Attention Problems in Relation to Sleeping Problems in Those that Experience Low Frequency Noise

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Abstract

Nuisance due to noise can be a serious health hazard. A specific type of noise, Low Frequency Noise (LFN), is currently still understudied. Nevertheless, those experiencing LFN often report physical, social, and (neuro)psychological problems. Therefore, this study aimed to further investigate the neuropsychological complaints of attention difficulties and sleeping problems. It was hypothesized that the LFN group would score significantly worse on subjective and objective attention measures, as well as the subjective sleep measure compared to controls. Additionally, since sleep and attention are related in the general population, it was hypothesized that the relationship between LFN and attention deficits was mediated by sleeping problems. The study had an observational design where those that experience nuisance due to LFN (n=194) were compared on the subjective measure to those that do not (n=668). Additionally, a subsample was compared on neuropsychological performance measures. Results showed that the LFN group reported significantly more subjective attention and sleep problems compared to controls. However, no differences were found on the objective attention measures. Furthermore, sleeping problems mediated the relationship between LFN and subjective attention deficits. These results suggest that nuisance due to LFN might affect attention on a day-to-day basis, but peak performance might be intact. Furthermore, the possibility that the observed subjective sleeping problems are better predicted by attitudes towards LFN as opposed to the LFN itself is discussed. Lastly, the mediating role of sleep suggests that some complaints, like attention difficulties, might be secondary and therefore not directly caused by the perception of LFN.

Keywords: Low Frequency Noise, Neuropsychological complaints, Attention Deficits, Sleep Problems

The Relationship between Sleeping Problems and Attention Deficits in Those that experience Low Frequency Noise

Introduction

Noise has become the number one leading environmental nuisance in Europe according to the World Health Organization (WHO) (2010). Furthermore, the WHO reports that exposure to environmental noise can negatively impact health (e.g., by annoyance, sleep disturbance, cardiovascular disorders). Despite extensive research on environmental noise in general, a specific stressor called Low Frequency Noise (LFN) is understudied in scientific literature (Erdélyi et al., 2019). LFN is defined as noise around the human hearing threshold (around 100/125 Hz) that is annoying or unpleasant for those who perceive it (Rijksinstituut voor Volksgezondheid en Milieu, 2014). This type of noise is often generated by mechanical sources such as wind turbines, air coolers, or (air) traffic, however, noise produced by nature, such as the wind or sea, are also possible sources. Nevertheless, it is often difficult to attribute the noise to one source. Additionally, currently used measuring instruments to assess noise are not suitable for measuring LFN specifically (Leventhall et al, 2003). This can result in an underestimation or a missing LFN detection altogether. Still, around 2-10% of the Dutch adult population is estimated to experience severe nuisance due to LFN (Van Kamp et al., 2018). Yet, it is still unclear why some people are more sensitive to this type of noise than others (Erdélyi et al., 2019). Common complaints are a broad scope of medical and physical complaints (e.g., sleeping problems, headache, or heart palpitations), as well as psychological and social problems (e.g., stress, depression, or incapacity to work) (Erasmus et al., 2018). Specific neuropsychological complaints are problems with concentration, attention, memory, or completing cognitively demanding tasks (Erdélyi et al., 2019).

However, previous scientific findings on these neuropsychological complaints have been inconclusive due to inconsistencies in methods used and results found. Examples of differences in methodologies are the use of subjective measures such as questionnaires (Pohl et al., 2018) or objective measures such as neuropsychological tests (Alimohammadi et al, 2012), and experimental designs where LFN was manipulated (Waye et al., 2001) opposing correlational designs where people living near LFN sources were assessed (Bakker et al., 2012). Additionally, the consistency of samples diverges from exclusively students (Alimohammadi & Ebrahimi, 2017) to people living near one specific source of LFN (Pohl et al., 2018) and to participants who normally do not experience nuisance due to LFN (Waye et al. 2001). Besides, few studies differentiate between participants with high and those with low sensitivity for LFN (Erdélyi et al., 2019), even though it has been found that those highly sensitive to LFN experience higher rates of annoyance and impaired working capacity compared to those low in sensitivity (Waye et al., 2001). Ultimately, the differences in measures, study design, and sampling complicate the comparison of results. Additionally, the studies on the effect of LFN on mental performance show mixed results and support different conclusions. These include both positive (Alimohammadi & Ebrahimi, 2017) and negative (Kyriakides & Leventhall, 1976) effects of LFN on task performance, as well as no differences (Waye et al., 2001). Therefore, a definite conclusion on the effects of LFN on neuropsychological functioning has not been drawn yet. Additional research into the neuropsychological complaints experienced by those perceiving LFN is needed to move toward consensus.

One of the complaints that show inconsistent results and which are frequently reported by people who experience LFN are deficits in attention (Erdélyi et al., 2019). Attention, being defined as the differential allocation of information processing resources (Klein & Lawrence., 2012), is inherently linked to other cognitive functions (Petersen & Posner, 2012). To successfully carry out various tasks, a certain extent of attention is required, for instance allocating attention to relevant objects, suppressing distractions, or sustaining attention for a longer period of time. These different properties of attention are summarized in a multicomponent model of attention proposed by Van Zomeren and Brouwer (1994). Namely, the properties of intensity, selectivity, and supervisory control. This study will only consider the intensity aspect of attention, which refers to the ability to be prepared to react over time. This aspect comprises both, alertness and vigilance. Alertness is the ability to activate attention in response to the environment like a state of generalized readiness, which is used in tasks such as responding quickly when trying to catch something that is falling. Vigilance refers to the ability to sustain attention over a long period of time and focus on one or more sources of information while being able to detect and respond to (small) changes. Typically, relevant stimuli appear rarely and infrequently compared to irrelevant stimuli. This is used, for instance, while driving on a quiet highway. Consequently, attention deficits often lead to problems in everyday functioning. This emphasizes the importance of delineating the subjective reports of individuals perceiving LFN with objective measures.

However, experimental studies using objective measures of attention to determine the effect of LFN report mixed results. Regarding alertness, Pawlaczyk-łuszczyńska and colleagues (2005) used a task in which participants had to indicate whether a couple of words appearing in two columns were identical. No significant differences in task performance, meaning the number of errors made, were observed for both the exposure conditions (LFN or flat frequency noise of 500Hz) and the sensitivity conditions (high or low sensitivity to noise in general). Concerning reaction times, Waye and colleagues (2001) used an attention task in which participants had to push a button when a red square appeared on the screen. Results showed no main effect on reaction time between a LFN and a Flat Frequency Noise condition. Nevertheless, they did find longer reaction times in the LFN condition for those sensitive to noise in general compared to the flat frequency noise condition, whilst the reaction times of those low in sensitivity were similar in both conditions. On the other hand, two studies by Alimohammadi and colleagues observed faster task completion and improved performance on an alertness task when participants were exposed to LFN compared to a silence condition (Alimohammadi et al., 2012; Alimohammadi & Ebrahimi, 2017). This task entailed indicating whether figures appearing on a screen were identical by pressing a green button if the answer was yes and a red button if no. However, faster task completion and improved performance were also found in a High Frequency Noise (500 to 8000 Hz) condition compared to a silence condition. Still, those in the LFN condition had a faster completion time than those in the High Frequency Noise condition. Taken together, since the main significant findings are between noise and no noise conditions, this could mean that short-term exposure to noise (Low, High, or Flat frequency) may increase arousal and therefore elevate alertness. Yet, this does not fit the findings of Waye and colleagues (2001) where those sensitive to noise in general had longer reaction times. Also, it remains unclear what the effects of long-term exposure to LFN on alertness are. Notably, all mentioned studies contained a sample of participants who do not experience nuisance due to LFN in daily life. However, the sensitivity aspect could be tied to long-term exposure since LFN can be perceived in daily life. As for now, previously discussed results suggest that sensitivity to noise may influence speed but not performance during short-term exposure.

Concerning vigilance, experimental studies using objective attention measures also showcase mixed results. For instance, Kyriakides and Leventhall (1976) report a performance decrement on their measures. For 40 minutes, participants executed a task that resembled driving a car during which they simultaneously performed a task that entailed responding to four lamps. Two of which were in the front of the participants' visual field and two in the periphery. Their results showed that when participants were exposed to infrasound (2 to 15 Hz) there were no differences on performance or speed compared to when they were exposed to the control condition consisting of background noise at a 70dB level. However, they did observe a decrement in both, the pointer task and the lamp task (central and peripheral) on speed and performance. Kyriakides and Leventhall (1976) argue that when the task would have a longer duration, this decrease might become significant. This could mean that short-term exposure to LFN might leave task performance and speed relatively unaffected, however, daily and thus prolonged exposure might lead to significant changes. In a similar experiment, participants had to carry out a attention task whilst simultaneously reacting to four lamps (Waye et al., 2001). Here all lamps were placed in the periphery of the visual field. The total amount of time executing the task was 12 minutes. Results showed no significant differences on speed or performance measures in general between a flat and a low frequency noise condition. However, participants who were sensitive to LFN had a longer reaction time on the lamp task in both the Low and Flat Frequency Noise condition. Based on this finding, it could be a possibility that Kyriakides and Leventhall's (1976) decrement in reaction time was not significant because there was no differentiation between those sensitive to LFN and those who are not. This suggests that significantly longer reaction times might already be present during short-term exposure for those sensitive to LFN. Since both studies found no significant difference on task performance, this might stay relatively unaffected or might only show up when tasks take up a larger amount of time than the discussed studies. All in all, the literature concerning LFN and attention cannot give an unequivocal explanation of the subjective attention deficits of those experiencing nuisance due to LFN.

Another common complaint among people who experience LFN is sleeping problems (Erdélyi et al., 2019; Van Kamp et al., 2018; Leventhall et al., 2003). This is illustrated by a descriptive study where 90% of those experiencing nuisance due to LFN reported sleeping difficulties (Erdélyi et al., 2023). Additionally, a systematic review by Baliatsas and colleagues (2016) found a significant association between being exposed to LFN and sleep-related problems. In general, sleep is an influential factor in a variety of daily functions, among which are emotion regulation, memory, reasoning, dietary behaviors, exercise habits, and more (Grandner & Fernandez, 2021). Thus, compromised sleep could heavily affect daily functioning in those who experience LFN. Even though sleep is often a variable measured in past research, the majority of studies measure sleep quite unspecific. For example, questionnaires would only ask how frequently sleep disturbance is experienced (Bakker et al., 2012), but not report the type of sleeping problems. Some studies report somewhat specific problems such as loss of sleep (Leventhall et al., 2003) or being hindered from falling asleep and reduced sleep quality (Pohl et al., 2018). However, most questions about sleep are a small part of a self-report questionnaire and focus on whether or not sleeping problems in general are present.

Moreover, sleep and attention are concepts that are found to be related in the general population (Leproult et al., 2003; Van Dongen et al., 2003). Accordingly, feeling less attentive as a result of lack of sleep is a common complaint heard. Specifically, concerning alertness, it has been established that sleep deprivation in a study by Leproult and colleagues (2003), measured by extending the wakefulness period to 27 hours, results in an increase in the number of attention lapses as well as an increase in reaction time. Attention lapses were a measure of task performance and were defined as a reaction time that exceeded the ninety-ninth percentile of the distribution of reaction times measured during the normal wakefulness period (10:00-23:00). Similar results have been found for vigilance, showing that multiple successive nights of sleep restriction led to an increase in attention lapses (Van Dongen et al., 2003). The fewer hours of sleep participants got; the more attention lapses they had. These lapses were defined in this study as a reaction time greater than 500 ms, again being a measure of both, task performance and speed. In summation, compromised sleep seems to affect the intensity aspect of attention in the general population. As mentioned before, those who perceive LFN, frequently describe sleeping problems as well as attention deficits. Therefore, the relationship between perceiving LFN and reported attention deficits might be mediated by sleeping problems.

Considering all information provided, it can be stated that the perception of LFN can have a great negative impact on daily living. Yet, research findings are still inconclusive, especially regarding objective measurements of neuropsychological functioning, including alertness and vigilance. Additionally, those perceiving LFN often report sleeping problems. Since lack of sleep is found to be negatively associated with alertness and vigilance in the general population, the question arises whether this association is similar for those who experience LFN. Accordingly, this study aims to explore the attention functioning in those that experience LFN in daily life. Secondly, this study aims to investigate the sleeping problems and their possible mediating role between LFN and attention problems. An observational research design will be used to compare a group of people who experience nuisance due to LFN in their daily life with a control group who does not perceive nuisance due to LFN. Subjective attention and sleep measures will be used to assess whether the LFN group experiences more attention deficits and more sleeping difficulties compared to the control group. Further, objective attention measures will be used to assess how the LFN group performs on psychometric performance tests compared to the control group. The following hypothesis will be explored:

H1: The LFN group will score significantly worse on subjective and objective measures of attention compared to the control group.

H2: The LFN group will report significantly more sleeping problems compared to the control group.

H3: The relationship between LFN and attention deficits is mediated by sleeping problems.

Methods

Participants

The sample consisted of Dutch adults divided into an LFN group and a control group. Inclusion criteria for the LFN group were reports on perceiving LFN and complaints regarding daily living due to LFN. Participants of the control group did not perceive LFN. Exclusion criteria for both groups were neurological or psychiatric disorders (e.g., dementia or epilepsy), which could confound the perception of LFN, the complaints in daily living, or the outcome measures of sleep or attention. Furthermore, participants were asked whether they had tinnitus. Tinnitus is defined as "a prevalent auditory perception in absence of a corresponding acoustic source, usually described as ringing in one or both ears." (Czornik et al., 2022, p. 40). Tinnitus and LFN have similar symptoms and can be difficult to distinguish, however, they are not mutually exclusive. Hence, in this study, it was decided not to exclude participants with tinnitus.

For the subjective attention and sleep measures, the LFN group (n = 194) was recruited via the Stichting LaagFrequentgeluid, a foundation where people who perceive LFN can report complaints and find information, and snowball sampling. The control group (n = 668) was mainly (C_1 = 639) recruited via PanelInzicht, an online research platform. On this platform, the control group was recruited to show similar demographic characteristics to the LFN group in terms of gender (female/male), age (divided into the age categories of 18–34, 35–49, and 50–87 years), and education (low, middle, high). Since the questionnaire's duration was longer than allowed according to the guidelines of the platform, it was split into two parts. Therefore, both halves were filled in by different participants (C_{1a} = 366, C_{1b} = 273) but with the same group demographics. The remainder of the control group consisted of a subsample of the control group of the objective measures (C_0 = 29) (see below for details).

For the objective attention measures, the LFN group (n = 73) consisted of those who filled in the subjective attention measures and were interested in participating in a neuropsychological assessment. Control participants (n = 38) were recruited amongst acquaintances of the LFN group and amongst people who participated in previous scientific research at the Clinical Neuropsychology Department of the University of Groningen and indicated that they would want to participate again in other research. Additionally, master students recruited people from their environment.

In terms of demographic characteristics participants' education level was assessed according to the Dutch education system and coded as follows: 0 = 'Lagere school', 1 = 'LBO, VMBO basis, VMBO kader, VMBO-gl, LTS or LEAO', 2 = 'MBO, VMBO-t, MULO, MAVO, MTS or MEAO', 3 = 'HAVO', 4 = 'Atheneum or Gymnasium', 5 = 'HBO, HEAO, Pabo or HTS', 6 = 'University Bachelor', 7 = 'University Master', or 8 = 'Different, namely'. Education level 0 to 1 was considered 'low', 2 to 4 'middle', and 5 to 7 'high'. Regarding education, in both the objective and subjective measures sample the LFN group showed significantly more participants to be in the "low" category compared to the control group, χ^2 = 27.10, df = 2, $p < .001$, φ = .17, χ^2 = 33.10, df = 2, $p < .001$, φ = .20. Additionally, due to the deletion of 84 participants (24.9%) because of incomplete questionnaires in the sample that filled out the subjective measures, the demographics of the final data set shifted. This resulted in the control group being significantly older than the LFN group, t (353) = -2,023, $p = 0.44$, d = -0.15. However, the range was similar and the difference between the mean ages entailed two years. Therefore, the difference was deemed to be negligible. Furthermore, C_0 was found to have a significantly lower mean age compared to C_{1a}, t (366) = 5,783, $p < .001$, $d = 0.58$ and C_{1b}, t (273) = 5,788, $p < .001$, $d = 0.67$. This can be explained by the fact that these participants were recruited amongst acquaintances of master students. A detailed description of the sample characteristics can be found in Table 1.

Materials

Subjective Measures

Attention. The Questionnaire for Complaints of Cognitive Disorders (FLei) is a questionnaire with 35 items that assesses subjective complaints of cognitive disturbances (Beblo et al., 2010). The questionnaire was translated into Dutch. Only the subscale 'attention' (α = .93) (comprising items 1, 2, 9, 17, 18, 20, 23, 27, 31, and 35) was used in data analysis. Respondents were asked to rate statements such as "I find it difficult to concentrate for half an hour." or "When reading a novel I lose track of the plot and characters." on a scale from 0 (never) to 4 (very often). Summation of the ratings on the subscale results in a total score ranging from 0 to 40, where higher scores indicate more subjective disturbance in attention. Moreover, participants were categorized as "impaired" or "nonimpaired" on their attention function based on their percentile scores. Participants with percentile scores

Table 1

Demographic Characteristics of the LFN and Control Groups

	Subjective measures					Objective measures	
	LFN n=(194)	Control total n=(668)	Control C_0 n=(29)	Control C_{1a} n=(366)	Control C_{1b} n=(273)	LFN n=(73)	Control n=(38)
Sex							
Females (%)	130 (67.0)	437 (65.4)	16 (55.2)	241 (65.8)	180 (65.9)	46 (63.0)	18 (47.4)
Education* (%)							
Low	13 (6.7)	3 (0.5)	1 (3.4)	2 (0.5)	0 (0.0)	4 (5.6)	1 (2.9)
Middle	59 (30.4)	240 (35.9)	6 (20.7)	141 (38.5)	93 (34.1)	20 (27.8)	10 (29.4)
High	119 (61.3)	418 (62.6)	21 (72.4)	221 (60.4)	176 (64.5)	48 (66.7)	23 (67.6)
	Mean ± SD (Range)						
Age	57.17 ± 11.71 (18-87)	59.16 ± 13.40 (18-89)	44.83 ± 19.10 (20-77)	59.86 ± 12.94 (18-89)	59.76 ± 12.44 (24-85)	57.63 ± 10.39 (33-83)	58.86 ± 11.77 (28-75)

Note. *In total 12 participants did not fill in their education level or reported a different education than the provided categories.

above 84%, thus one standard deviation above a normative average score, were considered to have reported above average attention disturbances and were therefore regarded to show impaired attention functioning. For the FLei attention scale, Beblo and colleagues (2010) report a mean of 9.67 with a standard deviation of 6.53 in a healthy control sample. Consequently, a score above 9.67 + 6.53 = 16.2 was used as a cut-off for attention impairment.

Sleep. The Pittsburgh Sleep Quality Index (PSQI) is a self-report questionnaire to assess sleeping problems ($\alpha = .83$) (Buysse et al., 1989). The questionnaire was translated into Dutch and consists of nineteen items. Examples are: "During the past month, at what time did you usually go to bed?" and "How often do you have problems staying awake while driving, eating, or doing social activities?". The scoring is subdivided into seven components (i.e., subjective sleep quality, sleep latency, sleep duration, habitual sleep efficiency, sleep disturbances, use of sleeping medication, and daytime dysfunction), which are individually scored from 0 to 3 with higher scores indicating worse sleep quality. The summation of scores per component calculates a global score, ranging from 0 to 21. Buysse and colleagues (1989) found that global scores greater than 5 suggest poor sleep quality. Moreover, this cutoff score has a sensitivity of 89.6% and a specificity of 86.5% (kappa = .75, $p < 0.001$) in discriminating between good and poor sleepers. Accordingly, this cut-off was used to determine whether or not an individual was regarded to show impaired sleeping in this study.

Objective Measures

The objective attention measures in this study are part of the Vienna Test System (VTS), a test system for computerized psychological assessments (Schuhfried, 2018). Their Perception and Attention Functions (WAF) test battery comprises tests for all aspects of attention. The whole battery was validated by conducting a factor analysis and a linear structural equation, showcasing good construct validity (Sturm, 2011).

Alertness. The WAFA is a psychometric performance test that assesses alertness (Sturm, 2011). In this study the subtest 'intrinsic (visual) S2' was used ($\alpha = .93$). During this test black circles are presented on the screen to which participants must react as fast as possible by pressing a button. A circle is presented for 1500 ms and then disappears. The test takes approximately five minutes. Across all trials, the mean reaction time was calculated and compared with normative data provided by the VTS which results in a percentile rank score. The norm sample consists of 295 individuals and accounts for age, sex, and education. According to the test manual, individuals with a percentile rank score below 16 were categorized as 'below average', between 16 to 24 as 'low average to slightly below average', between 25 to 75 as ‘average’, between 76 to 84 as “high average to slightly above average’ and above 84 as ‘above average’. Additionally, individuals with percentiles score below 16%, thus one standard deviation below a normative average score, were considered to perform below average and were therefore regarded to show impaired attention functioning on the alertness aspect.

Vigilance. The WAFV is a psychometric performance test that assesses vigilance (Sturm, 2012). In this study the subtest ‘visual -short form S1’ of the WAFV was used (α = .96). During this test squares are presented on the screen. When the square becomes darker, the participant has to react as fast as possible by pressing a button. This color change happens very seldom. The stimuli are presented for 1500 ms; color change may take place after 500 ms. The interstimulus interval between stimuli has a duration of 500 ms. The task has a duration of 15 minutes. The mean reaction time and percentile rank score were calculated and categorized in the same manner as the WAFA. In addition, for the WAFV, mean reaction times for the first and second half of the test were calculated and afterward compared with normative data of the VTS to calculate percentile rank scores. The norm sample for the WAFV consists of 295 individuals and accounts for age, sex, and education. Furthermore, individuals were regarded to show impaired attention functioning on the aspect of vigilance according to the same criteria as stated by the WAFA.

Design

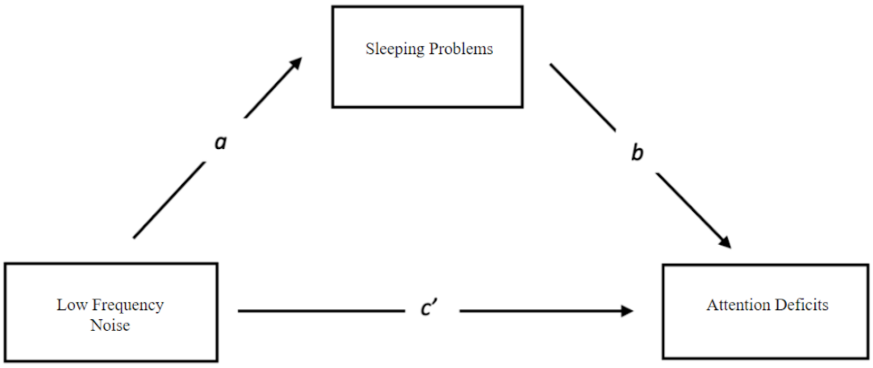
This study has a observational design and is part of a larger study on the effects of perceiving LFN on (neuro)psychological and daily functioning. Participants of the LFN group received an invitation in the form of an online information letter. When interested, participants responded via email and received the questionnaires at home. In total, participants were asked to fill out fourteen questionnaires, including the FLei and PSQI. The complete questionnaire took approximately one and a half hours to complete, and the questionnaires considered in this research approximately 10-15 minutes. Because the control group was split into three groups, C_0 filled in both questionnaires, C_{1a} the Flei, and C_{1b} the PSQI. Upon further interest, participants from the LFN group as well as control participants were invited to come to the Department of Clinical and Developmental Neuropsychology of the University of Groningen for a neuropsychological assessment. This assessment consisted of eighteen separate tests measuring the following domains: attention, executive functioning, memory, IQ, psychiatric symptoms, and performance validity. The WAFA and WAFV were among these measures. In total, the assessment lasted approximately four hours including two breaks of 15 minutes. No financial compensation was provided, however, participants coming for a neuropsychological assessment received travel reimbursements. Control participants recruited by the online research panel received financial compensation according to the panel's policy. All participants gave informed consent. The research was approved by the Ethics Committee of the Faculty of Behavioral and Social Sciences of the University of Groningen.

Analysis

To compare the LFN group to the control group on all attention and sleep measures ANOVAs will be used. Beforehand, to check for normality the Komogorov-Smirnov test will be carried out. The assumption of equal variance will be assessed using boxplots. When assumptions are met, raw scores, as well as percentile scores, will be used to establish group differences. Additionally, the effect size will be estimated using Cohen's *d* and interpreted as small ($d < 0.2$), medium ($0.2 \leq d < 0.5$), or large ($d \geq 0.5$) (Cohen, 1988). Furthermore, to investigate whether the LFN group is more often classified as 'impaired' on all attention and sleep measures compared to the control group, a chi-square test will be conducted. Here, to assess the magnitude of proportion differences, the effect size Cramer's φ will be used and interpreted as small ($\varphi < 0.1$), medium ($0.1 \leq \varphi < 0.25$), or large ($\varphi \geq 0.25$) (Cohen, 1988). Subsequently, to explore the possible mediating role of sleeping problems in the relationship between perceiving LFN and attention deficits, a regression analysis will be carried out (see Figure 1). Firstly, path c, between the variable 'group' and the individual attention measures, will be assessed. Here, for the objective measures, only the raw scores will be used. Furthermore, only significant paths will be taken into account in further analysis. Secondly, path a, between 'group' and sleeping problems, will be assessed. Thirdly, path b, between the sleeping problems and the attention measures will be assessed. Lastly, both 'group' and sleeping problems will be regressed on the attention measures to determine whether or not these variables are significant predictors of the attention measures. The effect size of these predictors will be assessed using R^2 and interpreted as small ($R^2 < 0.2$), medium ($0.2 \leq R^2 < 0.51$), or large ($R^2 \geq 0.51$) (Cohen, 1988).

Figure 1

Schematic Overview of the Hypothesized Mediating Role of Sleeping Problems in the Relation between LFN Perception and Attention Deficits.



Results

Preceding data analysis, outliers were identified using boxplots. This resulted in deleting the WAFV data of six participants because these data points were located outside one and a half times the interquartile range. Additionally, one participants' data of the WAFV was missing most likely due to not finishing the test. Furthermore, the data of one participant on the WAFA was deleted because in the remarks it was stated that the participant had forgotten the rules of the assignment during the assessment. Additionally, the data of one participant was missing most likely due to not finishing the test. A detailed overview of the deleted data points can be found in Appendix A. Furthermore, since the calculation of the total score on the Flei and the global score on the PSQI relies on a complete and correct filled-in questionnaire, some data was not usable to calculate these scores. Hence, data on the PSQI was deleted when participants did not give usable answers (i.e., not answering the question, giving unclear answers like broad time slots, or giving multiple answers). Additionally, data on the FLei was deleted when answers were missing. For a detailed overview of the deleted data on the subjective measures see Appendix B. Moreover, the sample characteristics (see Table 1) were calculated after data removal. Additionally, the Kolmogorov-Smirnov test of normality demonstrated that most data was not normally distributed. Therefore, instead of an ANOVA, the independent samples Mann-Whitney U Test was carried out to compare the LFN and control group. Consequently, to interpret the magnitude of the group differences Cohen's r was used and interpreted as small ($0.1 < r < 0.3$), medium ($0.3 \leq r < 0.5$), or large ($r \geq 0.5$) (Cohen, 1988).

Objective and Subjective Attention Measures

Regarding the first hypothesis, no significant differences in the raw scores or percentile scores between the LFN and control group were found on objective measures of attention (see Table 2). Congruently, participants in the LFN group were found to not be classified as 'impaired' more often compared to the control group for both the WAFA, $\chi^2 = 2.08$, df = 4, $p = .720$, φ = .14, and the WAFV, $\chi^2 = 3.35$, df = 4, $p = .501$, φ = .18. However, the LFN group did report significantly more subjective attention problems compared to the control group with a medium effect size (see Table 2). In line with this finding, significantly more individuals in the LFN group were categorized as 'impaired' (45% of the group) on the subscale attention of the FLei compared to the control group, $\chi^2 = 85.03$, df = 1, $p < .001$, φ = -.38 (see Table 3). This difference was found to have a large effect size.

Table 2

Group Comparisons between the LFN and Control Group on the Sleep and Attention Measures.

		LFN	Control			
Domain	Measure	Mean (SD)	Mean (SD)	*U*	*p*	*r*
		Objective measures				
Alertness - WAFA	Mean RT (raw)	219.19 (30.31)	219.72 (23.20)	1374.50	.697	.037
	Mean RT (perc.)	54.82 (28.03)	51.56 (25.16)	1227.50	.577	-.053
Vigilance - WAFV	Mean RT (raw)	451.77 (72.84)	440.46 (96.38)	1176.00	.828	-.021
	Mean RT (perc.)	50.91 (31.82)	47.24 (28.74)	1144.50	.665	-.042
	First half Mean RT (raw)	431.95 (74.45)	437.12 (62.32)	1199.50	.849	.019
	Second half Mean RT (perc.)	488.22 (86.91)	478.13 (72.90)	1128.00	.754	-0.031
		Subjective measures				
Attention - Flei	Subscale attention	15.18 (9.06)	7.65 (6.35)	18986.50	< .001*	-0.398
Sleep - PSQI	Global score	8.34 (4.58)	5.66 (3.64)	14735.50	< .001*	-0.279

Note. WAFA = Perception and Attention Functions - Alertness. WAFV = Perception and Attention Functions - Vigilance. FLei = Questionnaire for Complaints of Cognitive Disorders. PSQI = Pittsburgh Sleep Quality Index. RT = reaction time. Perc. = percentile score. SD= standard deviation. *Significant at p ≤ .001.

Table 3

Distribution of Impairment on the Objective and Subjective Attention Measures between the LFN and Control Group

	LFN	Control
WAFA		
Impaired (%)	6 (8)	2 (6)
Nonimpaired (%)	67 (92)	34 (94)
WAFV		
Impaired (%)	13 (19)	5 (14)
Nonimpaired (%)	56 (81)	30 (86)
FLei		
Impaired (%)	85 (45)	44 (11)
Nonimpaired (%)	104 (55)	351 (89)
PSQI		
Impaired (%)	104 (69)	133 (45)
Nonimpaired (%)	46 (31)	165 (55)

Note. WAFA = Perception and Attention Functions - Alertness. WAFV = Perception and Attention Functions - Vigilance. FLei = Questionnaire for Complaints of Cognitive Disorders. PSQI = Pittsburgh Sleep Quality Index.

Sleep Measures

As for the second hypothesis, the LFN group reported significantly more sleeping problems compared to the LFN group with a small effect size (see Table 2). Here too, significantly more individuals in the LFN group were categorized as ‘impaired’ (69% of the group) on the global score of the PSQI compared to the control group, χ^2= 24.44 df = 1, $p <$ 0.001, φ= .23 (see Table 3). This difference was found to have a medium effect size. Additionally, a larger proportion of the control group than expected based on the normal distribution was categorized as impaired, namely 45%.

Mediation Analysis

For the mediation analysis (see Table 4), results on the objective attention measures were in line with the findings of the first hypothesis, and no significant results were obtained on the relation between group and the WAFA, b = .53, t (107) = .09, p = .927 or WAFV, b = -11.31, t(102) = -.67, p = .51. However, it was found that being in the LFN group was a predictor of more subjective attention deficits (path c), b = 7.53, t(582) = -11.61, p < .001, R^2

= .19. Similarly, being in the LFN group was associated with more sleeping problems (path a), *b* = 2.68, *t*(446) = -6.72, $p < .001$, R^2 = .09. Additionally, more sleeping problems were a predictor of more subjective attention deficits regardless of group (path b), *b* = 0.85, *t*(168) = 6.07, $p < .001$, R^2 = .18. After accounting for the mediating role of sleeping problems, belonging to the LFN group was no longer a significant predictor for subjective attention deficits (path c'), *b* = 3.230, *t*(167) = -1.56, *p* = .121. Yet, sleeping problems remained a significant predictor for subjective attention deficits, thus, sleeping problems mediated the relationship between LFN and subjective attention deficits (path c'), *b* = 0.75, *t*(167) = 4.90, $p < .001$, R^2 = .19. Overall, sleeping problems were able to explain 18% of the variance of the outcome measure subjective attention deficits, *b* = 0.85, *t*(168) = 6.07, $p < .001$, R^2 = .18. Thus, showing that greater reported sleeping problems were positively associated with greater subjective attention deficits in both the LFN and control group (Figure 2). Although, the effect sizes of all associations were small.

Table 4

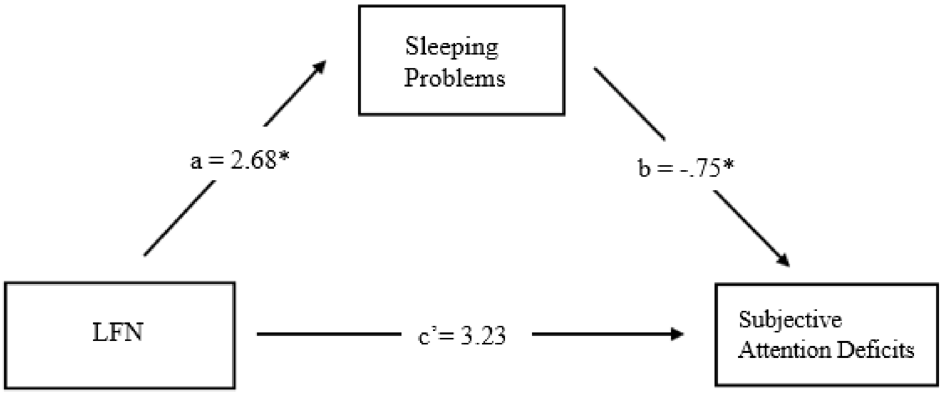
ANOVA results of the Mediation Analysis

Regression model	*F*	*df*	*p*	R^2
Path c				
Group on WAFA	0.01	1,107	.927	.00
Group on WAFV	0.45	1,102	.505	.00
Group on FLei	134.84	1,582	< .001*	.19
Path a				
Group on PSQI	45.17	1,446	< .001*	.09
Path b				
PSQI on FLei	36.84	1,168	< .001*	.18
Path c'				
Group and PSQI on FLei	19.79	2,167	< .001*	.19

Note. Df= Degrees of Freedom. WAFA = Perception and Attention Functions - Alertness. WAFV = Perception and Attention Functions - Vigilance. FLei = Questionnaire for Complaints of Cognitive Disorders. PSQI = Pittsburgh Sleep Quality Index.
*Significant result at $p \leq .001$.

Figure 2

Visualization of the Mediating Role of Sleeping Problems on the association between perceiving Low Frequency Noise and reporting Subjective Attention Deficits



Note. *p < .001.

Discussion

This study aimed to investigate the relationship between perceiving LFN and the attention and sleep problems that are commonly reported by those who experience nuisance due to LFN. Firstly, it was hypothesized that the LFN group, compared to the control group, would score significantly worse on subjective and objective measures of attention. The data partly supported this hypothesis, namely only a difference on subjective attention measures was found. It was shown that the LFN group reported more attention complaints than the control group by a medium effect size. Adding to that, a greater proportion of the LFN group compared to controls were classified as having impaired attention by a large effect size. Secondly, it was hypothesized that the LFN group would report more sleeping problems than the control group, which was supported by our data by a small effect size. Consequently, the LFN group was more likely to be classified as impaired on the sleep measure compared to the controls, by a medium effect size. Lastly, it was hypothesized that the relationship between LFN and attention deficits was mediated by sleeping problems. Again, no support was found for the relation between the variable group and the objective attention measures. But, being in the LFN group was a significant predictor of more subjective attention deficits. Similarly, being in the LFN group was also a significant predictor of more sleeping problems. Furthermore, greater reported sleeping problems predicted greater subjective attention deficits. Lastly, the variable group was no longer a significant predictor for subjective attention deficits after the mediating role of sleep problems was accounted for. Thus, supporting the last hypothesis that the relationship between LFN and attention deficits is mediated by sleeping problems.

As for the hypothesis on attention problems, regarding the subjective measures, the data was in line with our expectations that the LFN group would report more attention problems. This corresponds to previous reports where subjective attention complaints are often observed in those that experience nuisance due to LFN (Erasmus et al., 2018; Erdélyi et al., 2019; Van Kamp et al., 2018). Yet, these complaints were not seen on the objective attention measures of alertness and vigilance. As stated before, previous studies on these measures were inconclusive. That our study did not observe a difference in speed between the LFN and control group, contradicts these previous findings. Regarding alertness, shorter reaction times (Alimohammadi et al., 2012; Alimohammadi & Ebrahimi, 2017) as well as longer reaction times for those sensitive to noise (Waye et al., 2001) were reported. Regarding vigilance, even though previous literature found no significant difference in speed, a decrement that could become significant was observed (Kyriakides & Leventhall., 1976). Additionally, those sensitive to noise were found to have longer reaction times compared to controls (Waye et al., 2001). Assuming that the LFN group in our research is sensitive to noise and the control group is not or less sensitive, it would be expected that the LFN group would show longer reaction times on both alertness and vigilance measures compared to controls. A possible explanation for this contradiction could be that these previous studies were carried out in a setting where LFN was presented during the task, whereas in this research LFN exposure was not manipulated. Therefore, the attention of people who perceive LFN in their daily life might not be affected in the absence of LFN. However, in the presence of LFN, attention might be altered. Hence, the LFN group reported more subjective attention complaints, since that measure covers perceived attention deficits in the last six months retrospectively, which also includes moments where LFN is present.

Another possible explanation might be that objective attention measures inherently assess different concepts of cognition compared to subjective measures (Fuermaier et al., 2015; Toplak et al., 2013). Objective attention measures aim to measure peak or optimal performance. For instance, distractions are minimized in these conditions, tasks are already structured, and the participants are instructed to perform at their best. Toplak and colleagues (2013) argue that these types of measures tap into the efficiency of cognitive processes. This is an intrinsically different concept than what subjective measures capture. Namely, the day-to-day performance and the ability to pursue and achieve goals in an unstructured environment. Subsequently, it has been found that in a sample of individuals with ADHD, objective and subjective attention measures did not predict each other even though individuals were found to be impaired on both measures (Fuermaier et al., 2015). Regarding this current study, it could be that the LFN group their peak performance under optimal conditions might be intact, hence no differences were found on objective attention measures. However, in daily life, when tasks are often unstructured and performance is not peaking, attention functioning might be impaired.

To sum up, future research regarding attention deficits in those that experience nuisance due to LFN perception could focus on the following three suggestions. Firstly, to delineate whether there is a difference in attention functioning when exposed to LFN for those who experience nuisance due to LFN, further experimental research should be conducted. For instance, by comparing attention functioning in these individuals in a laboratory condition where LFN is presented to a silent condition. Secondly, to look further into the reported subjective complaints that are related to day-to-day attention functioning, a suggestion could be to conduct attention measures in a setting more similar to daily life, such as an office. Lastly, in this research, only speed was taken into consideration when comparing the groups on the objective attention measures. However, it could be that attention deficits occur on task performance, meaning how well a task is executed, and not on the amount of time taken to complete the task. Therefore, looking into if and when errors are made might shed light on how attention tasks are executed. This possible performance decrement or impairment might also give insight into the subjective attention deficits since the questionnaire assess to what extent participants feel able to execute a task instead of how fast they can react to certain stimuli.

Concerning the second hypothesis, results were in line with previous findings, where sleeping problems due to the perception of LFN are frequently reported (Bakker et al., 2012; Erasmus et al., 2018; Erdélyi et al., 2019). Those belonging to the LFN group reported worse sleep on average compared to controls, by a small effect size. Moreover, participants in the LFN group were more likely to be categorized as impaired compared to controls, showcasing a medium effect size. However, in the LFN group in this research, 69% were classified as impaired, which is a considerably higher percentage in comparison to the 1.5%-15.2% (Bakker et al., 2012; Pohl et al., 2018) found previously using subjective sleeping measures. This might be explained by the fact that these studies assessed participants that live near an LFN-producing source, meaning that these studies also included participants who did not have LFN-related complaints. Our LFN group consists of people that indicated experiencing nuisance due to LFN in their daily life prior to our study. This would indicate that LFN perception, as well as nuisance, might be more relevant predictors of sleeping problems than the vicinity of an LFN source.

Regarding this possibility, it could be that nuisance due to LFN might be a mediator between perceiving LFN and subjective sleeping problems. Concerning nuisance, Bakker and colleagues (2012) report that annoyance, among those who indicated noticing the sound of the wind turbines, was found to be the only factor that predicted sleep disturbance. Moreover, a systematic review including both subjective and objective measurements of sleep regarding wind turbine noise revealed no significant effects of exposure to wind turbine noise on the time taken to fall asleep, total sleep time, or sleep efficiency on objective measures in comparison to those not exposed to this noise (Liebich et al., 2021). Furthermore, they report findings that changes on the PSQI before and after exposure to wind turbine noise were strongly associated with negative attitudes towards wind turbines. Additionally, it can be noted that in this systematic review, more significant differences are reported on retrospective subjective measures that focus on sleep in general. Namely, the Epworth Sleepiness Scale, Insomnia Severity Index, and the PSQI. This is in opposition to the use of sleep diaries that assess sleep directly after awakening, which more often report no significant differences. Since this current research used a retrospective sleep measure, there is a possibility that the results of the LFN group were biased due to negative attitudes toward LFN. This suggests that sleep in the LFN group might not be that different from the control group, hence the small effect sizes on the between-group differences and the regression of the variable group on sleep.

To sum up, future research should look further into the relationship between LFN, sleep, and attitudes towards LFN (sources). Firstly, it should be established whether or not sleep is disturbed by LFN. This could be done by conducting a laboratory study where participants are exposed to LFN during nocturnal times. Secondly, future research should make use of prospective sleep measures, such as sleeping diaries or objective sleep measures (e.g., actigraphy), because as argued above retrospective measures seem to be less true to daily life. Additionally, to account for mediating variables, subjective measures can be used to assess whether and how (e.g., loudness) participants perceive the presented LFN. Moreover, the possible mediating role of attitudes towards LFN should be taken into consideration when looking at the relationship between LFN and sleep.

Furthermore, a striking 45% of the control group was categorized as having impaired sleep. This is a large proportion compared to the expected 16% based on the normal distribution. The first possible factor that could have influenced this result is the mean age of

59.76 in the control group that filled in the sleep measure, which is older than the mean age of 42.20 years in the general Dutch population (Centraal Bureau voor de Statistiek, 2022). Older age is found to be associated with more sleep complaints (Jaussent et al., 2011; Reid et al., 2006) and therefore the number of participants categorized as impaired could be skewed. A second influential factor could be that the control group consists of 65.9% females. Previous research found females to report a larger amount of sleep complaints compared to males (Jaussent et al., 2011). Subsequently, the overrepresentation of females in the control group could have skewed the proportions. Lastly, the deletion of participants could have influenced the results. Sleeping problems are found to be related to worry and rumination about sleeping problems (Hiller et al., 2015), therefore it could be assumed that those with impaired sleep are well aware of their sleeping habits. In the control group, a set of participants was deleted. Their answers were unusable to calculate a global score, for instance, because they reported not knowing exactly how long it took them to fall asleep. It could be that people with unimpaired sleep could be less aware of this type of information and therefore be more likely to have given unusable answers. This subsequently could have led to the deletion of relatively more unimpaired sleepers compared to impaired sleepers.

As for the third hypothesis, the mediation analysis, it was found that sleep problems were a significant predictor of subjective attention deficits even when the variable group was accounted for. This discloses the possibility that some complaints are secondary symptoms and therefore not directly caused by LFN perception. Thus, LFN perception might lead to sleeping problems which in turn lead to attention deficits. Additionally, since sleep is such an important factor for many aspects of daily living, sleep might also be a predictor for other complaints reported by those who experience nuisance due to LFN. For instance, sleep is found to be related to depression (Steiger & Pawlowski, 2019), cognition (Dzierzewski et al., 2018), and physical and mental health-related quality of life (Reid et al., 2006). However, based on the current research design, causality cannot be inferred. Moreover, since the questionnaires were conducted at a different time than the objective attention measures, the relationship between them is limited. Therefore, the suggested sleep measures should be done within the same time frame as the attention measures. Thus, to determine whether LFN exposure leads to sleeping problems, experimental research should be conducted. This could be done in a laboratory setting where LFN exposure can be controlled and sleep measures can be done objectively as well as subjectively.

Furthermore, in the mediation model, sleep explained 18% of the variance of subjective attention deficits. This suggests that even though sleep is a significant factor influencing attention for both groups, it is evident that other factors are probably contributing as well, hence the unexplained variance. One such factor could be personality traits, specifically introversion. For instance, during attention tasks introverts, compared to extroverts, are found to have faster reaction times when exposed to LFN compared to silence conditions (Alimohammadi et al., 2012; Rossi et al., 2018). This could possibly be explained by a heightened stress response to noise since Rossi and colleagues (2018) found that introverts had an increase in heart rate whilst carrying out the task, which was not seen for extroverted participants. Moreover, introverts' heart rate peaks were higher when noise was presented as opposed to silence. This can be linked to introverts reporting being more annoyed by LFN and perceiving the noise as louder than extroverts (Abbasi et al., 2021). This could have two implications. Firstly, it is a possibility that introversion is a predictor of nuisance due to LFN and therefore a possible predictor of our variable group. Secondly, introversion could be another mediator in the relationship between LFN perception and attention. In the short term, this could mean that introverts can react faster because their stress response is activated, as seen in Rossi and colleagues' (2018) experiment. However, in the long term, it could be expected that introverts experience chronic stress responses due to the perception of LFN, which could then possibly result in impaired attention in the long run.

To shed light on these two possible implications it would be useful to assess whether introversion is a predictor of nuisance due to LFN or if introversion is a mediator between LFN and attention deficits. The larger study of which this research was part contained a personality inventory assessing introversion, thus additional analysis on the mediating or predicting role of introversion in this current research could be done. In addition, further research should also look into how exactly LFN affects attention in introverts in the short term because, next to better performance (Alimohammadi et al., 2012; Rossi et al., 2018), worse performance has also been found (Babamiri et al., 2017). For instance, by comparing the performance of introverts, whilst being exposed to LFN, on objective attention measures including both task performance, as well as speed. Additionally, subjective measures of their attentional performance could be added to gain insight into ongoing cognitive processes whilst executing an attentional task or their attitudes towards LFN. Moreover, the effects of long term exposure are yet to be determined. This could be done by comparing the attentional performance of introverts that experience nuisance in daily life due to LFN to those that do not, whilst being exposed to LFN in a laboratory setting.

Lastly, since self-report and psychometric measurement rely on participants' honesty and maximal effort, a crucial part of (neuro)psychological research is the assessment of performance and symptom validity. Considering that those who experience LFN feel unheard and have a high need for seeking help (Erasmus et al., 2018), symptom exaggeration and overreporting could be occurring in at least a subsample of this population. This could partly be controlled for by using measures that assess for symptom exaggeration, which were incorporated into the larger test battery but due to feasibility not included in this analysis. However, it could be valuable to look into how participants scored on these and whether there are group differences between the LFN and control group.

Implications

This study aimed to give further insight into the complaints of those who experience nuisance due to LFN. Data suggests that subjective sleep problems are an important factor in relation to subjective attention deficits. Likewise, sleep might also be associated with other complaints such as depression or cognitive dysfunction. Therefore, it is important for healthcare workers that come in contact with those with LFN complaints, such as physicians, to be aware of the role of sleep for those experiencing nuisance due to LFN. Subsequently, it should be assessed whether sleep is impaired and therefore should be treated. However, causality was not established in this study and therefore future research should look into the causal role of sleep on to LFN-related complaints.

Even though subjective attention deficits did not correspond with objective attention test performance, this study shows that those perceiving LFN report experiencing impairment in daily life. It needs to be taken into account that this group reports severe impact on their daily lives and yet not much is done to help them (Erasmus et al., 2018). This should not be taken lightly and further research into how these people can be helped should be pursued. For instance, by researching the efficacy of interventions that better sleep (e.g., sleep hygiene interventions) to reduce or resolve attention deficits and possible other secondary complaints. Additionally, healthcare providers and policymakers should be open to offering support for the consequences that people who experience nuisance due to LFN face. In the first place by assessing these complaints and acknowledging the burden of the impact of them. In the second place by providing support for the problems that arise in daily life such as marital difficulties or incapacity to work.

Conclusion

Nuisance due to noise can be a health hazard. A specific type of noise, LFN, is currently still understudied in the literature. Nevertheless, those experiencing LFN report physical, social, and psychological problems as a consequence. This study aimed to further investigate the neuropsychological complaints of attention and sleeping problems that are often reported by those that experience nuisance due to LFN perception. Furthermore, since sleep and attention are inherently related to each other, it was researched whether sleeping problems mediated the relationship between LFN and attention deficits. Results showed that the LFN group reported significantly more subjective attention and sleeping difficulties than the control group. However, objective attention measures were found to not be different from controls. Because objective measures assess peak performance and subjective measures assess day-to-day performance, it is a possibility that attention deficits are only present during daily life tasks, and peak performance is not affected by nuisance due to LFN perception. Regarding sleeping problems, it was found that the LFN group reported significantly more sleeping problems compared to the control group. Additionally, it was discussed that there is a possibility that these results are mediated by attitudes towards LFN, such as annoyance. Therefore, future research should establish whether LFN influences sleep and take attitudes toward LFN (sources) into account when assessing this relationship. Lastly, the mediation analysis suggested that the subjective attention deficits are better explained by subjective sleep problems as opposed to whether or not participants perceive LFN. This gives rise to the idea that some complaints reported by those that experience nuisance due to LFN are secondary and therefore not directly caused by LFN perception. Future experimental research should look into the causal relationship between sleeping and attention deficits in this population. Additionally, it would be interesting to investigate whether other complaints, such as depression, are related to the experienced sleeping problems. Still, a large part of the variance could not be explained by the sleeping problems. Therefore, it was discussed that other factors are probably playing an important role as well. For example, introverted people seem to have a stronger stress response towards LFN in the short term and could this therefore lead to a chronic long term stress response when LFN is perceived frequently. However, here again, experimental research should investigate how exactly LFN affects introverts in both the short and long term. In conclusion, this study shed light on the day-to-day complaints of those who experience nuisance due to LFN. This illustrates that healthcare professionals and policymakers should assess and acknowledge these complaints and consequently offer support to relieve these complaints and their consequences.

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Appendix A

Details on the Deleted Data Points on the Objective Measures

Table 5

Deleted Data Points of the Objective Attention Measures

Deleted data point(s)	Mean*	SD*
	WAFV dispersion of reaction times raw score	
68 ms	1.87 ms	6.37 ms
	WAFV number of false alarms raw score	
89, 55, 40, 34	3.84	11.01
	WAFV first half dispersion of reaction times raw score**	
5.5 ms; 3.71 ms	1.30 ms	0.49 ms

Note. *Deleted data points included. **Both participants' data points in the second half were located inside one and a half times the interquartile range.

Appendix B

Details on the Deleted Data on the Subjective Measures

Table 6

Deleted Data on the Subjective Measures

Grounds of Removal	Consequence
C_0	
Incomplete data on the PSQI.	Deletion of 4 participants' data on the PSQI.
C_{1b}	
Incomplete data on the PSQI.	Deletion of 84 participants.
LFN	
Incomplete data on both the PSQI and FLei.	Deletion of 5 participants.