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Health problems near wind turbines: A nationwide epidemiological study based on primary healthcare data

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ABSTRACT

Epidemiological research on the association between wind turbines (WTs) and adverse health effects remains limited. This study integrated data from electronic health records from general practitioners with geospatial data on WT locations and noise emissions. Spanning a decade (2012–2021) and a yearly sample of 350,000 to 560,000 individuals living within 5 km of WTs, it investigated a broad range of health symptoms and conditions diagnosed in primary care, as well as medication prescriptions. Multilevel regression analyses generally indicated a lack of consistent and significant associations between distance (0–500, 500–1000 and 1000–2000 m) to WTs and prevalence of health problems, accounting for demographic and socioeconomic factors. While the prevalence of certain symptoms such as tension headache and depressive feelings increased within 500 m from WTs in later years, results were not statistically significant. Higher average noise levels (above 42 dB Lden) were associated with increased painkiller prescriptions in the most recent years. Only a small part of the sample lived within 500 m from WTs and was exposed to higher noise levels – a methodological challenge inherent to this topic. In light of the expanding deployment of WTs, more comprehensive epidemiological studies are necessary, combining objective morbidity data with self-reported symptoms, using the largest feasible samples near WTs. Refining exposure assessment with precise geospatial data at the individual level, incorporating information on sound characteristics such as amplitude modulation, and thoroughly controlling for relevant confounding and moderating variables are critical aspects that need to be considered in future research endeavors.

1. Introduction

The deployment of wind turbines (WTs) has been one of the cornerstones of the gradual transition towards sources of renewable energy; especially in recent years, the scale and capacity of WTs have grown substantially [1]. However, the increasing operation of WTs has been triggering societal debates as well as concerns regarding potential adverse ecological and human health effects [2]. The World Health Organization (WHO) has recommended a maximum limit of 45 dB Lden (Level Day–Evening–Night) for WT noise [3]. However, obligatory limits can deviate or vary, even within the European Union – for instance the limit in the Netherlands is 47 dB, while there are often no mandatory minimum distance requirements for residential areas [4].

It is well-documented, on the basis of a growing body of evidence, that living near WTs is associated, to some degree, with higher annoyance levels [5–11]. Studies also indicate that noise annoyance can occur independently of objective exposure indicators such as distance from the nearest turbine and sound pressure levels [12,13], while both acoustic (e.g., sound quality, amplitude modulation) and non-acoustic factors (e.g., visibility of turbines, individual perceptions on wind energy) can be important determinants of annoyance among nearby residents [11–16].

However, epidemiological research on specific health outcomes such as symptoms and chronic diseases is still scarce and remains inconclusive [11,17]. Using distance to the nearest wind turbine or exposure to modeled broadband sound pressure levels as exposure surrogates, existing evidence generally shows no consistent associations with acute symptomatology or chronic conditions such as headache, dizziness, tinnitus, sleep problems, heart diseases or medication [10,18–27]. Apart from the almost explicit focus on annoyance, most studies in the existing

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literature rely on data collected at a single time point, self-reported surveys and relatively small sample sizes, potentially introducing biases such as recall and selection bias [11]. Given the expected increase in the number of WTs in the coming years, epidemiological research on potential health effects is crucial to inform evidence-based policies and mitigate possible health risks.

The present study aims to address these gaps, on the basis of recent data from a nationwide primary health care database, to explore the association between distance to WTs and both acute symptoms and chronic conditions presented and diagnosed in general practice. This paper also aims to address and draw attention to important methodological aspects to be considered in epidemiological research on WTs and health. More specifically, the following main research question is addressed: Are there differences in acute symptoms and chronic conditions presented in general practice as well as prescribed medications among residents living closer to WTs compared to residents living farther away?

2. Methods

2.1. Study design and population

This epidemiological study included ten years (2012–2021) of retrospective health data from a dynamic cohort on different health problems and medication. Pseudonymized data were extracted from electronic health records (EHRs) of general practices in the Netherlands, using the Primary Care Database of Nivel (Netherlands Institute for Health Services Research), referred to as Nivel-PCD (data request number: NZR-00322.039). Residents of the Netherlands are obliged to be registered in one general practice in the broader vicinity of their home. General practitioners (GPs) coordinate access to secondary health care and the population registered in family practice can be used as the denominator in epidemiological studies, with inclusion of both consulting and non-consulting populations. The Nivel-PCD is a large research infrastructure consisting of about 500 general practices in all over the country, approximating a representative sample of almost 2 million registered individuals.

The study does not fall within the scope of the Medical Research Involving Human Subjects Act and therefore did not require ethical approval. The use of EHRs for research purposes is allowed under certain conditions. When these conditions are fulfilled, approval by a medical ethics committee is not obligatory for this type of observational studies containing no directly identifiable data (art. 24 GDPR implementation Act jo art. 9.2 sub j GDPR). The privacy aspects of data utilization underwent evaluation and received approval from the Privacy Commission of Nivel.

2.2. Exposure assessment

As a primary proxy of exposure to WTs, different close distance categories to WTs were used. Location of WTs was determined based on publicly available national maps on WT locations from the Environmental Health Atlas, which contain various information on active WTs [28]. In particular, the National Institute for Public Health and the Environment (RIVM) generates and regularly updates these maps combining data from various sources such as the RIVM, Rijkswaterstaat (governmental agency responsible for the design, construction, management, and maintenance of the country's primary infrastructure facilities), OpenStreetMap, the External Security Register (REV) (a central database that keeps track of all environmentally hazardous activities with an external safety risk) and the Large-Scale Topography Base Registration (BGT) (detailed, uniform digital map of the Netherlands, providing topographical features at a large scale).

During the sampling process summarized in Fig. 1, health records from the Nivel-PCR were linked with WT exposure data at the four-digit postal code (PC4) level (neighborhood level) for each analysis year. Specifically, information on the location of all active WTs at the national level, along with the pool of eligible addresses from EHRs of individuals registered with general practices in Nivel-PCD, was imported into the Geographic Information System (GIS) operated by Nivel. Using this system, the centroids of PC4 areas—defined as the center of the built-up area rather than the geographic center—were mapped to assess their distance from the WTs. Individuals were categorized into spherical distance ranges from WTs: 0–500 m, 0–1000 m, 0–2000 m, and 0–5000 m, based on the proximity of the most densely populated centroid of their PC4 to the nearest WT. This process resulted in a yearly sample size ranging from 350,000 to 560,000 individuals with available data on health outcomes and WT exposure. Exposure data were not available for all years, necessitating the use of estimates from one year as a proxy for another. Specifically, the 2013 exposure data were used for 2014, the 2015 exposure data were used for 2016, 2017, and 2018, and the 2020 exposure data were employed for 2019.

2.3. Health outcome assessment

Health symptoms and conditions, as well as social problems in general practice, are registered based on the International Classification of Primary Care (ICPC) [29], which is universally applied in all general

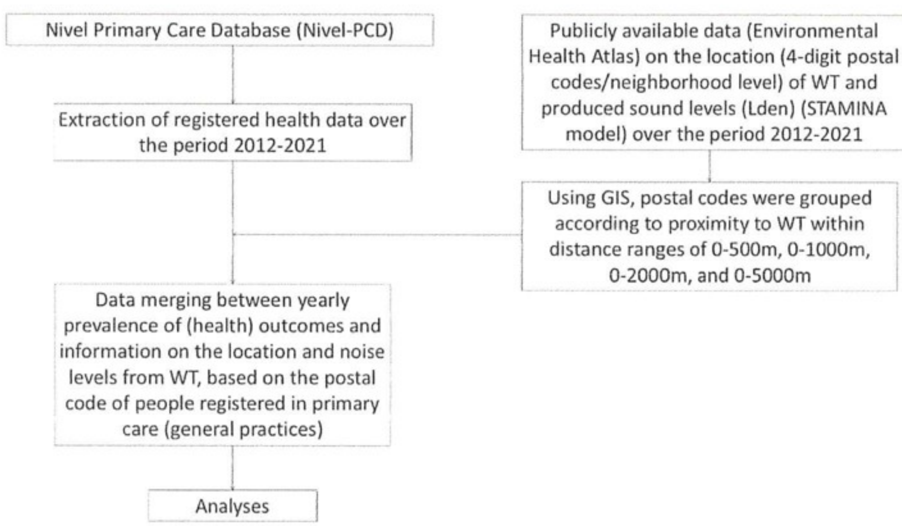

Fig. 1. Flow diagram outlining the data selection process.

practices in the Netherlands. Medication prescriptions are recorded according to the Anatomical Therapeutic Chemical (ATC) classification system [30]. The analysis included a thorough selection of outcomes (Appendix A, Table A1), guided primarily by the relevant literature on wind turbines and health [11,31–33], as well as broader research on the health effects of environmental noise [34]. The prevalence of the investigated outcomes (defined as the proportion of individuals diagnosed with a specific health or social problem, or being prescribed medication at any point during a given year) was estimated for each year from 2012 to 2021. Morbidity data were based on episodes of care constructed from the EHRs [35], which consist of all patient encounters within a primary care registration code (ICPC code) from the onset of symptoms or initial diagnosis through to the completion of treatment. The ICPC codes classify conditions into acute, long-lasting reversible, and chronic irreversible categories [35]. Each category has a defined symptom-free period that determines whether consecutive ICPC records belong to the same episode. Acute conditions require a specific symptom-free period for episode closure, long-lasting reversible conditions require one or two years, and episodes for chronic irreversible conditions remain "open" indefinitely, as no symptom-free period is defined. Additionally, we analyzed the variable "housing/neighborhood problems", classified as a social problem in the ICPC, including issues such as housing quality and availability aspects, neighborhood disturbances, and noise due to surroundings. We used it as a broad proxy for possible annoyance due to WTs, since annoyance is not specifically recorded as a health problem in primary care.

2.4. Statistical methods

For the primary analysis, potential associations between distance to WTs and prevalence of health problems were investigated on the basis of multilevel logistic regression analyses, to also account for the hierarchical structure of the data, (registered individuals clustered within general practices). The dependent variable was each of the analyzed health outcomes, while distance categories to WTs were included as independent variables in the regression models. In particular, the prevalence of registered symptoms and conditions among residents living closer to WTs, focusing on distance categories of 0–500 m, 500–1000 m, and 1000–2000 m, was compared to people living further away (2000–5000 m as reference category). All analyses were adjusted for sex and age (polynomial, in order to allow for a potential nonlinear trend between age and morbidity) and registry duration (proportion of the year in which a given patient was registered at a general practice; the vast majority of the individuals in the sample were registered for the whole year).

Given the exploratory nature of the study and the extensive number of planned analyses, to mitigate multiple testing issues, a more conservative significance level of $p < 0.01$ was applied, alongside False Discovery Rate correction (FDR) [36,37]; FDR was applied on all primary analyses, on all outcomes related to the same independent variable in the same year. Results are presented as odds ratios (ORs) with 99% confidence intervals (CIs). The numerator in the OR represents the odds of a health outcome occurring in individuals living closer to WTs, while the denominator the odds of the same outcome in people living farther away (reference category), accounting for possible confounders. An OR greater than 1 indicates a higher likelihood of the outcome in the exposed groups, while an OR less than 1 indicates a lower likelihood. Analyses were carried out with STATA, version 16.0 (StataCorp LP, College Station, TX, USA).

2.5. Sensitivity analyses

Additional analyses were conducted to further explore the robustness of the main analyses and provide more insight into potential exposure-outcome associations. Specifically:

- *Analyses on noise levels*: Analyses were conducted using annual average (outdoor) noise levels above 42 dB as an independent variable, serving as a proxy for high noise exposure. Previous research indicates that most people notice noise at levels of 40 dBA or higher produced by wind turbines [38,39]. Particularly between 40 and 45 dBA, a significant percentage of nearby residents experience some to considerable annoyance [11]. Noise levels due to WTs were estimated using the STAMINA model (Standard Model Instrumentation for Noise Assessments) [40], based on characteristics such as turbine's generator power and hub height. The model provides average estimates of the day–evening–night noise levels (Lden) in decibels (dB), with evening and night noise weighted more heavily than daytime noise. The dependence of the noise emissions on the generator power is based on a logarithmic fit derived from sound power levels of multiple wind turbine models commonly used in the Netherlands, applying correction factors to account for daily variability in wind conditions [40]. Information on sound levels was initially provided on a fine grid scale (10×10 m), which was subsequently aggregated to provide an average noise level for each postal code area. The STAMINA model does not provide estimates on low-frequency noise (LFN) (below 250 Hz), and infrasound (below 20 Hz). A multiple testing correction was applied, similar to the primary analysis [36,37].
- *Correction for socioeconomic status (SES)*: The main analyses on distance and the sensitivity analyses on noise levels were adjusted for an index [41,42] of SES indicators (average household income, proportion of low family incomes, percentage of low-educated residents, unemployment rates among residents) at the neighborhood level, based on available data from the Netherlands Institute for Social Research (2017) [42]. This adjustment was made to determine if findings were independent of SES factors. Correction for SES was not part of the primary analysis because SES data was unavailable for some postal codes, potentially reducing statistical power due to the relatively limited number of people living near wind turbines.
- *Stratified/Subgroup analyses*: Analyses on both distance and noise levels were repeated for chronic heart problems, hypertension, palpitations, and medication prescriptions among the elderly ($\geq$65 years), taking into account recent findings [25]. Analyses related to Attention-Deficit/Hyperactivity Disorder (ADHD) were also replicated for the age group 5–18 years. These analyses were also corrected for multiple testing [36,37].
- *Explorative longitudinal model on noise and health*: Given that multilevel longitudinal models were not feasible in most cases due to the small number of patients near wind turbines and the low prevalence of some outcomes, several ICPC codes were combined into a single prevalence variable to enhance statistical power. This combined variable was analyzed in relation to continuous average noise levels over the study period, including *noise*year* interactions. The selection of ICPC codes (N05, N17, P01, P02, P03, P04, P06, P20, P21, P74, P76, N01, N02, K04, K05, K01, K02, K03, A04, D09, H01, H02, H03, H13, H29 – see Appendix A, Table A1) was based on symptoms/conditions that are often attributed to wind turbine noise or could be potentially linked to noise annoyance [11,15,31]. To ensure robustness, two types of longitudinal multilevel models were employed: logistic regression and Poisson regression. Both models were adjusted for age, sex, and registry duration, accounting for clustering and repeated measures within the data. Associations are expressed in ORs and relative risks (RRs) for the logistic and Poisson model respectively, with 95 % CIs. A RR greater than 1 indicates that the investigated health problem is more likely to occur at higher exposure, while an RR less than 1 would indicate a lower risk in this case. This analysis was performed with MLwiN (Centre for Multilevel Modelling, University of Bristol, Bristol, UK).

2.6. Evaluation of findings

The overall strength of the findings was assessed based on several a priori established parameters, in addition to the research design and methodological aspects of the study:

- *Statistical significance*: Evaluating the significance of the examined associations and differences.
- *Strength of associations*: Assessing the magnitude of the observed associations as reflected by the risk estimates (ORs, RRs).
- *Consistency*: Checking for consistency of the observed associations across different years and subgroups.
- *Patterns of associations*: Examining whether the strength of a given association increased with greater exposure (or vice versa) and whether there was a consistent, clear (increasing or decreasing) trend in the relationship between the dependent and independent variables ("monotonic trend").
- *Plausibility and relevance*: Determining whether the observed associations align with existing knowledge and mechanisms from the literature, as well as their relevance to public health or clinical practice.

3. Results

3.1. Descriptive characteristics

Table 1 presents an overview of sample characteristics for each analysis year (2012–2021). The mean age of the total sample varied slightly between 39.0 years (SD 22.5) and 42.3 years (SD 23.3). The distribution of female and male participants was almost equal over the ten-year period, with the percentage of female participants being about 51 %.

The percentage of individuals living in the closest distance category (≤500 m) varied between 0.1 % (n = 337) and 1.2 % (n = 6,576) over the years, with the majority of the analysis years remaining below 1 % (Table 1). Mean noise levels (Lden) in the total sample ranged from 11.1 dB (SD 10.7) in 2012 to a peak of 13.9 dB (SD 11.8) in 2019, before decreasing slightly to 12.3 dB (SD 11.6) in 2021. The percentage of individuals exposed to noise levels exceeding 42 dB remained consistently low from 2012 to 2018 (≤0.04 %), increasing in recent years to 0.6 % in 2020 and 0.7 % in 2019 and 2021.

3.2. Association between distance to wind turbines and health problems

Analyses revealed limited statistically significant associations between distance to WTs and health problems. After correcting for multiple testing, the only statistically significant finding was a higher likelihood of housing or neighborhood-related problems observed within 500–1000 m from WTs in 2016 (OR 3.65, 99 % CI: 1.22–10.9), indicating a more than three times higher odds within this distance, though concerning a small number of observations as suggested by the wide CIs.

Additionally, some sporadic, mostly weak, negative associations were found. In 2015, there was a lower risk of hypertension within 500–1000 m (OR 0.79, 99 % CI: 0.71–0.88) and irritability between 1 and 2 km. In 2016, there was a lower risk of hypertension both within 500–1000 m (OR 0.70, 99 % CI: 0.61–0.81) and 1–2 km (OR 0.94, 99 % CI: 0.90–0.99). In 2021, a reduced risk of being prescribed antidepressants was observed for those living within 500–1000 m (OR 0.65, 99 % CI: 0.42–0.99) as well as 1–2 km (OR 0.82, 99 % CI: 0.70–0.95).

Despite the overall lack of statistical significance and consistency in the observed associations for most investigated outcomes, some acute symptoms, such as tension headaches and depressive feelings, showed increased odds with closer distance to WTs in recent years (Figs. 2 and 3).

Detailed results of the multilevel regression analyses on the annual prevalence of various acute symptoms and long-term or chronic conditions are presented in Appendix B, Tables B1 – B3.

3.3. Sensitivity analyses

Significant associations were found between higher noise levels (>42 dB) and painkillers in multiple recent years, particularly in 2019 (OR 1.36, 99 % CI: 1.09–1.70), 2020 (OR 1.46, 99 % CI: 1.16–1.83), and 2021 (OR 1.56, 99 % CI: 1.24–1.97), suggesting a moderate increase in the odds of painkiller prescriptions among those with higher noise exposure, with the association becoming stronger over time. Detailed results are presented in Appendix C, Table C1. After repeating the primary and aforementioned sensitivity analyses adjusting for the SES-index, significant results remained unchanged (details available upon request).

Stratified analyses by age showed no statistically significant associations between distance to WTs and chronic heart conditions, palpitations, hypertension, and medication prescriptions among individuals

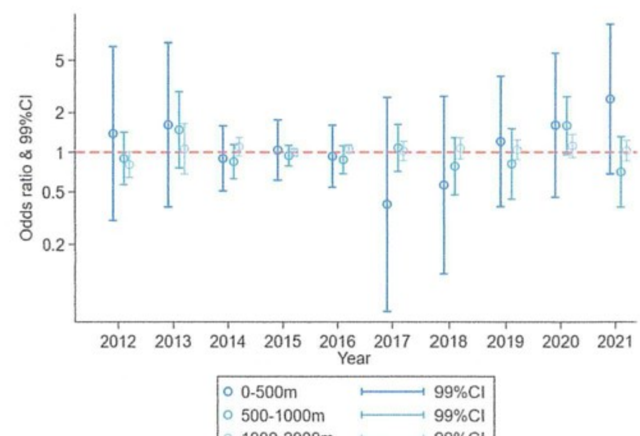

Fig. 2. Risk of tension headache by distance category, for each year included in the analysis.

Table 1
Sample characteristics and distribution by distance category for each year included in the analysis.

Characteristics	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
N registered individuals within 5 km from WTs	351,031	508,182	560,754	558,755	370,252	513,270	463,499	545,808	448,179	518,523
Mean age (SD)	39.1 (22.6)	39.0 (22.5)	40.21 (22.8)	40.9 (22.9)	42.3 (23.3)	40.9 (22.9)	41.2 (23.0)	41.5 (23.2)	41.2 (23.1)	42.0 (23.3)
% Female	50.7	50.6	50.6	50.6	50.5	50.7	50.6	50.6	50.6	50.6
N living within 500 m from WTs	337	3,397	6,576	903	869	908	948	925	745	397
N living within 1000 m from WTs	15,906	21,221	23,501	9,090	4,922	9,035	7,879	6,051	5,378	5,838
N living within 2000 m from WTs	74,728	68,822	103,379	105,333	68,996	89,495	77,732	93,005	76,824	86,624

Abbreviations: SD: Standard deviation.

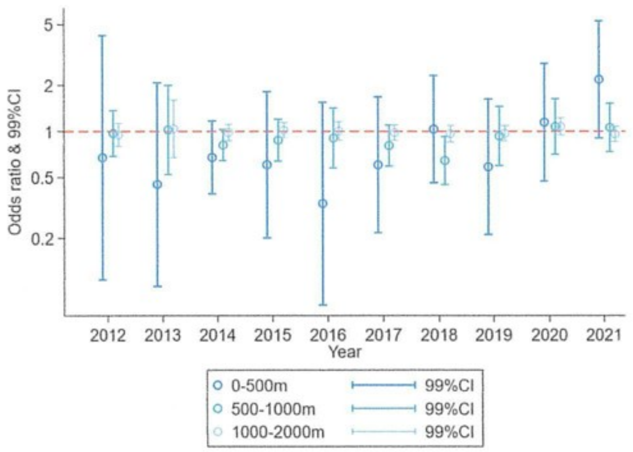

Fig. 3. Risk of feeling down/depressed by distance category, for each year included in the analysis.

older than 65 years (details available upon request). In line with the findings from the total sample, elderly individuals exposed to average noise levels greater than 42 dB from WTs had a higher risk of painkiller prescriptions in the three most recently examined years (2019, 2020, 2021): OR 1.56 (99 % CI: 1.04–2.32), OR 1.53 (99 % CI: 1.03–2.67), and OR 1.68 (99 % CI: 1.12–2.53), respectively. Analyses among children aged 5–18 years showed no statistically significant increased risk of ADHD in the nearer distance categories or the higher noise exposure group (details available upon request).

Finally, both the multilevel logistic and Poisson longitudinal models yielded no statistically significant association between noise levels and the combined outcome variable on health problems over the ten-year period (OR 1.02, 95 % CI: 0.86–1.21; RR 1.01, 95 % CI: 0.89–1.16). There was also no significant interaction between years and noise exposure (OR 0.99999, 95 % CI: 0.99991–1.0001; RR 0.99999, 95 % CI: 0.99992–1.0001).

4. Discussion

This comprehensive study explored associations between residing in the proximity of wind turbines, and the prevalence of registered health problems in primary care over a ten-year period (2012–2021). We analyzed the distance to the WTs as the primary exposure proxy, recognizing the importance of visual aspects, which are strongly intertwined with auditory aspects in relation to potential adverse health effects [11]. Despite an extensive analysis into a broad range of relevant health effects, there were no consistent patterns regarding an association between distance to WTs and an increased prevalence of symptoms, certain physical and mental disorders, prescription of three medication groups and housing/neighborhood problems. While certain symptoms such as tension headaches and depressive feelings exhibited some increases among individuals living closer to WTs in later years, results lacked statistical significance.

A significantly higher risk of housing/neighborhood problems was found, among individuals residing within 500–1000 m of wind turbines. However, this was only observed in the year 2016. Additional analyses showed that higher noise levels (above 42 dB) were associated with a higher likelihood of GP-prescribed painkillers in the three most recent year of the analysis (2019–2021). However, the number of individuals within the high exposure category was small (less than 1 % of the sample) and such associations were absent in earlier years, and also in relation to distance to WTs.

A few significant weak associations suggesting a potential protective effect of closer distance to WTs were also observed, in certain years, for hypertension, irritability and antidepressants. This may be partly due to the relatively low number of cases at the closest distance category, which could have influenced the observed (lack of) associations. In addition, this might indicate the so called "healthy farmer effect" [43]: Earlier findings from the Netherlands suggest that a significant proportion of people living close to WTs are relatively young and physically healthy individuals who are often financially invested in wind energy, and also report health problems such as hypertension less often [43]. Interestingly, in our dataset residents within 500 m were consistently older compared to those living further away (mean age 42 vs. 40 years), except for 2016. However, this age pattern reversed within 1000 m, suggesting that the "healthy farmer effect" might indeed, to a certain degree, play a role in masking adverse outcomes within certain proximities.

Most earlier population studies focused on annoyance [11,31], which makes current results not directly comparable. Annoyance was not a focus of this study nor is it registered as a health problem in primary care. Despite methodological differences such as outcome assessment, results of the present study are generally in line with the growing but still limited body of epidemiological research on the association between WTs and specific health problems, such as symptoms and chronic diseases [11]. In particular, two recent studies in Finland observed no consistent associations between self-reported symptoms such as headache, dizziness, fatigue, sleep difficulties, stress, and chronic conditions such as hypertension, heart problems and diabetes and distance to WTs [10] or produced sound pressure levels [27]. A Canadian study [8,19,44] also found no association between WTs and objectively measured sleep activity or self-reported symptoms (including sleep disturbances) and conditions such as chronic pain, hypertension, diabetes and heart problems. Similarly, evidence from Denmark [18] and Poland [20] suggests no association between distance to or noise from WTs and symptomatology or well-being. A questionnaire study in Japan observed no association between multiple symptoms and outdoor nighttime WT noise, except for a higher risk of insomnia among highly exposed people [45]. In the Netherlands, no direct dose-response association was shown between modeled WT noise and self-reported sleep disturbance and stress [5]. Findings from the large cohort study of Poulsen et al. [21–25], also suggest no conclusive evidence of an association between nighttime noise from WTs and registered antihypertensive medication, diabetes, stroke and myocardial infarction. Regarding the latter, elevated but non-significant risk estimates were observed in relation to higher noise exposure levels [24].

Regarding medication, our findings differ from the study by Poulsen et al. [25] that showed associations between sleep medication and antidepressants and outdoor nighttime noise from WTs. However, results are not directly comparable, mainly due to differences in design and exposure assessment. In addition, we used anxiolytics as a proxy for medication that is often prescribed for sleep problems (e.g., benzodiazepines), among other reasons. Other recent studies have examined associations between WT distance and medication on the basis of self-reports, showing no statistically significant findings for sleep medication, anxiolytics, antidepressants, antihypertensives and painkillers [10].

4.1. *Strengths and limitations*

To our knowledge, the present study, along with those by Poulsen et al. in Denmark [21–25] represents the largest epidemiological research to date on wind turbines and health in terms of sample size, with both studies being the only ones in the literature using objective, diagnosed morbidity data. Additionally, this is the first study that relied on EHRs from general practices. This approach ensures that there was no participant burden in terms of data collection, while the risk of outcome misclassification and selection bias is minimized. Participants in questionnaire surveys on WTs and health are typically aware of the study's objective, increasing the risk of selection and response bias.

Furthermore, the current research is the most extensive to date in terms of outcome assessment, including an analysis period of ten consecutive years on a nationwide sample, including the period during the COVID-19 pandemic (2020–21). The latter could have potentially resulted to prolonged exposure to nearby wind turbines, considering the precautionary measures (e.g., lockdowns) in the different pandemic waves that mandated reducing outdoor activities and spending more time at home [46,47]. This aspect might add weight to the (potential strength of) the observed associations.

Alongside these strengths, there are a number of limitations and methodological challenges inherent to this topic, that need consideration, also in light of future investigations: Health and exposure data were linked at neighborhood level and not on the basis of individual addresses: We used the centroids of the built-up area for each postal code to more accurately reflect the residential population, avoiding possible over-representation of uninhabited land in rural areas. While the centroid of the PC4 is a useful indicator of how close a neighborhood is to WTs, its size depends on the geographic context and size of the area. In sparsely populated regions, some outlying buildings may fall into a different distance buffer, introducing a degree of misclassification regarding precise distances to WTs. However, such deviations are expected, and the use of broad distance categories likely minimizes the impact of potential misclassification for outliers. Furthermore, the availability of data on the location of WTs was not consistent across all research years, resulting in the use of estimates from one year as a proxy for another, in some cases. Additionally, the model on which the noise metric was based [40] does not include information on sound characteristics such as amplitude modulation and sound quality and pattern that are important determinants of WT-annoyance [13,48], nor distinguishes between different noise types, such as LFN and infrasound, to which symptomatic groups often attribute annoyance and health symptoms [49–51].

A challenge in epidemiological research on WTs and health internationally, is the limited number of people living close to WTs and being highly exposed to the accompanied noise emissions. The present investigation confronted the same issue: Despite using a large nationwide sample of people registered in primary care, only a relatively small percentage of the population resides in the direct vicinity of a wind turbine (especially within 500 m) limiting statistical power and therefore the ability to detect potential statistically significant associations.

Another challenge in this field, is adequately correcting for potential confounding factors, given that some significant exposure-outcome associations could be the byproduct of residual confounding [18]. While in the current study we were able to adjust for age and sex as well as SES indicators, information on environmental (co) exposures such as road traffic noise was not available. The potential importance of road traffic noise when studying the effects of WT noise has been recently emphasized [27]. However, our analyses generally showed no consistent significant associations that could potentially be explained by the presence of other exposures, apart from the association between average noise emissions above 42 dB and painkiller prescriptions. Moreover, wind turbines or wind parks in the Netherlands are often situated in rural areas where road traffic noise is minimal. Previous research has also shown that the association between WT noise emissions and annoyance is not substantially influenced by the levels of road traffic sound [52] – in fact, noise from WTs can be considered more annoying compared to traffic noise [7,38], while the role of non-acoustic factors such as concerns about potential health effects, noise sensitivity and area characteristics may be even more important than WT sound itself [11,16].

Another limitation, is that analyses focused on associations for individual years. A proper longitudinal analysis for each individual outcome was not feasible due to power issues in the closest distance categories (relatively limited number of residents combined with small prevalence of several investigated health problems in the general population) and fluctuations in data availability/completeness. This makes it challenging to establish causal inferences. However, the analysis involved 10 consecutive years, which allows for the thorough investigation of association patterns and consistency. Moreover, we also conducted a sensitivity analysis on longitudinal dose-response associations between noise emissions and cumulative prevalence of various health problems, which confirmed the results of the main analysis. Finally, it should also be noted that a large part of self-reported symptoms is not presented in primary care [53]. Not everyone with a headache, sleep problems or even long-term conditions will (immediately) visit the GP, as individual factors such as illness beliefs, including perceived severity of the health complaints, play a pivotal role in the decision to seek medical help [54–57].

4.2. Recommendations for future research

More epidemiological research is needed, primarily on symptoms and medication, to confirm the present findings and address these limitations. This can be achieved by combining objective morbidity data from primary care registries and self-reported data from validated questionnaires on symptoms and perceptions [58], in order to obtain a complete picture of the health status of the population at risk. While logistically complex, this approach can be feasible for a fraction of the general practice population, similar to approaches implemented in the context of other environmental exposures [59]. Also crucial is the use of precise information on the location of WTs, as well as individual estimates of corresponding noise emissions based on up-to-date prediction models, while adequately correcting for potential confounding factors in the analyses. Conducting longitudinal studies with large samples is essential to capture differences in health problems that may occur over time. In addition to this, an important methodological aspect is to be able to take into account the duration of residence after the installation of the WTs, to better assess the potential effect of prolonged exposure on health outcomes. A "before-after" design comparing health data from before and after a wind park becomes operational, would be a straightforward approach to monitor health outcome changes potentially related to the deployment of WTs. In this case, a cumulative analysis at national level would be imperative to mitigate privacy risks and methodological biases while improving statistical power, as focusing on a single wind park may involve too few participants.

The quantitative synthesis, regular update and critical assessment of the international epidemiological evidence is also of importance; conducting meta-analyses on multiple, similarly exposed samples can increase statistical power and provide more insight into potential health effects compared to an individual study.

The potential overlap or contrast between perceived and actual sound exposure is also an important aspect. As has also been shown in the context of other environmental exposures, objectively measured and perceived exposures do not always align [59], which can have significant implications for the mechanisms leading to symptom reporting. Considering the importance of non-acoustic factors in individual responses to sound [60], the disruptive, mediating, and/or moderating role of aspects such as socio-demographic characteristics, subjective sensitivity to noise, and environmental concerns should be further explored [39]. Noise-sensitive individuals in particular, are underrepresented in epidemiological research on noise and health [49], despite often experiencing multiple symptoms, independently of noise exposure [61]. Assessing perceptions of risk as well as stress symptoms has been important for understanding noise annoyance in relation to WTs [13,14,17], and these factors should be considered in research on specific health problems as well. Integrating findings from various noise exposure settings can also enhance our understanding of the non-acoustic factors influencing symptomatic effects [13,14,17]. Finally, the systematic registration of symptoms attributed to or potentially associated with environmental exposures in routinely collected general practice records, could open new possibilities in epidemiological research and population health monitoring by enabling more comprehensive approaches, facilitating the identification of populations at risk and signal emerging trends for further investigation.

5. Conclusions

The present study does not provide support for an association between living in the vicinity of WTs and prevalence of acute symptoms and chronic diseases at the population level. These findings do not rule out the experience of increased annoyance by nearby residents, or symptoms that, for certain reasons, do not prompt individuals to consult a GP. While certain symptoms such as tension headaches and depressive feelings exhibited increases in individuals living closer to WTs in later years, these lacked statistical significance, which could partly be a result of the small number of people living in the direct vicinity of WTs. Sensitivity analyses also showed that higher noise levels from WTs (above 42 dB) were associated with a higher risk of prescribed painkillers in later years. Further research is required to confirm these findings and improve on the existing limitations, to better understand the mechanisms behind any observed associations or lack thereof.

These conclusions are generally in line with existing epidemiological evidence on WT exposure that adheres to the established noise standards, in relation to acute symptoms and chronic health problems. However, epidemiological research on specific health outcomes remains scarce, while there are many important methodological challenges to be addressed. Therefore, a possible impact of long-term exposure to WTs on human health should not be excluded. In addition, localized effects, such as high annoyance or community concern regarding adverse effects, may still occur and should be taken into account when addressing mitigation measures. Targeted case- and context-specific approaches could help balance the promotion of wind energy while protecting the well-being of local communities.

CRediT authorship contribution statement

Christos Baliatsas: Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization, Supervision, Project administration. **C. Joris Yzermans:** Conceptualization, Methodology, Investigation, Writing – review & editing, Supervision. **Mariette Hooiveld:** Resources, Data curation, Writing – review & editing. **Raymond Kenens:** Resources, Data curation, Software, Writing – review & editing. **Peter Spreeuwenberg:** Formal analysis, Writing – review & editing. **Irene van Kamp:** Writing – review & editing. **Michel Dückers:** Conceptualization, Funding acquisition, Project administration, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.rser.2025.115642.

Data availability

The authors do not have permission to share data.

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