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# Impact of wind turbine sound on annoyance, self-reported sleep disturbance and psychological distress

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ABSTRACT

*Purpose of the research:* The present government in the Netherlands intends to realize a substantial growth of wind energy before 2020, both onshore and offshore. Wind turbines, when positioned in the neighborhood of residents may cause visual annoyance and noise annoyance. Studies on other environmental sound sources, such as railway, road traffic, industry and aircraft noise show that (long-term) exposure to sound can have negative effects other than annoyance from noise. This study aims to elucidate the relation between exposure to the sound of wind turbines and annoyance, self-reported sleep disturbance and psychological distress of people that live in their vicinity. Data were gathered by questionnaire that was sent by mail to a representative sample of residents of the Netherlands living in the vicinity of wind turbines

*Principal results:* A dose–response relationship was found between immission levels of wind turbine sound and selfreported noise annoyance. Sound exposure was also related to sleep disturbance and psychological distress among those who reported that they could hear the sound, however not directly but with noise annoyance acting as a mediator. Respondents living in areas with other background sounds were less affected than respondents in quiet areas.

*Major conclusions:* People living in the vicinity of wind turbines are at risk of being annoyed by the noise, an adverse effect in itself. Noise annoyance in turn could lead to sleep disturbance and psychological distress. No direct effects of wind turbine noise on sleep disturbance or psychological stress has been demonstrated, which means that residents, who do not hear the sound, or do not feel disturbed, are not adversely affected.
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## 1. Introduction

In 2007 the European Union leaders committed themselves to the "20–20–20" targets, aiming for a reduction in greenhouse gases of 20%, a reduction of 20% in primary energy use and renewables contributing 20% to the energy consumption in the EU in the year 2020 (EU, 2011). One way to achieve this is by increasing the contribution of wind energy at the expense of energy based on fossil fuels. In the Netherlands wind energy generation is rapidly expanding; at the moment it amounts to nine percent of the national electricity consumption which is just over one percent of the entire national energy consumption. The Dutch government has the intention to realize a substantial growth of wind energy before 2020, both onshore and offshore. The production capacity to be realized onshore during this period is about 4000 MW, equivalent to 800 to 2000 wind turbines of 2 to 5 MW capacity each. However, when positioned in residential areas wind turbines may cause noise annoyance as reported in international literature (Persson Waye and Öhrström, 2002; Pedersen and Persson Waye, 2004, 2007; Pedersen et al., 2009, 2010). Dose–response curves between levels of wind turbine sound and percentages of annoyed residents show that wind turbine sound induces a higher proportion of annoyed residents than traffic noise does at comparable sound levels (Janssen et al., 2011). Noise annoyance has an adverse effect on health-related quality of life according to the World Health Organization (WHO, 2000) and is also an indicator of other possible adverse health effects (Klaeboe, 2011), and therefore studies of such effects, other than those of noise annoyance, are needed.

A major effect of environmental noise is sleep disturbance (WHO, 2009). Associations between levels of sound and impaired sleep have been found for road traffic noise (Miedema and Vos, 2007). Residents in noisy urban areas of Belgrad more frequently reported waking up than residents in less exposed areas (Jakovljević et al., 2006). Furthermore, De Kluizenaar et al. (2009) found that long-term road traffic noise exposure is associated with an increased risk of getting up tired and not rested in the morning in the general population. Passchier-

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Vermeer et al. (2007) performed a field study on the effects of nighttime road and railway noise. Nighttime noise turned out to have adverse effects on sleep. Motility, motility onset and heart rate (monitored with ECG-equipment) increased with increasing road and railway noise exposure indoors during sleep. Griefahn and Spreng (2004) found similar effects. Levels of environmental sound only explain part of the effects; noise induced disturbances vary according to the physical characteristics of the noise events (Muzet, 2007). Dose–response relationships between night sound levels of aircraft noise and effects on sleep could be substantially improved by adding the number of noise events (Basner et al., 2010). Saremi et al. (2008) found that railway noise disturbs both the macro- and microstructure of sleep and indicated that for the same maximum level and the same patterns during the night, sleep would be more fragmented by freight trains than by passenger and automotive trains. The more harmful effect of freight trains is attributed to their length, influencing the duration of being exposed to their sound in addition to the enhanced risk of vibration exposure and the low frequency character of the sound. Sound occurrence and sound levels from wind turbines at a nearby dwelling are dependent on wind speed and wind direction and hence differ unpredictably in duration and intensity. The sound is furthermore amplitude modulated, by residents reported as "swishing" or "lashing" (Pedersen et al., 2009). These properties indicate that sleep disturbance due to wind turbine noise could be a problem despite often lower sound levels than those previously known to have adverse effects.

Environmental noise has been found to be associated with psychological distress other than annoyance in the form of increased anxiety (Stansfeld et al., 1996; Hardoy et al., 2005), depressed mood (Öhrström, 1989) and cognitive impairment (Elmenhorst et al., 2010). Interaction effects between annoyance and psychological distress (Stansfeld and Matheson, 2003; Stansfeld and Clark, 2011) as well as between annoyance and sleep (Klaeboe, 2011) can be expected. Annoyance due to aircraft noise has been found to be related to psychological distress as measured with the General Health Questionnaire (GHQ) in a study among residents living in the vicinity of Heathrow airport (Tarnopolsky et al., 1978). An association between noise annoyance and sleep disturbance was found among residents highly exposed to aircraft noise, but not among those that were exposed at lower levels (Bronzaft et al., 1998). A large Norwegian study on the impact of road traffic sound found significant relationships between noise annoyance and sleeping problems (Fyhri and Aasvang, 2010) and strong links between pseudoneurological complaints (palpitation, heat flushes, dizziness, anxiety and depression), annoyance and sleep.

Until now it is not clear if the sound of wind turbines has an adverse effect on sleep disturbance and psychological distress and if so, how such an effect comes about. The aims of the study presented here were to add knowledge about the impact of wind turbines on sleep and psychological distress of people living in their vicinity and to contribute to the clarification of the process underlying such an impact. Knowledge about this process can lead to better recommendations with regard to wind farm planning in the neighborhood of residential areas. The study focuses on the following questions:

1. Are residents annoyed and if so, does the extent of exposure have a proportional impact on the level of annoyance: i.e. the more one is exposed (in terms of decibels) the more one gets annoyed?
2. Does annoyance lead to (self-reported) impaired sleep?
3. Does annoyance lead to psychological distress?
4. Does exposure to wind turbine sound (in terms of decibels) lead to (self-reported) impaired sleep and/or psychological distress?
5. If such a (direct) relation does not exist, can annoyance and/or sleep quality be regarded as intermediate states?

The research questions are visualized in Fig. 1. Exposure to the sound of wind turbines may lead to annoyance (arrow 1) and/or to sleep disturbance (arrow 2) and/or to psychological distress (arrow 3). Alternatively, annoyance may (also) lead to sleep disturbance (arrow 4) and/or (in the direct sense) to psychological distress (arrow 5). Finally, sleep disturbance may lead directly to psychological distress (arrow 6).

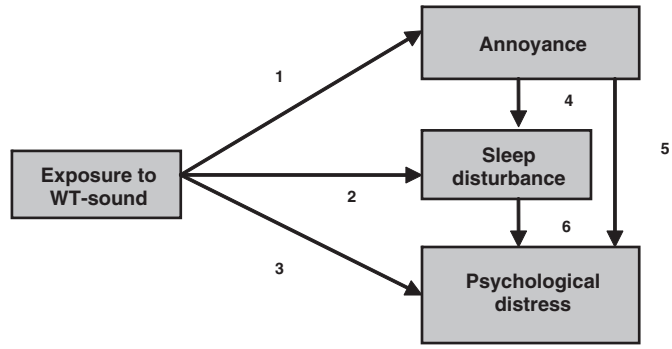


**Fig. 1.** Model of possible associations between sound exposure, annoyance, sleep disturbance and psychological distress.

In this study psychological distress was considered as the major dependent variable, ignoring the possibility that it could also act as an independent variable or determinant.

When looking for answers to these questions, ownership of wind turbines or shares in wind turbines will be taken into account. The reason is that economic interests could more strongly play a role as a confounder or moderator compared to (financial) interests in other environmental sound sources, such as road traffic and aircraft noise. In case of ownership wind turbines are often set up on the property of the owner. Moreover, from literature it is known that economic benefits have a major impact on the way exposure to the sound of wind turbines is experienced (Pedersen et al., 2009).

## 2. Method

A questionnaire, partly based on a Swedish questionnaire used by Pedersen and Persson Waye (2004, 2007) and translated into Dutch, was sent by mail to a representative sample of residents of the Netherlands living in the vicinity of wind turbines in April 2007. Reminders were sent 3 weeks later. Questions about other environmental factors and about road traffic noise preceded similar questions about wind turbine noise, to mask the main research topic of the questionnaire: measuring the effect of wind turbines on annoyance, sleep disturbance and psychological distress. The questionnaire questions are listed in an appendix of the study report (Van den Berg et al., 2008).

### 2.1. Sample

With the GIS application Arcmap 9.2, a software program which is used for mapping and editing tasks and for map-based queries and analyses, postal codes were selected in relation to their distance to the closest wind turbine, using a list of all wind turbines in the Netherlands. Postal code selection yielded 50,375 addresses with individual x and y coordinates. From these a selection was made of addresses within 2.5 km from a wind turbine with a nominal electric power of at least 500 kW and with another wind turbine ($\geq$500 kW) present within 500 m of the first turbine. The 2.5 km was chosen because at this distance the sound of a modern, tall wind turbine must be considered inaudible when staying indoors and usually not or only faintly audible when outdoors. As the focus of this study was on modern wind farms, turbines of at least 0.5 MW nominal electric power were considered with at least one adjacent similar turbine. It was expected that for visual impact a distinction between rural and built-up areas would be important. For acoustic impact the background noise was expected to be relevant. Apart from natural sources, the background sound in the selected areas was usually determined

by road traffic. Therefore, all addresses were divided into three types of environment:

- rural area (with no major road within 500 m from the closest wind turbine);
- rural area with a major road within 500 m from the closest wind turbine;
- more densely populated built-up area.

Later, more detailed information on background noise was obtained from the National Institute for Public Health and the Environment or RIVM (see below). This background noise level due to transportation sound consisted predominantly of road traffic sound, as other noise sources (air, rail) were usually distant. The average background level at the respondents' dwellings was 41 dB(A) in rural areas and 49 dB(A) (both Lden) in both rural areas with a major road and built-up areas. In the text below the strictly rural area will be denoted as the quiet area type, both other areas as the noisy area type.

It was estimated that at least 50 respondents in each sound exposure class (<30, 30–35, 36–40, 41–45, >45 dB(A) for each of the three area types were necessary to obtain statistically reliable results. This estimate was based on the possibility to detect a difference between 10% and 30% annoyed (Pedersen and Persson Waye, 2004), for two-sided tests, with a probability level of 0.05 and a statistical power of 0.8. With an expected response rate of 30% we thus aimed for 150 participants in each group. In the low exposure groups, containing most of the addresses, addresses were randomly selected. In the highest exposure groups (≥45 dB(A)) and in the second highest exposure group in the built up area type all addresses were used. Details are in the study report (Van den Berg et al., 2008).

An agency that enriched addresses with names and telephone numbers provided 2056 names and telephone numbers for the 3727 addresses we had selected. Only addresses that contained private names were used for this study – businesses or organizations were left out –, finally yielding 1948 addresses evenly distributed over the three area types. At each address the adult with a birth date closest to a fixed date was asked to complete the questionnaire.

### 2.2. Sound exposure

Information on wind turbines and their sound power levels was collected from various sources such as Wind Service Holland. Sound power data of 1182 of the 1846 turbines in this project sound power data were available. When sound power data were not available (usually of older and smaller wind turbines), data of comparable types with the same electric power were used. For all respondents the immission sound level was calculated from the sound power level at high electric power according to a sound propagation model that takes each resident's distance from a wind turbine into account (Pedersen et al., 2009). The immission levels represent A-weighted sound pressure levels outside the dwellings averaged over the time with an 8 m/s downwind. Van den Berg (2008) has shown that this level is closely related to the Lden. The RIVM supplied information about transportation sound levels. These levels were available on a square grid with cells of 25 m × 25 m, covering the entire country.

The sound propagation models used for both the wind turbines and the RIVM sources are those that comply with the Dutch noise regulations. The propagation model for wind turbine sound is very similar to the ISO9613.2 sound propagation model and yielded nearly identical results (Van den Berg et al., 2008). When calculating sound levels at respondents' locations the contributions of all wind turbines (including<500 kW) were taken into account. Topographical effects were disregarded as all wind farms are in flat terrain where only low, local elevations (dikes, elevated roads) may exist. Reflections and screening were not expected as all addresses in the rural areas were from either farms or countryside dwellings, but they could occur very locally (perhaps due to barns) and in the built up area.

### 2.3. Psychological distress

Non-specific psychological distress was assessed with the 12-item version of the General Health Questionnaire (Goldberg and Williams, 1988; Koeter and Ormel, 1991) designed to detect psychiatric disorders in community samples and non-psychiatric clinical settings. An example of a positive GHQ item is 'Have you recently been able to enjoy your normal day-to-day activities?'. An example of a negative GHQ item is 'Have you recently lost much sleep over worry?'. For each of the 6 positive items, respondents were asked to indicate whether their present state was (1) better than, (2) the same as, (3) worse or (4) much worse than usual. For each of the 6 negative items, respondents could either indicate that the statement (1) did not apply at all, or that their current state was (2) the same as, (3) worse or (4) much worse than usual. The scale score was calculated in accordance with the C-GHQ scoring method suggested by Goodchild and Duncan-Jones (1985). For positive items only the last two answering categories were considered as signs of distress; for negative items also the second answering category ("the same as") too was regarded as a distress score. This has resulted in a score range of 0–12.

### 2.4. Annoyance

Annoyance was assessed in two different ways. Firstly by two questions 'Please indicate whatever you have noticed or whether you are annoyed by …. [sound from wind turbines]' (one for the indoor and one for the outdoor situation) which could be answered on a 5-point ordinal scale ranging from 'do not notice' to 'do notice, very much annoyed'. Secondly by two Likert scales in the questionnaire ranging from 0 ('I am not annoyed at all') to 10 ('I am extremely annoyed'), also for both the situation indoors and outdoors.

### 2.5. Sleep disturbance

Sleep disturbance was measured by one question in the questionnaire dealing with the frequency of sleep disturbance by environmental sound ('how often are you disturbed by sound?'). Answers could be given on an ordinal scale with the items '(almost) never', 'at least once a year', 'at least once a month', 'at least once a week', and '(almost) daily'. Exposure of wind turbine sound occurs irregularly and people living in the vicinity of the turbines are not exposed every night. A minimal reported frequency of 'at least once a month' was therefore in this study considered as sleep disturbance.

### 2.6. Non-response analysis

A non-response analysis was carried out, aiming to answer two questions:

- are respondents and non-respondents equally exposed to the sound of wind turbines?
- are respondents and non-respondents equally annoyed by the sound of wind turbines?

The first question can be answered by comparing the immission sound levels that respondents and non-respondents had been exposed to. The second question was answered by sending a separate short questionnaire to a randomly chosen sub sample of 200 non-respondents. This short questionnaire consisted of two questions from the original questionnaire that could be regarded as 'core questions' of our study. These questions dealt with the level of annoyance respondents experienced from the sound of wind-turbines *outside* and *inside* their dwelling. On both questions respondents could circle a figure between 0 and 10, which corresponded closest to their perceived annoyance.

### 2.7. Statistics

The model in Fig. 1 was tested through Structural Equation Models (SEM) analysis, also known as LISREL (Jöreskog, 1990). The SEM analysis consists of two components: factor analysis and a regression model defining the associations between the latent variables. As indicators of the goodness of fit of the model the Root Mean Square Error of Approximation (RMSEA) and the Chi-square with the p-value were used. For the RMSEA a value below .05 is supposed to indicate a good fit; values up to .08 being accepted as well (Kaplan, 2000). A small p-value of the Chi-square statistic corresponds with a bad fit of the model, while a large p-value corresponds with a good fit.

According to Jöreskog (1990) it is preferable to use Maximum Likelihood (ML) instead of Weighted Least Squares (WLS) if the variables in the model are not normally distributed and the sample size is not sufficiently large to produce an accurate estimate of the asymptotic covariance matrix. Therefore, SEM analyses presented in this article will be based on ML.

According to Herzog and Boomsma (2009) traditional estimators of fit measures that are based on the noncentral chi-square distribution, such as Root Mean Square Error of Approximation (RMSEA), tend to overreject acceptable models when the sample size is small. Herzog et al. propose a method to handle this problem, the so-called Swain correction. This correction has been applied to correct the chi-square en p-values in the structural equation models presented in Appendix 1. Presented regression weights are all standardized.

The model was tested with age as a moderating variable as both sleep quality (Muzet, 2007) and psychological distress (Nilsson et al., 2010) are related to age. Fyhri and Aasvang (2010) have shown in a structural model with noise, sleeping problems and health complaints, that age could be positively related to sleep quality and negatively related to sleeping problems. Aasvang et al. (2008) reported a statistically non significant decrease in self-reported sleep disturbance with age. Aasvang et al. (2007) further found that younger people were more annoyed than older people by noise from railway tunnels. However, the relationship between age and sleep disturbance remains puzzling, since it is also known that sleep patterns from healthy older adults differ from that of younger adults, with decreased total sleep time and less time in the deeper stages of sleep (Missildine et al., 2010). Saremi et al. (2008) found that age related sleep disturbances are not aggravated by noise and hypothesize that this could be due to the fact that older subjects are more often awake during the night. Moreover, scientific findings regarding age and sleep are sometimes controversial, since there are also studies who report a decreased nocturnal noise tolerance in older subjects (Busby et al., 1994; De Gennaro and Ferrara, 2003; Dang-Vu et al., 2010). Annoyance due to transportation noise has previously been found to have an inversed U-shaped relationship with age, so that people around 45 years old showed the largest number of highly annoyed, while the lowest number was found in the youngest and oldest age segments (van Gerven et al., 2009). However, noise annoyance correlated positively to age in this study so that older respondents were more likely to be annoyed by wind turbine noise than younger respondents (van den Berg et al., 2008). Pathways from age to annoyance, sleep disturbance and psychological distress were included in the model to correct for any age effects, also allowing age and sound exposure to be correlated.

The two 11-point Likert scales (see paragraph 2 in Method section) were used as an indicator for annoyance in SEM analyses, one representing annoyance outdoors and one annoyance indoors. Sleep disturbance and psychological distress were entered as described in the Method section.

The model was tested in two sets of sub-samples: (i) respondents who did not notice sound from wind turbines (annoyance was omitted in this model) versus respondents who noticed the sound, and (ii) respondents who noticed the sound and lived in areas that were classified as quiet versus noisy with regard to background sound levels. Respondents that reported economic benefits from wind turbines were excluded from all model testing.

## 3. Results

### 3.1. Response rate

1948 residents received a questionnaire and 725 completed and returned it, yielding a response rate of 37%. Table 1 shows the percentages of responding residents in relation to immission levels and the three area types.

Table 1 shows that the percentage of responding residents (summed over all area types) was almost evenly divided with regard to immission levels; only the highest immission level is slightly underrepresented. Also, the number of respondents in built-up areas with immission levels over 35 dB(A) is relatively small, due to the smaller number of people exposed to high immission levels in built-up areas. As a result the percentage of respondents shows underrepresentation in this area type ($\chi^2 = 57.012$, df = 8, $p < 0.001$).

The sound levels in the study group (at 8 m/s wind speed) ranged from 21 to 54 dB(A) with an arithmetic average of 35 dB(A) (not in the Table).

### 3.2. Non response analysis

#### 3.2.1. Exposure

The exposure to background sound (predominantly road traffic) and to the sound of wind turbines was tested between respondents (n = 725) and non-respondents (n = 1223) with independent t-tests (t = −0.759 and t = −0.382 respectively, not significant (NS)). For both sound exposures no statistically significant difference could be found between the two groups.

#### 3.2.2. Annoyance

Ninety-five non-respondents completed and returned the small questionnaires on annoyance (response rate 48%). The mean score on both questions was compared between responders (n = 725) and these 95 'responding non-responders', using independent t-tests (for the main questions: t = −0.82, p = 0.412 and t = −0.74 and p = 0.458, NS). No statistically significant (NS) differences in annoyance between the two groups was found, implying that there is no evidence that respondents form a selective group with regard to annoyance within our sample of all approached people living in the vicinity of wind turbines (n = 1948).

### 3.3. Demographic factors

The mean age of the respondents was 51 years. There was a statistically significant relationship between age and sound exposure in the sense that decreasing age correlated with increasing sound levels (Spearman's rho = −0.198, df = 8, $p < 0.001$). The proportion of men and women was almost equal, 51% vs. 49%. The proportion of higher educated respondents was larger in the group of highly exposed

**Table 1**
Percentage of respondents in three area types and different immission levels.

| | Sound pressure level, in dB(A) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | <30 | | 30–35 | | 36–40 | | 41–45 | | >45 | | Total | |
| | n | % | n | % | n | % | n | % | n | % | n | % |
| Built-up area | 68 | 37 | 84 | 38 | 28 | 17 | 18 | 19 | 1 | 2 | 199 | 23 |
| Rural with main road | 50 | 27 | 70 | 32 | 59 | 38 | 36 | 38 | 30 | 46 | 245 | 36 |
| Rural without main road | 67 | 36 | 65 | 30 | 75 | 47 | 40 | 43 | 34 | 52 | 281 | 41 |
| Total | 185 | 38 | 219 | 37 | 162 | 38 | 94 | 38 | 65 | 33 | 725 | 100 |

**Table 2**
Response to wind turbine sound, outdoors and indoors.

| | Response | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Do not notice | | Notice, not annoyed | | Slightly annoyed | | Rather annoyed | | Very annoyed | | Total | |
| | n | % | n | % | n | % | n | % | n | % | n | % |
| Sound outdoors | 284 | 40 | 259 | 37 | 92 | 13 | 44 | 6 | 29 | 4 | 708 | 100 |
| Sound indoors | 465 | 67 | 139 | 20 | 54 | 8 | 21 | 3 | 20 | 3 | 699 | 100 |

respondents (>45 dB(A)) with regard to the sound of wind turbines ($\chi^2 = 26{,}51$, df = 8, p<.001).

### 3.4. Annoyance due to wind turbine sound

23% of the respondents reported (on the 5-point annoyance scale) that they were slightly, rather or very annoyed with wind turbine noise when spending time outside their dwelling and 14% when indoors (Table 2). Those who stated that they benefited from wind turbines as owners or otherwise were less annoyed (Table 3 and 4).

Among those who did and did not benefit an equal proportion of respondents reported to be *slightly annoyed* with wind turbine noise outdoor. The proportion of benefiting respondents who were *rather* or *very annoyed* by wind turbine sound was four times lower compared to the non-benefiters (12 versus 3%), a statistically significant difference ($Z_{mwu} = -2.55$, $p<0.05$) despite the fact that respondents who benefited economically were exposed to higher levels of wind turbine sound ($t = -16.1$, $p<0.001$) and noticed the sound of wind turbines more often (Table 3). In the indoor situation serious annoyance from the sound of wind turbines has not been reported at all by economically benefiting respondents. A Fisher Exact test showed a significant difference between benefiting and non-benefiting respondents in the indoor situation as well (Fisher Exact = 27.9, $p<0.01$). In order to control for the influence of the factor 'economical benefit', benefiting respondents were eliminated from further analysis.

In Tables 5 and 6 the relation between perception/annoyance and the exposure to the sound of wind turbines is presented for both outdoor and indoor situations. Exposure was categorized in five sound pressure levels (outdoor sound pressure level<30, 30–35, 36–40, 41–45, >45 dB(A) for illustrative purposes.

As can be seen in Table 5, at higher sound pressure levels respondents outdoors reported more annoyance (Spearman's rho = 0.508, $p<0.001$). At a low sound pressure level of <30 dB(A), 4% of the respondents reported annoyance, while at a level of >45 dB(A) this percentage has risen to 66%. The same, though less strongly, holds for the indoor response: at a sound pressure level of <30 dB(A), 2% of the respondents were annoyed by the sound, while at a level of >45 dB(A) 29% of the respondents reported annoyance. Also indoors a significant dose (exposure) response (annoyance) relationship was found (Spearman's rho = .373, $p<0.001$).

### 3.5. Sleep disturbance

In Fig. 2 the relation between the level of wind turbine sound and reported sleep disturbance (waking up at least once a month) due to sound is shown for all respondents (including those with economical benefit). Sleep disturbance increased with increasing sound pressure level, especially at levels over 45 dB(A) where 48% of the respondents reported sleep disturbance. When respondents exposed to sound levels from wind turbines below 30 dB(A) were chosen as controls in a binary logistic regression, while adjusting for age, gender and economical benefit, being disturbed in sleep was statistically higher among respondents exposed to sound pressure levels above 45 dB(A) (OR 2.98, 95% Cl 1.347–6.597).

Table 7 shows the sound sources to which sleep disturbance was attributed. Two thirds of all respondents reported not to be disturbed by any sound at all. Disturbance by traffic noise or other mechanical sounds was reported by 15.2% of the respondents. Disturbance by the sound of people (varying from 'teenagers leaving the disco' to 'snoring partner') and of animals (such as barking dogs and crowing roosters) was reported by 13.4% and disturbance by the sound of wind turbines by almost 4.7% of the respondents (6% in a quiet area type and 4% in a noisy area type). As can be expected, sleep disturbance by the sound of people and/or animals and by the sound of traffic and/or mechanical sounds is more frequently reported in noisy areas, while sleep disturbance by the sound of wind turbines is more frequently reported in quiet areas.

### 3.6. Psychological distress

As can be seen in the correlation matrices in the appendix there is a positive relation between sound exposure and the C-GHQ-score that indicates the level of psychological distress. The more one is exposed to the sound of wind turbines, the more psychological distress is reported. This correlation is significant in quiet areas ($r = 0.208$, $p<0.05$) and in all (quiet and noisy) area types ($r = 0.160$, $p<0.01$).

**Table 3**
Response to outdoor wind turbine sound among economically benefitting and non-benefitting respondents.

| | Response | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Do not notice | | Notice, not annoyed | | Slightly annoyed | | Rather annoyed | | Very annoyed | | Total | |
| | n | % | n | % | n | % | n | % | n | % | n | % |
| No economical benefit | 255 | 44 | 184 | 31 | 78 | 13 | 41 | 7 | 28 | 5 | 586 | 100 |
| Economical benefit | 15 | 15 | 68 | 69 | 13 | 13 | 2 | 2 | 1 | 1 | 99 | 100 |

**Table 4**
Response to indoor wind turbine sound among economically benefitting and non-benefitting respondents.

| | Response | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Do not notice | | Notice, not annoyed | | Slightly annoyed | | Rather annoyed | | Very annoyed | | Total | |
| | n | % | n | % | n | % | n | % | n | % | n | % |
| No economical benefit | 394 | 68 | 98 | 17 | 46 | 8 | 21 | 4 | 20 | 4 | 579 | 100 |
| Economical benefit | 53 | 54 | 39 | 39 | 7 | 7 | 0 | 0 | 0 | 0 | 99 | 100 |

**Table 5**
Response to wind turbine sound outdoors in relation to 5 dBA-intervals of sound levels; only respondents who did not benefit economically from wind turbines.

| Response outdoors | Sound pressure level, in dBA | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | <30 | | 30–35 | | 36–40 | | 41–45 | | >45 | | Total | |
| | n | % | n | % | n | % | n | % | n | % | n | % |
| Do not notice | 124 | 75 | 92 | 46 | 30 | 21 | 7 | 12 | 2 | 10 | 255 | 44 |
| Notice, but not annoyed | 34 | 21 | 71 | 36 | 52 | 37 | 22 | 37 | 5 | 24 | 184 | 31 |
| Slightly annoyed | 4 | 2 | 20 | 10 | 30 | 21 | 16 | 27 | 8 | 38 | 78 | 13 |
| Rather annoyed | 2 | 1 | 13 | 7 | 19 | 14 | 4 | 7 | 3 | 14 | 41 | 7 |
| Very annoyed | 2 | 1 | 3 | 2 | 9 | 6 | 11 | 18 | 3 | 14 | 28 | 5 |
| Total | 166 | 100 | 199 | 100 | 140 | 100 | 60 | 100 | 21 | 100 | 586 | 100 |

### 3.7. Not noticing versus noticing wind turbine sound

The hypothesized model was tested with SEM among respondents who did not notice sound from wind turbines (n = 323) and among those who reported that they noticed and/or were annoyed by the sound (n = 243). Among those who did not notice wind turbine sound exposure to this sound has no impact on either sleep disturbance or psychological distress, but sleep disturbance predicted psychological distress (r = 0.17) (Fig. 3). The explained variance of psychological distress in this model was 5%. The model showed good fit with the data (Swain corrected chi-square 1.49, df = 1, p = 0.22, RMSEA = 0.04).

Among respondents who reported that they noticed or/and were annoyed by wind turbine sound psychological distress was also not predicted directly by sound exposure (Fig. 4). Exposure led however to annoyance (r = 0.27) that in turn predicted psychological distress directly (r = 0.17) as well as sleep disturbance (r = 0.55). The regression weight between sleep disturbance and psychological distress did not reach statistical significance. The model fit was acceptable (Swain corrected chi-square 0.042, df = 3, Swain corrected p-value = 0.042, RMSEA = 0.08) and 9% of the variance in psychological distress was explained.

### 3.8. Noisy versus quiet area

Exposure to sound from wind turbines did not lead to noise annoyance among respondents who lived in areas classified as noisy and reported that they could hear the wind turbine sound (n = 147). Annoyance with wind turbine noise was in this group highly related to sleep disturbance (r = 0.60), but not statistically significant to psychological distress (Fig. 5). The model showed good fit (Swain corrected chi-square 2.8, df = 3, Swain corrected p-value = 0.42, RMSEA < 0.001).

Sound exposure predicted noise annoyance (r = 0.54) among respondents who reported that they could hear wind turbine sound and lived in areas classified as quiet (n = 118). Annoyance was in turn related to sleep disturbance (r = 0.46). Psychological distress was not statistically significantly explained by any of the included variables (Fig. 6). The model showed an acceptable fit (Swain corrected chi-square 10.0, df = 3, Swain corrected p-value = 0.02, RMSEA = 0.14).

**Table 6**
Response to wind turbine sound indoors in relation to 5 dBA-intervals of sound levels; only respondents who did not benefit economically from wind turbines.

| Response indoors | Sound pressure level, in dBA | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | <30 | | 30–35 | | 36–40 | | 41–45 | | >45 | | Total | |
| | N | % | n | % | n | % | n | % | n | % | n | % |
| Do not notice | 144 | 86 | 140 | 73 | 85 | 61 | 18 | 30 | 7 | 33 | 394 | 68 |
| Notice, but not annoyed | 19 | 11 | 27 | 14 | 29 | 21 | 15 | 25 | 8 | 38 | 98 | 17 |
| Slightly annoyed | 2 | 1 | 16 | 8 | 14 | 10 | 12 | 20 | 2 | 10 | 46 | 18 |
| Rather annoyed | 0 | 0 | 6 | 3 | 6 | 4 | 6 | 10 | 3 | 14 | 21 | 4 |
| Very annoyed | 2 | 1 | 2 | 1 | 6 | 4 | 9 | 15 | 1 | 5 | 20 | 4 |
| Total | 167 | 100 | 191 | 100 | 140 | 100 | 60 | 100 | 21 | 100 | 579 | 100 |

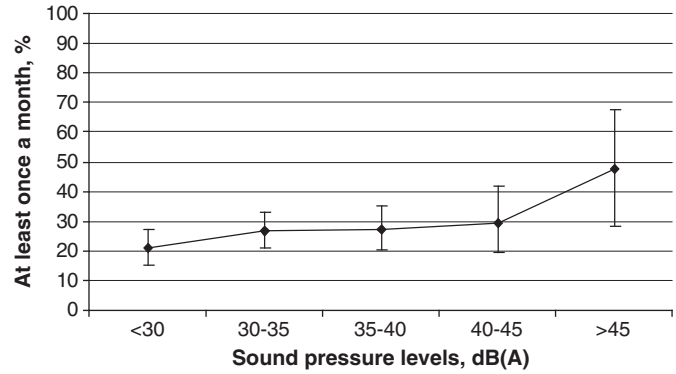


**Fig. 2.** Relation between levels of wind turbine sound and reported sleep disturbance (any sound source) with 95% confidence intervals.

## 4. Discussion and conclusion

This study was guided by five research questions, presented in the Introduction and visualized in Fig. 1. Based on the results of this study we will formulate answers to these questions and discuss the plausibility of the model.

### 4.1. Sound exposure and annoyance

Part of the respondents living in the vicinity of wind turbines reported to be annoyed by their sound, both outdoors (24%) and indoors (14%). Of those that noticed the sound two out of three respondents were not or only slightly annoyed. As can be expected, the level of annoyance depended on the level of exposure to their sound; a higher exposure increased the chance of being annoyed. Obviously, no annoyance was reported among respondents who did not notice the sound of wind turbines. Apart from the level of sound exposure, there are indications that annoyance also depends on psychological factors. Among respondents that benefited economically from wind turbines the proportion of people who were rather or very annoyed was significantly lower, as if wind turbine sound was differently valued by them compared to non-benefiting respondents. This finding is in line with literature (Pulles et al., 1990). This was despite the fact that benefiting respondents were generally exposed to higher sound levels.

Sound exposure predicted annoyance when the proposed model was tested among those who reported that they noticed the sound. This prediction was statistically significant for respondents living in quiet areas, but not for those in noisy areas. A simple explanation may be that in the built-up area type (part of the noisy area type) the high exposure class is underrepresented (Table 1), so there is a smaller range of exposure. It could also be due to the presence of higher levels of background sound reducing annoyance due to masking effects, even if this is not always the case as discussed below. Other differences

**Table 7**
Sound sources of sleep disturbance in rural and urban area types, only respondents who did not benefit economically from wind turbines.

| Sound source of sleep disturbance | Rural | | Urban | | Total | |
|---|---|---|---|---|---|---|
| | n | % | n | % | n | % |
| Not disturbed | 196 | 69.8 | 288 | 64.9 | 484 | 66.8 |
| Disturbed by people/ animals | 33 | 11.7 | 64 | 14.4 | 97 | 13.4 |
| Disturbed by traffic/ mechanical sounds | 35 | 12.5 | 75 | 16.9 | 110 | 15.2 |
| Disturbed by wind turbines | 17 | 6.0 | 17 | 3.8 | 34 | 4.7 |
| Total | 281 | 100 | 444 | 100 | 725 | 100 |

between the area types also could influence the dose response relationship. The visual impact of wind turbines has been previously shown to be more pronounced in rural areas when compared to more densely populated areas (Pedersen and Larsman, 2008). Finally, reactions to environmental sound and people's perceptions can be influenced by their expectations about future exposures. Schreckenberg et al. (2010) conducted a survey on the environmental and health related quality of life among residents living near Frankfurt Airport. The results of their study indicate a higher noise annoyance than could be predicted from general exposure–response curves, leading them to the conclusion that source related attitudes, such as expectations concerning future airport expansion and trust in authorities' efforts to reduce aircraft noise, were also associated with being annoyed by aircraft noise.

### 4.2. Annoyance and sleep disturbance

As is the case with annoyance, sleep disturbance increased with increasing sound pressure level due to wind turbines, but this increase is significant only at high levels. Sleep disturbance may not be caused by the sound of wind turbines only, but also by other environmental sounds such as traffic noise or other mechanical sounds or sounds of people and animals. It is not clear from this study if there is a primary source causing sleep disturbance and how respondents attribute being awakened by different environmental sound sources. Wind turbines are less frequently reported as a sleep disturbing sound source than these other environmental sounds, irrespective of the area type. Nevertheless, the Structural Equation Models show that among respondents who notice the sound of wind turbines annoyance is the only factor in the equation that predicts sleep disturbance. This holds for all area types, i.e. quiet, noisy and total (both combined). A possible explanation might be that being annoyed contributes to a person's sensibility for any environmental sound, and the reaction may be caused by the combination of all sounds present. The significant increase in sleep disturbance at sound pressure levels of 45 dB(A) and higher is close to the recommendation of the WHO that an average outdoor noise level at night should be no more than 40 dB(A) (see Introduction).

### 4.3. Annoyance and psychological distress

Psychological distress was in the model predicted by annoyance due to wind turbine sound among those who noticed the sound. In the separated (noisy or quiet) area types the associations were no longer statistically significant, possibly due to the lower number of respondents in these sub samples. One could argue that in noisy or quiet area types sleep disturbance could act as an intermediate variable, but the structural model does not support this assumption, since in none of the models sleep disturbance and psychological distress are significantly related.

### 4.4. Sound exposure and psychological distress

Sound exposure and psychological distress showed a significant positive correlation, indicating that higher exposure leads to more distress. In the SEM-analyses such a relation did not show up in the direct sense, but indirectly with annoyance as an intermediate variable. Among those who reported that they noticed the sound, annoyance due to wind turbine sound can be considered as a mediator between sound exposure and sleep disturbance and also between sound exposure and psychological distress.

Among people who were not noticing the sound of wind turbines no significant pathways between sound exposure and psychological distress can be distinguished in the SEM analyses. However, there seems to be a relation between sleep disturbance and psychological distress irrespective of exposure to wind turbine noise (Fig. 3 in Appendix 1), but here sleep disturbance only explains 5% of the variation of psychological distress.

### 4.5. Is the model supported?

Based on the structural equation models of this study it can be concluded that the model that has been presented in Fig. 1 can partially be supported. The extent of exposure to the sound of wind turbines appears to have a proportional impact on the level of annoyance of people living in their vicinity: the more one is exposed, the more one is annoyed. This conclusion holds not for those who are economically benefiting from wind turbines. Though they are mostly highly exposed, they report significantly less annoyance than non-benefitting respondents do. This study indicates that annoyance can lead to sleep disturbance and psychological distress. There appears to be no 'direct' relation between exposure to the sound of wind turbines and self-perceived sleep disturbance or psychological distress. Annoyance can be regarded as an intermediate state between sound exposure and psychological distress in the combined (quiet and noisy) area, and between sound exposure and sleep disturbance in combined and quiet areas. The hypothesis that sleep quality would be an intermediate factor between sound exposure and psychological distress was not confirmed.

The fact that the model is tested in different subsamples allows us to draw conclusions that are worth considering when planning new wind farms close to residents. People who live close to wind turbines and do not benefit economically will be at risk to experience sleep disturbance and psychological distress. This risk increases with increasing sound levels. However, this will not apply to all residents, but only to those who are annoyed by the sound. People who do not notice the sound will not be adversely affected by non-audible sound as the test of the model among not noticing respondents showed. Among those who do notice the sound there appears to be no direct influence of the sound on sleep disturbance or psychological distress, meaning that those who are not annoyed by the noise will not be affected. Only those who are annoyed by the noise are at risk of being disturbed in their sleep and/or of being distressed. This risk is more pronounced in quiet areas compared to noisy areas as the link between the sound levels and annoyance is stronger in these areas.

### 4.6. Suggestions for further research

In this study design we worked with a model that was based on hypotheses regarding relations between five central variables that stem from the literature on the impact of environmental sound sources on psychological distress and health. It is obvious that explanatory variables are missing, because sleep disturbance and psychological distress do not depend on noise exposure only. This is reflected by the low percentages of explained variance in the structural models; percentages however that are quite common in field research. Future research should add possible factors of influence, both individual and social, in order to further increase the understanding of adverse effects related to wind turbine noise.

Such research could also address the question if in noisy areas the absence of significant relations between sound exposure and annoyance on the one hand and between annoyance and psychological distress on the other can be explained by the noisier environment, which might in part mask the sound of wind turbines. Another question that is worth considering is the question whether people who live in noisier areas are perhaps better habituated to noise.

Data on psychological distress were gathered through questionnaires in this study. A recent Dutch study showed that self-reported data and primary care data from general practitioners (GPs) in urban and rural areas render different results (Kroneman et al., 2010). Self-reported health problems point to a perceived better health in rural than in urban areas, whereas, according to GP records, acute somatic and chronic diseases occur more often in rural than in urban areas. Although self-reported physical and mental health are important health indicators, these findings indicate that more

objective data can be useful when exploring the complicated relationship between (wind turbine) noise and psychological distress.

## Appendix 1. Structural equation models (Figs. 3 through 6)

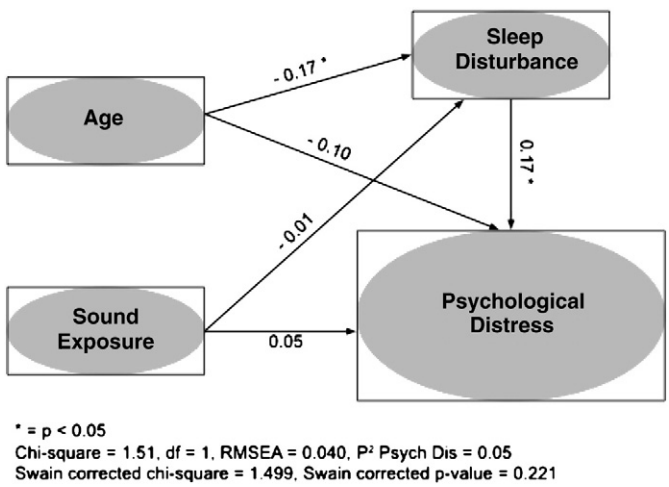


**Fig. 3.** Structural model with age, sleep disturbance, exposure to wind turbines and psychological distress (as a dependent variable) among people who were not noticing the sound of wind turbines and have no economical benefit (n = 265).

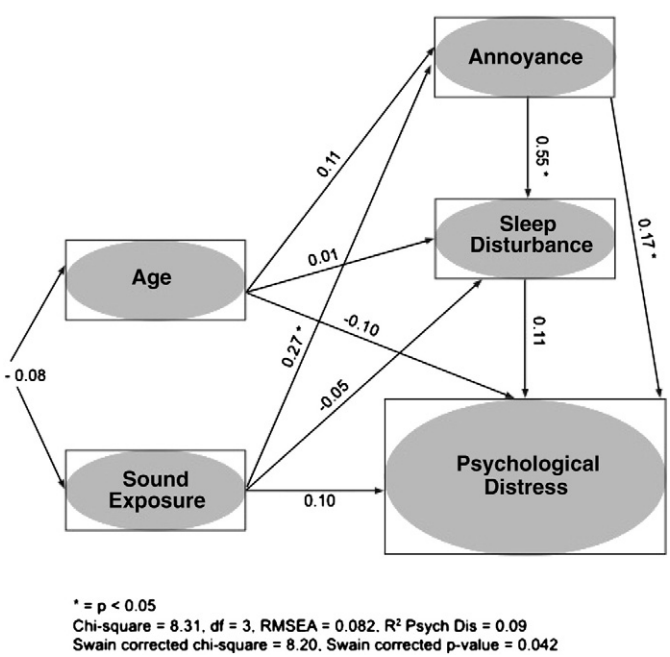


**Fig. 4.** Structural model with age, annoyance, sleep disturbance, exposure to wind turbines and psychological distress (as a dependent variable) among people who were noticing the sound of wind turbines and have no economical benefit (n = 265).

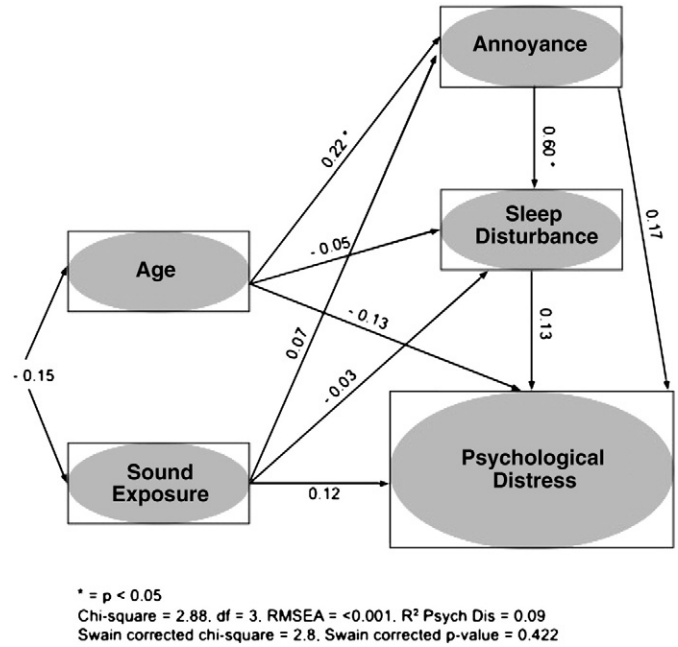


**Fig. 5.** Structural model with age, annoyance, sleep disturbance, exposure to wind turbines and psychological distress (as a dependent variable) among people who were noticing the sound of wind turbines, have no economical benefit and live in noisy area types (n = 147).

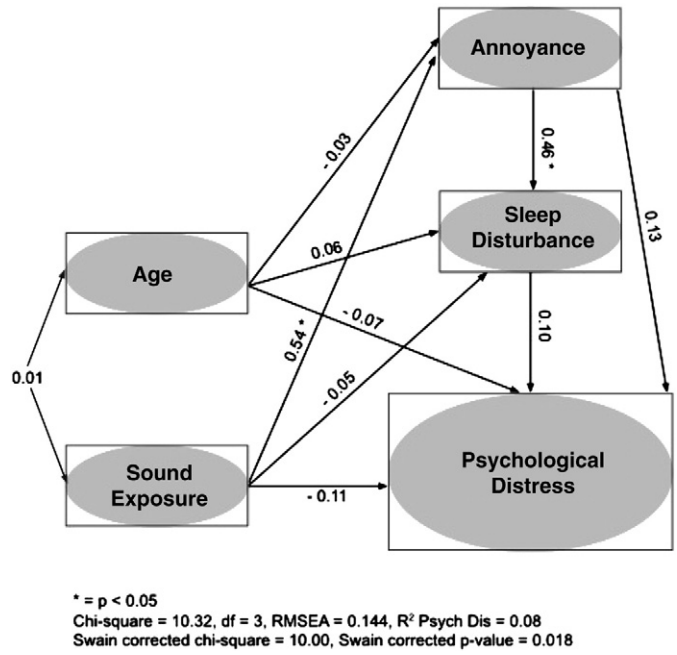


**Fig. 6.** Structural model with age, annoyance, sleep disturbance, exposure to wind turbines and psychological distress (as a dependent variable) among people who were noticing the sound of wind turbines, who have no economical benefit and who live in quiet area types (n = 118).

## Appendix 2. Table 8 Correlation matrices

| | Sleep disturbance | Psychological distress | Age |
|---|---|---|---|
| *Quiet + noisy do not notice (n = 323)* | | | |
| Sleep disturbance (m = 1.7, SD = 1.2) | | | |
| Psychological distress (m = 3.3, SD = 2.8) | .191 ** | | |
| Age (m = 56.8, SD = 15.9) | .172 ** | −.129 * | |
| Sound exposure (m = 31.4, SD = 4.2) | .005 | .053 | −.068 |

| | Annoyance outside | Annoyance inside | Sleep disturbance | Psychological distress | Age |
|---|---|---|---|---|---|
| *Quiet + noisy do notice (n = 265)* | | | | | |
| Annoyance outside (m = 3.4, SD = 3.2) | | | | | |
| Annoyance inside (m = 1.9 SD = 3.0) | .781** | | | | |
| Sleep disturbance (m = 2.0, SD = 1.3) | .444** | .493** | | | |
| Psychological distress (m = 3.7, SD = 2.8) | .184** | .243** | .205** | | |
| Age (m = 53.4, SD = 13.8) | .116 | .084 | .071 | −.077 | |
| Sound exposure (m = 36.9, SD = 4.9) | .281** | .206** | .094 | .160** | −.084 |
| *Noisy do notice (n = 147)* | | | | | |
| Annoyance outside (m = 3.5, SD = 3.1) | | | | | |
| Annoyance inside (m = 2.0, SD = 3.0) | .782** | | | | |
| Sleep disturbance (m = 2.1, SD = 1.3) | .499** | .534** | | | |
| Psychological distress (m = 3.7, SD = 3.0) | .174* | .217** | .220** | | |
| Age (m = 54.7, SD = 13.8) | .236** | .157 | .084 | −.087 | |
| Sound exposure (m = 36.6, SD = 4.9) | .057 | .065 | .014 | .130 | −.146 |
| *Quiet do notice (n = 118)* | | | | | |
| Annoyance outside (m = 3.3, SD = 3.4) | | | | | |
| Annoyance inside (m = 1.9, SD = 2.9) | .783** | | | | |
| Sleep disturbance (m = 2.0, SD = 1.3) | .380** | .438** | | | |
| Psychological distress (m = 3.6, SD = 2.5) | .201* | .282** | .182* | | |
| Age (m = 51.8, SD = 13.6) | −.027 | −.012 | .045 | −.065 | |
| Sound exposure (m = 37.2, SD = 5.1) | .533** | .382** | .200* | .208* | .007 |

* = p < 0.05, ** = p < 0.01.

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