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Evaluating the impact of wind turbine noise on health-related quality of life

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Abstract

We report a cross-sectional study comparing the health-related quality of life (HRQOL) of individuals residing in the proximity of a wind farm to those residing in a demographically matched area sufficiently displaced from wind turbines. The study employed a nonequivalent comparison group posttest-only design. Self-administered questionnaires, which included the brief version of the World Health Organization quality of life scale, were delivered to residents in two adjacent areas in semirural New Zealand. Participants were also asked to identify annoying noises, indicate their degree of noise sensitivity, and rate amenity. Statistically significant differences were noted in some HRQOL domain scores, with residents living within 2 km of a turbine installation reporting lower overall quality of life, physical quality of life, and environmental quality of life. Those exposed to turbine noise also reported significantly lower sleep quality, and rated their environment as less restful. Our data suggest that wind farm noise can negatively impact facets of HRQOL.

Keywords: *Amenity, annoyance, health-related quality of life, sleep quality, wind turbine noise*

Introduction

Wind turbines transform wind energy into electricity, a practice dating back over 100 years. However, in the last decade industrial-scale harvesting of wind energy has increased, driven by a desire to generate sustainable energy and to lessen the impact of fossil fuel depletion. Whether located in isolation or as components of a "wind farm", wind turbines were initially welcomed by many communities due to their environmental credentials, though reference to the mainstream media shows that public opposition to wind turbines has increased substantially in the past few years.[1] Complaints against established wind farms, or concern elicited by proposed wind farms, focus on the noise they produce, or the visual impact they have on the environment.

The desire to maximize electricity production while minimizing transmission costs means that in many countries wind farms have been constructed in semirural areas (also known as "greenbelt" or "life-style" areas) close to major towns and cities. Noise from wind farms located in semirural areas is of interest because it is typically a low amplitude noise impeding on a well-characterized and generally cherished soundscape. Consequently, there has been considerable debate over whether wind farm noise poses a significant health threat to those living in their vicinity. It has been suggested that wind turbines can directly impact health via the emission of low-frequency sound energy (i.e., infrasound below 20 Hz), though this is currently an area of controversy.[2,3] Additionally, wind turbines may compromise health by producing sound that is annoying and/or can disturb sleep. In this respect, it can be classified as community noise along side industrial or transportation noise. When built in semirural settings, the visual impact of wind farms can also degrade amenity and interact with wind turbine noise to exacerbate annoyance reactions,[4] possibly due to a violation of the landscape--soundscape continuum constructed by those who choose to live in these areas.[5]

Figure 1 represents a simple model informed by the literature[6,7] demonstrating that, in the semirural context, there are feasible mechanisms by which wind turbine exposure can degrade health and well-being. Turbine noise can lead directly to annoyance and sleep disturbance (primary health effects), or can induce annoyance by degrading amenity. Additionally, the trait of noise sensitivity, which describes individuals who are more likely to pay attention to sound, evaluate sound negatively, and have stronger emotional reactions to noise,[8] constitutes a major risk factor. The secondary heath effects would be immediate reductions in

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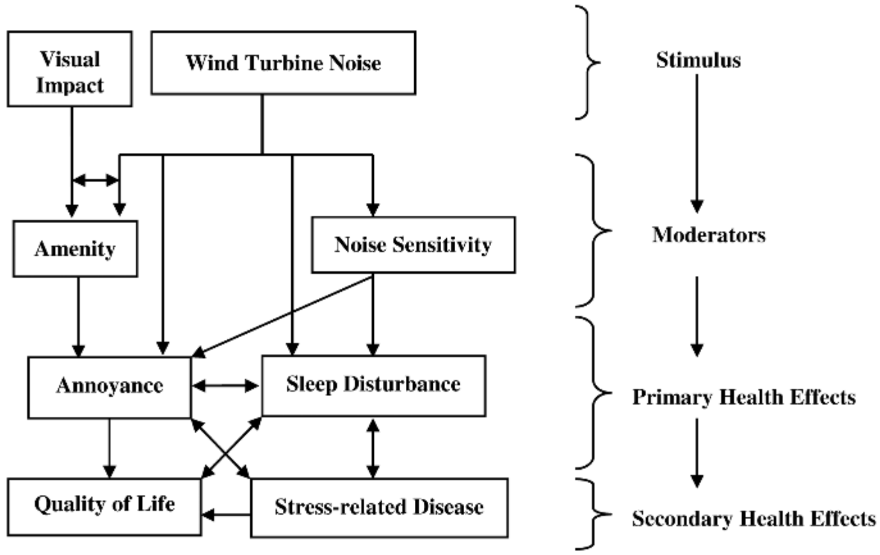

Figure 1: A schematic representation of the relationship between wind turbines and health in a semirural setting. The multiplicity of relationships emerges due to variability in the response of individuals to noise

general well-being, with stress-related disease emerging from chronic annoyance and sleep disturbance. Irrespective of source, chronic noise exposure is a psychosocial stressor that can induce maladaptive psychological responses and negatively impact health via interactions between the autonomic nervous system, the neuroendocrine system, and the immune system.[7] A chronic stress response will, in turn, degrade quality of life [Figure 1].

Quantifying the impact of wind turbines on individual health will inform wind turbine operational guidelines, and in this respect constitutes an important process that is currently not far advanced. A variety of outcome measures have been proposed to assess the impacts of community noise, including annoyance, sleep disturbance, cardiovascular disease, and cortisol levels.[9] An alternative approach to health assessment involves the subjective appraisal of health-related quality of life (HRQOL), a concept that measures general well-being and well-being in the physical, psychological, and social domains. Because changes in HRQOL are expected to closely co-vary with changes in health, the WHO recommends the use of HRQOL measures as an outcome variable, arguing that the effects of noise are strongest for those outcomes classified under HRQOL rather than illness.[9] HRQOL is related to health by the WHO (1948) definition of health as "a state of complete physical, mental and social well-being and not merely the absence of disease or infirmity," and can be considered as an operationalization of the well-being concept.[10]

There is scientific evidence linking community noise to health problems.[7,9,10] The WHO reports that chronic noise-induced annoyance and sleep disturbance can compromise health and HRQOL.[9,11,12] However, there has been little research examining the relationship between noise and HRQOL. An exception is Dratva *et al.*,[13] who, using the Short Form (SF36) health survey, reported an inverse relationship between annoyance from traffic noise and HRQOL. They argued that HRQOL would be expected to co-vary more with annoyance than with noise level as level is generally a poor predictor of the human response to noise, and its role in health is commonly overemphasized. As alternatives to noise level, other factors associated with the listener should be considered,[6] including the perceived control a person has over the noise, as well as their attitudes, personality, and age (all of which could be added to Figure 1 as moderators).

This exploratory study examines the association between HRQOL and proximity to an industrial wind farm in a semirural area, adding to the small number of peer-reviewed studies into the health impacts of wind turbines that are only beginning to appear in the literature. Case studies supported by qualitative analyses[2,14,15] suggest a negative relationship between wind turbine noise and well-being. There have been no previous quantitative investigations of the impact of wind farms on HRQOL, though correlations have been observed between wind turbine noise, annoyance, and sleep disruption.[16,17] Given these findings, and with reference to Figure 1, it would be expected that both mean amenity and sleep satisfaction scores would be lower in individuals residing around turbines, and that the proportion of individuals annoyed by noise would be greater for those exposed to turbines than those not. Additionally, lowered amenity and greater annoyance should result in lower mean HRQOL domains in those residing close to wind turbines.

Materials and Methods

Design

A nonequivalent comparison group posttest-only study design was utilized. Strict socioeconomic matching was undertaken using the New Zealand Deprivation Index 2006,[18] as described elsewhere.[19] Both areas are classified as semirural,[20] with a population density of less than 15 people per square kilometer.

Sample

Samples were drawn from two demographically matched areas differing only in their distances from a wind farm in the Makara Valley, a coastal area 10 km west of New Zealand's capital city, Wellington. The Makara Valley is characterized by hilly terrain, with long ridges running 250-450 m above sea level, on which 66 125 m high wind turbines are positioned as part of the "West Winds" project. Figure 2 is a map showing the positions of a subset of wind turbines relative to some of the houses in valley. The first sample (the *Turbine* group) was drawn from residents in the South Makara Valley who resided in 56 houses located within 2 km of a wind turbine. A comprehensive noise survey of the area was undertaken independently, indicating intrusive elements of the turbine noise such as the "rumble-thump."[21] The Makara turbines, operational since May 2009, have measured levels that are consistent with levels reported in European studies,[17] in which typical noise exposures from wind turbines ranged from between 24 dB(A) and 54 dB(A). Long-term measurements undertaken by the wind farm developers at various residences show that while average outdoor levels ($L_{95\ (10\ min)}$ dB(A)) are largely compliant with consent conditions, they still range between 20 dB(A) and 50 dB(A) depending on meteorological conditions.[22] The second sample (the *Comparison* group) was taken from residents in 250 houses in a geographically and socioeconomically matched area, but which were located at least 8 km from any wind farm in the region.

Questionnaire

The coversheet of the questionnaire bore the title *2010 Well-being and Neighbourhood Survey*, designed to mask the true intent of the study. Each house received two copies of the questionnaire. Potential participants were invited to participate in the research investigating their place of living and their well-being if they resided at the address to which the questionnaire had been delivered and if they were 18 years or older. The order of the questions was a prime consideration: HRQOL (26 items), amenity (2 items), neighbourhood problems (14 items), annoyance (7 items), demographic information (7 items), and a single item probing noise sensitivity. All scale items were presented on a numbered five-point scale with appropriate descriptors anchoring the terminals. Self-reported HRQOL was measured using the abbreviated version of the WHOQOL-BREF which affords composite measures of physical (7 items), psychological (6 items), and social (3 items) HRQOL. Additionally, the WHOQOL-BREF has two generic items asking about general health and overall quality of life, and an additional domain measuring and

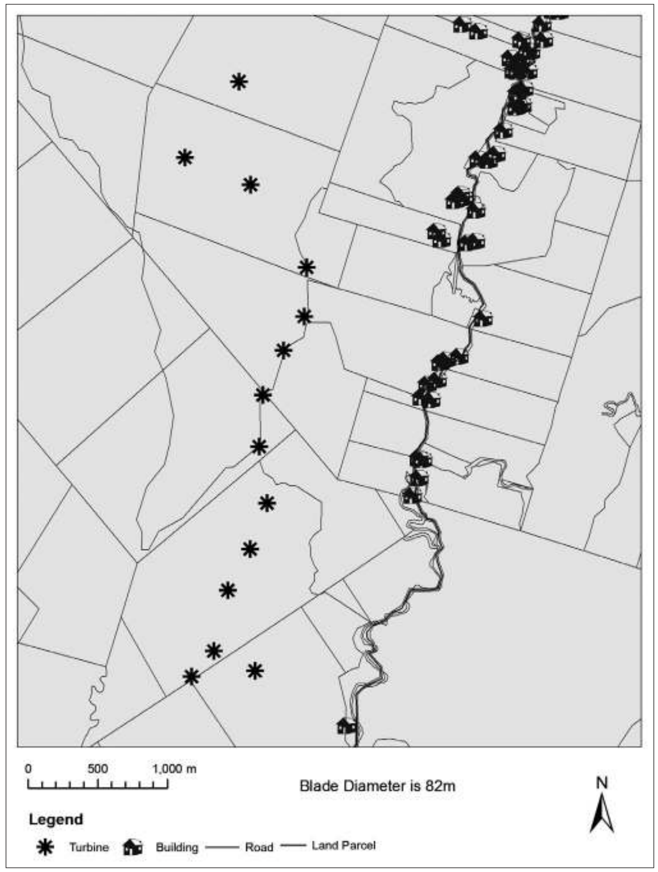

Figure 2: Map showing a part of the Makara Valley and the relative distances between houses and 14 of the 66 turbines. The wind turbines (Siemens SWT-2.3-82 VS) have 68 m high towers and rotor diameters of 82 m (Map generated by Rachel Summers, and displayed with permission).

environmental QOL (8 items). The two amenity items were: "I am satisfied with my neighbourhood/living environment" and "My neighbourhood /living environment makes it difficult for me to relax at home." A modified neighbourhood problem scale[23] consisted of 14 distracter items that were not relevant to the current study and were not included in the analysis. Seven items on annoyance were included, four distracter items asking about air quality, and three items probing annoyance to traffic, other neighbours, or other noise (*please specify*). Additionally, participants were asked if they were not noise sensitive, moderately noise sensitive, or very noise sensitive. The questionnaire terminated with an open-ended item asking "If you would like to share any comments relating to your neighbourhood or this survey then please do so in the box below." Participants were asked to respond to all items and to return surveys by post in the prepaid envelopes provided.

Demographics

Self-reported age and sex measures were obtained and self-reported level of educational status used as a further indicator of socioeconomic status. Additionally, participants were asked what their current employment status was, and whether they were currently ill or had a medical condition.

Participants were also asked how long they had lived at their current residence.

Statistical analysis

Analysis commenced after an evaluation of each scale's psychometric properties, including inspection for floor and ceiling effects and tests of internal consistency (Cronbach's alpha) and to validate dimensionality (corrected item-total correlations). Differences in HRQOL and amenity between the turbine and comparison groups were calculated using univariate analysis of covariance (ANCOVA), with length of residence selected *a priori* as a covariate. All testing was undertaken in accordance with Tabachnick and Fidell's[24] guidelines for testing between groups with unequal sample sizes, and Bonferroni corrections were applied where appropriate. Because of the unequal sizes between the two groups the assumptions of normality and homogeneity of variance were assessed carefully. Five cases were excluded from the comparison group because they were multivariate outliers as defined by extreme Mahalanobis distances, with response set acquiescence clearly evident in all five cases.

Table 1: Demographic profile of the turbine and comparison groups

Variables	Turbine group (*n*=39) *n* (%)	Comparison group (*n*=158) *n** (%)
Sex		
Male	16 (41)	63 (41)
Female	23 (59)	91 (58)
Age group, years		
18-20	1 (2.6)	2 (1.2)
21-30	1 (2.6)	1 (0.5)
31-40	5 (12.8)	22 (13.9)
41-50	10 (25.6)	53 (33.5)
51-60	11 (28.2)	44 (27.8)
61-70	7 (17.9)	27 (17.1)
71+ –	3 (7.7)	9 (5.6)
Education (completed)		
High school	11 (28.2)	55 (34.8)
Polytechnic	11 (28.2)	48 (30.3)
University	17 (43.6)	54 (34.2)
Employment status		
Full time	21 (53.8)	83 (52.5)
Part time	0 (0)	3 (1.8)
Unpaid work	1 (2.6)	3 (1.8)
Unemployed	6 (15.3)	27 (17.1)
Retired	10 (25.6)	40 (25.3)
Noise sensitivity		
None	13 (33.3)	60 (37.9)
Moderate	21 (55.3)	76 (48.1)
Severe	5 (12.8)	20 (12.7)
Current illness		
Yes	10 (27)	50 (31.6)
No	27 (69.2)	104 (65.8)

*Totals may differ due to missing data

Results

The response rates, 34% and 32% from the turbine and comparison groups, respectively, are typical for this type of research (e.g., van den Berg and colleagues[17] report a 37% response rate). Table 1 presents demographic information for the comparison and turbine groups. Prior to analyses the data were screened to identify potential confounds. The proportions of males and females in each area were equivalent ($\chi^2(1)$ = 0.001, P = 0.967), while a Mann--Whitney U indicated no age difference between the two areas ($U(n_1$= 158 , n_2=39) = 16022.5, P = 0.802). Education ($\chi^2(2)$ = 2.474, P = 0.291), noise sensitivity ($\chi^2(2)$ = 0.553, P = 0.758), and self-reported illness ($\chi^2(1)$ = 0.414, P = 0.562) were not associated with area.

Table 2 displays correlation coefficients (Pearson's *r*) between noise-related and health-related variables for both groups. Of remark is the negative correlation between annoyance and self-rated health for both groups, and a different pattern of correlations between noise sensitivity and annoyance across the two groups. Separate ANCOVA's revealed differences and similarities between the two areas in terms of HRQOL [Table 3]. Firstly, the turbine group reported a lower (F(1,194) = 5.816 , P = 0.017) mean physical HRQOL domain score than the comparison group. Scrutiny of the seven facets of the physical domain showed a difference in perceived sleep quality between the two areas (t(195) = 3.089, P = 0.006),

Table 2: Pearson product-moment correlation coefficients (*r*) for noise-related and HRQOL variables. Statistics to the right of the major diagonal are for the comparison group, while those to the left are for the turbine group

	Sensitivity	Annoyance	Sleep	Health	Health-related quality of life				
					Physical	Psychological	Social	Environment	Overall
Sensitivity	1	0.134	−0.017	0.082	−0.017	−0.069	0.006	−0.066	−0.109
Annoyance	0.440**	1	0.042	−0.258**	−0.209*	−0.135	−0.155*	−0.319**	−0.097
Sleep	−0.433**	−0.147	1	0.337**	0.378**	0.489**	0.327**	0.279**	0.198*
Health	−0.234	−0.308	0.471**	1	0.706**	0.493**	0.158*	0.284**	0.327**
Physical§	−0.24	−0.212	0.364*	0.524**	1	0.655**	0.29**	0.455**	0.475**
Psychological	−0.404*	−0.113	0.473**	0.329*	0.268	1	0.55**	0.608**	0.589**
Social	−0.359*	−0.236	0.116	−0.021	0.036	0.212	1	0.456**	0.457**
Environment	−0.235	0.028	0.404**	0.2	0.474*	0.468*	−0.17	1	0.546**
Overall	−0.203	0.16	0.471**	0.289	0.282	0.286	0.162	0.380*	1

*P < 0.05, **P < 0.001, §Item 16 (satisfaction with sleep) was removed from the Physical HRQOL domain when correlated with sleep satisfaction

Table 3: Mean (M) and standard deviation (SD) statistics for the four HRQOL domains of the WHOQOL-BREF and amenity total scores, presented for both the comparison group and the turbine group

Measure	Turbine group		Comparison group	
	M	*SD*	*M*	*SD*
Physical	27.38	3.14	29.14	3.89
Psychological	22.36	2.67	23.29	2.91
Social	12.53	1.83	12.54	2.13
Environmental	29.92	3.76	32.76	4.41
Amenity	7.46	1.42	8.91	2.64

and between self-reported energy levels ($t(195)= 2.217$, $P = 0.028$). Secondly, the turbine group had lower ($F(1,194) = 5.694$, $P = 0.018$) environmental QOL scores than the comparison group. This domain is the sum of eight items, and further analysis of these revealed that the turbine group considered their environment to be less healthy ($t(195)= 3.272$, $P < 0.007$) and were less satisfied with the conditions of their living space ($t(195)= 2.176$, $P = 0.031$). Thirdly, there were no statistical differences in social ($F(1,194) = 0.002$, $P = 0.963$) or psychological ($F(1,194) = 3.334$, $P = 0.069$) HRQOL, although the latter was marginal and the mean for the turbine group was lower. Of the two generic WHOQOL-BREF items, the mean of the self-rated general health item was equivalent between turbine and comparison groups ($t(195) = 0.374$, $P = 0.709$), while the mean ratings for an overall quality of life item was lower ($t(195) = 2.364$, $P = 0.019$) in the turbine group.

The turbine group reported lower amenity than the comparison group ($F(1,194) = 18.88$, $P < 0.001$). There were no differences between groups for traffic ($t(195) = 0.568$, $P = 0.154$) or neighborhood ($t(195) = 1.458$, $P = 0.144$) noise annoyance. A comparison between ratings of turbine noise was not possible, but the mean annoyance rating for turbine group individuals who specifically identified wind turbine noise as annoying (n=23) was 4.59 (SD = 0.65), indicating that the turbine noise was perceived as extremely annoying. For the comparison group, seven "other" annoying noises were identified: barking dogs (x2), farm machinery (x2), and racing cars (x3).

Discussion

Our results link exposure to wind turbines to degraded HRQOL, a finding that is consistent with the model described in Figure 1. Specifically, those residing in the immediate vicinity of a wind farm scored worse than a matched comparison group in terms of physical HRQOL and environmental QOL, and HRQOL in general. No differences were found in terms of psychological and social HRQOL, or in self-rated health. The high incidence of annoyance from turbine noise in the turbine group is consistent with the theory that exposure to wind turbine noise is the cause of these differences. Importantly, we also found a reduction in sleep satisfaction ratings, suggesting that both annoyance and sleep disruption may mediate the relationship between noise and HRQOL. These findings are consistent with those reported in relation to aviation noise[25] and traffic noise.[10,11]

Of further interest are the likely mechanisms involved in the degradation of HRQOL when exposed to turbine noise. Studies show that the level of turbine noise is a poor predictor of human response, and dose-response relationships typically explain little of the association between turbine noise and annoyance.[26] Pedersen *et al*.[4,26] and van den Berg *et al*.[15] show that, for equivalent noise levels, people judge wind turbine noise to be of greater annoyance than aircraft, road traffic, or railway noise. This may be due to the unique characteristics of turbine noise, that is, clusters of turbines present a cumulative effect characterized by a dynamic or modulating sound as turbines synchronise. The characteristic swishing or thumping noise associated with larger turbines[21] is audible over long distances, up to 5 km and beyond in some reports.[1]

van den Berg[17] showed that sound is the most annoying aspect of wind turbines, and is more of a problem at night. A large proportion (23/39) of respondents from the turbine group identified turbine noise as a problem and rated it to be extremely annoying. It should be noted that, in contemporary medicine, annoyance exists as a precise technical term describing a mental state characterized by distress and aversion, which if maintained, can lead to a deterioration of health and well-being.[25] A Swedish study[26] reported that, for respondents who were annoyed by wind turbine noise, feelings of resignation, violation, strain, and fatigue were statistically greater than for respondents not annoyed by turbine noise. An attempt at constructing dose-response relationships between turbine noise level and annoyance in a European sample suggests that at calculated noise levels of 30-35 dB(A), 10% of the sample was rather or very annoyed at wind turbine sound, increasing to 20% at 35-40 dB(A) and 25% at 40-43 dB(A).[15]

We also observed lower sleep satisfaction in the turbine group than in the comparison group, a finding which is consistent with previous research.[2,4,17] One study directly related to wind turbine noise reported that 16% of respondents experiencing 35 dB(A) or more of noise suffered sleep disturbances due to turbine noise.[4] Another study investigating the effects of wind turbine noise on sleep showed that 36% of respondents who were annoyed at wind turbine noise also reported that they suffered disturbed sleep (versus 9% of those not annoyed).[15] A case-study approach examining exposure to turbine noise likewise identified turbine noise as an agent of sleep disturbance.[11] In relation to turbine noise levels, one study reported that even at the lowest noise levels (≈25 dB(A)), 20% of respondents reported disturbed sleep at least one night per month,[17] and that interrupted sleep and difficulty in returning to sleep increased with calculated noise level. Demonstrably, our data have also captured the effects of wind turbine noise on sleep, reinforcing previous studies suggesting that the acoustic characteristics of turbine noise are well suited to disturb the sleep of exposed individuals.

While strong correlations exist between the sound level and the perceived loudness of a sound, there is no clear relationship between level and the psychological responses that individuals have to a sound. Noise sensitivity is one psychological factor that is increasingly being related to noise annoyance in literature.[8] We found that, for the turbine group, noise sensitivity is a strong predictor of noise annoyance and is correlated with facets of HRQOL, supporting other studies suggesting that annoyance mediates the relationship between noise sensitivity and HRQOL.[25] Other studies show that noise sensitivity has a large impact on noise annoyance ratings, lowering annoyance thresholds by up to 10 dB.[8] The lack of statistical significance in the comparison group may indicate that, in the absence of annoying noise, the impact of noise sensitivity on HRQOL may be underestimated.

Another finding emerging from our data is that living close to wind turbines is associated with degraded amenity. This is consistent with previous research showing that wind turbine noise was judged incongruent with the natural soundscape of the area.[23] Amenity values are based upon what people feel about an area, its pleasantness, or some other value that makes it a desirable place to live. There is an expectation of "peace and quiet" when living in a rural area, and most choose to live in rural areas for this reason.[25] Furthermore, those who live in rural areas have different expectations about community noise than those living elsewhere.[4] Other studies[27,28] report that wind turbines are viewed as eyesores and visual spoilers of the environment, and from an aesthetic perspective, those who view the wind turbines as ugly are likely to disassociate them from the landscape and react more strongly to turbine noise. The measurement of the perceived visual impact of the wind farm was beyond the scope of the current study, specifically due to the masking of the study's intent. Scrutiny of the comments provided by the turbine group, however, revealed no mention of the impact of turbines on the landscape, reinforcing suggestions made by others,[5] that wind farm noise is more dominant than their visual aspects.

Strengths and limitations

A strength of this study is the masking of the primary intent of the questionnaire by giving the impression that general neighborhood factors (e.g., street lighting, rubbish collection), and not wind turbine exposure, constituted the study's core aims. Concealing the study's objectives should reduce response bias, and our placing of the HRQOL items at the beginning of the survey, well before the three items probing noise annoyance, would serve to elicit subjective ratings of HRQOL without first being primed with potentially upsetting noise items. A further strength is the use of a nationally validated inventory that adopts a multidimensional approach to HRQOL.

The main limitation of the study, partly forced by our desire to conceal the aim of the survey, was that coincident noise measurements were not obtained. While independent estimates of wind farm noise in the Makara Valley have been reported,[21,22] it would have been desirable to undertake measurements in both the turbine and the control areas. That said, on the basis of the very few noise complaints made by those in the control areas (as described in the Results section), we are confident that the control areas provide typical semirural soundscapes that are not encroached by intrusive noise. An additional limitation of the study is the sample size of the turbine group. While the response rate compares favorably to other wind turbine research reported in the literature,[17] the sparsely populated locales surrounding wind farms in rural New Zealand presents a recruitment challenge. A larger sample of residents exposed to wind turbines would have afforded more analytical options. However, that the effects were found with such a modest sample size may be indicative of genuine differences between the two groups.

Any future adoption of the model presented in Figure 1 should increase the number of moderators, and include factors such as attitudes to the noise source and individual coping strategies. For example, the conflict between the Makara community and the wind farm developers could also potentially reduce HRQOL or amplify annoyance reactions and sleep difficulties. A telephone complaint line, set up by the wind farm developer as a condition of consent, attracted over 1000 noise complaints in the first year. Such conflict would induce stress and emotional reactions that would be expected to degrade psychological HRQOL, though this was not found to be different from the control group. An explanation of this null result on the psychological domain may be derived from the open-ended comments from the control group, which reveal that they themselves are in conflict with local governance bodies attempting to increase residential dwellings in the area.

Conclusion

A thorough investigation of wind turbine noise and its effects on health is important given the prevalence of exposed individuals, a nontrivial number that is increasing with the popularity of wind energy.[29] For example, in the Netherlands it is reported that 440,000 inhabitants (2.5% of the population) are exposed to significant levels of wind turbine noise.[30] Additionally, policy makers are demanding more information on the possible link between wind turbines and health in order to inform setback distances. Our results suggest that utility-scale wind energy generation is not without adverse health impacts on nearby residents. Thus, nations undertaking large-scale deployment of wind turbines need to consider the impact of noise on the HRQOL of exposed individuals. Along with others,[31] we conclude that night-time wind turbine noise limits should be set conservatively to minimize harm, and, on the basis of our data, suggest that setback distances need to be greater than 2 km in hilly terrain.

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