between long-term high annoyance toward WTN and several self-reported and measured endpoints, which included elevated hair cortisol concentrations and blood pressure. Collectively, these findings support efforts aimed at mitigating community annoyance that may be associated with new wind power projects and concomitant changes in community noise levels.

V. CONCLUDING REMARKS

The complex relationship that exists between community annoyance and noise is a well-established phenomenon that has been further illustrated in the current study. This study found that the R^2 for the model with only WTN levels was merely 9% and that any efforts aimed at mitigating the community response to WTN will profit from considering other factors associated with annoyance. Although the final models had R^2's of up to 58%, their predictive strength for WTN annoyance was still rather limited. It has been shown in previous studies that trust or misfeasance with source authorities, community engagement in project development in addition to community expectations, all have an influence on community annoyance (Guski, 1999). There is also strong support for considering attitudinal factors (Job, 1988; Pawlaczyk-Łuszczyńska, 2014; Pedersen *et al.*, 2009). The relative importance of these and many other unknown factors will fluctuate across different communities. This makes it exceedingly difficult, if not impossible, to fully account for their influence on annoyance in any given community. Recently, it has been demonstrated that predicting the prevalence of annoyance to transportation noise can be much more effectively achieved using a simple one-parameter model. The analysis in the Appendix extends this methodology to WTN annoyance.

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APPENDIX: ESTIMATING COMMUNITY TOLERANCE LEVEL FOR WIND TURBINE NOISE EXPOSURE

The multiple regression models presented in the current paper demonstrate that the R^2 for the prevalence of high annoyance to wind turbine noise (WTN) exposure using a long term energy average (LAeq) alone is less than 10%. Although this increases substantially after consideration is given to several non-LAeq parameters, the predictive strength still only reaches approximately 60%. This makes it difficult to compare the prevalence of WTN annoyance to other socio-acoustic surveys and offers little confidence in estimating the prevalence of annoyance using only LAeq. Fidell *et al.* (2011) demonstrated that the wide scatter in the prevalence of aircraft noise annoyance within and between studies can be effectively accounted for with a simple model that includes only one single variable parameter, a "Community Tolerance Level" or CTL. For a detailed description of the CTL model the reader should refer to Fidell *et al.* (2011). The CTL model is based on well-accepted assumptions that in a homogenous community the prevalence of annoyance will be low or non-existent at very low sound pressure levels, and that it will increase monotonically with increasing sound pressure levels. For aircraft noise, the rate of increase in annoyance can be effectively estimated using a loudness function (i.e., sound pressure raised to the power of 0.3) and the assumption that annoyance increases monotonically with increasing sound pressure levels as shown in Eq. (A1) (Fidell *et al.*, 2011),

$$\%HA = 100\ \exp\left(-\left(1/\left[10^{(DNL-CTL+5.306)/10}\right]^{0.3}\right)\right). \tag{A1}$$

The CTL in Eq. (A1) adjusts the horizontal position of the transition function on the abscissa. The value of the CTL was obtained statistically using maximum likelihood estimation, which is a suitable approach to obtain estimates for binary data (i.e., being highly annoyed compared to not being highly annoyed). Schomer *et al.* (2012) recently demonstrated that the CTL model can also be applied to road and rail noise.

1. Calculating annual average day-night sound level (DNL) from wind turbine noise studies

Determination of CTL requires the yearly average DNL. In the current study, the yearly averaged WTN DNL was calculated at each dwelling by taking into account the effect of wind speed on the WTN sound power level (Keith *et al.*, 2016b). Wind turbine electrical power output in 10 min periods was used to derive the associated sound power. The day-night sound power level was then estimated by adding 10 dB to levels that occurred between 10 p.m. and 7 a.m. and the resulting 52 560 values were averaged over a 1 year period. At each dwelling, corrections were based on the wind park associated with the closest wind turbine. The correction applied to the sound pressure level at each dwelling was the difference between the nominal 8 m/s WTN sound power level and the yearly average day-night WTN sound power level. As described by Keith *et al.* (2016b), WTN sound pressure levels at each dwelling had been calculated for nominal 8 m/s wind speed (i.e., wind speed at 10 m height under standardised conditions according to IEC, 2012). For the few cases where operational data were not available, wind speed data were obtained from the closest wind turbines for which data were available.

For Pedersen's studies (Pedersen and Persson Waye, 2004, 2007; Pedersen *et al.,* 2009) the DNL was estimated by adding 4.7 dB to the 8 m/s LAeq data (van den Berg, 2008; Janssen *et al.*, 2011). Based on van den Berg (2008), DNL was assumed to be approximately equal to LDEN. In a Japanese study by Kuwano *et al.* (2014) the DNL was estimated by adding 6 dB to the measured nighttime average sound pressure level (Yano, 2015).

Not all studies in this area could be included in the current analysis because not all research designs permitted an estimate of high annoyance as a function of DNL. This was either because an equivalent to the percentage highly annoyed could not be estimated and/or the analysis of annoyance was estimated without an exposure metric that could readily be converted to DNL (e.g., distance only).

2. Applying CTL to WTN annoyance

In comparison to the large databases available for transportation noise, there are relatively few socio-acoustic surveys related to WTN annoyance. Nevertheless, the data that are currently available suggests that the loudness function in the CTL model provides an effective prediction of WTN annoyance. After converting all noise metrics to DNL, CTL can be used to quantify the differences between exposure-response relationships. By convention, the value of the CTL is the DNL from Eq. (A1) where 50% of the community would be highly annoyed. It would appear from the plots presented in Fig. 1 that the CTL model provides a reasonable fit to the available data from six field studies. It would be difficult to find a loudness function that has better

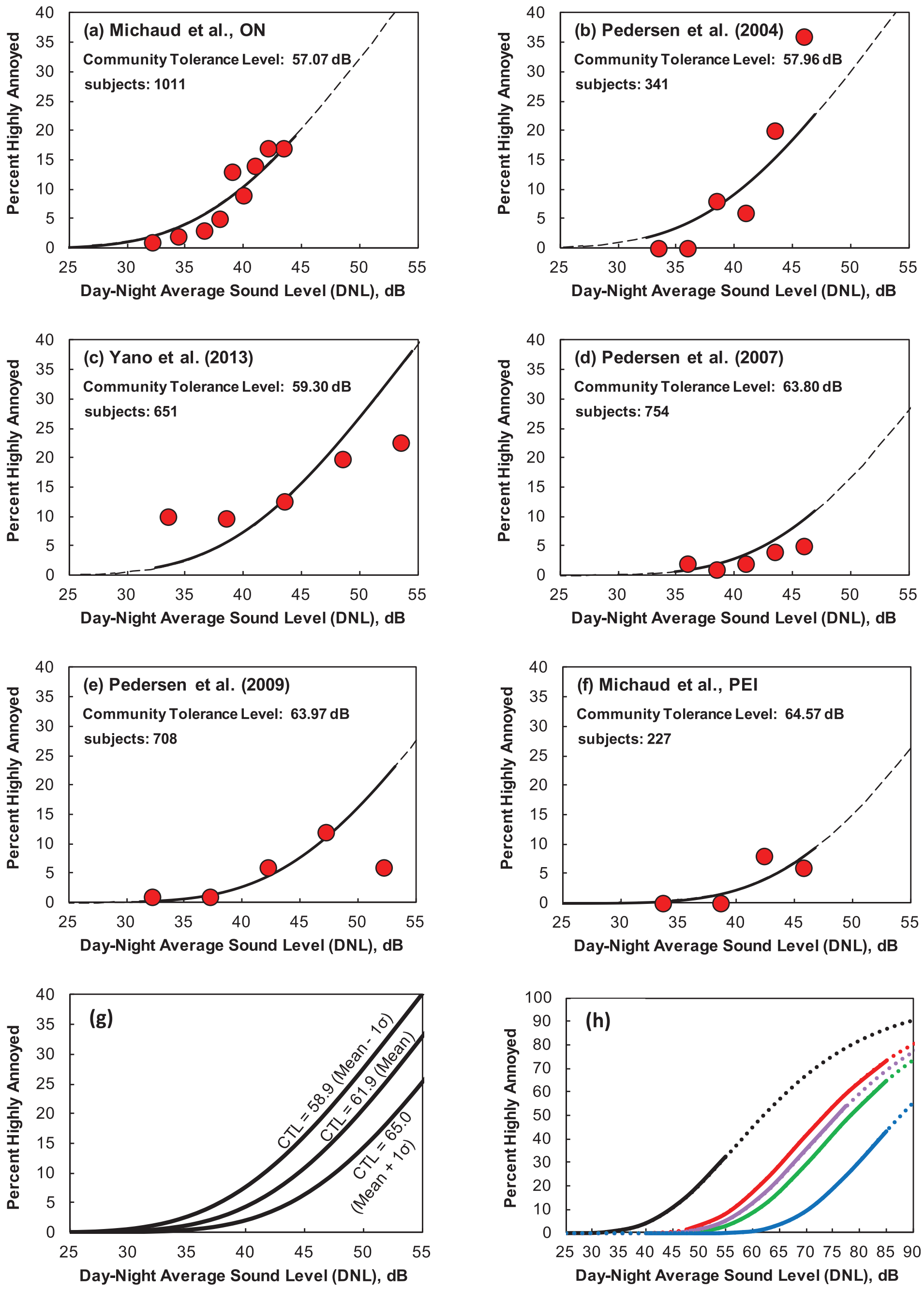

FIG. 1. Panels (a)–(f) show the best fit for the available field studies of wind turbine noise and the prevalence of high annoyance to Eq. (A1). (g) Exposure-response relationship for the prevalence of high annoyance with wind turbine noise exposure in communities of average, +1 standard deviation, and −1 standard deviation tolerance for wind turbine noise exposure. (h) Exposure-response relationship in communities with average tolerance for the prevalence of high annoyance with wind turbine noise (leftmost line, black online), aircraft noise (second line from left, red online), rail noise with high vibration (middle line, purple online), road traffic noise (right of middle line, green online), and rail noise without vibration (rightmost line, blue online).

TABLE IV. Prevalence of high annoyance in communities with an average tolerance. CTL$_{50}$ for WTN (61.9 dB), aircraft noise (73.3 dB), road traffic noise (78.3 dB), rail noise with vibrations (75.8 dB), and rail noise without heavy vibrations (87.8 dB).

	Noise source				
DNL	WTN	Aircraft	Road	Rail + vib.	Rail − vib.
20	0	0	0	0	0
25	0	0	0	0	0
30	0	0	0	0	0
35	1	0	0	0	0
40	4	0	0	0	0
45	11	1	0	0	0
50	21	3	1	2	0
55	33	9	3	5	0
60	45	18	9	13	1
65	57	29	18	23	4
70	67	42	29	36	9
75	76	54	42	48	19
80	82	65	54	60	30
85	87	73	65	69	43

agreement. The CTL for WTN ranges from 57.1 to 64.6 DNL with the grand mean of 62 and a standard deviation of 3. The calculated prevalence of WTN annoyance as a function of DNL for communities that are 1 standard deviation above and below the grand mean is provided in Tables IV–VI.

In the CNHS, the prevalence of high annoyance was nearly non-existent among the 110 participants that reported to receive personal benefit from having wind turbines in the area. This was found to have a negligible impact on CTL (∼1 dB) and for this reason they were retained in the plots shown in Fig. 1.

Quantifying WTN with an A-weighted metric has become a source of debate because wind turbines are a known source of low frequency noise (LFN) that may be undermined with an A-weighted filter. If LFN were the cause of annoyance, the loudness function would be expected to be steeper because the perception of loudness increases more rapidly once low frequencies become audible (ISO, 2003b). The only fit that would be improved with a steeper loudness function is Pedersen and Persson Waye (2004). In contrast, the data from Yano *et al.* (2013) would seem to require a shallower curve and the remaining studies can all be approximated with the same loudness function used for aircraft, road, and rail (Fidell *et al.*, 2011; Schomer *et al.*, 2012). Therefore, based on the field studies that are currently available the argument can be made that the change in high annoyance due to WTN is not driven by LFN and is effectively approximated by a long-term A-weighted metric.

TABLE V. Prevalence of high annoyance in communities 1 standard deviation less tolerant. CTL$_{50}$ for WTN (58.9 dB), aircraft noise (66 dB), road traffic noise (73.2 dB), rail noise with vibrations (72.3 dB), and rail noise without heavy vibrations (83.8 dB).

	Noise Source				
DNL	WTN	Aircraft	Road	Rail + vib.	Rail − vib.
20	0	0	0	0	0
25	0	0	0	0	0
30	1	0	0	0	0
35	3	0	0	0	0
40	8	1	0	0	0
45	16	5	1	1	0
50	28	12	3	4	0
55	40	22	9	11	1
60	53	34	18	21	2
65	64	47	29	33	7
70	73	58	42	46	16
75	80	68	54	57	27
80	85	76	65	67	39
85	89	83	74	76	52

TABLE VI. Prevalence of high annoyance in communities 1 standard deviation more tolerant. CTL$_{50}$ for WTN (64.9 dB), aircraft noise (80.3 dB), road traffic noise (83.4 dB), rail noise with vibrations (79.3 dB), and rail noise without heavy vibrations (91.8 dB).

	Noise Source				
DNL	WTN	Aircraft	Road	Rail + vib.	Rail − vib.
20	0	0	0	0	0
25	0	0	0	0	0
30	0	0	0	0	0
35	0	0	0	0	0
40	2	0	0	0	0
45	6	0	0	0	0
50	14	0	0	0	0
55	25	2	1	2	0
60	38	6	3	7	0
65	50	14	8	15	1
70	61	24	17	26	5
75	71	37	29	38	12
80	78	49	42	50	22
85	84	61	54	62	34

3. Using CTL to make source comparisons

With the CTL calculated, direct comparisons can be made to other noise sources. The corresponding overall average CTL values for aircraft, road, rail with vibration and rail without vibration are 73.3, 78.3, 75.8, and 87.8 DNL, respectively (Fidell *et al.*, 2011; Schomer *et al.*, 2012). This can be interpreted to mean that, on average, communities are about 11 dB less tolerant of WTN than of aircraft noise, 16 dB less tolerant of WTN than of road traffic noise, 14 dB less tolerant of WTN than of rail noise accompanied with high vibrations, and 26 dB less tolerant of WTN than of rail noise without vibrations. Confidence in these source differences will increase as future studies in this area produce additional estimates for the relationship between WTN levels and the prevalence of high annoyance.

4. Conclusions

The advantage of using the CTL model over multiple regression is that CTL provides a quantification in decibels for the differences between data sets that may originate from different communities and/or reflect responses to different noise sources. However, this approach does not identify the origins of the non-acoustic determinants of annoyance. By contrast, the multiple regression models have the advantage of identifying and quantifying non-DNL factors that are associated with individual differences in annoyance. For reflections on the advantages and disadvantages of the CTL model and multiple regressions, see Janssen and Vos (2011) and Fidell *et al.* (2011). The reality faced by jurisdictions that govern community noise policy is that they may never fully understand the myriad of reasons why communities may differ in their annoyance at comparable noise exposure levels. An assessment based on CTL side-steps the need for this type of speculation. The analysis presented here is obviously based on a limited number of field studies, and supports only preliminary conclusions. Nonetheless, further systematic collection and analysis of the relationship between WTN exposure and the prevalence of high annoyance can test and strengthen the current conclusions.

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[1] See supplemental material at http://dx.doi.org/10.1121/1.4942390 for the univariate analysis results.

Agresti, A. (**2002**). *Categorical Data Analysis*, 2nd ed. (Wiley, New York).

Alberta Utilities Commission (AUC) (**2013**). "Rule 012-Noise Control," http://www.auc.ab.ca/acts-regulations-and-auc-rules/rules/Pages/Rule012.aspx (Last viewed 11/24/2014).

American National Standards Institute (ANSI) (**1996**). *S12.9-1996, Quantities and Procedures for Description and Measurement of Environmental Sound—Part 4: Noise Assessment and Predication of Long-Term Community Response* (American Standards Association, New York).

Amundsen, A. H., Klæboe, R., and Aasvang, G. M. (**2013**). "Long-term effects of noise reduction measures on noise annoyance and sleep disturbance: The Norwegian facade insulation study," J. Acoust. Soc. Am. **133**(6), 3921–3928.

Asensio, C., Recuero, M., and Pavón, I. (**2014**). "Citizens' perception of the efficacy of airport noise insulation programmes in Spain," Appl. Acoust. **84**, 107–115.

Bakker, R. H., Pedersen, E., van den Berg, G. P., Stewart, R. E., Lok, W., and Bouma, J. (**2012**). "Impact of wind turbine sound on annoyance, self-reported sleep disturbance and psychological distress," Sci. Total Environ. **425**, 42–51.

Basner, M., Babisch, W., Davis, A., Brink, M., Clark, C., Janssen, S., and Stansfeld, S. (**2014**). "Auditory and non-auditory effects of noise on health," Lancet **383**(9925), 1325–1332.

Buysse, D. J., Reynolds, C. F., Monk, T. H., Berman, S. R., and Kupfer, D. J. (**1989**). "The Pittsburgh sleep quality index: A new instrument for psychiatric practice and research," Psych. Res. **28**, 193–213.

Cohen, S., Kamarck, T., and Mermelstein, R. (**1983**). "A global measure of perceived stress," J. Health Soc. Behav. **24**(4), 385–396.

DataKustik® GmbH (**2014**). "CadnaA version 4.4," software for emission protection, www.datakustik.com (Last viewed 11/24/2014).

European Network on Noise and Health (ENNAH) (**2013**). "Final Report," edited by J. Lekaviciute, S. Kephalopoulos, S. Stansfeld, and C. Clark, Inspra Italy: European Commission Joint Research Centre Scientific and Policy Report, Report No. EUR 25809 EN.

Feder, K., Michaud, D. S., Keith, S. E., Voicescu, S. A., Marro, L., Than, J., Guay, M., Denning, A., Bower, T. J., Lavigne, E., Whelan, C., and van den Berg, F. (**2015**). "An assessment of quality of life using the WHOQOL-BREF among participants living in the vicinity of wind turbines," Environ. Res. **142**, 227–238.

Fidell, S., Mestre, V., Schomer, P., Berry, B., Gjestland, T., Vallet, M., and Reid, T. (**2011**). "A first-principles model for estimating the prevalence of annoyance with aircraft noise exposure," J. Acoust. Soc. Am. **130**(2), 791–806.

Fields, J. M. (**1993**). "Effect of personal and situational variables on noise annoyance in residential areas," J. Acoust. Soc. Am. **93**(5), 2753–2763.

Guski, R. (**1999**). "Personal and social variables as co-determinants of noise annoyance," Noise Health **1**(3), 45–56.

International Electrotechnical Commission (IEC) (**2012**). IEC-61400-11 Ed. 3.0, *Wind Turbine Generator Systems–Part 11: Acoustic Noise Measurement Techniques* (IEC, Geneva).

ISO (**1993**). ISO 9613-1, *Acoustics. Attenuation of Sound During Propagation Outdoors. Part 1: Calculation of the Absorption of Sound by the Atmosphere* (International Organization for Standardization, Geneva).

ISO (**1996**). ISO 9613-2, *Acoustics. Attenuation of Sound During Propagation Outdoors. Part 2: General Method of Calculation* (International Organization for Standardization, Geneva).

ISO (**2003a**). ISO/TS-15666, *Acoustics—Assessment of Noise Annoyance by Means of Social and Socio-Acoustic Surveys* (International Organization for Standardization, Geneva).

ISO (**2003b**). ISO 226:2003, *Acoustics—Normal Equal-Loudness Level Contours*, 2nd ed. (International Organization for Standardization, Geneva).

ISO (**2003c**). ISO 1996-1:2003(E), *Acoustics—Description, Measurement and Assessment of Environmental Noise—Part 1: Basic Quantities and Assessment Procedures* (International Organization for Standardization, Geneva).

Janssen, S., Vos, H., Eisses, A. R., and Pedersen, E. (**2011**). "A comparison between exposure-response relationships for wind turbine annoyance and annoyance due to other noise sources," J. Acoust. Soc. Am. **130**(6), 3746–3753.

Job, R. F. S. (**1988**). "Community response to noise: A review of factors influencing the relationship between noise exposure and reaction," J. Acoust. Soc. Am. **83**, 991–1001.

Keith, S. E., Feder, K., Voicescu, S., Soukhovtsev, V., Denning, A., Tsang, J., Broner, N., Richarz, W., and van den Berg, F. (**2016a**). "Wind turbine sound power measurements," J. Acoust. Soc. Am. **139**(3), 1431–1435.

Keith, S. E., Feder, K., Voicescu, S., Soukhovtsev, V., Denning, A., Tsang, J., Broner, N., Richarz, W., and van den Berg, F. (**2016b**). "Wind turbine sound pressure level calculations at dwellings," J. Acoust. Soc. Am. **139**(3), 1436–1442.

Krogh, C. M. E., Gillis, L., Kouwen, N., and Aramini, J. (**2011**). "WindVOiCe, a self-reporting survey: Adverse health effects, industrial wind turbines, and the need for vigilance monitoring," Bull. Sci. Technol. Soc. **31**(4), 334–345.

Kuwano, S., Yano, T., Kageyama, T., Sueoka, S., and Tachibana, H. (**2014**). "Social survey on wind turbine noise in Japan," Noise Control Eng. J. **62**(6), 503–520.

Michaud, D. S., Bly, S. H. P., and Keith, S. E. (**2008a**). "Using a change in percent highly annoyed with noise as a potential health effect measure for projects under the *Canadian Environmental Assessment Act*," Can. Acoust. **36**(2), 13–28.

Michaud, D. S., Feder, K., Keith, S. E., Voicescu, S. A., Marro, L., Than, J., Guay, M., Denning, A., Bower, T., Villeneuve, P., Russell, E., Koren, G., and van den Berg, F. (**2016a**). "Self-reported and measured stress related responses associated with exposure to wind turbine noise," J. Acoust. Soc. Am. **139**(3), 1467–1479.

Michaud, D. S., Feder, K., Keith, S. E., Voicescu, S. A., Marro, L., Than, J., Guay, M., Denning, A., McGuire, D., Bower, T., Lavigne, E., Murray, B. J., Weiss, S. K., and van den Berg, F. (**2016b**). "Exposure to wind turbine noise: Perceptual responses and reported health effects," J. Acoust. Soc. Am. **139**(3), 1443–1454.

Michaud, D. S., Feder, K., Keith, S. E., Voicescu, S. A., Marro, L., Than, J., Guay, M., Denning, A., Murray, B. J., Weiss, S. K., Villeneuve, P., van den Berg, F., and Bower, T. (**2016c**). "Effects of wind turbine noise on self-reported and objective measures of sleep," SLEEP **39**(1), 97–109.

Michaud, D. S., Keith, S. E., Feder, K., Soukhovtsev, V., Marro, L., Denning, A., McGuire, D., Broner, N., Richarz, W., Tsang, J., Legault, S., Poulin, D., Bryan, S., Duddeck, C., Lavigne, E., Villeneuve, P. J., Leroux, T., Weiss, S. K., Murray, B. J., and Bower, T. (**2013**). "Self-reported and objectively measured health indicators among a sample of Canadians living within the vicinity of industrial wind turbines: Social survey and sound level modelling methodology," Noise News Int. **21**, 14–27.

Michaud, D. S., Keith, S. E., and McMurchy, D. (**2008b**). "Annoyance and disturbance of daily activities from road traffic noise in Canada," J. Acoust. Soc. Am. **123**(2), 784–792.

Miedema, H. M., and Vos, H. (**1998**). "Exposure-response relationships for transportation noise," J. Acoust. Soc. Am. **104**(6), 3432–3445.

Miedema, H. M., and Vos, H. (**2003**). "Noise sensitivity and reactions to noise and other environmental conditions," J. Acoust. Soc. Am. **113**(3), 1492–1504.

Mroczek, B., Kurpas, D., and Karakiewicz, B. (**2012**). "Influence of distances between places of residence and wind farms on the quality of life in nearby areas," Ann. Agr. Environ. Med. **19**(4), 692–696.

Niemann, H., Bonnefoy, X., Braubach, M., Hecht, K., Maschke, C., Rodrigues, C., and Röbbel, N. (**2006**). "Noise-induced annoyance and morbidity results from the pan-European LARES study," Noise Health **8**(31), 63–79.

Nissenbaum, M. A., Aramini, J. J., and Hanning, C. D. (**2012**). "Effects of industrial wind turbine noise on sleep and health," Noise Health **14**(60), 237–243.

Pawlaczyk-Łuszczyńska, M., Dudarewicz, A., Zaborowski, K., Zamojska-Daniszewska, M., and Waszkowska, M. (**2014**). "Evaluation of annoyance from the wind turbine noise: A pilot study," Int. J. Occup. Med. Environ. Health **27**(3), 364–388.

Pedersen, E., and Persson Waye, K. (**2004**). "Perception and annoyance due to wind turbine noise—A dose-response relationship," J. Acoust. Soc. Am. **116**(6), 3460–3470.

Pedersen, E., and Persson Waye, K. (**2007**). "Wind turbine noise, annoyance and self-reported health and wellbeing in different living environments," Occup. Environ. Med. **64**(7), 480–486.

Pedersen, E., van den Berg, F., Bakker, R., and Bouma, J. (**2009**). "Response to noise from modern wind farms in the Netherlands," J. Acoust. Soc. Am. **126**(2), 634–643.

Pedersen, E., van den Berg, F., Bakker, R., and Bouma, J. (**2010a**). "Can road traffic mask sound from wind turbines? Response to wind turbine sound at different levels of road traffic sound," Energ. Pol. **38**(5), 2520–2527.

Pedersen, E., van den Berg, F., Bakker, R., and Bouma, J. (**2010b**). "Why is wind turbine noise so poorly masked by road traffic noise?," in *Proceedings of INTERNOISE, 39th Congress of Noise Control Engineering*, Lisbon, Portugal, June 13–16, 2010.

Rubin, G. J., Burns, M., and Wessely, S. (**2014**). "Possible psychological mechanisms for 'wind turbine syndrome.' On the windmills of your mind," Noise Health **16**(69), 116–122.

SAS Institute Inc. (**2014**). *SAS (Statistical Analysis System) Software package Version 9.2* (SAS Institute, Cary, NC).

Schomer, P., Mestre, V., Fidell, S., Berry, B., Gjestland, T., Vallet, M., and Reid, T. (**2012**). "Role of community tolerance level (CTL) in predicting the prevalence of the annoyance of road and rail noise," J. Acoust. Soc. Am. **131**(4), 2772–2786.

Schultz, T. J. (**1978**). "Synthesis of social surveys on noise annoyance," J. Acoust. Soc. Am. **64**(2), 377–405.

Shepherd, D., McBride, D., Welch, D., Dirks, K. N., and Hill, E. M. (**2011**). "Evaluating the impact of wind turbine noise on health-related quality of life," Noise Health **13**(54), 333–339.

Skevington, S. M., Lotfy, M., and O'Connell, K. A. (**2004**). "The World Health Organization's WHOQOL-BREF quality of life assessment: Psychometric properties and results of the international field trial—A report from the WHOQOL group," Qual. Life Res. **13**(2), 299–310.

Statistics Canada (**2014**). "Community noise and health study," http://www.statcan.gc.ca/daily-quotidien/141106/dq141106c-eng.htm (Last viewed 11/6/2014).

Stokes, M. E., Davis, C. S., and Koch, G. G. (**2000**). "Categorical data analysis using the SAS system," 2nd ed. (SAS Institute, Cary, NC).

Tachibana, H., Yano, H., Sakamoto, S., and Sueoka, S. (**2012**). "Synthetic research program on wind turbine noise in Japan," in *Proceedings of INTERNOISE, 41st Congress of Noise Control Engineering*, New York, NY, August 19–22, 2012, pp. 8505–8514.

United States Department of Transportation (**1998**). FHWA Traffic Noise Model®, technical manual (Federal Highway Administration, Washington, DC).

van den Berg, F. (**2008**). "Criteria for wind farm noise: Lmac and Lden," in *Proceedings of Acoustics '08*, Paris, June 29–July 4, 2008, pp. 4043–4048.

van den Berg, F., Verhagen, C., and Uitenbroek, D. (**2015**). "The relation between self-reported worry and annoyance from air and road traffic," Int. J. Environ. Res. Public Health **13**(3), 2486–2500.

World Health Organization (WHO) (**1999**). *Guidelines for Community Noise*, edited by B. Berglund, T. Lindvall, and D. H. Schwela (World Health Organization, Geneva).

WHO (**2011**). *Burden of Disease from Environmental Noise. Quantification of Healthy Life Years Lost in Europe*, edited by L. Fritschi, A. L. Brown, R. Kim, D. Schwela, and S. Kephalopolous (World Health Organization, Regional Office for Europe, Bonn).

WHOQOL Group (**1998**). "Development of the World Health Organization WHOQOL-BREF quality of life assessment," Psychol. Med. **28**(3), 551–558.

Yano, T. (**2015**). (personal communication).

Yano, T., Kuwano, S., Kageyama, T., Sueoka, S., and Tachibana, H. (**2013**). "Dose-response relationships for wind turbine noise in Japan," in *Proceedings of INTERNOISE, 42nd International Congress and Exposition on Noise Control Engineering*, Innsbruck, Austria, September 15–18, 2013, pp. 4591–4598.

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

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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 μl 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 (α) for the PSS. Cronbach's α is a measure of the internal consistency or reliability of test scores. Cronbach's α 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 α
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 ≥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*)

		Hair cortisol (ng/g) ($R^2 = 0.14$, $n = 528$)		
(b) Variable	Groups in variable	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

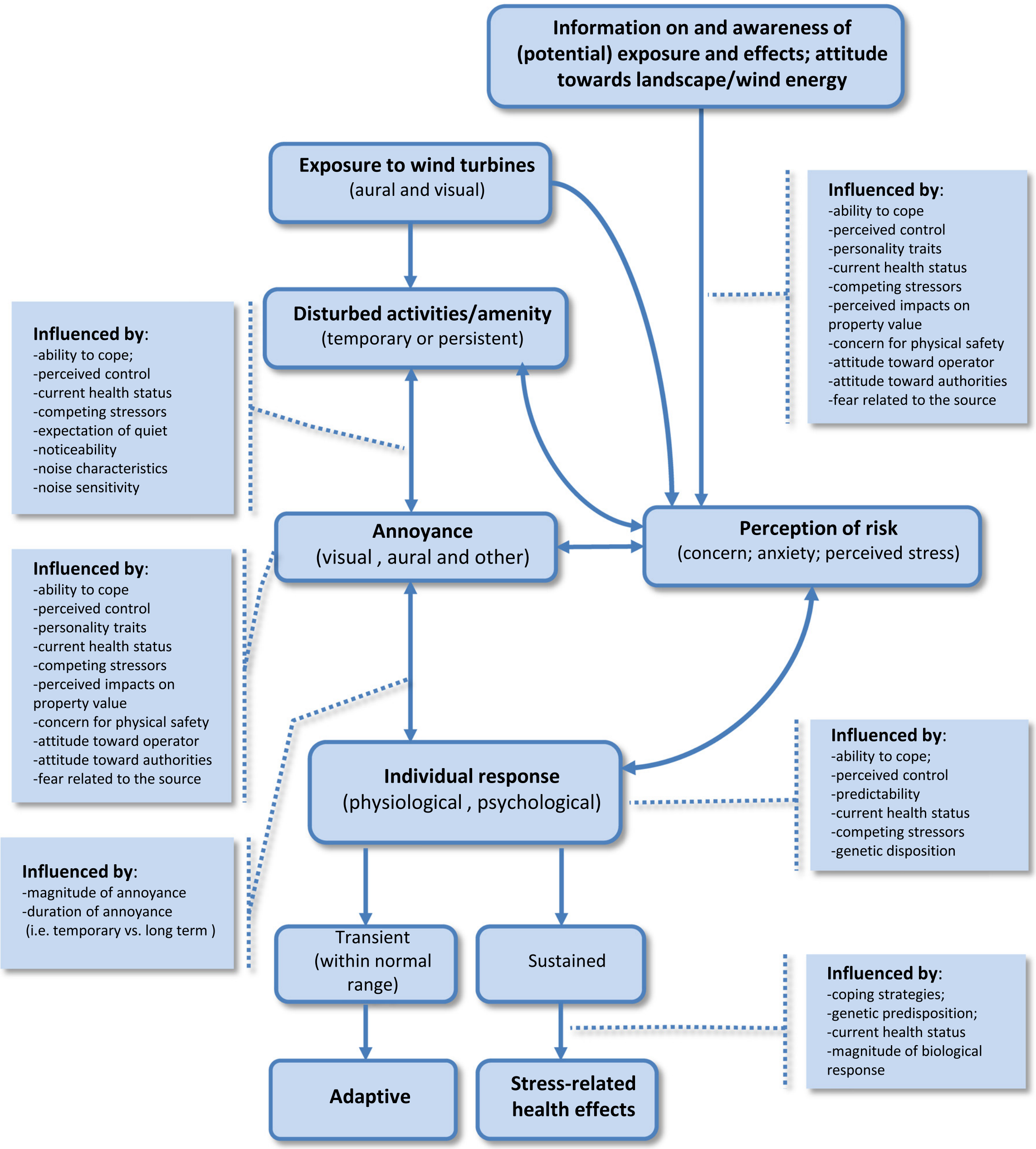

FIG. 1. (Color online) A theoretical model demonstrating the complex processes that may be involved in the potential progression towards indirect health effects from community noise exposure.

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.

Al kalaldeh, M. T., and Shosha, G. M. A. (**2012**). "Application of the perceived stress scale in health care studies. An analysis of literature," Int. J. Academ. Res. Part B **4**(4), 45–50.

Babisch, W. (**1998**). "Epidemiological studies on cardiovascular effects of traffic noise,"in *Advances in Noise Research, Volume I, Biological Effects of Noise*, edited by D. Prasher, and L. Luxon (Whurr, London, UK).

Babisch, W., Fromme, H., Beyer, A., and Ising, H. (**2001**). "Increased catecholamine levels in urine in subjects exposed to road traffic noise: The role of stress hormones in noise research," Environ. Int. **26**(7-8), 475–481.

Bakker, R. H., Pedersen, E., van den Berg, G. P., Stewart, R. E., Lok, W., and Bouma, J. (**2012**). "Impact of wind turbine sound on annoyance, self-reported sleep disturbance and psychological distress," Sci. Total Env. **425**, 42–51.

Borsky, P. N. (**1979**). "Sociopsychological factors affecting the human response to noise exposure," Otolaryngol. Clin. North Am. **12**(3), 521–535.

Broderick, J. E., Arnold, D., Kudielka, B. M., and Kirschbaum, C. (**2004**). "Salivary cortisol sampling compliance: Comparison of patients and healthy volunteers," Psychoneuroendocrinology **29**(5), 636–650.

Bryan, S., St. Pierre-Larose, M., Campbell, N., Clarke, J., and Tremblay, M. S. (**2010**). "Resting blood pressure and heart rate measurements in the Canadian Health Measures Survey, cycle 1," Health Rep. **21**(1), 71–78.

Cohen, S., Kamarck, T., and Mermelstein, R. (**1983**). "A global measure of perceived stress," J. Health Soc. Behav. **24**(4), 385–396.

DataKustik GmbH®. (**2014**). "Cadna A version 4.4 software for immission protection," available at www.datakustik.com (Last viewed 11/24/2014).

Edwards, S., Evans, P., Hucklebridge, F., and Clow, A. (**2001**). "Association between time of awakening and diurnal cortisol secretory activity," Psychoneuroendocrinology **26**(6), 613–622.

Feder, K., Michaud, D. S., Keith, S. E., Voicescu, S. A., Marro, L., Than, J., Guay, M., Denning, A., Bower, T. J., Lavigne, E., Whelan, C., and van den Berg, F. (**2015**). "An assessment of quality of life using the WHOQOL-BREF among participants living in the vicinity of wind turbines," Environ. Res. **142**, 227–238.

Fiorentini, A., Valente, R., Perciaccante, A., and Tubani, L. (**2007**). "Sleep's quality disorders in patients with hypertension and type 2 diabetes mellitus," Int. J. Cardiol. **114**(2), E50–E52.

Gerber, M., Kalak, N., Elliot, C., Holsboer-Trachsler, E., Pühse, U., and Brand, S. (**2013**). "Both hair cortisol levels and perceived stress predict increased symptoms of depression: An exploratory study in young adults," Neuropsychobiology **68**(2), 100–109.

Grunau, R. E., Cepeda, I. L., Chau, C. M. Y., Brummelte, S., Weinberg, J., Lavoie, P. M., Ladd, M., Hirschfeld, A. F., Russell, E., Koren, G., Van Uum, S., Brant, R., and Turvey, S. E. (**2013**). "Neonatal pain-related stress and NFKBIA genotype are associated with altered cortisol levels in preterm boys at school age," PLoS One **8**(9), 73–81.

Guski, R. (**2001**). "Effects of noise on health," in *Environmental Urban Noise*, edited by A. García (WIT, Ashurst Lodge, Ashurst, Southampton, UK).

Haralabidis, A. S., Dimakopoulou, K., Vigna-Taglianti, F., Giampaolo, M., Borgini, A., Dudley, M. L., Pershagen, G., Bluhm, G., Houthuijs, D., Babisch, W., Velonakis, M., Katsouyanni, K., Jarup, L., and HYENA Consortium. (**2008**). "Acute effects of night-time noise exposure on blood pressure in populations living near airports," Eur. Heart J. **29**(5), 658–664.

Hennig, J., Friebe, J., Ryl, I., Krämer, B., Böttcher, J., and Netter, P. (**2000**). "Upright posture influences salivary cortisol," Psychoneuroendocrinology **25**(1), 69–83.

Hinkelmann, K., Muhtz, C., Dettenborn, L., Agorastos, A., Wingenfeld, K., Spitzer, C., Gao, W., Kirschbaum, C., Wiedemann, K., and Otte, C. (**2013**). "Association between childhood trauma and low hair cortisol in depressed patients and healthy control subjects," Biol. Psychiatry. **74**(9), e15–e17.

Institute of Medicine. (**2001**). "Health and behavior: The interplay of biological, behavioral, and societal influences," Committee on Health and Behavior: Research, Practice, and Policy (National Academies, Washington, DC).

ISO (**1993**). ISO 9613-1, "Acoustics. Attenuation of sound during propagation outdoors. Part 1: Calculation of the absorption of sound by the atmosphere" (International Organization for Standardization, Geneva, Switzerland).

ISO (**1996**). ISO 9613-2, "Acoustics. Attenuation of sound during propagation outdoors. Part 2: General method of calculation" (International Organization for Standardization, Geneva, Switzerland).

ISO/TS-15666 (**2003**). "Acoustics—Assessment of noise annoyance by means of social and socio-acoustic surveys" (International Organization for Standardization, Geneva, Switzerland).

Job, R. F. S. (**1988**). "Community response to noise: A review of factors influencing the relationship between noise exposure and reaction," J. Acoust. Soc. Am. **83**, 991–1001.

Job, R. F. S. (**1996**). "The influence of subjective reactions to noise on health effects of noise," Environ. Int. **22**(1), 93–104.

Keith, S. E., Feder, K., Voicescu, S., Soukhovtsev, V., Denning, A., Tsang, J., Broner, N., Richarz, W., and van den Berg, F. (**2016a**). "Wind turbine sound pressure level calculations at dwellings," J. Acoust. Soc. Am. **139**(3), 1436–1442.

Keith, S. E., Feder, K., Voicescu, S., Soukhovtsev, V., Denning, A., Tsang, J., Broner, N., Richarz, W., and van den Berg, F. (**2016b**). "Wind turbine sound power measurements," J. Acoust. Soc. Am. **139**(3), 1431–1435.

Knutson, K. L., Van Cauter, E., Rathouz, P. J., Yan, L. L., Hulley, S. B., Liu, K., and Lauderdale, D. S. (**2009**). "Association between sleep and blood pressure in midlife: The CARDIA sleep study," Arch. Intern. Med. **169**(11), 1055–1061.

Legler, M., Brandenberger, G., Hietter, B., Siméoni, M., and Reinhardt, B. (**1982**). "Diurnal cortisol peaks and their relationships to meals," J. Clin. Endocrinol. Metab. **55**(4), 757–761.

Manenschijn, L., Schaap, L., van Schoor, N. M., van der Pas, S., Peeters, G. M., Lips, P., Koper, J. W., and van Rossum, E. F. (**2013**). "High long-term cortisol levels, measured in scalp hair, are associated with a history of cardiovascular disease," J. Clin. Endocrinol. Metab. **98**(5), 2078–2083.

McCunney, R. J., Mundt, K. A., Colby, W. D., Dobie, R., Kaliski, K., and Blais, M. (**2014**). "Wind turbines and health: A critical review of the scientific literature," J. Occup. Environ. Med. **56**(11), e108–e130.

Michaud, D. S., Feder, K., Keith, S. E., Voicescu, S. A., Marro, L., Than, J., Guay, M., Denning, A., McGuire, D., Bower, T., Lavigne, E., Murray, B. J., Weiss, S. K., and van den Berg, F. (**2016a**). "Exposure to wind turbine noise: Perceptual responses and reported health effects," J. Acoust. Soc. Am. **139**(3), 1443–1454.

Michaud, D. S., Feder, K., Keith, S. E., Voicescu, S., Marro, L., Than, J., Guay, M., Denning, A., Murray, B. J., Weiss, S. K., Villeneuve, P., and van den Berg, F. (**2016c**). "Effects of wind turbine noise on self-reported and objective measures of sleep," Sleep **39**, 97–109.

Michaud, D. S., Keith, S. E., Feder, K., Soukhovtsev, V., Marro, L., Denning, A., McGuire, D., Broner, N., Richarz, W., Tsang, J., Legault, S., Poulin, D., Bryan, S., Duddeck, C., Lavigne, E., Villeneuve, P. J., Leroux, T., Weiss, S. K., Murray, B. J., and Bower, T. (**2013**). "Self-reported and objectively measured health indicators among a sample of Canadians living within the vicinity of industrial wind turbines: Social survey and sound level modelling methodology," Noise News Int. **21**, 14–27.

Michaud, D. S., Keith, S. E., Feder, K., Voicescu, S. A., Marro, L., Than, J., Guay, M., Bower, T., Denning, A., Lavigne, E., Janssen, S. A., Leroux, T., and van den Berg, F. (**2016b**). "Personal and situational variables associated with wind turbine noise annoyance," J. Acoust. Soc. Am. **139**(3), 1455–1466.

Miedema, H. M., and Vos, H. (**1998**). "Exposure-response relationships for transportation noise," J. Acoust. Soc. Am. **104**(6), 3432–3445.

Niemann, H., Bonnefoy, X., Braubach, M., Hecht, K., Maschke, C., Rodrigues, C., and Röbbel, N. (**2006**). "Noise-induced annoyance and morbidity results from the pan-European LARES study," Noise Health **8**(31), 63–79.

Pereg, D., Chan, J., Russell, E., Berlin, T., Mosseri, M., Seabrook, J. A., Koren, G., and Van Uum, S. H. (**2013**). "Cortisol and testosterone in hair as biological markers of systolic heart failure," Psychoneuroendocrinology **38**(12), 2875–2882.

Pereg, D., Gow, R., Mosseri, M., Lishner, M., Rieder, M., Van Uum, S. H., and Koren, G. (**2011**). "Hair cortisol and the risk for acute myocardial infarction in adult men," Stress **14**(1), 73–81.

Russell, E., Koren, G., Rieder, M., and Van Uum, S. H. (**2012**). "Hair cortisol as a biological marker of chronic stress: Current status, future directions and unanswered questions," Psychoneuroendocrinology **37**(5), 589–601.

SAS Institute Inc. (**2014**). "SAS (Statistical Analysis System) software package version 9.2" (SAS Institute Inc., Cary, NC).

Stalder, T., and Kirschbaum, C. (**2012**). "Analysis of cortisol in hair—State of the art and future directions," Brain Behav. Immun. **26**(7), 1019–1029.

Stalder, T., Kirschbaum, C., Alexander, N., Bornstein, S. R., Gao, W., Miller, R., Stark, S., Bosch, J. A., and Fischer, J. E. (**2013**). "Cortisol in hair and the metabolic syndrome," J. Clin. Endocrinol. Metab. **98**(6), 2573–2580.

Stansfeld, S. A., and Marmot, M. G. (eds). (**2002**). *Stress and the Heart: Psychosocial Pathways to Coronary Heart Disease* (BMJ Books, Williston, VA).

Stansfeld, S. A., and Matheson, M. P. (**2003**). "Noise pollution: Non-auditory effects on health," Br. Med. Bull. **68**, 243–257.

Vallet, M. (**2001**). "Effects of noise on health," in *Environmental Urban Noise*, edited by A. García (WIT, Ashurst Lodge, Ashurst, Southampton, UK).

Van Uum, S. H., Sauvé, B., Fraser, L. A., Morley-Forster, P., Paul, T. L., and Koren, G. (**2008**). "Elevated content of cortisol in hair of patients with severe chronic pain: A novel biomarker for stress," Stress **11**(6), 483–488.

Veldhorst, M. A., Noppe, G., Jongejan, M. H., Kok, C. B., Mekic, S., Koper, J. W., van Rossum, E. F., and van den Akker, E. L. (**2014**). "Increased scalp hair cortisol concentrations in obese children," J. Clin. Endocrinol. Metab. **99**(1), 285–290.

Walton, D. M., Macdermid, J. C., Russell, E., Koren, G., and Van Uum, S. (**2013**). "Hair-normalized cortisol waking response as a novel biomarker of hypothalamic-pituitary-adrenal axis activity following acute trauma: A proof-of-concept study with pilot results," Pain Res. Treat. **2013**, 876871.

Webb, E., Thomson, S., Nelson, A., White, C., Koren, G., Rieder, M., and van Uum, S. H. (**2010**). "Assessing individual systemic stress through cortisol analysis of archaeological hair," J. Archaeol. Sci. **37**(4), 807–812.

Wells, S., Tremblay, P. F., Flynn, A., Russell, E., Kennedy, J., Rehm, J., Van Uum, S. H., Koren, G., and Graham, K. (**2014**). "Associations of hair cortisol concentration with self-reported measures of stress and mental health-related factors in a pooled database of diverse community samples," Stress **17**(4), 334–342.

Wennig, R. (**2000**). "Potential problems with the interpretation of hair analysis results," Forensic Sci. Int. **107**(103), 5–12.

Wester, V. L., Staufenbiel, S. M., Veldhorst, M. A., Visser, J. A., Manenschijn, L., Koper, J. W., Klessens-Godfroy, F. J., van den Akker, E. L., and van Rossum, E. F. (**2014**). "Long-term cortisol levels measured in scalp hair of obese patients," Obesity (Silver Spring) **22**(9), 1956–1958.

World Health Organization (WHO). (**1999**). *Guidelines for Community Noise*, edited by B. Berglund, T. Lindvall, and D. H. Schwela (World Health Organization, Geneva, Switzerland).

World Health Organization (WHO). (**2011**). *Burden of Disease from Environmental Noise. Quantification of Healthy Life Years Lost in Europe*, edited by L. Fritschi, A. L. Brown, R. Kim, D. Schwela, and S. Kephalopolous (World Health Organization, Geneva, Switzerland).

Estimating annoyance to calculated wind turbine shadow flicker is improved when variables associated with wind turbine noise exposure are considered

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The *Community Noise and Health Study* conducted by Health Canada included randomly selected participants aged 18–79 yrs (606 males, 632 females, response rate 78.9%), living between 0.25 and 11.22 km from operational wind turbines. Annoyance to wind turbine noise (WTN) and other features, including shadow flicker (SF) was assessed. The current analysis reports on the degree to which estimating high annoyance to wind turbine shadow flicker (HA_{WTSF}) was improved when variables known to be related to WTN exposure were also considered. As SF exposure increased [calculated as maximum minutes per day (SF_m)], HA_{WTSF} increased from 3.8% at $0 \leq SF_m < 10$ to 21.1% at $SF_m \geq 30$, $p < 0.0001$. For each unit increase in SF_m the odds ratio was 2.02 [95% confidence interval: (1.68,2.43)]. Stepwise regression models for HA_{WTSF} had a predictive strength of up to 53% with 10% attributed to SF_m. Variables associated with HA_{WTSF} included, but were not limited to, annoyance to other wind turbine-related features, concern for physical safety, and noise sensitivity. Reported dizziness was also retained in the final model at $p = 0.0581$. Study findings add to the growing science base in this area and may be helpful in identifying factors associated with community reactions to SF exposure from wind turbines. [http://dx.doi.org/10.1121/1.4942403]

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I. INTRODUCTION

There are a growing number of studies that have assessed community annoyance to wind turbine noise (WTN) exposure using modeled WTN levels and/or proximity to wind turbines (WTs) (Pedersen and Persson Waye, 2004, 2007; Pedersen *et al.*, 2007; Pedersen *et al.*, 2009; Pedersen, 2011; Verheijen *et al.*, 2011; Pawlaczyk-Łuszczyńska *et al.*, 2014; Tachibana *et al.*, 2014). Adding to these findings are the results from the Health Canada *Community Noise and Health Study* (CNHS) where it was found that the prevalence of self-reported high annoyance to several WT features, including noise, vibrations, visual impact, blinking lights, and shadow flicker (SF) increased with increasing exposure to modeled outdoor A-weighted WTN levels (Michaud *et al.*, 2016b).

This suggests that in addition to providing an estimate of WTN annoyance, modeled WTN levels could also be used to estimate annoyance from other WT-related variables. Although there is a benefit to using WTN to estimate multiple community reactions, the advantages of a more parsimonious exposure assessment may not necessarily be the best approach for estimating annoyance responses that are based on visual

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perception. These reactions may be estimated with more accuracy with an exposure model that estimates the visual exposure that is presumably causing annoyance. In this regard, there was an opportunity in the CNHS to investigate the prevalence of high annoyance to wind turbine shadow flicker (HA_{WTSF}) using a commercially available model for SF exposure.

WT SF is a phenomenon that occurs when rotating blades from a WT cast periodic shadows on adjacent land or properties [Bolton, 2007; Department of Energy and Climate Change (DECC), 2011; Saidur *et al.*, 2011]. The occurrence of SF is determined by a specific set of variables that include the hub height of the turbine, its rotor diameter and blade width, the position of the Sun, and varying weather patterns, such as wind direction, wind speed, and cloud cover [Harding *et al.*, 2008; Massachusetts Department of Environmental Protection (MassDEP) and Massachusetts Department of Public Health (MDPH), 2012; Katsaprakakis, 2012]. As the onset of shadow flickering will only occur when the WT blades are in motion, it will always be associated with at least some level of WTN emissions. When studying the effects of SF, it is therefore important to also consider personal and situational variables that have been assessed in relation to WTN annoyance. These include, but are not limited to, noise sensitivity, concern for physical safety, reported health effects, property ownership, presence of WTs on property, type of dwelling, personal benefit, etc. (Michaud *et al.*, 2016a). Unlike annoyance reactions, conceptually, "*concern for physical safety*" from having WTs in the area was not considered to necessarily be a response to operational WTs. Rather, this is more likely to reflect an attitudinal variable that could exert an influence on the response to SF. This would align with the research that has repeatedly demonstrated that "*fear of the source*," but not its associated noise, has been found to have an influence on noise annoyance (Fields, 1993).

The current analysis follows the approach presented by Michaud *et al.* (2016a). Two multiple regression models are provided for HA_{WTSF}. The first model is *unrestricted*, with variables retained in the model based solely on their statistical strength of association with HA_{WTSF}. In contrast, the second model can be viewed as *restricted*, insofar as variables that are *reactions* to WT operations are not considered. The rationale for two models is that while the unrestricted model reports on all of the variables that were found to be most strongly associated with HA_{WTSF} in the current study, the restricted model may yield information that could be used to identify annoyance mitigation measures and other methods of accounting for HA_{WTSF}, over and above reducing SF exposure levels.

II. METHODS

A. Sample design

1. Target population, sample size and sampling frame strategy

A detailed description of the study design and methodology, the target population, final sample size, and allocation of participants, as well as the strategy used to develop the sampling frame has been described by Michaud *et al.* (2013) and Michaud *et al.* (2016b). Briefly, the study locations were drawn from areas in southwestern Ontario (ON) and Prince Edward Island (PEI) having a relatively high density of dwellings within the vicinity of WTs. Preference was also given to areas that shared similar features (i.e., rural/semirural, flat terrain, and free of significant/regular aircraft exposure that could confound the response to WTN). There were 2004 potential dwellings identified from the ON and PEI sampling regions which included a total of 315 and 84 WTs, respectively. The WT electrical power outputs ranged between 660 kW and 3 MW, with hub heights that were predominantly 80 m. To optimize the statistical power[1] of the study in order to detect an association between WTN and health effects, all identified dwellings within 600 m from a WT were sampled, as occupants in these dwellings would be exposed to the highest WTN levels. Dwellings at further distances were randomly selected up to 11.22 km from a WT. This distance was selected in response to public consultation, and to ensure that exposure-response assessments would include participants unexposed to WTN. The target population consisted of adults aged 18 to 79 yrs.

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. Data collection

1. Questionnaire content and administration

A detailed description of the questionnaire content, pilot testing, administration, and the approaches used to increase participation have been described in detail by Michaud *et al.* (2016b), Michaud *et al.* (2013), and Feder *et al.* (2015). Briefly, the questionnaire instrument included modules on basic demographics, noise and shadow annoyance, health effects (e.g., tinnitus, migraines, dizziness), quality of life, sleep quality, perceived stress, lifestyle behaviours, and chronic diseases.

Data were collected by Statistics Canada who communicated all aspects of the study as the CNHS. This was an attempt to mask the study's true intent, which was to assess the community response to WTs. This approach is commonly used to avoid a disproportionate contribution from any group that may have distinct views toward the study subject. Sixteen (16) interviewers collected study data through in-person interviews between May and September 2013 in southwestern ON and PEI. Once a roster of all adults aged 18 to 79 yrs living in the dwelling was compiled, a computerized method was used to randomly select one adult from each household. No substitution was permitted under any circumstances.

2. Defining percent highly annoyed by SF exposure

As part of the household interview, participants were asked if they could see WTs from anywhere on their property. Participants that indicated they could see WTs were then asked to rate their magnitude of annoyance with "*shadows or flickers of light*" (hereafter referred to as SF annoyance) from WTs by selecting one of the following categories: "*not at all*," "*slightly*," "*moderately*," "*very*," or "*extremely*." Consistent with the approach recommended in ISO/TS-15666 (2003), the top two categories were collapsed to create a "*highly annoyed*" group (i.e., $\mathrm{HA}_{\mathrm{WTSF}}$). This group was compared to a group defined as "*not highly annoyed*" which consisted of all other categories, including those who did not see WTs. The same approach was taken for defining the percentage highly annoyed by WTN (Michaud *et al.*, 2016a).

C. Modeling WT SF

SF exposure was calculated for all dwellings with WindPro v. 2.9 software (EMD International®, 2013a,b). The model estimated SF exposure from all possible visible WTs from a particular dwelling. WindPro sets the maximum default distance that is used to create this exposure area to be 2 km from a WT, based on available German nationwide requirements (German Federal Ministry of Justice, 2011; EMD International®, 2013a,b). Beyond this distance, the model assumes that shadow exposure will dissipate before reaching dwellings. At 2 km an object must be at least 17.5 m wide to be able to fully cover the Sun's disk and thus cause a maximum variation in light intensity. As WT blades are much narrower, the sunlight will only be partially blocked and the variation in light intensity will be considerably decreased. Other calculation parameters were set for the astronomical maximum shadow durations (i.e., worst case) including: solar elevation angles greater than 3° above the horizon; no clouds; constant WT operation; and rotor and dwelling facade perpendicular to the rays of the Sun (German Federal Ministry of Justice, 2011). Base maps set within the appropriate UTM grid zones for the studied areas were fitted with local height contours and land cover data for forested areas (Natural Resources Canada, 2016). Average tree heights for the most common tree species were estimated for both provinces (Gaudet and Profitt, 1958; Peng, 1999; Sharma and Parton, 2007; Schneider and Pautler, 2009; Ontario Ministry of Natural Resources, 2014) as vegetation can block the line of sight of a turbine and thus may reduce SF exposure [Massachusetts Department of Environmental Protection (MassDEP) and Massachusetts Department of Public Health (MDPH), 2012; EMD International®, 2013a,b]. The model calculates SF exposure at the dwelling window, which factors in window dimensions, window height above ground, and window distance from room floor for all dwellings. In the current study, the WindPro default window dimension (1 m × 1 m) and distance from the bottom of the window to the room floor (1 m) were considered to be representative of the dwellings in the CNHS. With regards to dwelling height, the default value in WindPro is 1.5 m from the ground; however, in order to be consistent with modeled WTN and standard practice in Canada (ONMOE, 2008; Keith *et al.*, 2016), a dwelling height of 4 m was chosen. The "*greenhouse*" mode for SF exposure calculation was used, which considers that the dwelling window can be affected by SF from all possible directions by all WTs within the line of sight of a dwelling. As a result, the calculations provided worst-case SF exposure for all dwelling windows from each facade.

As mentioned above, SF occurs together with noise emissions. Therefore, WTN levels considered in this analysis are based on the calculations presented by Keith *et al.* (2016).

D. Model uncertainties

There are some limitations associated with the current available SF calculation models, which may have an influence on the analysis of the study responses. With regards to this particular model, there are uncertainties regarding the specific distance from a WT where SF ceases to be visible, when the worst-case scenario method is employed (EMD International, 2013a,b). However, when applying Weber's Law of Just Noticeable Difference (Ross, 1997) to the turbines in this study, the distance at which the shadow flickering ceases to be noticeable falls within the 2 km exposure range, which is in line with the software default parameters. Even the combined uncertainty of ±55 m that is associated with using GPS to estimate the location of the dwellings and the location of the WTs in the study (Keith *et al.*, 2016), is not likely to have a large impact on SF exposure near the WindPro 2 km default exposure limit. The impact of this uncertainty increases with decreasing distance between the dwelling and WT (Fig. 1). This is especially the case in the North to South orientation relative to the WT (e.g., dwelling H, Fig. 1). In a worst case scenario, due to the nature of SF exposure, at close distances to the WT it is possible that dwellings could be misclassified as having no exposure when they may in fact receive high levels of SF exposure or vice-versa (e.g., dwelling E, Fig. 1).

Shadow areas as well as turbine and dwelling points were plotted using WindPro v. 3.0 (EMD International®, 2015) and Global Mapper v.14 (Blue Marble Geographics®, 2012). These plots indicate that approximately 10% of the dwellings included in the analysis are at risk of being misclassified with regards to their respective SF exposure groups (Sec. II E).

E. Statistical analysis

The analysis for categorical outcomes follows very closely the description as outlined in Michaud *et al.* (2013). SF exposure groups were delineated in the following manner:

- in hours per year (SF_h): (i) $0 \leq \mathrm{SF}_h < 10$, (ii) $10 \leq \mathrm{SF}_h < 30$, and (iii) $\mathrm{SF}_h \geq 30$;
- in days per year (SF_d): (i) $0 \leq \mathrm{SF}_d < 15$, (ii) $15 \leq \mathrm{SF}_d < 45$, and (iii) $\mathrm{SF}_d \geq 45$;
- in maximum minutes per day (SF_m): (i) $0 \leq \mathrm{SF}_m < 10$, (ii) $10 \leq \mathrm{SF}_m < 20$, (iii) $20 \leq \mathrm{SF}_m < 30$, and (iv) $\mathrm{SF}_m \geq 30$.

The Cochran-Mantel-Haenszel (CMH) chi-square test was used to detect associations between sample characteristics and SF exposure groups while controlling for province. As a first step to develop the best predictive model, univariate logistic regression models for $\mathrm{HA}_{\mathrm{WTSF}}$ were fitted, with SF_m categories as the exposure of interest, adjusted for province and a predictor of interest. It should be emphasized that potential predictors 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. In the absence of other possibly important predictors, the interpretation

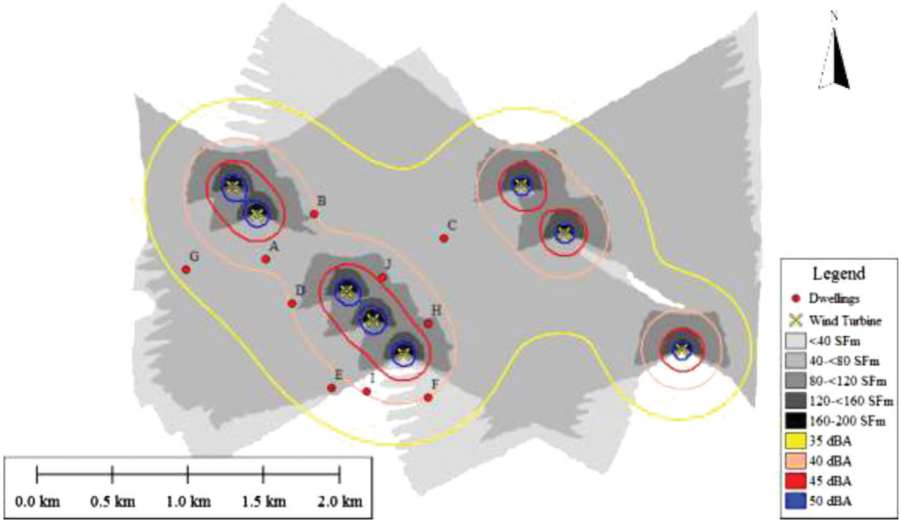

FIG. 1. A theoretical illustration of co-exposure to modeled WT SF and WTN levels. This figure presents a simulation of SF and noise exposure generated by eight WTs on flat terrain, with shadow coverage and WTN level contours described by the sequential color palettes in the legend box. The particular shape of the shadow coverage is created as the Sun moves behind the turbines throughout the day, generating a bowtie-shaped coverage area that is due to longer shadows at sunrise and sunset and shorter shadows at mid-day. In an actual WT park, dwellings are exposed to the combination of SF exposure from multiple turbines, as illustrated in this figure. As can be seen in the case of dwelling I, it is theoretically possible for a dwelling to be located relatively close to a WT, where WTN levels exceed 40 dBA, but outside the SF exposure area. For this demonstration, calculations were carried out with WindPro 3.0 (EMD International®, 2015) and projected with Global Mapper v.14 (Blue Marble Geographics®, 2012). WindPro 3.0 is used here in order to simultaneously present both WTN levels and shadow exposure. Shadow exposure is quantified in SF_m, while WTN noise levels are expressed in A-weighted decibels (dBA).

of any individual relationship in the univariate analysis must be made with caution as it may be tenuous.

The unrestricted and restricted multiple logistic regression models for HA_{WTSF} were developed using stepwise regression with a 20% significance entry criterion for predictors (based upon univariate analyses) and a 10% significance criterion to remain in the model. The stepwise regression was carried out in three different ways: (1) the base model included exposure to SF_m categories and province; (2) the base model included exposure to SF_m categories, province, and an adjustment for participants who reported receiving personal benefit from having WTs in the area; and (3) the base model included exposure to SF_m categories and province, conditioned on those who reported receiving no personal benefit. In all models, SF_m categories were treated as a continuous variable. The unrestricted model aimed to identify variables that have the strongest overall association with HA_{WTSF}. In the restricted model, the variables not considered for entry were those that were subjective responses to WT operations, such as high annoyances to visual, blinking lights, noise, vibrations, the World Health Organization (WHO) domain score, as well as the two standalone WHO questions (Quality of Life and Satisfaction with Health) and the perceived stress scale (PSS) scores.

Exact tests were used in cases when cell frequencies were <5 in the contingency tables or logistic regression models (Stokes *et al.*, 2000; Agresti, 2002). All models were adjusted for provincial differences. Province was initially assessed as an effect modifier. Since the interaction between modeled SF exposure and province was never statistically significant, province was treated as a confounder in all of the regression models. The Nagelkerke pseudo R^2 and Hosmer-Lemeshow (H-L) p-value are reported for all logistic regression models. The Nagelkerke pseudo R^2 indicates how useful the explanatory variables are in predicting the response variable. When the p-value from the H-L goodness of fit test is >0.05, it indicates a good fit.

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

III. RESULTS

A. Response rates, WT SF and WTN levels at dwellings

Of the 2004 potential dwellings, 1570 were valid dwellings[2] and 1238 individuals agreed to participate in the study (606 males, 632 females). This produced a final response rate of 78.9%. Table I presents information about the study population by the SF_m categories, as this exposure parameter was found to be the most strongly associated with HA_{WTSF} when compared to shadow exposure in hours per year (SF_h) and total shadow days per year (SF_d) (see Sec. III B). The majority of respondents were located in the two lowest SF exposure groups, i.e., $0 \leq SF_m < 10$ ($n = 654$, 53.0%) and $10 \leq SF_m < 20$ ($n = 233$, 18.9%), and the least number of respondents ($n = 161$, 13.1%) were situated in areas where $SF_m \geq 30$. Employment ($p = 0.0186$), household annual income ($p = 0.0002$), and ownership of property in PEI ($p < 0.0001$) were significantly related to SF categories (Table I). Participants receiving personal benefits from having WTs on their properties were not equally distributed between SF categories ($p < 0.0001$) with the greatest proportion of these participants situated in areas with $SF_m \geq 20$. Self-reported prevalence of health effects such as migraines/

TABLE I. Sample characteristics by SF exposure.

Variable	Shadow flicker exposure (SF_m)					
	$0 \le SF_m < 10$	$10 \le SF_m < 20$	$20 \le SF_m < 30$	$SF_m \ge 30$	Overall	CMH *p*-value[a]
n	657[b]	234[b]	185[b]	162[b]	1238[b]	
SF_h min–max[c]	0–4.5	1.67–24.10	6.07–62.65	15.05–136.67		
SF_d min–max[d]	0–62	14–133	28–228	39–242		
Distance between dwellings and nearest WT (km) min–max	0.40–11.22	0.44–1.46	0.33–1.18	0.25–0.84		
Distance between dwellings and nearest WT (km) 50th, 95th percentiles	1.38, 8.54	1.02, 1.38	0.81, 1.05	0.60, 0.78		
WTN level (dB) min–max	<25–43	29–43	32–45	35–46		
WTN level (dB) 50th, 95th percentiles	33, 41	36, 41	38, 42	40, 45		
Do not see WT *n* (%)	133 (20.3)	11 (4.7)	3 (1.6)	2 (1.2)	149 (12.1)	
Highly annoyed to WTSF[e] *n* (%)	25 (3.8)	12 (5.2)	25 (13.5)	34 (21.1)	96 (7.8)	<0.0001
Highly annoyed by WTN (either indoors or outdoors)[e] *n* (%)	38 (5.8)	14 (6.0)	18 (9.7)	19 (11.8)	89 (7.2)	0.0013
Highly annoyed by WTN indoors[e] *n* (%)	20 (3.1)	10 (4.3)	6 (3.2)	11 (6.8)	47 (3.8)	0.0275
Highly annoyed by WTN outdoors[e] *n* (%)	44 (6.7)	15 (6.4)	22 (11.9)	21 (13.0)	102 (8.3)	0.0012
Highly annoyed by WT blinking lights[e] *n* (%)	54 (8.3)	21 (9.0)	26 (14.1)	21 (13.0)	122 (9.9)	0.0033
Highly annoyed visually by WT[e] *n* (%)	70 (10.7)	33 (14.1)	30 (16.2)	26 (16.2)	159 (12.9)	0.0054
Highly annoyed by WT vibrations[e] *n* (%)	8 (1.2)	0 (0.0)	5 (2.7)	6 (3.8)	19 (1.5)	0.0147
Sex *n* (%males)	318 (48.4)	120 (51.3)	95 (51.4)	73 (45.1)	606 (49.0)	0.9432
Age mean (SE)	51.91 (0.71)	50.71 (1.13)	50.44 (1.21)	51.01 (1.25)	51.61 (0.44)	0.5854[f]
Marital Status (PEI) *n* (%)						0.0724[g]
Married/Common-law	73 (60.3)	16 (80.0)	29 (87.9)	38 (71.7)	156 (68.7)	
Widowed/Separated/Divorced	22 (18.2)	2 (10.0)	1 (3.0)	8 (15.1)	33 (14.5)	
Single, never been married	26 (21.5)	2 (10.0)	3 (9.1)	7 (13.2)	38 (16.7)	
Marital Status (ON) *n* (%)						0.1939 [g]
Married/Common-law	371 (69.5)	137 (64.0)	110 (72.8)	74 (67.9)	692 (68.7)	
Widowed/Separated/Divorced	103 (19.3)	38 (17.8)	21 (13.9)	20 (18.3)	182 (18.1)	
Single, never been married	60 (11.2)	39 (18.2)	20 (13.2)	15 (13.8)	134 (13.3)	
Employment *n* (%employed)	359 (54.7)	149 (63.7)	111 (60.0)	103 (63.6)	722 (58.4)	0.0186
Agricultural employment *n* (%)	50 (14.0)	25 (16.9)	6 (5.5)	17 (16.7)	98 (13.7)	0.6272
Level of education *n* (%)						0.8435
≤High School	357 (54.4)	130 (55.6)	100 (54.1)	91 (56.2)	678 (54.8)	
Trade/Certificate/College	254 (38.7)	87 (37.2)	72 (38.9)	56 (34.6)	469 (37.9)	
University	45 (6.9)	17 (7.3)	13 (7.0)	15 (9.3)	90 (7.3)	
Household income (×\$1000) *n* (%)						0.0002
<60	300 (53.3)	111 (55.5)	70 (45.5)	50 (37.3)	531 (50.5)	
60–100	155 (27.5)	56 (28.0)	43 (27.9)	46 (34.3)	300 (28.5)	
≥100	108 (19.2)	33 (16.5)	41 (26.6)	38 (28.4)	220 (20.9)	
Property ownership (PEI) *n* (%)	83 (68.6)	20 (100.0)	31 (93.9)	48 (90.6)	182 (80.2)	<0.0001[e]
Property ownership (ON) *n* (%)	471 (87.9)	188 (87.9)	134 (88.2)	101 (92.7)	894 (88.4)	0.5419[e]
Receive personal benefits *n* (%)	37 (6.0)	19 (8.4)	23 (12.6)	31 (19.5)	110 (9.3)	<0.0001

[a] The CMH chi-square test is used to adjust for province unless otherwise indicated.

[b] Totals may differ due to missing data.

[c] SF_h, maximum number of hours of SF in hours per day.

[d] SF_d, maximum amount of SF exposure in days per year.

[e] Highly annoyed includes the ratings *very* or *extremely*.

[f] Two-way analysis of variance adjusted for province.

[g] Chi-square test of independence.

headaches, chronic pain, dizziness, and tinnitus were all found to be equally distributed across SF categories (data not shown). The corresponding A-weighted WTN levels and proximity to the nearest WT are also shown in Table I.

B. Percentage highly annoyed by SF exposure from WTs

Regardless of the parameter used to quantify SF exposure, in all cases the predictive strength of the base model was statistically weak. Nevertheless, an analysis based on SF_m had the largest R^2 ($R^2 = 11\%$, compared to 10% for SF_h and 8% for SF_d; data not shown). Therefore, results are presented for HA_{WTSF} with respect to SF_m.

A statistically significant exposure-response relationship was found between SF_m and reporting to be HA_{WTSF}. As such, the prevalence of HA_{WTSF} increased from 3.8% in the lowest modeled SF exposure group ($0 \le SF_m < 10$) to 21.1% when modeled shadow exposure was above or equal to 30 min per day, which represents almost a six-fold increase in the prevalence of HA_{WTSF} from the lowest exposure category to the highest. In comparison to an exposure duration of $0 \le SF_m < 10$, the OR for HA_{WTSF} was statistically similar to

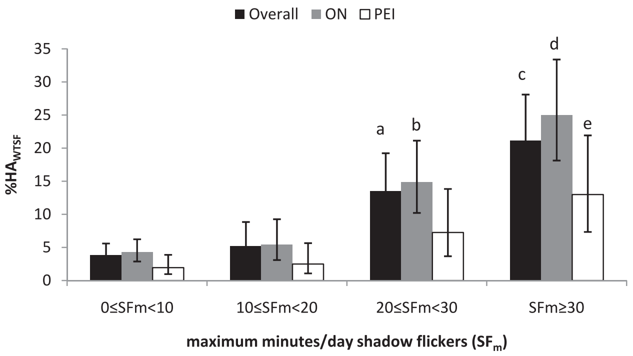

FIG. 2. Illustrates the percentage of participants that reported to be either very or extremely (i.e., highly) bothered, disturbed, or annoyed over the last year or so while at home (either indoors or outdoors) by shadows or flickers of light from WTs. Results are presented by province and as an overall average as a function of modeled SF exposure time (SF_m). Fitted data are plotted along with their 95% CIs. The models fit the data well (H-L test p-value >0.9). Bonferroni corrections were made to account for all pairwise comparisons. [(a), (b), (c)] Significantly different from $0 \le SF_m < 10$ and $10 \le SF_m < 20$; respective p-values for pairwise comparisons, $p \le 0.0138$, $p \le 0.0012$, and $p < 0.0006$. (d) Significantly different compared to all other categories, $p \le 0.0126$; (e) Significantly different compared to $0 \le SF_m < 10$, $p = 0.0162$.

that for $10 \le SF_m < 20$ [1.29, 95% confidence interval (CI): (0.50, 3.33)]; and then significantly increased with increasing SF_m from 3.94 [95% CI: (1.80, 8.63)] at $20 \le SF_m < 30$ to 7.51 [95% CI: (3.54, 15.96)] for $SF_m \ge 30$. Significant increases were also observed between the two highest SF exposure groups ($20 \le SF_m < 30$, $SF_m \ge 30$) and those exposed to $10 \le SF_m < 20$ (see Fig. 2).

1. Univariate analysis of variables related to HA_{WTSF}

Several variables were considered for their potential association with HA_{WTSF} (see Table II). A cautious approach should be taken when interpreting univariate results as these models do not account for the potential influence from other variables. The base model had an R^2 of 11%, compared to a base model of 10% when modeled using outdoor A-weighted WTN as a surrogate of SF exposure (data not shown). Prior to adjusting for other factors, the prevalence of HA_{WTSF} was significantly higher in ON ($p = 0.0193$). As WTN exposure and SF can occur simultaneously, the interaction between WTN levels and SF_m was also tested to assess the possible influence that such an interaction may have on HA_{WTSF}. As can be seen from Table II, the interaction between WTN levels and SF exposure was statistically significant ($p = 0.0260$), and increased the R^2 to 15%. This is somewhat better than the 11% obtained from the base model.

Factors beyond SF and WTN exposure were also considered for their potential influence on HA_{WTSF}. Participants who owned their property had 6.38 times higher odds of reporting HA_{WTSF} compared to those who were renting property [95% CI: (1.54, 26.39)]. Those who did not receive a personal benefit from having WTs in the area were found to have 4.03 times higher odds of being HA_{WTSF} compared to those who did receive personal benefits [95% CI: (1.42, 11.44)]. Those who reported to have migraines, dizziness, and tinnitus had 3 times higher odds of reporting HA_{WTSF} compared to those who did not report these health conditions. Participants that reported having chronic pain, arthritis, or restless leg syndrome had at least one and a half times the odds of reporting HA_{WTSF} compared to those who did not report suffering from these conditions (Table II). Participants who self-identified as being highly sensitive to noise had 3.49 times higher odds of being HA_{WTSF} compared to those who did not self-identify as being highly sensitive to noise [95% CI: (2.14, 5.69)]. Those who reported that WTs were audible had 10.68 times higher odds of HA_{WTSF} compared to those who could not hear WTs [95% CI: (5.07, 22.51)]. This variable was further categorized into the length of time that the participant heard the WT (do not hear, <1 year, ≥1 year); it was found that both those who heard WTs for less than 1 year and 1 year or greater had higher odds of being HA_{WTSF} compared to those who could not hear the WTs. Furthermore, there was no statistical difference in the proportion HA_{WTSF} among those who heard the WTs for less than 1 year or greater than or equal to 1 year ($p = 0.0924$). People who did not have a WT on their property had higher odds of reporting HA_{WTSF} compared to those who had at least one WT on their property [OR = 11.07, 95% CI: (1.49, 82.14)]. Annoyance variables were significantly correlated (Table III) and participants who were highly annoyed to any of the aspects of WT (noise, blinking lights, visual, and vibrations) tended to be also HA_{WTSF}.

The OR for these annoyances ranged from 13 to 34, with annoyance to vibrations and blinking lights having the lowest and highest OR, respectively. Concern for physical safety due to the presence of WTs in the studied communities (i.e., *concern for physical safety* variable) was also highly associated with HA_{WTSF}; participants who were highly concerned about their physical safety had 14.15 times higher odds of HA_{WTSF} compared to those who were not highly concerned about their physical safety [95% CI: (8.17, 24.53)]. Those who identified that their quality of life was "*Poor*" or were "*Dissatisfied*" with their health had 2 times higher odds of reporting HA_{WTSF} compared to their counterparts. Both the physical health domain and the environmental domain from the abbreviated World Health Organization Quality of Life questionnaire were negatively associated with being HA_{WTSF} (Feder *et al.*, 2015). That is to say that as the domain value increased (indicating an improved domain value), the prevalence of HA_{WTSF} decreased. Additionally, as the PSS scores of participants increased, so did the prevalence of HA_{WTSF} by 3% [95% CI: (1.00, 1.07)] (Table II).

2. Multiple logistic regression analyses of variables related to HA_{WTSF}

Table IV presents the unrestricted multiple logistic regression model for HA_{WTSF}. The first variable to enter the model was annoyance with WT blinking lights, which increased the R^2 from 11% at the base model level to 42%. This was followed by annoyance to WTN when outdoors, annoyance to the visual aspect of WTs, concern for physical safety, audibility of WTs, and annoyance to vibrations caused by WTs, which together increased the R^2 of the final model to 53%. Personal economic benefit associated with WTs has been found to have a strong impact on reducing

TABLE II. Univariate analysis of variables related to HA$_{\mathrm{WTSF}}$.

			SF$_m$[b]		Explanatory variable		Province[c]		
Variable	Groups in variable[a]	Nagelkerke pseudo R^2	OR (CI)[d]	*p*-value	OR (CI)[d]	*p*-value	OR (CI)[d]	*p*-value	H-L test[e]
Base model[f,b]		0.11	2.02 (1.68, 2.43)	<0.0001			2.16 (1.13, 4.12)	0.0193	0.7699
SF$_m$ × WTN level[g]		0.15	—[h]		—[h]		2.03 (1.04, 3.98)	0.0381	0.4851
Sex	Male/Female	0.11	2.02 (1.68, 2.43)	<0.0001	1.10 (0.72, 1.70)	0.6527	2.15 (1.13, 4.10)	0.0203	0.6015
Age group	≤24	0.12	2.03 (1.69, 2.45)	<0.0001	0.55 (0.15, 1.98)	0.3611	2.23 (1.17, 4.27)	0.0153	0.5879
	25–44				1.40 (0.74, 2.65)	0.3002			
	45–64				1.47 (0.83, 2.62)	0.1901			
	65+				reference				
Education	≤High School	0.11	2.02 (1.68, 2.43)	<0.0001	1.19 (0.48, 2.92)	0.7112	2.12 (1.11, 4.05)	0.0225	0.8936
	Trade/Certificate/College				1.40 (0.56, 3.50)	0.4695			
	University				reference				
Income (×$1000)	<60	0.12	1.99 (1.63, 2.44)	<0.0001	0.71 (0.39, 1.29)	0.2617	1.68 (0.85, 3.33)	0.1390	0.1722
	60–100				1.08 (0.59, 1.98)	0.8041			
	≥100				reference				
Marital Status	Married/Common-law	0.12	2.02 (1.68, 2.43)	<0.0001	1.76 (0.85, 3.65)	0.1274	2.20 (1.15, 4.21)	0.0169	0.5600
	Widowed/Separated/Divorced				1.21 (0.50, 2.97)	0.6746			
	Single, never been married				reference				
Property ownership	Own/rent	0.13	1.99 (1.65, 2.39)	<0.0001	6.38 (1.54, 26.39)	0.0105	2.11 (1.10, 4.04)	0.0246	0.8715
Type of dwelling	Single detached/Other	0.11	1.99 (1.65, 2.40)	<0.0001	1.67 (0.51, 5.52)	0.3969	2.10 (1.10, 4.02)	0.0246	0.6535
Employment	Employed/not employed	0.12	2.00 (1.67, 2.41)	<0.0001	1.43 (0.91, 2.26)	0.1247	2.18 (1.14, 4.16)	0.0183	0.3034
Type of employment	Agriculture/ Other	0.13	2.03 (1.61, 2.57)	<0.0001	0.95 (0.43, 2.12)	0.9017	3.27 (1.34, 7.98)	0.0094	0.8071
Personal benefit	No/Yes	0.13	2.09 (1.73, 2.52)	<0.0001	4.03 (1.42, 11.44)	0.0088	2.16 (1.13, 4.13)	0.0205	0.7111
Migraines	Yes/No	0.16	2.06 (1.70, 2.48)	<0.0001	3.15 (2.02, 4.94)	<0.0001	1.91 (1.00, 3.68)	0.0518	0.4864
Dizziness	Yes/No	0.15	2.03 (1.69, 2.45)	<0.0001	2.81 (1.79, 4.41)	<0.0001	2.19 (1.14, 4.20)	0.0190	0.6998
Tinnitus	Yes/No	0.15	2.09 (1.73, 2.52)	<0.0001	2.91 (1.85, 4.58)	<0.0001	2.21 (1.15, 4.25)	0.0170	0.6902
Chronic Pain	Yes/No	0.13	2.06 (1.71, 2.48)	<0.0001	2.16 (1.37, 3.42)	0.0010	2.01 (1.05, 3.84)	0.0355	0.5661
Asthma	Yes/No	0.11	2.02 (1.68, 2.43)	<0.0001	1.19 (0.55, 2.60)	0.6606	2.16 (1.13, 4.12)	0.0194	0.6215
Arthritis	Yes/No	0.12	2.06 (1.71, 2.48)	<0.0001	1.57 (1.01, 2.45)	0.0461	2.20 (1.15, 4.21)	0.0170	0.5660
High Blood Pressure	Yes/No	0.11	2.02 (1.68, 2.43)	<0.0001	0.90 (0.56, 1.45)	0.6710	2.17 (1.14, 4.14)	0.0186	0.3444
Medication for high blood pressure, past month	Yes/No	0.12	2.02 (1.68, 2.43)	<0.0001	0.74 (0.45, 1.21)	0.2251	2.20 (1.15, 4.19)	0.0171	0.3238
History of high blood pressure in family	Yes/No	0.11	2.02 (1.67, 2.44)	<0.0001	1.03 (0.67, 1.60)	0.8926	2.03 (1.06, 3.88)	0.0334	0.7739
Chronic bronchitis/ emphysema/ COPD	Yes/No	0.11	2.01 (1.67, 2.42)	<0.0001	0.55 (0.16, 1.82)	0.3240	2.18 (1.14, 4.16)	0.0178	0.8001
Diabetes	Yes/No	0.12	2.02 (1.68, 2.44)	<0.0001	0.61 (0.25, 1.45)	0.2587	2.12 (1.11, 4.05)	0.0227	0.6111
Heart disease	Yes/No	0.11	2.02 (1.68, 2.43)	<0.0001	1.22 (0.56, 2.68)	0.6137	2.15 (1.13, 4.10)	0.0198	0.7954
Diagnosed sleep disorder	Yes/No	0.12	2.02 (1.68, 2.43)	<0.0001	1.57 (0.82, 2.98)	0.1716	2.11 (1.11, 4.03)	0.0236	0.7696
Restless leg syndrome	Yes/No	0.13	2.01 (1.67, 2.42)	<0.0001	2.12 (1.26, 3.55)	0.0044	2.01 (1.05, 3.85)	0.0342	0.5256
Sensitivity to Noise	High/Low	0.15	2.04 (1.69, 2.46)	<0.0001	3.49 (2.14, 5.69)	<0.0001	2.03 (1.06, 3.91)	0.0335	0.4659
See WT	Yes/No	0.14	1.88 (1.56, 2.27)	<0.0001	>999.999 (< 0.001, > 999.999)	0.9658	2.06 (1.08, 3.92)	0.0290	0.7480
Audible WT	Yes/No	0.23	1.66 (1.37, 2.02)	<0.0001	10.68 (5.07, 22.51)	<0.0001	2.42 (1.26, 4.67)	0.0083	0.7198
Number of years turbines audible	less than 1 year	0.23	1.66 (1.37, 2.02)	<0.0001	5.04 (1.56, 16.25)	0.0068	2.51 (1.30, 4.85)	0.0063	0.8472
	1 year or more				11.51 (5.45, 24.33)	<0.0001			
	Do not hear WTs				reference				

TABLE II. (*Continued.*)

			SF_m[b]		Explanatory variable		Province[c]		
Variable	Groups in variable[a]	Nagelkerke pseudo R^2	OR (CI)[d]	p-value	OR (CI)[d]	p-value	OR (CI)[d]	p-value	H-L test[e]
At least 1 WT on property	No/Yes	0.14	2.14 (1.77, 2.58)	<0.0001	11.07 (1.49, 82.14)	0.0187	2.07 (1.08, 3.95)	0.0279	0.4544
Visual annoyance to WTs	High/Low	0.37	2.17 (1.75, 2.71)	<0.0001	20.29 (12.24, 33.64)	<0.0001	1.68 (0.79, 3.56)	0.1785	0.9285
Annoyance with blinking lights	High/Low	0.42	2.22 (1.76, 2.80)	<0.0001	34.27 (19.68, 59.67)	<0.0001	1.23 (0.57, 2.66)	0.5984	0.7649
Annoyance to WTN	High/Low	0.30	2.02 (1.65, 2.48)	<0.0001	18.18 (10.58, 31.25)	<0.0001	1.72 (0.85, 3.48)	0.1336	0.3863
Annoyance to WTN from indoors	High/Low	0.23	2.05 (1.68, 2.50)	<0.0001	19.58 (9.80, 39.11)	<0.0001	1.65 (0.85, 3.21)	0.1388	0.4867
Annoyance to WTN from outdoors	High/Low	0.32	2.04 (1.66, 2.52)	<0.0001	19.49 (11.54, 32.93)	<0.0001	2.02 (0.99, 4.12)	0.0545	0.4643
Annoyance to vibrations/rattles	High/Low	0.16	2.01 (1.66, 2.43)	<0.0001	13.07 (4.71, 36.30)	<0.0001	2.07 (1.07, 4.01)	0.0309	0.9413
Concerned about physical safety	High/Low	0.26	1.92 (1.57, 2.34)	<0.0001	14.15 (8.17, 24.53)	<0.0001	2.09 (1.04, 4.18)	0.0379	0.6700
Quality of Life	Poor/Good[i]	0.12	2.04 (1.69, 2.45)	<0.0001	2.31 (1.14, 4.71)	0.0208	2.13 (1.12, 4.06)	0.0218	0.5909
Satisfaction with health	Dissatisfied/Satisfied[j]	0.12	2.04 (1.69, 2.45)	<0.0001	1.84 (1.07, 3.18)	0.0280	2.12 (1.11, 4.04)	0.0227	0.5133
Medication for anxiety/depression	No/Yes	0.11	2.02 (1.68, 2.43)	<0.0001	1.28 (0.62, 2.65)	0.5128	2.19 (1.15, 4.18)	0.0177	0.2842
Continuous scale explanatory variables									
Physical health domain (range 4–20)		0.13	2.06 (1.71, 2.48)	<0.0001	0.90 (0.85, 0.96)	0.0012	2.04 (1.07, 3.90)	0.0313	0.7547
Psychological domain (range 4–20)		0.11	2.02 (1.68, 2.43)	<0.0001	0.98 (0.90, 1.07)	0.6738	2.17 (1.14, 4.14)	0.0187	0.6490
Social relationships domain (range 4–20)		0.11	2.02 (1.68, 2.42)	<0.0001	0.98 (0.91, 1.06)	0.5701	2.14 (1.13, 4.09)	0.0205	0.7782
Environment domain (range 4–20)		0.13	2.05 (1.70, 2.47)	<0.0001	0.88 (0.80, 0.96)	0.0056	2.27 (1.19, 4.34)	0.0134	0.6815
Perceived stress scale (range 0–37)		0.12	2.01 (1.67, 2.42)	<0.0001	1.03 (1.00, 1.07)	0.0386	2.07 (1.08, 3.96)	0.0276	0.6513

[a] Where a reference group is not specified it is taken to be the last group.

[b] The exposure variable, SF_m, is treated as a continuous scale in the logistic regression model, giving an OR for each unit increase in shadow exposure.

[c] PEI is the reference group.

[d] Odds ratio (OR) and 95% CI based on logistic regression model, an OR > 1 indicates that annoyance levels were higher, relative to the reference group.

[e] H-L test, $p > 0.05$ indicates a good fit.

[f] The base model includes the modeled shadow exposure (SF_m) and province.

[g] WTN level is treated as a continuous scale in the logistic regression model, giving an OR for each unit increase in WTN level, where a unit reflects a 5 dB WTN category.

[h] The interaction between WTN levels and modeled shadow exposure was significant ($p = 0.0260$). When fitting separate logistic regression models to each shadow exposure group, it was observed that there was a positive significant relationship between high annoyance to SF and WTN levels only among those in the lowest shadow exposure group [OR and 95% confidence interval: 2.62 (1.64, 4.20)]. The relationship in the other three shadow exposure groups ($10 \leq SF_m < 20$, $20 \leq SF_m < 30$, and $SF_m \geq 30$) was not significant ($p > 0.05$, in all cases).

[i] "Poor" includes those that responded "poor" or "very poor."

[j] "Dissatisfied" includes those that responded "dissatisfied" or "very dissatisfied."

TABLE III. Spearman correlation coefficient (p-value) between annoyance variables.

Type of annoyance[a]	WTN inside	WTN outside	Visual	Blinking lights	SF	Vibrations inside
WTN in or out	0.98 ($p < 0.0001$)	0.99 ($p < 0.0001$)	0.49 ($p < 0.0001$)	0.48 ($p < 0.0001$)	0.51 ($p < 0.0001$)	0.25 ($p < 0.0001$)
WTN inside		0.98 ($p < 0.0001$)	0.46 ($p < 0.0001$)	0.46 ($p < 0.0001$)	0.50 ($p < 0.0001$)	0.23 ($p < 0.0001$)
WTN outside			0.49 ($p < 0.0001$)	0.48 ($p < 0.0001$)	0.51 ($p < 0.0001$)	0.25 ($p < 0.0001$)
Visual				0.79 ($p < 0.0001$)	0.70 ($p < 0.0001$)	0.19 ($p < 0.0001$)
Blinking lights					0.75 ($p < 0.0001$)	0.17 ($p < 0.0001$)
SF						0.18 ($p < 0.0001$)

[a] Participants were asked to indicate how bothered, disturbed, or annoyed they were over the last year or so while at home. Unless the participants' location was specified as indoors or outdoors, at home was defined as either indoors or outdoors. Vibrations were identified as being present during WT operations.

reported annoyance to WTN (Pedersen *et al.*, 2009). In the current study, directly or indirectly receiving personal benefit from having WTs in the area could include receiving payment, rent, or benefiting from community improvements ($n = 110$). When this variable was forced into the final model, it had no influence on the variables that entered the model, nor did it have any impact on the final R^2 (data not shown). Similarly, removing these participants had no influence on the strength of the overall final model (i.e., R^2 remained at 53%). The one change observed when participants receiving personal benefit were removed was that annoyance to vibrations was discarded and restless leg syndrome entered the model at a p-value of 0.0540 (data not shown). The statistically significant interaction between WTN levels and SF_m (see Sec. III B 1) was not found to be related to HA_{WTSF} after adjusting for the variables shown in Table IV.

Table V presents the restricted multiple logistic regression model for HA_{WTSF}. In this restricted model, the first variable to enter the model was concern for physical safety, increasing the R^2 from 11% at the base model level to 26%. The following variables then entered the model: audibility of WTs, sensitivity to noise, having at least one WT on the property, property ownership, and dizziness. The overall fit of the final restricted model was 37%. The last three variables (having at least one WT on the property, property ownership, and dizziness) collectively contributed only an additional 2% to the overall model and were all only significant at the 10% level, and not at the 5% level. Receiving personal benefits does not enter the final model, due to its redundancy given the other variables that did enter the model. However, when it is forced into the model it is significant at $p = 0.0343$ level (data not shown). In this case, the variable "*is there at least one wind turbine on your property*" is dropped in place of "*employment status*," which comes into the model with a p-value of 0.0722 (data not shown). The overall fit of the model improves slightly to 38% (data not shown). Finally, when conditioning on only those who do not receive benefits, the overall fit of the model drops slightly to 36%, with neither of the "*employment status*" nor the *"is there at least one wind turbine on your property"* variables coming into the final model (data not shown).

IV. DISCUSSION

The accumulated research on the potential health effects associated with SF from WTs has concluded that SF from WTs is unlikely to present a risk to the occurrence of seizures, even among individuals that have photosensitive epilepsy (Harding *et al.*, 2008; Knopper *et al.*, 2014; Smedley *et al.*, 2010). The knowledge gap that persists is the extent to which WT SF causes annoyance. Also unknown is how this annoyance may result from an interaction between SF and WTN levels, given that SF and at least some level of WTN emissions occur simultaneously. To date, there have been very few assessments that have evaluated the effect of SF on community response. A German field study performed by Pohl *et al.* (1999) investigated methods for the evaluation of SF exposure, which ultimately led to current SF exposure

TABLE IV. Multiple logistic regression analysis (unrestricted) of variables related to HA_{WTSF}.

		Stepwise Model 1		
Variable	Groups in variable[a]	OR (CI)[b]	p-value	Order of entry into model: R^2 at each step
HA_{WTSF} versus not HA_{WTSF}		($n = 1147$, $R^2 = 0.53$, H-L $p = 0.7536$)		
SF_m[c]		2.04 (1.56, 2.66)	<0.0001	Base: 0.11
Province	ON/PEI	1.20 (0.50, 2.89)	0.6811	Base: 0.11
Annoyance with blinking lights	High/Low	7.67 (3.84, 15.34)	<0.0001	Step 1: 0.42
Annoyance to WTN from outdoors	High/Low	2.25 (1.09, 4.66)	0.0287	Step 2: 0.47
Visual annoyance to WT	High/Low	4.09 (2.09, 7.99)	<0.0001	Step 3: 0.50
Concerned about physical safety	High/Low	2.89 (1.39, 6.01)	0.0045	Step 4: 0.51
Audible WT	Yes/No	3.15 (1.35, 7.34)	0.0080	Step 5: 0.52
Annoyance to vibrations/rattles	High/Low	3.49 (1.00, 12.23)	0.0503	Step 6: 0.53

[a] Where a reference group is not specified it is taken to be the last group.
[b] OR and 95% CI based on logistic regression model, an OR > 1 indicates that annoyance levels were higher, relative to the reference group.
[c] The exposure variable SF_m is treated as a continuous scale in the logistic regression model, giving an OR for each unit increase in shadow exposure.

TABLE V. Multiple logistic regression analysis (restricted) of variables related to HA_{WTSF}.

Variable	Groups in variable[a]	Stepwise Model 1 OR (CI)[b]	Stepwise Model 1 p-value	Order of entry into model: R^2 at each step
HA_{WTSF} versus not HA_{WTSF}		($n = 1159$, $R^2 = 0.37$, H-L $p = 0.7294$)		
SF_m[c]		1.70 (1.37, 2.11)	<0.0001	Base: 0.11
Province	ON/PEI	2.07 (1.00, 4.27)	0.0494	Base: 0.11
Concerned about physical safety	High/Low	7.01 (3.90, 12.60)	<0.0001	Step 1: 0.26
Audible WT	Yes/No	6.33 (2.90, 13.81)	<0.0001	Step 2: 0.32
Sensitivity to noise	High/Low	2.81 (1.57, 5.05)	0.0005	Step 3: 0.35
At least 1 WT on property	No/Yes	6.87 (0.88, 53.73)	0.0663	Step 4: 0.36
Property ownership	Own/rent	4.78 (0.95, 24.01)	0.0574	Step 5: 0.37
Dizziness	Yes/No	1.68 (0.98, 2.86)	0.0581	Step 6: 0.37

[a] Where a reference group is not specified it is taken to be the last group.

[b] OR and 95% CI based on logistic regression model, an OR > 1 indicates that annoyance levels were higher, relative to the reference group.

[c] The exposure variable SF_m is treated as a continuous scale in the logistic regression model, giving an OR for each unit increase in shadow exposure. Model is restricted insofar as variables that are reactions to WT operations are not considered.

limits in Germany, while a conference paper presented by Pedersen and Persson Waye (2003) assessed annoyance with SF as a function of modeled SF exposure. The conclusion from this conference paper was that modeled WTN levels were a better predictor of annoyance to SF from WTs than modeled SF exposure. A similar conclusion was reached in the current study wherein it was found that, regardless of how SF exposure was modeled, the R^2 for HA_{WTSF} by modeled SF was statistically weak and essentially the same as that found using WTN levels (i.e., 10% and 9%, respectively). Some improvement was found when the interaction between WTN levels and SF_m was considered, which increased the R^2 to 15%. However, after adjusting for other factors that were statistically related to HA_{WTSF}, this interaction was no longer significant in the final multiple regression models.

In spite of the obvious deficiencies in estimating HA_{WTSF} using either A-weighted WTN levels or SF_m alone (or together as an interaction term), a statistically significant exposure-response relationship was found between HA_{WTSF} and SF modeled as SF_m. The strength of the base model was markedly improved from 11% to 53% when adjusting for other factors. In this case, these other factors included those which are subjective and/or could be viewed as reactions to operational WTs (e.g., other annoyances). When the final model was restricted to variables conceptually viewed as objective and/or not contingent upon WT operations, the strength of the final model improved from 11% for the base model to 37%. Both of these models have merit, but as discussed below, the restricted model may be more valuable in situations where a wind farm is not yet operational.

It is not surprising that in the unrestricted model, the variables related to the visual perception of WTs were among those which had the strongest statistical association with $HA_{WTSF,}$ as these were found to be more highly correlated with each other than annoyance reactions mediated through tactile and/or auditory senses (see Table III). Their presence in the final model indicates that there were no issues related to multicollinearity. This should be interpreted to mean that each of these annoyance variables is a significant predictor of HA_{WTSF}. In this regard, most of the increase in the predictive strength of the model for HA_{WTSF} was observed once annoyance to blinking lights on WTs entered the model. This step increased the R^2 from 11% at the base level to 42%. Participants that reported being highly annoyed by blinking lights on WTs had almost 8 times higher odds of being HA_{WTSF}. In a study performed by Pohl *et al.* (2012), it was found that respondents were comparably as strongly annoyed by WT blinking lights as they were by SF, a finding which may also be reflected in this study. It is also worth mentioning that in the CNHS, annoyance to blinking lights on WTs was found to be related to actigraphy-measured sleep disturbance (Michaud *et al.*, 2016c). It is therefore possible that poorer sleep quality at night among these participants is associated with a heightened response to SF during the day.

In the current study, participants reported how annoyed they were by WTN while they were at home (either indoors or outdoors), indoors only, and outdoors only. Annoyance to WTN when inside does not make it into the final models; however, the finding that annoyance to WTN when outside had the stronger association with HA_{WTSF} seems to suggest that SF annoyance is more likely an outdoor phenomena. The results of the unrestricted multiple logistic regression model show that estimating HA_{WTSF} using SF_m can be significantly improved when considering these other annoyances.

Further improvements can be expected when concern for physical safety associated with having WTs in the area and the audibility of WTs are also accounted for. Although *concern for physical safety* may in some cases reflect a response to operational WTs, it could just as readily be treated as an attitudinal response triggered by the anticipated physical presence of industrial WTs. Although extremely rare, there have been reports of catastrophic failure that could exacerbate the level of concern for one's physical safety in the same way rare aircraft accidents are known to increase the fear of aircraft (Fields, 1993; Moran *et al.*, 1981; Reijneveld, 1994). As discussed below, concern for physical safety also appears in the restricted multiple regression model.

In the restricted model (see Table V), which only included variables that were not direct responses to WT operations, it was found that concern for physical safety was the variable that contributed the most to R^2, as it increased the base model R^2 from 11% to 26%. In this case, respondents that declared being highly concerned for their physical safety had, on average, 7 times higher odds of reporting $\mathrm{HA}_{\mathrm{WTSF}}$. The observation that this variable was present in both models suggests that actions taken to identify and reduce this concern at the planning stages of a WT facility may reduce $\mathrm{HA}_{\mathrm{WTSF}}$.

As already mentioned, exposure to SF from WTs will always occur with at least some level of WTN exposure. It is therefore not surprising that the audibility of WTs and noise sensitivity were also found to be statistically related to $\mathrm{HA}_{\mathrm{WTSF}}$. Noise sensitivity has long been known to have an influence on community noise annoyance. At equivalent noise levels, annoyance reactions are higher among people who report to be noise sensitive (Job, 1988).

Although property ownership, having a WT on one's property, and experiencing dizziness appear in the final model, together they only contribute an additional 2% to the overall strength of the model and all three variables are significant only at the 10% level. Therefore, only a very cautious interpretation of their influence on $\mathrm{HA}_{\mathrm{WTSF}}$ can be made. Property ownership could reflect a greater attachment to one's property and heightened response to any exposure that is perceived to have negative impacts on one's property. The negative association between having a WT on one's property and $\mathrm{HA}_{\mathrm{WTSF}}$ may be an indication that these participants are more likely to directly or indirectly benefit from having WTs in the area. While personal benefit does not enter any of the final multiple regression models, this is because only 110 participants received personal benefits. When considered alone, personal benefit had an influence on $\mathrm{HA}_{\mathrm{WTSF}}$. The presence of dizziness in the final model might be explained by the notion that dizziness can be a sensory-related variable and as such may have an influence on a visually-related parameter, such as $\mathrm{HA}_{\mathrm{WTSF}}$. Although both the unrestricted and restricted multiple regression models improved the strength of their corresponding base models substantially, their predictive strength for $\mathrm{HA}_{\mathrm{WTSF}}$ was still rather limited.

Possible explanations for this limited predictive strength could stem from the uncertainties in the model used to quantify SF_m, as discussed in Sec. II D, or from additional limitations. First and foremost, it should be emphasised that the SF model employed for this study was developed to quantify SF exposure for a specific period of time. Therefore, there may have been a mismatch between the parameter used to quantify SF exposure (i.e., maximum minutes per day at the dwelling window) and the subjective perception of SF from WTs assessed in the current study. Annoyance to SF exposure is not limited to dwelling window façades. It is much more likely to reflect an integrated response to shadow over one's entire property, or to any location where SF is perceived. Additionally, the current SF model presents worst-case SF exposure. A more refined assessment that included precise meteorological conditions, such as cloud coverage as well as wind speed and wind direction, could provide a more accurate evaluation of WT SF exposure. This may in turn provide a stronger association with community response to this variable. Finally, it is important to mention that the SF model only accounts for SF duration, and not shadow intensity. An assessment of SF intensity could potentially strengthen the association between SF exposure and community annoyance.

A careful examination of the SF annoyance question in the CNHS questionnaire itself is also warranted. There was ambiguity in the question used to assess $\mathrm{HA}_{\mathrm{WTSF}}$ that may have contributed to the weak association observed between SF_m and $\mathrm{HA}_{\mathrm{WTSF}}$. The question probed one's annoyance towards *shadows or flickers of light* from WTs while they are at home, where "*at home*" means either indoors or outdoors. This wording could have led the respondent to assess their annoyance from shadows caused by WTs with either stationary or rotating blades. By contrast, the wording of the question could also have led the respondent to assess their annoyance from flickers of light generated by rotating WT blades. However, the model used to quantify SF exposure only considers moving shadows and as such, there may have been a discrepancy between the modeled exposure, and the participants' response. Although improvements will only come as this research area matures, as a starting point the authors recommend that future research in this area refine the SF annoyance question to the following: *Thinking about the last year or so, while you are at home, how much do shadows created by rotating wind turbine blades bother, disturb or annoy you*?

V. CONCLUDING REMARKS

For reasons mentioned above, when used alone, modeled SF_m results represent an inadequate model for estimating the prevalence of $\mathrm{HA}_{\mathrm{WTSF}}$ as its predictive strength is only about 10%. This research domain is still in its infancy and there are enough sources of uncertainty in the model and the current annoyance question to expect that refinements in future research would yield improved estimates of SF annoyance. In addition to addressing some of the aforementioned shortcomings, future research may also benefit by considering variables that were not addressed in the current study. These may include, but not be limited to, personality types, attitudes toward WTs, and the level of community engagement between WT developers and the community. In the interim, this study identifies the variables, that when considered together with modeled SF exposure, improve the overall estimate of $\mathrm{HA}_{\mathrm{WTSF}}$. The applicability of these variables to areas beyond the current study sample will only become known as this research area matures.

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[1] Overall statistical power for the CNHS was based on the study's primary objective to assess WTN associated impacts on sleep quality. Based on an initial sample size of 2000 potential dwellings, it was estimated that there

would be 1120 completed questionnaires. For 1120 respondents there should be sufficient statistical power to detect at least a 7% difference in the prevalence of sleep disturbances with 80% power and a 5% false positive rate (Type I error). There was uncertainty in the power assessment because the CNHS was the first to implement objectively measured endpoints to study the impact that WTN may have on human health in general, and on sleep quality, in particular. In the absence of comparative studies, a conservative baseline prevalence for reported sleep disturbance of 10% was used (Tjepkema, 2005; Riemann *et al.*, 2011). Sample size calculation also incorporated the following assumptions: (1) approximately 20%–25% of the targeted dwellings would not be valid dwellings (i.e., demolished, unoccupied seasonal, vacant for unknown reasons, under construction, institutions, etc.); and (2) of the remaining dwellings, there would be a 70% participation rate. These assumptions were validated (Michaud *et al.*, 2016b).

[2] Four hundred and thirty-four potential dwellings were not valid locations; upon visiting the address Statistics Canada noted that the location was inhabitable but unoccupied at the time of the visit, newly constructed not yet inhabited, unoccupied trailer in trailer park, a business, a duplicate address, an address listed in error, summer cottage, ski chalet, hunting camps, or a location where residents were all above 79 yrs of age. See Michaud *et al.* (2016b) for more details.

Agresti, A. (**2002**). *Categorical Data Analysis*, 2nd ed. (Wiley & Sons, Inc., New York), pp. 97–98 and 251–257.

Blue Marble Geographics® (**2012**). Global Mapper v. 14 software for spatial data analysis, http://www.bluemarblegeo.com/products/global-mapper.php (Last viewed December 18, 2015).

Bolton, R. (**2007**). "Evaluation of Environmental Shadow Flicker Analysis for Dutch Hill Wind Power Project," Environ. Compliance Alliance, New York, 30 pp. Available at http://docs.wind-watch.org/shadow.pdf.

Department of Energy and Climate Change (DECC) (**2011**). "Update of UK Shadow Flicker Evidence Base: Final Report" (Parsons Brinckerhoff, London, UK). Available at https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/48052/1416-update-uk-shadow-flicker-evidence-base.pdf.

EMD International (**2013a**). WindPro 2.9 User Manual-Environment. Available at http://www.emd.dk/windpro/ (Last viewed February 2016).

EMD International® (**2013b**). WindPro 2.9. Software for Wind Energy Project Design and Planning.

EMD International® (**2015**). WindPro 3.0. Software for Wind Energy Project Design and Planning.

Feder, K., Michaud, D. S., Keith, S. E., Voicescu, S. A., Marro, L., Than, J., Guay, M., Denning, A., Bower, T. J., Lavigne, E., Whelan, C., and van den Berg, F. (**2015**). "An assessment of quality of life using the WHOQOL-BREF among participants living in the vicinity of wind turbines," Env. Res. **142**, 227–238.

Fields, J. M. (**1993**). "Effect of personal and situational variables on noise annoyance in residential areas," J. Acoust. Soc. Am. **93**(5), 2753–2762.

Gaudet, J. F., and Profitt, W. M. (**1958**). "Native trees of Prince Edward Island," Department of Agriculture, Charlottetown, 112 pp.

German Federal Ministry of Justice (Bundesministerium der Justiz) (**2011**). Law on protection against harmful environmental effects of air pollution, noise, vibration and similar phenomena, German Federal Emission Control Act.

Harding, G., Harding, P., and Wilkins, A. (**2008**). "Wind turbines, flicker, and photosensitive epilepsy: Characterizing the flashing that may precipitate seizures and optimizing guidelines to prevent them," Epilepsia **49**(6), 1095–1098.

ISO/TS-15666. (**2003**). "Acoustics—Assessment of noise annoyance by means of social and socio-acoustic surveys" (International Organization for Standardization, Geneva, Switzerland).

Job, R. F. S. (**1988**). "Community response to noise: A review of factors influencing the relationship between noise exposure and reaction," J. Acoust. Soc. Am. **83**, 991–1001.

Katsaprakakis, D. A. (**2012**). "A review of the environmental and human impacts from wind parks. A case study for the Prefecture of Lasithi, Crete," Renew. Sust. Energy Rev. **16**(5), 2850–2863.

Keith, S. E., Feder, K., Voicescu, S., Soukhovtsev, V., Denning, A., Tsang, J., Broner, N., Richarz, W., and van den Berg, F. (**2016**). "Wind turbine sound pressure level calculations at dwellings," J. Acoust. Soc. Am. **139**(3), 1436–1442.

Knopper, L. D., Ollson, C. A., McCallum, L. C., Whitfield Aslund, M. L., Berger, R. G., Souweine, K., and McDaniel, M. (**2014**). "Wind turbines and human health," Front Pub. Health. **2**, 63.

Massachusetts Department of Environmental Protection (MassDEP) and Massachusetts Department of Public Health (MDPH) (**2012**). "Wind Turbine Health Impact Study: Report of Independent Expert Panel," available at http://www.mass.gov/eea/docs/dep/energy/wind/turbine-impact-study.pdf (Last viewed February 25, 2016).

Michaud, D. S., Feder, K., Keith, S. E., Voicescu, S. A., Marro, L., Than, J., Guay, M., Bower, T., Denning, A., Lavigne, E., Whelan, C., Janssen, S. A., and van den Berg, F. (**2016a**). "Personal and situational variables associated with wind turbine noise annoyance," J. Acoust. Soc. Am. **139**(3), 1455–1466.

Michaud, D. S., Feder, K., Keith, S. E., Voicescu, S. A., Marro, L., Than, J., Guay, M., Denning, A., McGuire, D., Bower, T., Lavigne, E., Murray, B. J., Weiss, S. K., and van den Berg, F. (**2016b**). "Exposure to wind turbine noise: Perceptual responses and reported health effects," J. Acoust. Soc. Am. **139**(3), 1443–1454.

Michaud, D. S., Feder, K., Keith, S. E., Voicescu, S. A., Marro, L., Than, J., Guay, M., Denning, A., Murray, B. J., Weiss, S. K., Villeneuve, P., van den Berg, F., and Bower, T. (**2016c**). "Effects of wind turbine noise on self-reported and objective measures of sleep," SLEEP **39**(1), 97–109.

Michaud, D. S., Keith, S. E., Feder, K., Soukhovtsev, V., Marro, L., Denning, A., McGuire, D., Broner, N., Richarz, W., Tsang, J., Legault, S., Poulin, D., Bryan, S., Duddek, C., Lavigne, E., Villeneuve, P., Leroux, T., Weiss, S. K., Murray, B. J., and Bower, T. (**2013**). "Self-reported and objectively measured health indicators among a sample of Canadians living within the vicinity of industrial wind turbines: Social survey and sound level modelling methodology," Noise News Int. **21**(4), 14–27.

Moran, S. V., Gunn, W. J., and Loeb, M. (**1981**). "Annoyance by aircraft noise and fear of overflying aircraft in relation to attitudes toward the environment and community," J. Aud. Res. **21**(3), 217–225.

Natural Resources Canada (**2016**). Geogratis Data. Available at http://geogratis.gc.ca/api/en/nrcan-rncan/ess-sst/$categories?q=G%C3%A9oBase&scheme=urn:iso:series (Last viewed February 2016).

Ontario Ministry of the Environment (ONMOE) (**2008**). Noise Guidelines for Wind Farms—Interpretation for Applying MOE NPC Publications to Wind Power Generating Facilities, October 2008, PIBS 4709e.

Ontario Ministry of Natural Resources (**2014**). The Tree Atlas. Available at http://www.ontario.ca/environment-and-energy/tree-atlas (Last viewed February 2016).

Pawlaczyk-Łuszczyńska, M., Dudarewicz, A., Zaborowski, K., Zamojska-Daniszewska, M., and Waszkowska, M. (**2014**). "Evaluation of annoyance from the wind turbine noise: A pilot study," Int. J. Occup. Environ. Health **27**, 364–388.

Pedersen, E. (**2011**). "Health aspects associated with wind turbine noise—Results from three field studies," Noise Control Eng. J. **59**(1), 47–53.

Pedersen, E., Hallberg, L.-M., and Persson Waye, K. P. (**2007**). "Living in the vicinity of wind turbines—A grounded theory study," Qual. Res. Psych. **4**(1–2), 49–63.

Pedersen, E., and Persson Waye, K. (**2003**). "Audio-visual reactions to wind turbines," in *Proceedings of Euronoise*, Naples, Paper ID043, 6 pp.

Pedersen, E., and Persson Waye, K. P. (**2004**). "Perception and annoyance due to wind turbine noise—A dose–response relationship," J. Acoust. Soc. Am. **116**(6), 3460–3470.

Pedersen, E., and Persson Waye, K. P. (**2007**). "Wind turbine noise, annoyance and self-reported health and well-being in different living environments," Occup. Envir. Med. **64**, 480–486.

Pedersen, E., van den Berg, F., Bakker, R., and Bouma, J. (**2009**). "Response to noise from modern wind farms in The Netherlands," J. Acoust. Soc. Am. **126**(2), 634–643.

Peng, C. (**1999**). "Nonlinear Height-Diameter Models for Nine Boreal Forest Tree Species in Ontario," Ontario Ministry of Natural Resources, Forest Research Report Vol. 155, pp. 1–34.

Pohl, J., Faul, F., and Mausfeld, R. (**1999**). *Belästigung durch periodischen Schattenwurf von Windenergieanlagen (Annoyance Caused by Periodical Shadow-Casting of Wind Turbines)* (Institut für Psychologie der Christian-Albrechts-Universität, Kiel, Germany). Available at http://cvi.se/uploads/pdf/Kunskapsdatabas%20miljo/Ljud%20och%20Skuggor/Skuggor/Utredningar/Feldstudie.pdf.

Pohl, J., Hübner, G., and Mohs, A. (**2012**). "Acceptance and stress effects of aircraft obstruction markings of wind turbines," Energy Policy **50**, 592–600.

Reijneveld, S. A. (**1994**). "The impact of the Amsterdam aircraft disaster on reported annoyance by aircraft noise and on psychiatric disorders," Int. J. Epi. **23**(2), 333–340.

Riemann, D., Spiegelhalder, K., Espie, C., Pollmächer, T., Léger, D., Bassetti, C., and van Someren, E. (**2011**). "Chronic insomnia: Clinical and research challenges—An agenda," Pharmacopsychiatry **44**, 1–14.

Ross, H. E. (**1997**). "On the possible relations between discriminability and apparent magnitude," Br. J. Math. Stat. Psychol. **50**, 187–203.

Saidur, R., Rahim, N., Islam, M., and Solangi, K. (**2011**). "Environmental impact of wind energy," Renew. Sustain. Energ. Rev. **15**(5), 2423–2430.

Schneider, D., and Pautler, P. (**2009**). "Field trip: Coniferous trees," Ontario Nature Magazine, Available at http://onnaturemagazine.com/field-trip-coniferous-trees.html (Last viewed February 2016).

Sharma, M., and Parton, J. (**2007**). "Height-diameter equations for boreal tree species in Ontario using a mixed effects modelling approach," Forest Ecol. Mgmt. **249**, 187–198.

Smedley, A. R., Webb, A. R., and Wilkins, A. J. (**2010**). "Potential of wind turbines to elicit seizures under various meteorological conditions," Epilepsia **51**(7), 1146–1151.

Statistical Analysis System (SAS). (**2014**). Software package Version 9.2.

Stokes, M. E., Davis, C. S., and Koch, G. G. (**2000**). *Categorical Data Analysis Using the SAS System*, 2nd ed. (SAS Institute, Inc., Cary, NC), pp. 23–29 and 225–232.

Tachibana, H., Yano, H., Fukushima, A., and Shinichi, S. (**2014**). "Nationwide field measurement of wind turbine noise in Japan," Noise Control Eng. J. **62**(2), 90–101.

Tjepkema, M. (**2005**). Insomnia. Statistics Canada, Catalogue No. 82-003 Health Reports, Vol. 17, pp. 9–25.

Verheijen, E., Jabben, J., Schreurs, E., and Smith, K. B. (**2011**). "Impact of wind turbine noise in The Netherlands," Noise Health **13**(55), 459–463.

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SLEEP DURATION/SLEEP QUALITY

Effects of Wind Turbine Noise on Self-Reported and Objective Measures of Sleep

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Study Objectives: To investigate the association between self-reported and objective measures of sleep and wind turbine noise (WTN) exposure.
Methods: The Community Noise and Health Study, a cross-sectional epidemiological study, included an in-house computer-assisted interview and sleep pattern monitoring over a 7 d period. Outdoor WTN levels were calculated following international standards for conditions that typically approximate the highest long-term average levels at each dwelling. Study data were collected between May and September 2013 from adults, aged 18–79 y (606 males, 632 females) randomly selected from each household and living between 0.25 and 11.22 kilometers from operational wind turbines in two Canadian provinces. Self-reported sleep quality over the past 30 d was assessed using the Pittsburgh Sleep Quality Index. Additional questions assessed the prevalence of diagnosed sleep disorders and the magnitude of sleep disturbance over the previous year. Objective measures for sleep latency, sleep efficiency, total sleep time, rate of awakening bouts, and wake duration after sleep onset were recorded using the wrist worn Actiwatch2® from a subsample of 654 participants (289 males, 365 females) for a total of 3,772 sleep nights.
Results: Participant response rate for the interview was 78.9%. Outdoor WTN levels reached 46 dB(A) with an arithmetic mean of 35.6 and a standard deviation of 7.4. Self-reported and objectively measured sleep outcomes consistently revealed no apparent pattern or statistically significant relationship to WTN levels. However, sleep was significantly influenced by other factors, including, but not limited to, the use of sleep medication, other health conditions (including sleep disorders), caffeine consumption, and annoyance with blinking lights on wind turbines.
Conclusions: Study results do not support an association between exposure to outdoor WTN up to 46 dB(A) and an increase in the prevalence of disturbed sleep. Conclusions are based on WTN levels averaged over 1 y and, in some cases, may be strengthened with an analysis that examines sleep quality in relation to WTN levels calculated during the precise sleep period time.
Keywords: actigraphy, annoyance, multiple regression models, PSQI, sleep, wind turbine noise
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Significance

This study provides the most comprehensive assessment to date of the potential association between exposure to wind turbine noise (WTN) and sleep. As the only study to include both subjective and objective measures of sleep, the results provide a level of insight that was previously unavailable. The absence of an effect of WTN on sleep is based on an analysis of self-reported and objectively measured outcomes in relation to long term outdoor average sound levels. Knowledge in this area may be strengthened by future research to consider the potential transient changes in WTN levels throughout the night, which may influence subtle measures of sleep not assessed in the current study.

INTRODUCTION

Sleep loss has been implicated in a variety of negative health outcomes[1] including cardiovascular abnormalities,[2] immunological problems,[3] psychological health concerns,[4] and neurobehavioral impairment that can lead to accidents.[5] Sleep loss may be related to total sleep time restriction and/or reduced sleep quality in the sleep time obtained. Sleep disorders such as insomnia and obstructive sleep apnea are associated with an increased incidence of hypertension, heart failure, and stroke.[6,7]

Sleep can clearly be disrupted with noise.[8] It has long been recognized that electroencephalography (EEG) arousals can be induced with external environmental stimuli, but are modulated by sleep state.[9] The World Health Organization (WHO) Guidelines for Community Noise recommend that, for continuous noise, an indoor sound level of 30 dB(A) should not be exceeded during the sleep period time to avoid sleep disturbance.[10] More recently, the WHO's Night Noise Guidelines for Europe [11] suggest an annual average outdoor level of 40dB(A) to reduce negative health outcomes from sleep disturbance even among the most vulnerable groups.

Sleep can be measured by subjective and objective means[12] although due to the fundamental nature of unconsciousness in this state, people are unable to introspect on their sleep state. As such, an individual may surmise the quality of his or her sleep, with descriptions of what his or her presumed sleep was like, periods of awakening, and consequences of the state. However, sleep state misperception is a common clinical phenomenon, whereby patients with some degree of insomnia may report much worse quality of sleep than what actually occurred.[13] Subjective interpretation of sleep state is thus subject to biased reporting from the individual and therefore subjective and objective measures of sleep are frequently discordant. Therefore, objective physiological measures of sleep can provide a more accurate reflection of what actually happened during an individual's sleep and form the basis of an unprejudiced understanding of the actual biological effect of factors such as noise on sleep.

Although the current study is the first to include objective measures in the assessment of sleep quality in the context of wind turbine noise (WTN) exposure, the psychological experience of the individual must be considered, though this factor may be more prone to subjective interpretation. Numerous subjective scales of sleep have been devised. The Pittsburgh Sleep Quality Index (PSQI)[14] is a measure of the subjective experience of sleep that has had detailed psychometric assessment,[15] validation in numerous populations,[16–18] and is one of the most common subjective methodologies used in sleep research.

The PSQI has been administered in a study to compare subjective sleep quality among 79 subjects living near two different wind farms wherein it was reported that sleep quality was worse among the group living closer to the wind turbines.[19] Pedersen[20] found that self-reported sleep disturbance for any reason from any source was inconsistently related to the level of WTN. Bakker et al.[21] showed that self-reported sleep disturbance was correlated to WTN level, but when noise annoyance from wind turbines was brought into a multiple regression, sleep disturbance appeared to be highly correlated to the annoyance, but not to WTN level and only annoyance was statistically correlated to WTN level. This is consistent with the study by van den Berg et al.[22] wherein noise annoyance was reported as a better predictor of self-reported sleep disturbance than noise level for transportation, industrial, and neighbor noise.

Several studies have provided objectively measured assessments of transportation noise-induced sleep disturbance.[23–26] Although it is clear that noise is among the many factors that contribute to sleep disturbance [23,24,27,28] there has been no study to date that has provided an assessment of sleep disturbance in the context of WTN exposures using objective measures such as actigraphy.

The current study was designed to objectively measure sleep in relation to WTN exposure using actigraphy, which has emerged as a widely accepted tool for tracking sleep and wake behavior.[29,30] The objective measures of sleep, when considered together with self-report, provide a more comprehensive evaluation of the potential effect that WTN may have on sleep.

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

METHOD

Sample Design

Target population, sample size, and sampling frame strategy

Several factors influenced the determination of the final sample size, including having adequate statistical power to assess the study objectives, and adequate time allocation for collection of data, influenced by the length of the personal in-dwelling interview and the time needed to collect the physical measures. Overall statistical power for the study was based on the study's primary objective to assess WTN-associated effects on sleep quality. Based on an initial sample size of 2,000 potential dwellings, it was estimated that there would be 1,120 completed survey responses. For 1,120 survey responses there should be sufficient statistical power to detect at least a 7% difference in the prevalence of sleep disturbances with 80% power and a 5% false positive rate (Type I error). There was uncertainty in the power assessment because the current *Community Noise and Health Study*, was the first to implement objectively measured endpoints to study the possible effects of WTN on sleep. How these power calculations applied to actigraphy-measured sleep was also unknown. In the absence of comparative studies, a conservative baseline prevalence for reported sleep disturbance of 10% was used.[31,32] Sample size calculation also incorporated the following assumptions: (1) approximately 20% to 25% of the targeted dwellings would not be valid dwellings (i.e., demolished, unoccupied seasonal, vacant for unknown reasons, under construction, institutions, etc.); and (2) of the remaining dwellings, there would be a 70% participation rate. These assumptions were validated (see response rates and sample characteristics related to sleep).

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. The ON and PEI sampling regions included 315 and 84 wind turbines, respectively. The wind turbine electrical power outputs ranged between 660 kW to 3 MW (average 2.0 ± 0.4 MW). All turbines were modern monopole tower design with three pitch-controlled rotor blades (~80 m diameter) upwind of the tower and most had 80 m hub heights. All identified dwellings within approximately 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 y was randomly selected to participate. The final sample size in ON and PEI was 1,011 and 227, respectively. Participants were not compensated in any way for their participation.

Wind turbine sound pressure levels at dwellings

Outdoor sound pressure levels were estimated at each dwelling using both ISO 9613-1[33] and ISO 9613-2[34] as incorporated in the commercial software CadnaA version 4.4.[35] The resulting calculations represent long-term (1 y) A-weighted equivalent continuous outdoor sound pressure levels (LAeq). Therefore, calculated sound pressure levels can only approximate with a certain degree of uncertainty the sound pressure level at the dwelling during the reference time periods that are captured by each measure of sleep. The time reference period ranges from 1–7 d (actigraphy), to 30 d for the PSQI and the previous year for the assessment of the percentage highly sleep disturbed. Van den Berg[36] has shown that, in the Dutch temperate climate, the long-term average WTN level for outdoor conditions is 1.7 ± 1.5 dB(A) below the sound pressure level at 8 m/sec wind speed. Accordingly, a best estimate for the average nighttime WTN level is approximately 2 dB(A) below the calculated levels reported in this study.

Calculations included all wind turbines within a radius of 10 km, and were based on manufacturers' octave band sound power spectra at a standardized wind speed of 8 m/sec and favorable sound propagation conditions. Favorable conditions assume the dwelling is located downwind of the noise source, a stable atmosphere, and a moderate ground-based temperature inversion. Although variations in wind speeds and temperature as a function of height could not be considered in the model calculations due to a lack of relevant data, 8 m/sec was considered a reasonable estimate of the highest noise exposure conditions. The manufacturers' data were verified for consistency using on-site measurements of wind turbine sound power. The standard deviation in sound levels was estimated to be 4 dB(A) up to 1 km, and at 10 km the uncertainty was estimated to be between 10 dB(A) and 26 dB(A). Although calculations based on predictions of WTN levels reduces the risk of misclassification compared to direct measurements, the risk remains to some extent. The calculated levels in the current study represent reasonable worst-case estimates expected to yield outdoor WTN levels that typically approximate the highest long-term average levels at each dwelling and thereby optimize the chances of detecting WTN-induced sleep disturbance. The few dwellings beyond 10 km were assigned the same calculated WTN value as dwellings at 10 km. Unless otherwise stated, all decibel references are A-weighted. A-weighting filters out low frequencies in a sound that the human auditory system is less sensitive to at low sound pressure levels.

In the current study, low-frequency noise was estimated by calculating C-weighted sound pressure levels. No additional benefit was observed in assessing low frequency noise because C- and A-weighted levels were so highly correlated. Depending on how dB(C) was calculated and what range of data was assessed, the correlation between dB(C) and dB(A) ranged from $r = 0.84$ to $r = 0.97$.[37]

Background nighttime sound levels at dwellings

As a result of certain meteorological phenomena (atmospheric stability and wind gradient) coupled with a tendency for background sound levels to drop throughout the day in rural/semi-rural environments, WTN can be more perceptible at the dwelling during nighttime.[38–41] In Canada, it is possible to estimate background nighttime sound pressure levels according to the provincial noise regulations for Alberta, Canada,[42] which estimates ambient noise levels in rural and suburban environments. Estimates are based on dwelling density per quarter section, which represents an area with a 451 m radius and distance to heavily travelled roads or rail lines. When modeled in accordance with these regulations, estimated levels can range from 35 dB(A) to 51 dB(A). The possibility that exposure to high levels of road traffic noise may create a background sound pressure level higher than that estimated using the Alberta regulations was considered. In ON, road noise for the six-lane concrete Highway 401 was calculated using the United States Federal Highway Administration (FHWA) Traffic Noise Model[43] module in the CadnaA software.[35] This value was used when it exceeded the Alberta noise estimate, making it possible to have levels above 51 dB(A).

Data Collection

Questionnaire administration and refusal conversion strategies

The questionnaire instrument included modules on basic demographics, noise annoyance, health effects, quality of life, sleep quality, sleep disorders, perceived stress, lifestyle behaviors, and prevalence of chronic disease. To avoid bias, the true intent of the study, which was to assess the community response to wind turbines, was masked. Throughout the data collection, the study's official title was: *Community Noise and Health Study.* This approach is commonly used to avoid a disproportionate contribution from any group that may have distinct views toward wind turbines. Data collection took place through in-person interviews between May and September 2013 in southwestern ON and PEI. After a roster of all adults aged 18 to 79 y living in the dwelling was compiled, a computerized method was used to randomly select one adult from each household. No substitution was permitted; therefore, if the targeted individual was not at home or unavailable, alternate arrangements were made to invite them to participate at a later time.

All 16 interviewers were instructed to make every reasonable attempt to obtain interviews, which included visiting the dwelling at various times of the day on multiple occasions and making contact by telephone when necessary. If the individual refused to participate, they were then contacted a second time by either the senior interviewer or another interviewer. If, after a second contact, respondents refused to participate, the case was coded as a final refusal.

Self-reported sleep assessment

Long-term self-reported sleep disturbance included an assessment of the magnitude of sleep disturbance experienced at home (of any type for any reason) over the past year. Participants were requested to describe their level of sleep disturbance at home over the past year using one of the following categories: "not at all," "slightly," "moderately," "very" or "extremely," where the top two categories were collapsed and considered to reflect "highly sleep disturbed." For the purposes of this analysis the bottom three categories reflect "low sleep disturbance." These categories and the classification of "highly sleep disturbed" is consistent with the approach adopted for annoyance[44] and facilitates comparisons to self-reported sleep disturbance functions developed for transportation noise sources.[45] Data were collected on prevalence of diagnosed sleep disorders. In addition, participants completed the PSQI, which provided an assessment of sleep quality over the previous 30 d. The seven components of the PSQI are scored on a scale from 0 (better) to 3 (worse); therefore the global PSQI is a score ranging between 0–21, where a value of greater than 5 is thought to represent poor sleep quality.[14,16–18]

Objectively measured sleep

An Actiwatch2® (Philips Healthcare, Andover, MA, USA) sleep watch was given to all consenting and eligible participants aged 18 to 79 y who were expected to sleep at their current address for a minimum of 3 of the 7 nights following the interview. There were 450 devices at hand that were cycled throughout the study. In order to receive the device, respondents also needed to have full mobility in the arm on which the watch was to be worn. Respondents were asked to wear the device on their wrist during all hours of the day and night for the 7 d following their interview. The Actiwatch2® provides key information on sleep patterns (based on movement), including timing and duration of sleep as well as awakenings, and has been compared with polysomnography in some patient samples,[46] but does not replace polysomnography due to imperfect sensitivity and specificity for detecting wake periods. However, this tool can provide reasonable estimates for assessing subjects objectively for more prolonged periods of time than conventional assessment tools, with minimal participant burden.[47] The devices were configured to continuously record a data point every 60 sec for the entire 7 d period. Data analysis was conducted using Actiware® Version 5.1[48] with the software set to default settings (i.e., sensitivity setting of medium and a minimum minor rest interval size of 40 min). With these settings an epoch of 40 counts (i.e., accelerometer activity above threshold) or less is considered sleep and epochs above 40 counts are considered wake. However, any given epoch is scored using a 5-epoch weighting scheme. This procedure weighs the 2 epochs adjacent to the epoch in question. The 5-epoch weighting is achieved by multiplying the number of counts in each respective epoch by the following: 1/25, 1/5, 1, 1/5, 1/25, whereby an average above 40 indicates "awake" for the central epoch. The sleep start parameter was automatically calculated by the Actiware® software determined by the first 10 min period in which no more than one 60 sec epoch was scored as mobile. An epoch is scored as mobile if the number of activity counts recorded in the epoch is greater than or equal to the epoch length in 15 sec intervals (i.e., in a 60 sec epoch an activity value of 4 or higher). Endpoints of interest from wrist actigraphy included sleep efficiency (total sleep time divided by measured time in bed), sleep latency (how long it took to fall asleep), wake after sleep onset (WASO) (the total duration of awakenings), total sleep time, and the number of awakening bouts (WABT) (during a sleep period). The WABT data was analysed as the rate of awakening bouts per 60 min in bed.

To help interpret the measured data, respondents were asked to complete a basic sleep log each night of the study. The log contained information about whether the respondent slept at home or not, presence of windows in the room where they slept, and whether or not the windows were open. After the 7 d collection period, respondents were asked to return the completed sleep log with the actigraph in a prepaid package.

Statistical Methodology

The analysis follows the description in Michaud et al.,[49] which provides a summary of the study design and objectives, as well as a proposed data analysis. Briefly, the Cochran Mantel-Haenszel chi-square test was used to detect associations between self-reported magnitude or contributing sources of sleep disturbance and WTN exposure groups while controlling for province. Because a cut-off value of 5 for the global PSQI score provided a sensitive and specific measure distinguishing good and poor sleep, the PSQI score was dichotomized with the objective to model the proportion of individuals with poor sleep quality (i.e., PSQI > 5).[14] As a first step to develop the best model to predict the dichotomized PSQI score, univariate logistic regression models only adjusting for WTN exposure groups and province were carried out. 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. The analysis of each variable only adjusts for WTN category and province; therefore, interpretation of any individual relationship must be made with caution.

The primary objective in the current analysis was to use multiple regression models to identify the best predictors for (1) reporting a PSQI score greater than 5; and (2) the actigraphy endpoints. All explanatory variables that were statistically significant at the 20% level in the univariate analysis for each respective endpoint were considered in the multiple regression models. To develop the best model to predict each endpoint of interest, the stepwise method, which guards against issues of multicollinearity, was used for multiple regression models.

The stepwise regression was carried out in three different ways wherein the base model included: (1) WTN exposure category and province; (2) WTN exposure category, province, and an adjustment for individuals who reported receiving personal benefit from having wind turbines in the area; and (3) WTN category and province, stratified for those who received no personal benefit.

For the analysis of PSQI, multiple logistic regression models were developed using the stepwise method with a 20% significance entry criterion and a 10% significance criterion to remain in the model. The WTN groups were treated as a continuous variable, giving an odds ratio (OR) for each unit increase in WTN level, where a unit reflects a 5 dB(A) WTN category. The Nagelkerke pseudo R^2 is reported for logistic regression models.

Repeated-measures data from all wrist actigraphy measurements were modeled using the generalized estimating equations (GEE) method, as available in SAS (Statistical Analysis System) version 9.2 PROC GENMOD.[50–52] Univariate GEE regression models only adjusting for WTN exposure groups, province, day of the week, and the interaction between WTN groups and day of the week were carried out. The interaction between WTN and province was significant for the total sleep time outcome in the univariate models, but was no longer significant in the multiple GEE regression model. Therefore, the base model for the multiple GEE regression models included only WTN category, province, and day of the week. The same stepwise methodology that was applied to build the PSQI models was used to develop multiple GEE regression models for each actigraphy endpoint. The within-subjects correlations were examined with different working correlation matrix structures (unstructured, compound symmetry, and autoregressive of first order). An unstructured variance-covariance structure between sleep nights was applied to all endpoints with the exception of sleep latency, where compound symmetry was used. The advantage of the GEE method is that it uses all available data to estimate individual subject variability (i.e., if 1 or more nights of data is missing for an individual, the individual is still included in the analysis).

The wrist actigraphy endpoints of sleep efficiency and rate of awakening bouts do not follow a normal distribution, because one is a proportion ranging between 0 and 1 (sleep efficiency) and the other is a count (awakening bouts). Therefore, to analyze awakening bouts a Poisson distribution was assumed. The

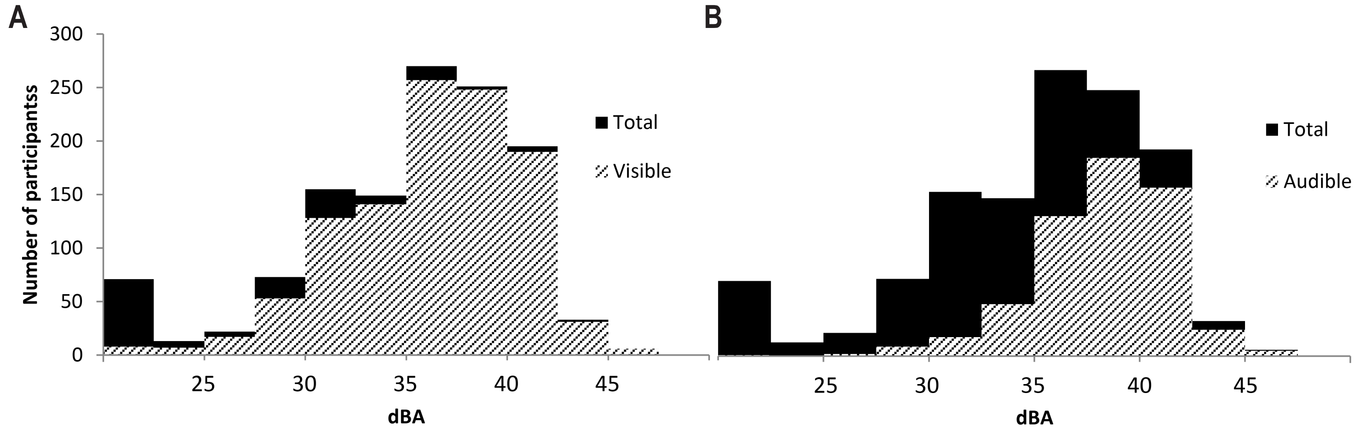

Figure 1—Histogram showing the distribution of participants as a function of calculated outdoor A-weighted wind turbine noise levels. **(A)** The number of participants who self-reported on the questionnaire that wind turbines were visible from anywhere on their property. **(B)** The number of participants who self-reported that wind turbines were audible from inside or outside their home.

number of awakening bouts was analyzed with respect to the total time spent in bed and is reported as a rate of awakening bouts per 60 min in bed. Sleep efficiency, sleep latency, and WASO were transformed in order to normalize the data and stabilize the variance.[53–55] In the GEE models, statistical tests were based on transformed data in order to satisfy the normality and constant variance assumptions. Because back-transformation was not possible for some endpoints, the arithmetic mean (least squares mean [LSM]) is presented for all endpoints.

All regression models for PSQI and actigraphy endpoints were adjusted for provincial differences. Province was initially assessed as an effect modifier. Because the interaction was not statistically significant for any of the multiple regression models, province was treated as a confounder in the models with associated adjustments, as required. Statistical analysis was performed using SAS version 9.2. A 5% statistical significance level was implemented throughout unless otherwise stated and Tukey corrections were applied to account for all pairwise comparisons to ensure that the overall Type I (false positive) error rate was less than 0.05.

Actigraphy Data Screening

The sleep actigraphy file consisted of 4,742 nights of actigraphy measured sleep (i.e., sleep nights) data from 781 participants. The following adjustments to the file were made to account for data that could not be processed: removal of sleep nights with no data (n = 15), data where the dates from the sleep watch and sleep log diary did not match (n = 61), recordings beyond 7 d (representing data collected off wrist or during return shipment) (n = 56), nights with shift work (n = 630), and data related to sleep nights away from home (n = 132). Removal of these data supported the objective to relate sleep behavior to noise exposure from wind turbines at the participants' dwelling. Sleep starting after 05:00 with awakening on the same day before 18:00 was considered day sleep and removed from the analysis (n = 70). One participant was removed where there appeared to be a watch malfunction (i.e., indicated nearly constant sleep). The final sample size consisted of 3,772 sleep nights and 654 participants. Any sleep that started after midnight, but before 05:00 was re-coded and considered as sleep for the previous night to avoid having two sleep observations for the same night. For the remaining data, all available data was used whether the person wore the watch for 1 d or for the maximum 7 d.

RESULTS

Wind Turbine Sound Pressure Levels at Dwellings

Calculated outdoor sound pressure levels at the dwellings determined by ISO 9613-1[33] and ISO 9613-2[34] reached levels as high as 46 dB(A). Results are considered to have an uncertainty of ± 4 dB(A) within distances that would have the strongest effect on sleep (i.e., ~600 m). Figure 1 illustrates the distribution of participants as a function of WTN levels and identifies the number of participants who reported wind turbines were visible from anywhere on their property (panel A) and audible (panel B) while they were either outside or inside their dwelling.

Background Nighttime Sound Pressure Levels

Modeled background nighttime sound (BNTS) levels ranged between 35 and 61 dB(A) in the sample. Average BNTS was highest in the WTN group 30–35 dB(A) and lowest in areas where modeled WTN levels were between 40–46 dB(A).[37] In the univariate analysis of global PSQI, the proportion of people with poor sleep (i.e., global scores above 5) was statistically similar among the BNTS levels (P = 0.9727). For actigraphy, BNTS levels were only statistically significant for the endpoint WASO (P = 0.0059), where it was found that individuals in areas with louder BNTS levels tended to have longer durations of awakenings. WASO increased from 50.7 min (95% confidence interval [CI]: 46.9, 54.4) in areas with < 40 dB(A) BNTS to 67.2 min (95% CI: 57.0, 77.5) in areas with ≥ 55 dB(A) BNTS levels (see supplemental material).

Response Rates and Sample Characteristics Related to Sleep

A detailed breakdown of the response rates, along with personal and situational variables by WTN category, is presented by Michaud.[37] Of the 2,004 potential dwellings, 1,570 were valid and 1,238 agreed to participate in the survey (606 males,

Table 1—Self-reported magnitude and contributing sources of sleep disturbance.

	Wind Turbine Noise, dB(A)						
Variable	**< 25**	**25–30**	**30–35**	**35–40**	**40–46**	**Overall**	**CMH P value**[a]
n	83	95	304	519	234	1,235	
Self-reported sleep disturbance n (%)							
Not at all	29 (34.9)	44 (46.3)	112 (36.8)	208 (40.1)	85 (36.3)	478 (38.7)	
At least slightly[b]	54 (65.1)	51 (53.7)	192 (63.2)	311 (59.9)	149 (63.7)	757 (61.3)	0.7535
Highly[c]	13 (15.7)	11 (11.6)	41 (13.5)	75 (14.5)	24 (10.3)	164 (13.3)	0.4300
Source of sleep disturbance (among participants at least slightly sleep disturbed) n (%)							
n[d]	53	51	186	298	138	726	
Wind turbine	0 (0.0)	2 (3.9)	4 (2.2)	45 (15.1)	31 (22.5)	82 (11.3)	< 0.0001
Children	9 (17.0)	12 (23.5)	21 (11.3)	36 (12.1)	20 (14.5)	98 (13.5)	0.2965
Pets	7 (13.2)	12 (23.5)	9 (4.8)	45 (15.1)	22 (15.9)	95 (13.1)	0.3582
Neighbors	6 (11.3)	5 (9.8)	9 (4.8)	13 (4.4)	5 (3.6)	38 (5.2)	0.0169
Other	41 (77.4)	35 (68.6)	162 (87.1)	232 (77.9)	87 (63.0)	557 (76.7)	0.0128
Stress/anxiety	6 (11.3)	2 (3.9)	21 (11.3)	33 (11.1)	11 (8.0)	73 (10.1)	0.8938
Physical pain	11 (20.8)	9 (17.6)	50 (26.9)	48 (16.1)	18 (13.0)	136 (18.7)	0.0289
Snoring	5 (9.4)	6 (11.8)	17 (9.1)	20 (6.7)	12 (8.7)	60 (8.3)	0.4126

Participants were asked to report their magnitude of sleep disturbance over the last year while at home by selecting one of the following five categories: not at all, slightly, moderately, very, or extremely. Participants that indicated at least a slight magnitude of sleep disturbance were asked to identify all sources perceived to be contributing to sleep disturbance. [a]The Cochran Mantel-Haenszel chi-square test was used to adjust for provinces. [b]At least slightly sleep disturbed includes participants indicating the slightly, moderately, very or extremely categories. [c]Highly sleep disturbed includes participants who reported the very or extremely categories. The prevalence of reported sleep disturbance was unrelated to wind turbine noise levels. [d]Of the 757 participants who reported at least a slight amount of sleep disturbance, 31 did not know what contributed to their sleep disturbance. Of the remaining 726, at least one source was identified. Columns may not add to sample size totals as some participants did not answer questions and/or identified more than one source as the cause of their sleep disturbance.

Table 2—Summary of Pittsburgh Sleep Quality Index scores.

	Wind Turbine Noise, dB(A)					
	< 25	**25–30**	**30–35**	**35–40**	**40–46**	**Overall**
Mean (95% CI)	6.22 (5.32, 7.11)	5.91 (5.05, 6.77)	6.00 (5.51, 6.50)	5.74 (5.33, 6.16)	6.09 (5.55, 6.64)	5.94 (5.72, 6.17)
n (%) score > 5[a]	40 (49.4)	45 (48.9)	138 (46.5)	227 (44.4)	106 (46.7)	556 (46.0)

[a]Pittsburgh Sleep Quality Index score above 5 is considered to represent poor sleep. CI, confidence interval.

632 females), resulting in a final overall response rate of 78.9%. Of the 1,238 participants, 1,208 completed the PSQI in its entirety (97.6%) and 781 participated in the sleep actigraphy portion of the study (63%). Sleep actigraphy participation rates were in line with projections based on an unpublished pilot study designed to assess different sleep watch devices and participant compliance. Participation rate was equally distributed across WTN categories.

The prevalence of reporting a diagnosed sleep disorder was unrelated to WTN levels (P = 0.3102).[27] In addition, the use of sleep medication at least once a week was significantly related to WTN levels (P = 0.0083). The prevalence was *higher* among the two lowest WTN categories (< 25 dB(A) and 25–30 dB(A)).[37] Factors that may affect sleep quality, such as self-reported prevalence of health conditions, chronic illnesses, quality of life, and noise sensitivity were all found to be equally distributed across WTN categories.[37,56] In response to the general question on magnitude of sleep disturbance for any reason over the past year while at home, a total of 757 participants (61.3%) reported at least a "slight" magnitude of sleep disturbance (includes ratings of "slightly," "moderately," "very" and "extremely"), with a total of 164 (13.3%) classified as "highly" sleep disturbed (i.e., either very or extremely). The levels of WTN were not found to have a statistically significant effect on the prevalence of sleep disturbance whether the analysis was restricted to only participants highly sleep disturbed (P = 0.4300), or if it included all participants with even a slight disturbance (P = 0.7535) (Table 1). When assessing the sources reported to contribute to sleep disturbance among all participants with even slight disturbance, reporting wind turbines was significantly associated with WTN categories (P < 0.0001). The prevalence was ≥ 15.1% among the participants living in areas where WTN levels were ≥ 35 dB(A) compared to ≤ 3.9% in areas where WTN levels were below 35 dB(A). However, wind turbines were not the only, nor the most prevalent, contributing source at these sound levels (see Table 1).

PSQI Scores

For the 1,208 participants who completed the PSQI in its entirety, the average PSQI score across the entire sample was

5.94 with 95% confidence interval (CI) (5.72, 6.17). The Cronbach alpha for the global PSQI was 0.76 (i.e., greater than the minimum value of 0.70 in order to validate the score). Table 2 presents the summary statistics for PSQI as both a continuous scale and a binary scale (the proportion of respondents with poor sleep; i.e., PSQI above 5) by WTN exposure categories. Analysis of variance was used to compare the average PSQI score across WTN exposure groups (after adjusting for provinces). There was no statistical difference observed in the mean PSQI scores between groups ($P = 0.7497$) as well as no significant difference between provinces ($P = 0.7871$) (data not shown). Similarly, when modeling the proportion of respondents with poor sleep ($PSQI > 5$) in the logistic regression model, no statistical differences between WTN exposure groups ($P = 0.4740$) or provinces ($P = 0.6997$) were observed (see supplemental material).

Effects of Personal and Situational Variables on PSQI Scores and Actigraphy

A univariate analysis of the personal and situational variables in relation to the PSQI scores (logistic regression) and actigraphy (GEE) was conducted. The list of variables considered was extensive and included, but was not limited to, age, sex, income, education, body mass index, caffeine consumption, housing features, diagnosed sleep disorders, health conditions, annoyance, household complaints, and personal benefit (i.e., rent, payments or other indirect benefits through community improvements) from having wind turbines in the area. The analysis of these and several other variables in relation to the endpoints has been made available in the supplemental material.

Multiple Logistic Regression Models for PSQI

Table 3 provides a summary of the variables retained in the multiple regressions for the PSQI and actigraphy endpoints. A detailed description of the statistical results, including the direction of change and the pairwise comparisons made among the groups within each variable is available in the supplemental material.

Table 4 presents the results from stepwise multiple logistic regression modeling of the proportion of respondents with "poor sleep" (i.e., scores above 5 on the PSQI). The final models for the three approaches to stepwise regression as listed in the Statistical Methods section produced nearly identical results to one another. Therefore, results are only presented for the regression method where the variables WTN category, province, and personal benefit were forced into the model that fit the data well (Hosmer-Lemeshow test, $P > 0.05$). Using stepwise regression, the predictive strength of the final model was 37%. There was no observed relationship between the proportion of respondents with poor sleep and WTN levels ($P = 0.3165$).

Participants who had improved sleep quality after closing their bedroom window were found to have the same odds of poor sleep when compared to those who did not need to close their window ($P = 0.0565$). Participants who stated that closing their window did not improve sleep quality had higher odds of poor sleep in comparison with both those who had improved sleep quality after closing windows and those who did not need to close windows ($P \leq 0.0006$, in both cases). Unemployed individuals had higher odds of poor sleep compared with those who were employed (OR [95% CI]: 1.55 [1.12, 2.15]).

Long-term sleep disturbance (of any type by any source) was included in the study because dose-response relationships have been published for this measure in relation to other community noise sources[45] and this endpoint provides a longer time reference period than the previous 30 d assessed using the PSQI. Those who reported a very or extremely high level of sleep disturbance (i.e., percentage highly sleep disturbed) by any source while at home had 6 times higher odds of poor sleep assessed with the PSQI (OR [95%CI]: 6.28 [3.46, 11.40]) when compared to those with no, slight, or moderate reported sleep disturbance. Finally, participants suffering from migraines/headaches, asthma, arthritis and a diagnosed sleep disorder (e.g., sleep apnea or insomnia) had higher odds of poor sleep when compared to those not suffering from these health and chronic conditions.

Sleep Actigraphy

The majority of participants (56%) wore the watch for the full 7 nights (mean number of days 5.77, SD = 1.85). The frequency across the days of the week was equally distributed (data not shown). Response rates for the actigraph were equally distributed across WTN exposure groups ($P = 0.5585$), although a higher proportion of participants were noted in PEI, in comparison to ON ($P = 0.0008$).

Table 5 presents the summary data for each sleep actigraphy endpoint analyzed. Although mean values appear stable between one sleep night to the next within an endpoint, the standard deviation is observed to fluctuate between sleep nights (data not shown). The observed correlations between the PSQI and the actigraphy endpoints are presented as supplemental material.

Multiple GEE Regression Models for Actigraphy

Multiple regression models for the five sleep actigraphy endpoints were developed. Variables that were associated with each endpoint (i.e., significant at the 10% level) are summarized in Table 3. Specific information on these variables, including the direction of change, P values, and pairwise comparisons has been made available in the supplemental material. Table 6 presents the LSM and the P values for the exposure of interest, the WTN exposure categories, obtained from the GEE regression models for the sleep actigraphy endpoints. Unadjusted results reflect the base model (including WTN, province, day of the week, and the interaction between WTN and day of the week) whereas adjusted results come from the multiple regression models obtained through the stepwise method and take into account factors beyond the base model. The level of exposure to WTN was not found to be related to sleep efficiency ($P = 0.3932$), sleep latency ($P = 0.6491$), total sleep time ($P = 0.8002$), or the number of awakening bouts ($P = 0.3726$). There was an inconsistent association found between WASO and WTN exposure where there was a statistically significant reduction in WASO time observed in areas where WTN levels were 25–30 dB(A), in comparison with < 25 dB(A) and 40–46

Table 3—Variables retained in multiple generalized estimating equations and multiple logistic regression models.

	Sleep Efficiency (%)	Sleep Latency (min)	Total Sleep Time (min)	WASO (min)	Rate of Awakening Bouts (per 60 min)	PSQI (scores > 5)
Base model						
WTN levels				++		
Province				+		+
Demographic variables						
Sex	++					
BMI group	+	++				
Age group		++				
Marital status					+	
Employment				++		++
Smoking status				++		
Caffeine consumption	++				+	
Education	++			++		
Situational variables						
Bedroom location				++		
Air conditioning unit in bedroom			++			
Bedroom on quiet side			+			
Bedroom window type			+			
Sleep improved by closing window						++
Closure of bedroom windows/other[a]		++				
BNTS level			++	++		
Audible rail noise						++
Audible aircraft noise				++		
Wind turbine related variables						
Complaint about wind turbines	+					
Personal benefits						++
Annoyance with blinking lights			++		++	
Personal and health related variables						
Self-reported sleep disturbance[b]						++
Sleep disturbed by pain			++		++	
Sleep disturbed by neighbors			++			
Sleep disturbed by other[c]						++
Annoyed by snoring						+
Sleep medication[d]				++		
Migraines						++
Dizziness						+
Chronic pain						+
Asthma		++				++
Arthritis						++
Diagnosed sleep disorder			+			++
Restless leg syndrome					++	

A summary of significant variables retained in multiple generalized estimating equations and multiple logistic regression models for objectively measured and self-reported sleep endpoints, respectively. The specific direction of change, level of statistical significance, pairwise comparisons between variable groups and full description of the variable names is provided in supplemental material. [a]The source identified by participants as the cause of closing bedroom windows to reduce noise levels was not road traffic, aircraft, rail or wind turbines. [b]Evaluates the magnitude of reported sleep disturbance at home from not at all to extremely, for any reason over the previous year. [c]The source identified by participants as contributing to their sleep disturbance was not wind turbines, children, pets or neighbors. [d]Use of sleep medication was note considered in the multiple regression model for PSQI since it is one of the seven components that make up the global PSQI score. +, ++ denotes statistically significant, $P < 0.10$, $P < 0.05$, respectively. BMI, body mass index; BNTS, background nighttime sound level; PSQI, Pittsburgh Sleep Quality Index; WTN, wind turbine noise.

Table 4—Multiple logistic regression model for Pittsburgh Sleep Quality Index.

		Model: WTN, Province, and Personal Benefit Forced in	
		PSQI[a]	
Variable	**Groups in Variable**[b]	**P value**[c] (n = 933, R^2 = 37%, H-L P = 0.9252)[h]	**OR (CI)**[d]
WTN, dB(A)[e]		0.3165	0.93 (0.80, 1.07)
Province	PEI/ON	0.0810	1.46 (0.95, 2.25)
Personal benefit	No/Yes	0.0499	1.82 (1.00, 3.30)
Sleep improved by closing window (overall P value < 0.0001)	Yes	0.0565	1.41 (0.99, 2.00)
	No	< 0.0001	8.48 (3.11, 23.14)
	Did not need to close windows	Reference	
Employment	No/Yes	0.0085	1.55 (1.12, 2.15)
Audible rail noise	No/Yes	0.0380	1.56 (1.03, 2.37)
Reported cause for sleep disturbance			
Other[f]	Yes/No	< 0.0001	2.55 (1.86, 3.48)
Self-reported sleep disturbance[g]	High/Low	< 0.0001	6.28 (3.46, 11.40)
Annoyed by snoring	High/Low	0.0693	2.16 (0.94, 4.94)
Migraines	Yes/No	0.0062	1.76 (1.17, 2.64)
Dizziness	Yes/No	0.0696	1.46 (0.97, 2.20)
Chronic pain	Yes/No	0.0754	1.47 (0.96, 2.25)
Asthma	Yes/No	0.0166	2.01 (1.14, 3.56)
Arthritis	Yes/No	0.0497	1.45 (1.00, 2.10)
Diagnosed sleep disorder	Yes/No	0.0001	2.99 (1.71, 5.23)

[a]The logistic regression is modeling the probability of having a PSQI score above 5. [b]Where a reference group is not specified it is taken to be the last group. [c]P value significance is relative to the reference group. [d]OR (CI) odds ratio and 95% confidence interval based on logistic regression model. [e]The exposure variable, WTN level, is treated as a continuous scale in the logistic regression model. [f]The source identified by participants as the cause of closing bedroom windows to reduce noise levels was not road traffic, aircraft, rail or wind turbines. [g]Evaluates the magnitude of reported sleep disturbance at home from not at all to extremely for any reason over the previous year. [h]H-L P > 0.05 indicates a good fit. CI, confidence interval; H-L, Hosmer-Lemeshow test; ON, Ontario; OR, odds ratio; PEI, Prince Edward Island; PSQI, Pittsburgh Sleep Quality Index; WTN, wind turbine noise.

dB(A) WTN categories. This was because of a higher mean WASO time among participants from PEI living in areas where WTN levels were less than 25 dB(A) (data not shown).

DISCUSSION

The effects on health and well-being associated with accumulated sleep debt have been well documented.[1–5,57] The sound pressure levels from wind turbines can exceed the WHO recommended annual average nighttime limit of 40 dB(A) for preventing health effects from noise-induced sleep disturbance.[11] The calculated outdoor A-weighted WTN levels in this study reached a maximum of 46 dB(A), with 19% of dwellings found to exceed 40 dB(A). Within an uncertainty of approximately 4 dB(A), the calculated A-weighted levels in the current study can be compared to the WHO outdoor nighttime annual average threshold of 40 dB(A).[11,58] With the average façade attenuation with windows completely opened of 14 ± 2 dB(A),[58] the average bedroom level at the highest façade level, 46 dB(A), will be 32 ± 2 dB(A), which is close to the 30 dB(A) indoor threshold in the WHO's Guidelines for Community Noise.[10] Considering the uncertainty in the calculation model and input data, only dwellings in the highest WTN category are expected to have indoor levels above 30 dB(A) and thus sensitivity to sleep disturbance. However, with windows closed, indoor outdoor level difference is approximately 26 dB, which should result in an indoor level around 20 dB(A) in the current study.

Factors including, but not limited to, medication use, other health effects (including sleep disorders), caffeine consumption, and annoyance with blinking lights on wind turbines were found to statistically influence reported and/or actigraphically measured sleep outcomes. However, there was no evidence for any form of sleep disturbance found in relation to WTN levels. Studies published to date have been inconsistent in terms of self-reported evidence that WTN disrupts sleep,[59,60] and none of these studies assessed sleep using an objectively measured method. These inconsistent findings are

Table 5—Summary of Actiwatch2® data.

		Wind Turbine Noise, dB(A)				
		< 25	25–30	30–35	35–40	40–46
n (weekday, weekend)		(198, 78)	(200, 68)	(705, 273)	(1114, 420)	(526, 190)
Sleep Actigraphy Endpoint	**Sleep Night**	**Mean (SD)**	**Mean (SD)**	**Mean (SD)**	**Mean (SD)**	**Mean (SD)**
Sleep latency, min	Weekday	14.53 (23.31)	13.89 (23.08)	13.02 (26.14)	13.01 (23.05)	13.01 (22.83)
	Weekend	22.85 (37.01)	10.02 (15.86)	13.23 (22.47)	15.36 (36.13)	12.94 (26.96)
Sleep efficiency, %	Weekday	84.69 (6.59)	85.64 (7.84)	84.92 (7.56)	85.24 (7.83)	85.01 (7.03)
	Weekend	83.62 (7.93)	87.73 (5.46)	84.37 (8.39)	85.01 (7.96)	84.28 (8.47)
WASO, min	Weekday	58.58 (29.45)	50.43 (34.80)	54.99 (31.63)	52.63 (30.14)	55.50 (34.19)
	Weekend	60.49 (37.14)	48.57 (27.00)	58.28 (38.69)	54.11 (35.56)	56.60 (37.53)
Total sleep time, min	Weekday	455.24 (160.65)	447.70 (165.62)	448.88 (169.37)	445.76 (166.52)	448.38 (179.82)
	Weekend	468.12 (163.83)	462.21 (139.61)	457.15 (167.15)	448.63 (155.09)	442.85 (174.23)
Number of awakening bouts, count	Weekday	24.41 (9.49)	22.04 (10.04)	25.05 (13.53)	23.56 (9.86)	24.01 (9.81)
	Weekend	24.89 (10.00)	22.09 (8.76)	26.09 (13.01)	24.60 (10.54)	24.35 (10.22)
Time in bed, min	Weekday	536.05 (173.73)	521.39 (176.46)	526.53 (180.77)	520.55 (173.97)	524.48 (187.30)
	Weekend	559.85 (184.18)	526.99 (154.00)	540.13 (179.72)	527.18 (166.46)	522.57 (176.14)
Rate of awakening bouts per 60 min in bed	Weekday	2.83 (1.00)	2.64 (1.12)	2.94 (1.27)	2.82 (1.08)	2.89 (1.09)
	Weekend	2.77 (1.06)	2.60 (1.06)	2.97 (1.18)	2.87 (1.08)	2.93 (1.14)

SD, standard deviation; WASO, wake after sleep onset.

Table 6—Generalized estimating equations regression models for sleep actigraphy endpoints.

	Sleep Efficiency, %	Sleep Latency, min	Total Sleep Time,[d] min	WASO, min	Number of Awakening Bouts during Sleep
n	618	526	619	647	626
Sleep nights [c]	3,561	3,017	3,552	3,728	3,595
P value unadjusted [a]	0.2420	0.9051	0.7222	0.0655	0.2460
P value adjusted [b]	0.3932	0.6491	0.8002	0.0056	0.3726
Unadjusted [a] WTN, dB(A)	**LSM (95% CI) [e]**	**LSM (95% CI) [e]**	**LSM (95% CI) [e]**	**LSM (95% CI) [e]**	**LSM (95% CI) [e]**
< 25	84.71 (83.25, 86.17)	16.34 (11.40, 21.28)	458.00 (428.08, 487.93)	58.83 (52.78, 64.87)	24.26 (22.28, 26.25)
25–30	86.49 (85.12, 87.87)	12.34 (8.88, 15.80)	462.68 (427.47, 497.90)	49.11 (43.72, 54.50)	21.08 (19.14, 23.02)
30–35	84.82 (83.86, 85.78)	12.51 (10.54, 14.49)	464.00 (441.44, 486.57)	55.39 (52.04, 58.74)	24.57 (23.01, 26.14)
35–40	85.33 (84.60, 86.05)	13.02 (11.39, 14.65)	449.10 (433.95, 464.24)	53.08 (50.35, 55.80)	23.37 (22.40, 24.35)
40–46	85.01 (84.05, 85.98)	12.64 (10.50, 14.78)	445.78 (426.60, 464.96)	55.46 (51.45, 59.47)	23.84 (22.55, 25.13)
Adjusted [b] WTN, dB(A)	**LSM (95% CI) [e]**	**LSM (95% CI) [e]**	**LSM (95% CI) [e]**	**LSM (95% CI) [e]**	**LSM (95% CI) [e]**
< 25	85.62 (83.97, 87.28)	15.08 (10.03, 20.13)	462.41 (407.97, 516.84)	62.00 (55.14, 68.85)	23.19 (20.58, 25.79)
25–30	87.28 (85.55, 89.01)	10.88 (6.45, 15.32)	453.43 (401.10, 505.76)	51.67 (44.14, 59.20)	20.57 (17.87, 23.26)
30–35	85.82 (84.52, 87.13)	9.95 (7.02, 12.87)	455.22 (406.72, 503.72)	56.11 (50.81, 61.42)	24.00 (21.26, 26.75)
35–40	85.97 (84.86, 87.08)	10.71 (7.88, 13.54)	466.12 (416.21, 516.02)	57.80 (52.36, 63.24)	22.56 (20.57, 24.56)
40–46	86.16 (84.84, 87.48)	10.92 (7.01, 14.82)	472.95 (422.09, 523.81)	62.06 (55.64, 68.48)	22.85 (20.68, 25.02)

[a] The base model for the multiple generalized estimating equations (GEE) regression models for all endpoints included wind turbine noise (WTN) exposure groups, province, day of the week, and the interaction between WTN groups and day of the week. [b] A complete list of the other variables included in each multiple GEE regression model based on the stepwise methodology is presented in Table 3. [c] Sample size for the adjusted GEE regression models. [d] The base model for total sleep time includes the interaction between WTN groups and province. [e] LSM, least squares means, for each group after adjusting for all other variables in the multiple GEE regression model and corresponding 95% confidence interval (CI). P values for both the adjusted and unadjusted models are based on the transformed variable in order to satisfy model assumptions of normality and constant variance.

not entirely surprising considering that sleep disturbance reported as a result of transportation noise exposure occurs at sound pressure levels that exceed WTN levels calculated in the current study.[27,28,45] Study results concur with those of Bakker et al.,[21] with outdoor WTN levels up to 54 dB(A), wherein it was concluded that there was no association between the levels of WTN and sleep disturbance when noise annoyance was taken into account.

The current study employed a wide range of self-reported and objectively measured endpoints related to sleep to provide a comprehensive assessment of the potential effects that WTN exposure may have on sleep. Self-reported diagnosed sleep disorders[37] and self-reported highly sleep disturbed for any reason were factors found to be unrelated to WTN exposure. Furthermore, taking medication at least once per week was more commonly reported among participants living in areas where WTN levels were below 30 dB(A). Scores on the PSQI, either analyzed as a proportion above 5, or as a mean score, were also unrelated to WTN level. Actigraphy-measured sleep latency, sleep efficiency, the rate of awakening bouts, and total sleep time were all found to be unrelated to WTN exposure. The only statistically significant finding found between WTN level and actigraphy was a reduced wake time after sleep onset among participants living in areas where WTN levels were 25–30 dB(A) and this was because of a higher WASO time at the lowest WTN category among PEI participants. The results of the current study do not support conclusions that exposure to WTN up to 46 dB(A) has any statistically significant effect on self-reported or objectively measured sleep. However, annoyance with blinking lights on wind turbines (used as aircraft warning signals) may be related to a higher rate of awakening bouts and reduced total sleep time.

This study has some important limitations. Objective measures of sleep were assessed for up to 7 d, whereas the PSQI and the reported highly sleep disturbed outcomes represent time periods of 30 d and 1 y, respectively. The concern is that 7 d of actigraphy may not represent long-term average sleep patterns. However, the selected time frame for actigraphy measures is typical, and supported in the literature and considered more than adequate for evaluating sleep in a nonclinical study sample.[30,61] If there were situational factors (e.g. an ill child) that made sleep worse in the actigraphy-assessed week, it would not be expected to bias against the effect of wind turbines on sleep, and in fact, would overstate the effect of recent situational events as compared to the long-term theoretical concern about WTN-induced sleep disturbance. As previously discussed, the analysis of actigraphy results was based on nightly average sleep patterns in relation to long-term WTN levels. Although WTN calculations would be expected to produce the highest sound pressure levels at the dwelling, they do not take into consideration the influence that night-to-night variations in outdoor WTN levels may have had on actigraphy results. Similarly, an analysis based on long-term average sound level does not fully account for transient deviations in WTN levels that could potentially interfere with sleep. An analysis based on a time-matched comparison between operational turbine data and actigraphy would permit a more refined assessment of the possible effect that night-to-night variations in WTN levels may have on sleep. These limitations extend to the fact that fluctuations in indoor sound levels during sleep remain unknown.

The possibility that wind turbine operators may have intentionally altered the output of their turbines in order to reduce potential WTN effects on sleep has been one of the concerns raised during the external peer review of this paper. When the *Community Noise and Health Study* was originally announced several months preceding data collection the study locations were unknown. Although awareness of the precise study locations would have become greater as data collection commenced, the deployment of the sleep watches took place over several months among a subsample of participants across the entire study sample. Furthermore, the reference period time for self-reported sleep disturbance was over the previous year and previous 30 d (PSQI). Finally, the subsets of sound power measurements were consistent with manufacturer-supplied data. In the authors' opinion, there is no evidence to suggest that wind turbine operators intentionally altered the output of their turbines to minimize potential effects on sleep at any point in the study.

CONCLUSIONS

The potential association between WTN levels and sleep quality was assessed over the previous 30 d using the PSQI, the previous year using percentage highly sleep disturbed, together with an assessment of diagnosed sleep disorders. These self-reported measures were considered in addition to several objective measures including total sleep time, sleep onset latency, awakenings, and sleep efficiency. In all cases, in the final analysis there was no consistent pattern observed between any of the self-reported or actigraphy-measured endpoints and WTN levels up to 46 dB(A). Given the lack of an association between WTN levels and sleep, it should be considered that the study design may not have been sensitive enough to reveal effects on sleep. However, in the current study it was demonstrated that the factors that influence sleep quality (e.g. age, body mass index, caffeine, health conditions) were related to one or more self-reported and objective measures of sleep. This demonstrated sensitivity, together with the observation that there was consistency between multiple measures of self-reported sleep disturbance and among some of the self-reported and actigraphy measures, lends strength to the robustness of the conclusion that WTN levels up to 46 dB(A) had no statistically significant effect on any measure of sleep quality.

The WHO's[11] health-based limit for protecting against sleep disturbance is an annual average outdoor level of 40 dB(A). This level was exceeded in 19% of the cases, but by no more than 6 dB(A) and as such represents a limit to detecting a potential effect on sleep. It is therefore important to acknowledge that no inferences can be drawn from the current results to areas where WTN levels exceed 46 dB(A). Likewise, assuming a baseline prevalence of 10%, the study was designed so that the statistical power would be sufficient to detect at least a 7% difference in the prevalence of self-reported sleep disturbance. A larger sample size would be required to detect smaller differences. The statistical power of a study design is a limitation that applies to all epidemiological studies.

Although it may be tempting to generalize the current study findings to other areas, this would have required random selection of study locations from all communities living near wind turbines in Canada. Despite the fact that participants in the study were randomly selected, the locations were not and for this reason the level of confidence one has in generalizing the results to other areas can only be based on a certain level of scientific judgment regarding the level of exposure and the similarity between the current study sample and others. Despite limitations in generalizing the results of this analysis beyond the study sample, the current study is the largest and most comprehensive analysis of both self-reported and objectively measured sleep disturbance in relation to WTN levels published to date.

REFERENCES

1. Zaharna M, Guilleminault C. Sleep, noise and health: review. Noise Health 2010;12:64–9.
2. Schwartz SW, Cornoni-Huntley J, Cole SR, Hays JC, Blazer DG, Schocken D. Are sleep complaints an independent risk factor for myocardial infarction? Ann Epidemiol 1998;8:384–92.
3. Orzeł-Gryglewska J. Consequences of sleep deprivation. Int J Occ Med Environ Health 2010;23:95–114.
4. Pilcher JJ, Huffcutt AI. Effects of sleep deprivation on performance: a meta-analysis. Sleep 1996;19:318–26.
5. George CF. Sleep apnea, alertness, and motor vehicle crashes. Am J Respir Crit Care Med 2007;176:954–6.
6. Young T, Peppard PE, Gottlieb DJ. Epidemiology of obstructive sleep apnea: a population health perspective. Am J Respir Crit Care Med 2002;165:1217–39.
7. Grandner MA, Perlis ML. Short sleep duration and insomnia associated with hypertension incidence. Hypertens Res 2013;36:932–3.
8. Hume KI, Brink M, Basner M. Effects of environmental noise on sleep. Noise Health 2012;14:297–302.
9. Dang-Vu TT, Bonjean M, Schabus M, et al. Interplay between spontaneous and induced brain activity during human non-rapid eye movement sleep. Proc Nat Acad Sci U S A 2011;108:15438–43.
10. World Health Organization (WHO). Guidelines for Community Noise. Berglund B, Lindvall T, Schwela DH (eds). Geneva: World Health Organization. 1999. http://www.who.int/docstore/peh/noise/guidelines2.html.
11. WHO. Night Noise Guidelines for Europe. Hurtley C (ed). Copenhagen Denmark: WHO Regional Office for Europe. 2009. http://www.euro.who.int/data/assets/pdf_file/0017/43316/E92845.pdf.
12. Kirsch DB. A neurologist's guide to common subjective and objective sleep assessments. Neurol Clin 2012;30:987–1006.
13. McCall WV, Edinger JD. Subjective total insomnia: an example of sleep state misperception. Sleep 1992;15:71–3.
14. Buysse DJ, Reynolds CF, Monk TH, Berman SR, Kupfer DJ. The Pittsburgh Sleep Quality Index: a new instrument for psychiatric practice and research. Psych Res 1989;28:193–213.
15. Carpenter JS, Andrykowski MA. Psychometric evaluation of the Pittsburgh Sleep Quality Index. J Psychosom Res 1998;45:5–13.
16. Backhaus J, Junghanns K, Broocks A, Riemann D, Hohagen F. Test-retest reliability and validity of the Pittsburgh Sleep Quality Index in primary insomnia. J Psychosom Res 2002;53:737–40.
17. Smyth CA. Evaluating sleep quality in older adults: the Pittsburgh Sleep Quality Index can be used to detect sleep disturbances or deficits. Am J Nurs 2008;108:42–50; quiz 50–1.
18. Spira AP, Beaudreau SA, Stone KL, et al. Reliability and validity of the Pittsburgh Sleep Quality Index and the Epworth Sleepiness Scale in older men. J Gerontol A Biol Sci Med Sci 2012;67:433–9.
19. Nissenbaum MA, Aramini JJ, Hanning CD. Effects of industrial wind turbine noise on sleep and health. Noise Health 2012;14:237–43.
20. Pedersen E. Health aspects associated with wind turbine noise: results from three field studies. Noise Control Eng J 2011;59:47–53.
21. Bakker, RH, Pedersen E, van den Berg GP, Stewart RE, Lok W, Bouma J. Impact of wind turbine sound on annoyance, self-reported sleep disturbance and psychological distress. Sci Total Environ 2012;425:42–51.
22. van den Berg F, Verhagen C, Uitenbroek D. The relation between scores on noise annoyance and noise disturbed sleep in a public health survey. Int J Environ Res Public Health 2014;11:2314–27.
23. Horne JA, Pankhurst FL, Reyner LA, Hume K, Diamond ID. A field study of sleep disturbance: effects of aircraft noise and other factors on 5,742 nights of actimetrically monitored sleep in a large subject sample. Sleep 1994;17:146–59.
24. Öhrström E, Hadzibajramovic E, Holmes M, Svensson H. Effects of road traffic noise on sleep: studies on children and adults. J Environ Psychol 2006;26:116–26.
25. Muzet A. Environmental noise, sleep and health. Sleep Med Rev 2007;11:135–42.
26. Fyhri A, Aasvang GM. Noise, sleep and poor health: modeling the relationship between road traffic noise and cardiovascular problems. Sci Total Environ 2010;408:4935–42.
27. Fidell S, Pearsons K, Tabachnick BG, Howe R. Effects on sleep disturbance of changes in aircraft noise near three airports. J Acoust Soc Am 2000;107:2535–47.
28. Michaud DS, Fidell S, Pearsons K, Campbell KC, Keith SE. Review of field studies of aircraft noise-induced sleep disturbance. J Acoust Soc Am 2007;121:32–41.
29. Ancoli-Israel S, Cole R, Alessi C, Chambers M, Moorcroft W, Pollak CP. The role of actigraphy in the study of sleep and circadian rhythms. Sleep 2003;26:342–92.
30. Sadeh A. The role and validity of actigraphy in sleep medicine: an update. Sleep Med Rev 2011;15:259–67.
31. Riemann D, Spiegelhalder K, Espie C, et al. Chronic insomnia: clinical and research challenges -- an agenda. Pharmacopsychiatry 2011;44:1–14.
32. Tjepkema M. Insomnia. Toronto: Statistics Canada, Catalogue 82-003 Health Reports. 2005;17:9–25. http://www.statcan.gc.ca/pub/82-003-x/2005001/article/8707-eng.pdf.
33. International Organization for Standardization (ISO). ISO 9613-1 - Acoustics. Attenuation of sound during propagation outdoors. Part 1: calculation of the absorption of sound by the atmosphere. Geneva: International Organization for Standardization, 1993.
34. ISO. ISO-9613-2 - Acoustics. Attenuation of sound during propagation outdoors. Part 2: general method of calculation. Geneva: International Organization for Standardization, 1996.
35. DataKustik GmbH®. CadnaA version 4.4. Software for Immission Protection. 2014. www.datakustik.com.
36. Van den Berg F. Criteria for wind farm Noise: Lmax and Lden. Proc. Acoustics '08, Paris, June 29-July 4 2008. http://docs.wind-watch.org/vandenberg-wind-farm-noise-Lmax-Lden.pdf
37. Michaud DS. Self-reported and objectively measured outcomes assessed in the Health Canada wind turbine noise and health study: results support an increase in community annoyance. San Francisco, CA: Internoise, INCE USA, August 9–12, 2015.
38. Pedersen E, van den Berg F, Bakker R, Bouma, J. Can road traffic mask sound from wind turbines? Response to wind turbine sound at different levels of road traffic sound. Energ Pol 2010:38:2520–7.
39. Pedersen E, van den Berg F. Why is wind turbine noise so poorly masked by road traffic noise? Lisbon, Portugal: Internoise, June 13–16, 2010.
40. van den Berg F. The effects of wind turbine noise on people. In Bowdler R, Leventhall G, eds. Wind turbine noise. Brentwood, UK: Multi-Science, 2011:129–52.
41. van den Berg F. Wind turbine noise: an overview of acoustical performance and effects on residents. Victor Harbor, Australia: Proceedings of Acoustics, November 17–20, 2013.
42. Alberta Utilities Commission (AUC). Rule 012-Noise Control. 2013. http://www.auc.ab.ca/acts-regulations-and-auc-rules/rules/Pages/Rule012.aspx.
43. United States Department of Transportation. FHWA Traffic Noise Model®. Technical Manual. Washington D.C.: Federal Highway Administration, 1998.

44. ISO. ISO/TS-15666 - Acoustics - Assessment of noise annoyance by means of social and socio-acoustic surveys. Geneva: International Organization for Standardization, 2003.
45. Miedema HM, Vos H. Associations between self-reported sleep disturbance and environmental noise based on reanalyses of pooled data from 24 studies. Behav Sleep Med 2007;5:1–20.
46. Alsaadi, SM, McAuley JH, Hush JM, et al. Assessing sleep disturbance in low back pain: the validity of portable instruments. PLOS One 2014;9:e95824.
47. Martin JL, Hakim AD. Wrist actigraphy. Chest 2011;139:1514–27.
48. Philips Respironics. Actiware® and Actiware CT® Software Manual: Actiwatch® Communication and Sleep Analysis Software Version 5.1, 2008:3–47.
49. Michaud DS, Keith SE, Feder K, et al. Self-reported and objectively measured health indicators among a sample of Canadians living within the vicinity of industrial wind turbines: social survey and sound level modeling methodology. Noise News Int 2013;21:14–27.
50. SAS Institute Inc. SAS (Statistical Analysis System) Software package Version 9.2. Cary, NC: SAS Institute Inc., 2014. www.sas.com.
51. Liang KY, Zeger SL. Longitudinal data analysis using generalized linear models. Biometrika 1986;73:13–22.
52. Stokes ME, Davis CS, Koch GG. Categorical data analysis using the SAS System, Second Edition. Cary, NC: SAS Institute Inc., 2000.
53. Sokal RR, Rohlf JF. Biometry: the principles and practice of statistics in biological research. 2nd edition. San Francisco, CA: W H Freeman and Company, 1981:859.
54. Snedecor GW, Cochran WG. Statistical Methods, 8th edition. Ames, IA: Iowa State University Press, 1989.
55. Rao PV. Statistical research methods in the life sciences. Pacific Grove, CA: Duxbury Press, 1998.
56. Feder K, Michaud DS, Marro L, et al. Impacts on quality of life associated with exposure to wind turbine noise. Environ Res 2015;142:227–38.
57. Lim AS, Kowgier M, Yu L, Buchman AS, Bennett DA. Sleep fragmentation and the risk of incident Alzheimer's disease and cognitive decline in older persons. Sleep 2013;36:1027–32.
58. Health Canada. Wind Turbine Noise and Health Study: Summary of Results. Ottawa, Health Canada, November, 2014. http://www.hc-sc.gc.ca/ewh-semt/noise-bruit/turbine-eoliennes/summary-resume-eng.php.
59. Knopper LD, Ollson CA. Health effects and wind turbines: a review of the literature. Environ Health 2011;10:78.
60. McCunney R, Mundt KA, Colby WD, Dobie R, Kaliski K, Blais K. Wind turbines and health: a critical review of the scientific literature. J Occ Environ Med 2014;56:e108–30.
61. Littner M, Kushida CA, Anderson WM, et al. Practice parameters for the role of actigraphy in the study of sleep and circadian rhythms: an update for 2002. Sleep 2003;26:337–41.

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