Primary and secondary effects of nocturnal traffic noise with different audio frequencies on sleep

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Nocturnal traffic noise disturbs sleep, causing arousals, sleep stage modifications, awakenings, increased body movements and experience of poor sleep quality. It has not, however, been established which acoustical properties (e.g., sound pressure level, number of noise events, audio frequencies) are the most detrimental to sleep. Low frequency traffic noises and high frequency traffic noises have not been previously compared on their effects on sleep. The main aim of this study was to analyse primary and secondary effects of nocturnal traffic noise with different audio frequencies.

Twenty-one healthy volunteers, aged 20–30 years, slept four consecutive weekday nights in a sleep laboratory. After a habituation night, the participants slept in three rooms, with the order of the rooms counterbalanced. Each of these rooms had their own noise conditions: 1) engine noise dominating (low frequency noise room, the LF Room), 2) tyre noise dominating (high frequency noise room, the HF Room), and 3) quiet (the Q Room). The noise levels in the LF Room and the HF Room were equal, 38 dBA, but the rooms had two very different audio frequency ranges. The primary and secondary effects of traffic noise were assessed with polysomnography, questionnaires and the Psychomotor Vigilance Test.

Decrease in the amount of slow-wave sleep was observed during both nights with traffic noise compared to the quiet night. No other objectively measured primary effects were found. During the nights with traffic noise, participants were less satisfied with their sleep and evaluated having woken up more often than during the quiet night. Being exposed to traffic noise did not have any secondary effects, such as sleepiness, strain or performance deficits in the Psychomotor Vigilance Test in the following morning and evening.

The high frequency noise condition was experienced as the most obtrusive noise environment for sleep. However, there were no differences between the low frequency and the high frequency noise conditions in objectively and subjectively assessed sleep quality or performance. Results from this study do not highlight that either low frequency noise or high frequency noise is more disturbing for sleep than the other.

Keywords: road traffic noise, low frequency noise, high frequency noise, sleep quality, polysomnography, vigilance

Content

1. Introduction

In Europe, noise is acknowledged as the most significant environmental pollution, and its direct effects on both daytime functioning and sleep have been shown in many studies (Pirrera, De Valck, & Cluydts, 2010; Hurtley, 2009). Noise can be defined as any unwanted sound or set of sounds that detrimentally affects, or may affect people, both physiologically and psychologically (Muzet, 2007). The sources of noise are various, including different means of transportation (for example, vehicles, trains, and aeroplanes), wind farms, industrial plants, ventilation and neighbours' voices (Muzet, 2007). In particular, road traffic noise has become a major concern and more people are exposed to it because of urbanisation and increasing traffic densities (Muzet, 2007; Pirrera et al., 2010). Therefore, this study focuses on the effects of road traffic noise (hereafter referred to as *traffic noise*) on sleep.

The adverse impact of traffic noise occurs especially at night time when traffic noise disturbs sleep. Sleep is a biological necessity that is associated with both physical and mental health and well-being (Hurtley, 2009). A normal night's sleep usually lasts from seven to eight hours and proceeds in multiple 90–110-minute cycles consisting of rapid-eye-movement (REM) and non-rapid-eye-movement (NREM, stages N1–N3) sleep (Carskadon & Dement, 2011). According to electrical activity of the brain, sleep is categorized into four stages: REM, stage N1, stage N2 and stage N3 that is usually called slow-wave sleep (SWS). In healthy adults, SWS dominates the sleep cycles in the early night, and the amount of REM sleep increases in the latter portion of the night. Conscious perception of auditory stimuli is thought to occur only during wakefulness, but some auditory processing happens also during sleep (Portas et al., 2000).

According to the World Health Organisation's review (Hurtley, 2009) of the available studies, sufficient evidence was found for biological effects of nocturnal noise, which are increases in heart rate, arousals, sleep stage changes, motility and awakenings. That review also found evidence for self-reported sleep disturbances and increased use of sleep medication. Sleep disturbances caused by traffic noise can be viewed as a health problem in itself, but there is evidence from epidemiological studies that they are connected to further health issues, such as cardiovascular diseases (Babisch, 2008).

At night time, outside noise levels should not exceed 40 dB based on the *Night noise guidelines for Europe* (Hurtley, 2009). This threshold value is indicated as a "yearly average of night noise level outside at the façade”. It does not, however, take into account the noise profile (i.e. the number and placement of noise events within the nights) and acoustical properties that different noise conditions might have. Hence, noise conditions with the same value of noise level might differ in their effects on sleep (Fritschi, Brown, Kim, Schwela, & Kephalopoulos, 2011). The inside noise levels of new buildings should not exceed 30 dB during night time, according to Finnish government Res. № 993/1992 of reference values of noise levels. These guidelines direct the planning of soundproofing of façades so that these specified threshold values would not be exceeded. Thus, as the guidelines outline only the equivalent sound levels for the inside noise levels and do not acknowledge acoustical properties such as the frequency range of noise, different façades can follow the guidelines, but the noise conditions inside might be very different. For example, either low frequency noises or high frequency noises can dominate inside buildings because of different façade structures. Low frequency traffic noises and high frequency traffic noises have not previously been compared on their effects on sleep. The main aim of this study is to analyse the effects of traffic noises with different audio frequencies on sleep.

1.1 Noise in Sleep Studies

Currently, consensus is lacking on which are the most adequate exposure variables when the effects of traffic noise on sleep are studied (Basner, Müller, & Griefahn, 2010). The main acoustic properties of noise that have been of interest are equivalent noise levels (Griefahn, Marks, & Robens, 2006), maximum sound levels (Öhrstöm, & Rylander, 1982), number of noise events (Öhrström, 1995) and the intermittency of traffic noise (Eberhardt, Stråle, & Berlin, 1987). Equivalent noise level is a noise metric that integrates levels of fluctuating noise into a single value (dB). In contrast, maximum sound level is the maximum noise level that a single noise event reaches during the night. Nocturnal traffic noise tends to be intermittent by nature, as single noise events occur irregularly. To date, studies that assess the effects of audio frequencies of noise on sleep are limited. Audio frequency describes the number of sound vibrations per second and its unit is hertz (Hz). Audio frequency determines pitch of the heard noise and it has an influence on the auditory sensation in ears so that, for example, traffic noises with different audio frequencies sound different. Inside buildings, when low frequency traffic noises are predominant due to insulation structure, engine noises from the passing traffic dominate, whereas tyre noises dominate when high frequency traffic noises are predominant.

1.1.1 Audio Frequencies of Noise

Noises with different audio frequencies penetrate through walls and windows differently. For example, walls and windows usually attenuate low frequency noise less than high frequency noise (Berglund, Hassmén, & Job, 1996). Insulation structures can also differ in how they attenuate noises with different audio frequencies (Muellner, Frey, & Humer, 2008). Guidelines that direct the soundproofing of facades do not take into account the audio frequencies, as only the thresholds for noise levels are outlined. In some studies of wake participants it has been found that whether the sound has a strong low frequency content or a strong high frequency content has an effect on how satisfactory the sound is experienced (Hongisto, Oliva, & Rekola, 2015). In that study, low frequency sounds were found to be more satisfactory than high frequency sounds as masking sounds at workplaces, although low frequency noise are often associated to high annoyance (Berglund et al., 1996). Thus, it would be important to know as to whether differences in the disturbance of noises with different audio frequency ranges also occur during sleep. Until now, there have been no studies that take into account the differences in audio frequency ranges that result from different insulation structures, and thus compare the effects of low frequency and high frequency traffic noises on sleep. Nevertheless, some presumptions can be made from the studies in which the audio frequencies of noises have been of interest.

The importance of studying especially the effects of low frequency noise on sleep has been stressed by some researchers (Waye, 2004; Öhrström & Skånberg, 2004). These effects are of particular concern due to the pervasive nature of low frequency noises: its numerous sources and its penetration through many structures with little attenuation (Waye, 2004). Sources that emit low frequency noises are typically related to certain means of transportation (for example diesel busses) and ventilation of buildings (Berglund et al., 1996; Waye, 2004). Low frequency noise is particularly problematic because it can travel long distances with little energy loss (Waye, 2004). According to Waye, studies on the effects of low frequency noise on sleep are limited, but low frequency noise seems to disturb sleep.

Traffic noises with different audio frequency ranges have not been compared, but a few studies have compared the effects of traffic noise and low frequency ventilation noise on sleep (Waye, Clow, Edwards, Hucklebridge & Rylander, 2003; Waye, Agge, Clow & Hucklebridge, 2004, Öhrström & Skånberg, 2004). Conflicting results have been found on the effects of low frequency ventilation noise on falling asleep when it has been compared with traffic noise and a quiet condition. Studies have indicated both increased time to fall asleep (Waye et al., 2003) and no effects on falling asleep when nights with ventilation noise have been compared with quiet nights (Öhrström & Skånberg, 2004). According to the latter study, traffic noise was found to be more disturbing for subjective sleep quality than low frequency ventilation noise. One study found that the cortisol awakening response that is the normal reaction of the hypothalamic–pituitary–adrenal (HPA) axis to awakening that can be measured by increase in cortisol levels at 20–30 minutes after awakening, was attenuated following exposure to low frequency ventilation noise during the night (Waye et al., 2003). The attenuated levels of cortisol were related to tiredness and negative mood in the morning. However, this effect of low frequency noise on cortisol response was not reproduced in a subsequent study with a larger sample size (Waye et al, 2004).

1.1.2 Other Acoustical Properties and Their Effects on Sleep

Due to low traffic densities during the night, people are exposed to intermittent traffic noise with single noise events occurring (Fritschi, Brown, Kim, Schwela, & Kephalopoulos, 2011). Intermittent noise disturbs sleep more than continuous noise (Öhrström & Rylander, 1982; Eberhardt et al., 1987). Poorer subjective sleep quality and objectively measured more frequent body movements during sleep were found when intermittent noise was compared with continuous traffic noise (Öhrström & Rylander, 1982). The occurrence of body movements was in this study related to single noise events when the traffic noise was intermittent, but the continuous traffic noise did not influence the occurrence of movements over time. Continuous noise and intermittent noise influences the sleep structure differently; continuous traffic noise reduces REM sleep, while intermittent traffic noise causes transitions toward lighter sleep (stages N1 and N2), that is to say, reduction in SWS (Eberhardt et al., 1987).

Also, the number of noise events and maximum noise levels have been used as exposure variables in earlier sleep studies (e.g. Öhrström, 1995). Öhrström studied nights with a maximum noise level of 45 dB and found that when the number of noise events increased, the subjective sleep quality of participants decreased when compared with a quiet night. Nights with 16, 32, 64 and 128 noise events were compared and the threshold of number of noise events to have an effect on sleep quality seemed to be between 16 and 32 events per night. According to Öhrström (1990), when it comes to higher maximum noise level of 60 dB, the threshold for the number of noise events that cause sleep deficits might be even lower. Öhrström and Rylander (1982) compared nights with different maximum noise levels and found that according to questionnaires in their study, the maximum noise level of 70 dB caused more awakenings and shorter sleep time when it was compared to quiet nights and nights with the maximum noise level of 60 dB.

Equivalent continuous noise level is a single decibel value given for a period of time and it takes into account the total sound energy over that period of time. The equivalent noise level does not, however, take into account the number of noise events (Griefahn, Bröde, & Schwarzenau, 1993). According to Griefahn et al. (2006), the equivalent noise level might appropriately predict the subjective sleep quality but not physiological sleep disturbances. In their study, subjectively evaluated sleep quality decreased gradually with higher equivalent and maximum noise levels. Whereas, on physiological variables, both lower equivalent noise levels (39 and 44 dB) caused equal reactions, whereas the highest noise level (50 dB) caused considerably stronger reactions. Using the integrated noise metrics, such as the equivalent noise level, alone as a predictor of sleep disturbances has been questioned by some researchers (Griefahn et al., 1993; Griefahn et al., 2006). Indeed, equivalent noise level does not seem to be a reliable enough noise variable to be used in sleep studies alone.

1.2 Primary and Secondary Effects of Nocturnal Traffic Noise

Various sleep variables have been used as indicators for sleep disturbances caused by traffic noise (Pirrera et al., 2010). This is partly due to the fact that there is no clear definition for sleep quality. Both primary and secondary effects of noise have been assessed (Muzet, 2007). Primary effects of noise are the effects occurring simultaneously or immediately after noise exposure. Primary effects of traffic noise found in sleep studies include objectively measured nocturnal awakenings (depending, however, on the current sleep stage) (Griefahn & Muzet, 1978), redistribution of body movements (Öhrström, 1995), sleep-stage modifications (from SWS to lighter stages of sleep) (Muzet, 2007), and according to subjective evaluations, delayed sleep latency (Griefahn & Gros, 1986) and decreased sleep quality (Öhrström & Skånberg, 2004). Secondary effects are those observable on the following day or a few days after noise exposure. Some secondary effects reported in sleep studies are increased tiredness in the morning (Öhrström, 1995), changes in mood (Skånberg & Öhrström, 2006), and performance deficits in reaction-time tasks (Marks & Griefahn, 2007). Pirrera et al. (2010) suggest that these secondary effects following nocturnal noise might in fact be non-specific effects of partial sleep deprivation that the traffic noise has caused.

Both objective and subjective measurement techniques have been used to study primary and secondary effects of nocturnal traffic noise on sleep (Basner, Brink & Elmenhorst, 2012). With objective methods it is possible to detect physiological sleep disturbances, whereas subjective evaluations of sleep quality and secondary effects of noise can be acquired using questionnaires. In addition, performance deficits in the morning have been measured with psychomotor and reaction-time tasks.

Polysomnography (PSG) is regarded as the gold standard for measuring sleep (Basner et al., 2012). As a research method, PSG is very well standardized and information about subtle physiological changes during the night can be detected. However, it is a somewhat disruptive and invasive measurement technique that may impair sleep. Due to the associated costs and laboriousness of PSG, it is rarely used in studies with large sample sizes and field studies. Methods that detect body movements, for example accelerometers, have often been used as objective evaluations of sleep disturbance (Öhrström & Rylander, 1982; Öhrström, 1995; Griefahn, Schuemer-Kors, Schuemer, Moehler, & Mehnert, 2000; Öhrström & Skånberg, 2004). Actigraphs are inexpensive and they can be more easily applied for field settings (Basner et al., 2012). They do not, however, measure sleep depth, and detecting awakenings on the basis of body movements is problematic (Griefahn et al., 2006). Therefore in this study, PSG was chosen for measurement of objective sleep quality.

Simple questions (for example, "*How well did you sleep last night?"*) and more extensive questionnaires have been used to assess both the perceived sleep quality and secondary effects of noise, for example, tiredness and mood on the following day. These subjective evaluations of sleep disturbances are an easier and more affordable way to collect data than objective methods, and are thus practical especially in field settings (Muzet, 2007). However, subjective assessment of sleep quality is seldom in agreement with objective measures of sleep (Basner et al., 2012). Subjective evaluations might underestimate the number of nocturnal awakenings, for the awakening to be reported it has to be remembered, and for shorter awakenings the recollection might be missing (Pirrera et al., 2010). The subjective evaluations of total time spent in sleep seem to be overestimated when compared with objectively measured total sleep time (Silva et al., 2007). Many factors influence subjective evaluations of sleep quality, and noise sensitivity has been found to be one of the most important of these factors (Marks & Griefahn, 2007). Also among insomniacs, mismatch between objective and subjective sleep quality is more common than among normal sleepers, and they tend to overestimate their sleep latency, but underestimate total sleep time (Bianchi, Williams, Mckinney, & Ellenbogen, 2013). Despite their limitations, subjective evaluations provide important information on sleep quality.

Psychomotor and cognitive tasks can be used to measure secondary effects of nocturnal noise, specifically manifest sleepiness (Hirshkowitz, Sarwar, & Sharafkhaneh, 2011). Manifest sleepiness is a dimension of sleepiness that is related to behavioural signs of sleepiness, inability to remain awake, and performance deficits on psychomotor and cognitive tasks. The tasks are used to test a person's ability to remain vigilant and they can measure both arousal and attention. From various vigilance tests, the psychomotor vigilance test (PVT) (Dinges & Powell, 1985) is the most commonly used in sleep studies (Hirshkowitz, Sarwar, & Sharafkhaneh, 2011). The PVT is the leading paradigm used to measure performance impairment related to sleep deprivation as it is extremely sensitive to the effects of sleep loss and its reliability and validity have been well demonstrated (Lim & Dinges, 2008). Hence, in this study, the PVT was used as an objective measurement of secondary effects of nocturnal traffic noise. The findings of the effects of nocturnal noise on performance in vigilance tests are inconsistent, but some results suggest longer reaction times in the morning compared to the evening before nocturnal noise exposure (Öhrström & Rylander, 1990; Marks & Griefahn, 2007). It is difficult to distinguish whether performance deficits in the morning are caused by the nocturnal noise itself or whether they are due to partial sleep deprivation caused by the noise.

1.3 Aims of the Study

There is clear evidence of the adverse effects of nocturnal traffic noise on sleep. It is not yet known, however, which acoustical properties of traffic noise are the causes of these effects, and which are the most adequate methods for studying sleep disturbances caused by nocturnal traffic noise. The main interest of this study is to analyse the effects of traffic noises with different audio frequencies on sleep. Two noise conditions with different audio frequencies dominating were created for this study: 1) low frequency noise condition, with engine noise dominating and 2) high frequency noise condition, with tyre noise dominating. They were compared with each other and with a quiet condition. All participants slept in all of these three conditions. Primary effects of traffic noise were measured both objectively and subjectively with polysomnography and questionnaires, respectively. Secondary effects of nocturnal traffic noise were measured subjectively with questionnaires and objectively with the Psychomotor Vigilance Test.

The research questions of this study were:

1. Do the two noise conditions *differ from the quiet condition* in how they affect objective and subjective sleep quality, and secondary effects of noise, including vigilance?
2. Do the two noise conditions with different audio frequency ranges *differ from each other* in how they affect objective and subjective sleep quality, and secondary effects of noise, including vigilance?

2. Method

2.1 Participants and Experimental Design

Twenty-one healthy volunteers, aged 20–30 years (average age 24.71, SD 3.05) took part in the experiment. Nineteen of them were women and two were men. They were recruited by advertising via the email lists of several student organisations. Nineteen of the participants were university students and the rest were working full-time. On weekday nights, the participants reported sleeping on average 7.7 hours per night (SD 0.78) when asked in a background information questionnaire how much they normally sleep. Inclusion criteria for participation in this study were normal hearing, a fairly regular sleep-wake rhythm (from 22–00 to 06–08) and no difficulties with sleeping. There was also a check that none of the participants used earplugs regularly while sleeping. Noise sensitivity of the participants was assessed with sleep related items from The Noise Sensitivity Questionnaire (NoiSeQ) (Schütte, Sandrock, & Griefahn, 2007) on the background information questionnaire. On the possible range from 7 to 49, participants' scores varied on a range from 13 to 33. Thus, none of the participants was particularly sensitive to noise in regard to sleep. All participants lived in apartment buildings that were situated along some busy road or nearby. The participants were given four 15 Euro gift tokens (one for every night they slept in the laboratory) as a compensation for their participation.

From all those who were interested in taking part in this study, individuals who had some medications and medical conditions that could interfere with the experiment, were excluded. A physician was consulted on this matter. Another exclusion criterion for participation in this study was that participants should not do shift or night work or take naps regularly. Twenty-three participants started the experiment, but after sleeping the first night in the sleep laboratory, two participants (12 %) discontinued the experiment, because they did not have enough time to participate. The final sample size of this study was 21.

The subjects slept four consecutive weekday nights in the sleep laboratory. For all subjects, the first night between Monday and Tuesday was for habituation to the laboratory conditions and the registration equipment. No noise was emitted on the habituation night. The following three nights (Tuesday–Friday), the subjects slept in three different rooms: 1) low frequency noise room (the LF Room), 2) high frequency noise room (the HF Room), and 3) quiet room (the Q Room). The order of the rooms in which the subjects slept was counterbalanced to reduce order effects. Thus, there were six possible orders in which the subjects were exposed to the noise conditions. The aim of this procedure was to reduce human errors that might have occurred, if participants had slept all nights in the same rooms, and the supervisor should have known, which noise to play in which room each night. Afterwards, it would not have been possible to check whether the right noises had been played. Therefore, it was settled on participants changing the rooms and each room having its own noise condition.

All rooms were soundproofed and were similar to each other in terms of essential parts, such as lighting and temperature. The equivalent noise levels in the LF Room and the HF Room were equal, 38 dB. The same audio tape was used in both rooms. The noise conditions in LF Room and HF Room were based on audio frequency ranges of traffic noises that were constructed with two façades that had very different soundproofing. The rooms had two different audio frequency ranges; in the LF Room, engine noise dominated and, in the HF Room, tyre noise dominated. Audio frequency ranges of the noise conditions of each room are shown in Figure 1. The frequency range of the traffic noise used in this study was 20–5000 Hz. In the Q Room, no traffic noise was emitted and it was used as a reference night. The equivalent noise level of the Q Room was 19 dB, and this background noise consisted mainly of ventilation noise.

The traffic noise used in this study was recorded in May 2014 at a junction of a busy road on a weekday night between 22:00 and 07:00. All noises that were not the main interest of the study (e.g., emergency vehicles and birdsong) were deleted from the audio tape. The noise profile of the audio tape was similar to that of a normal weekday night. That is to say, the number of noise events decreased for the night and increased again in the morning. In the sleep laboratory, the traffic noise was played through loudspeakers that were hidden behind fake windows and curtains to ensure a more widespread noise, instead of one identifiable source of noise. Verifying measurements were carried out every evening before the research nights so that the sound levels in the rooms with the traffic noise conditions were appropriate.

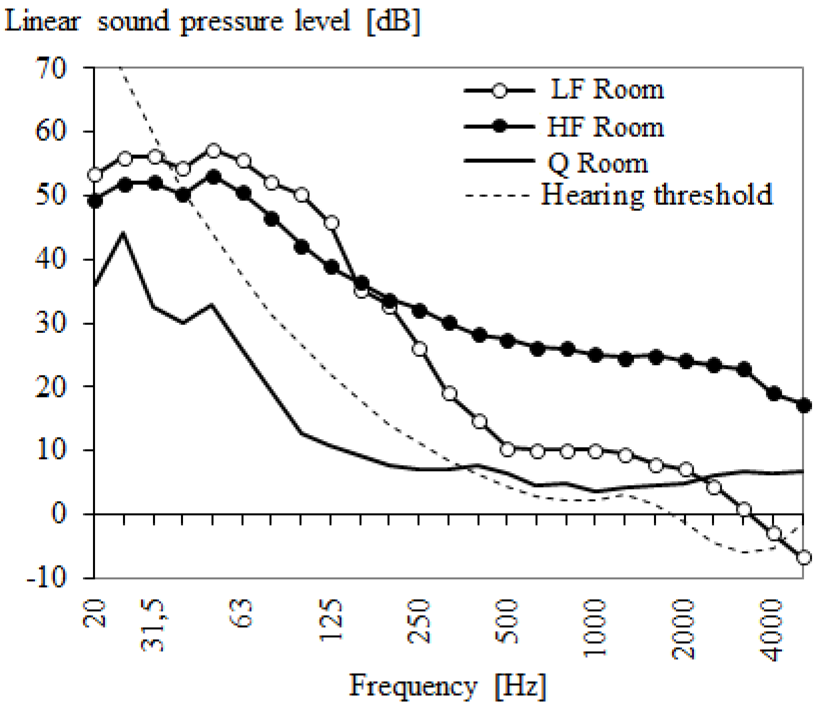

Figure 1. Audio frequency ranges of the noise conditions of LF Room, HF Room and Q Room with relation to hearing threshold defined in the international standard ISO 226:2003 (2003).

LF = low frequency noise, HF = high frequency noise, Q = quiet.

This study was a part of the ÄKK project (*Rakennusten ääniolosuhteiden käyttäjälähtöinen kehittäminen*, 2011–2014). It was a multidisciplinary research project that aimed to develop user-oriented sound insulation in buildings. It was carried out by the indoor environment laboratory of the Finnish Institute of Occupational Health, Structural Engineering of the Tampere University of Technology and the unit of psychology of the University of Turku. This study was approved by the coordinating ethics committee of the Hospital District of Helsinki and Uusimaa. All participants provided written informed consent.

2.2 Primary and Secondary Effects of Traffic Noise

The sleep quality of the participants was measured with both objective and subjective methods. During the research nights, physiological changes induced by traffic noise were detected with polysomnography (PSG), the main objective method used in this study. Participants' subjective experience on how they slept during the night and how they felt in the following morning, day and evening was surveyed with questionnaires. Secondary effects of nocturnal traffic noise were also objectively measured with the Psychomotor Vigilance Test.

2.2.1 Objectively Measured Primary Effects

Polysomnography is the simultaneous recording of electrical brain activity (electroencephalography, EEG), eye movements (electro-oculography, EOG) and muscle tone (electromyography, EMG), which is used to classify sleep stages and to score arousals. Also, the electrical activity of the heart (electrocardiography, ECG) was recorded to assess the functioning of the autonomic nervous system. The PSG system used in this study was the Embla N7000. The EEG electrodes were silver-silver chloride electrodes and, in the face area, disposable electrodes were used. The EEG electrodes were attached to the scalp and face of the subjects according to the International 10-20 system and Cz was used as a reference electrode. It was done as soon as the participants arrived at the sleep laboratory so the electrode paste had enough time to dry before the night. A bio-calibration, during which the participants were, for example, asked to blink or to clench their teeth, was done every night to ensure that all electrodes were functioning correctly and to acquire a baseline data to help the scoring of the polysomnogram.

Two trained nurses evaluated the polysomnograms according to the American Academy of Sleep Medicine (AASM) 2.0 manual. The EOG and EEG derivations that were used for the scoring of sleep stages along with EMG were E1-M2, E2-M2, Fz-Oz, Cz-Oz and C4-M1 (and C3-M2 as backup electrodes). In this study, total sleep time (i.e. how long the subject slept during each night), sleep latency (i.e. how long it took to fall asleep; transition from wakefulness to first sleep stage), wake after sleep onset (WASO; i.e. how long the subject was awake during the night after falling asleep) and arousals (i.e. abrupt shifts of EEG frequency that lasts at least 3 seconds) were recorded. In addition, time spent in stages N1, N2, N3 (SWS) and REM was analysed. Sleep stages were scored in 30-second sequential epochs and a sleep stage was assigned for each epoch. The sleep stage that comprised the greatest portion of the epoch was assigned, if two or more sleep stages coexisted during a single epoch.

2.2.2 Subjectively Measured Primary and Secondary Effects

For this study, two questionnaires were designed to measure participants' subjective experiences on how they slept in different rooms, and how they felt during the following day. These questionnaires consisted of several items and in this study, only those items were analysed that were relevant regarding the aims. Additionally, the participants completed a broad questionnaire on background information during the first evening. It concerned, for example, their health, sleeping habits, consumption of alcohol and caffeine and current mood. The purpose was to gather information widely on aspects that could affect their sleeping. Only a few items of this questionnaire were used in this study.

The participants completed a short evening questionnaire every evening in their rooms. The purpose of the questionnaire was to survey the secondary effects of traffic noise, and to find out how the participants felt during the day and in the evening after sleeping under different noise conditions during the night. Their sleepiness in the evening was measured with the Karolinska Sleepiness Scale (KSS) which consists of a nine-point scale (from 1.Very alert to 9.Very sleepy, great effort to stay awake, or fighting sleep). They were also asked how tired they had felt compared to a normal day (from 1.Much more awake to 5.Much more tired) and how strained they felt in the evening (from 1.Not at all to 5.Extremely).

A morning questionnaire was completed every morning approximately 30 minutes after being woken up. The purpose of this questionnaire was to find out how well the participants themselves felt they had slept during the night. They were asked to estimate how many times they had woken up during the night (1. Once or not at all, 2.Two or three times, 3.Four or five times, 4.More than five times). They also had to evaluate how different claims (e.g., "I had difficulties falling asleep.") corresponded to their experience of the previous night (from 1.Not at all to 5.Very much). In the morning questionnaire, there was also a question about how satisfied the participants were with their sleeping on the previous night (from 1.Very dissatisfied to 5.Very satisfied). In addition, participants had to judge how much different environmental factors (e.g., traffic noise) had interfered with their sleep the night before (from 1.Not at all to 5.Very much). Also, the secondary effects of traffic noise were surveyed in the morning questionnaire. Participants were asked to judge how strained they felt at the time (from 1.Not at all to 5.Extremely) and as in the evening, sleepiness was assessed using KSS.

After all the research nights on Friday evening (between 19:00–23:00), the subjects completed an evening questionnaire that was sent to them by email. The questionnaire was the same as the evening questionnaire they had completed on previous evenings, but it also had a question about the obtrusiveness of the noise in different rooms. Participants were asked which of the rooms had the most obtrusive noise environment. They were told that every room had their own noise environment, and a picture of the layout of the laboratory was provided to ease retention.

2.2.3 Objectively Measured Secondary Effects

It was also in the interests of this study to assess how performance was affected after being exposed to traffic noise during the night. Hence, the Psychomotor Vigilance Test (PVT) (Dinges & Powell, 1985) was used to measure vigilance. Participants performed the PVT with a tablet computer both in the evenings and in the mornings. The performance in the evenings itself was not in the interests of this study, but the aim was to compare measurements at these different times. The test was 10 minutes long and consisted of 160 stimuli of running numbers. The task was to immediately tap the screen every time the numbers started running on the screen. The reaction time remained visible for 1 second and the next stimulus appeared randomly after 1–3 seconds. From the PVT, three variables were analysed: reaction times (RT), the number of lapses and the number of anticipations. A reaction time of over 500 milliseconds was considered to be a lapse. Anticipation occurred when the screen was tapped before the next stimulus appeared.

Every evening after performing the PVT, the participants completed a short version of the National Aeronautics and Space Administration Task Load Index (NASA-TLX) (Hart & Staveland, 1988) to rate the perceived workload of the test. Participants rated the workload on six subscales that were mental demand, physical demand, temporal demand, performance, effort and frustration. Participants were provided with a specifying question to each subscale (e.g., Effort: How much did you have to strive to accomplish the test?). These subscales were rated on a visual analogue scale from “Very little” to “Very much”. The means of the subscales were added up and a summative score, the NASA-TLX Index, was formed for each room. For the index, a reversed version of the performance variable was used, as the original scale of this variable was opposite to the other variables. The reliability of this index was considered sufficient, as the Cronbach’s alphas were .68 for

HF Room, .72 for LF Room and .78 for Q Room. The possible range of the summative scores was 6–600 points. Higher scores on the NASA-TLX Index represent a higher perceived workload of the PVT.

2.3 Experimental Procedure

The experimental procedure is presented in Table 1. The first evening in the sleep laboratory (Monday) differed partly from the other evenings. On the first night, also airflow, snoring, limb movements and movements of the rib cage and abdomen were recorded so that any participants having some sleeping problems or sleep disorders, such as sleep apnoea or restless legs syndrome, could be identified. An information session lasting approximately 30 minutes was held in which the participants were informed about the practices and restrictions during the research week. For the rest, the first evening and night in the laboratory followed the same procedure as the actual research nights.

Participants were informed that the aim of this study was to assess the effects of road traffic noise on sleep. They were informed that they would sleep in different rooms every night, but they were not told that the rooms had different noise conditions. Participants were given very limited information about the noises used in this study, and they were only told that the noise conditions of interest did not have adverse health effects. They were also requested not to discuss with each other about the research nights or any issues related to the research. Participants were told that if they would wake up during the night, they should try to continue sleeping and, for example, reading was not allowed during the night.

Table 1.

Experimental Procedure

Time	**Monday**	**Tuesday**	**Wednesday**	**Thursday**	**Friday**
7:00		Waketime	Noise off Waketime	Noise off Waketime	Noise off Waketime
7:15		PVT NASA-TLX MQ Breakfast	PVT NASA-TLX MQ Breakfast	PVT NASA-TLX MQ Breakfast	PVT NASA-TLX MQ Breakfast
8:00		Allowed to leave SL	Allowed to leave SL	Allowed to leave SL	Allowed to leave SL
8:00 – 18:00					
18:00	to SL 18:00–20:00	to SL 19:00–20:30	to SL 19:00–20:30	to SL 19:00–20:30	
19:00					Friday's EQ is answered at home 19:00–23:00
20:00	PSG electrodes are attached	PSG electrodes are attached	PSG electrodes are attached	PSG electrodes are attached	
21:30	Info	Free time	Free time	Free time	
22:00	Snack	Snack	Snack	Snack	
22:15	PVT NASA-TLX EQ	PVT NASA-TLX EQ	PVT NASA-TLX EQ	EQ	
22:30	PSG on Biocalibration	PSG on Biocalibration	PSG on Biocalibration	PSG on Biocalibration	
22.45		Noise on in HF Room and LF Room	Noise on in HF Room and LF Room	Noise on in HF Room and LF Room	
23:00	Lights off	Lights off	Lights off	Lights off	

SL = Sleep laboratory; Info = 30 minutes information session; EQ = Evening questionnaire; PSG on = Registration of Polysomnography is started; MQ = Morning questionnaire.

Every evening the participants were given a light snack and they also had some free time. All the questionnaires and the PVT were completed in the rooms using tablet computers which were collected from the participants along with their personal electronic devices for the duration of the night. The playing of the noise was started 15 minutes before the lights were turned off and it was stopped just before the subjects were woken up at 7:00. Every morning the participants were given a small breakfast.

The participants were not allowed to take naps before the research nights (Monday–Thursday). Consumption of alcohol and caffeinated drinks was prohibited after 1500 o'clock before the research nights so that their effects on sleep could be minimized.

During the days of the research week, the participants were allowed to continue their daily lives, for example, work, study and exercise as usual. After the participants left the sleep laboratory on Friday morning, all restrictions related to the research were ceased. The participants wore a wrist actigraph until Wednesday of the following week so that their normal sleeping patterns could have been analysed if desired.

2.4 Statistical Analyses

Tests for repeated measures were used to analyse the differences between the rooms in the subjectively and objectively assessed primary and secondary effects of nocturnal traffic noise. The Shapiro-Wilk test was used to assess the assumption of normal distribution. Of the PSG-variables, N2, SWS and REM variables were normally distributed. Of the other variables, only the NASA-TLX Index was normally distributed. When these variables were analysed, the parametric repeated measures ANOVA was used. With the other variables, the non-parametric equivalent, the Friedman test, was used. In the case of repeated measures ANOVA, Mauchly's sphericity test was used to test the assumption of sphericity. If there were statistically significant differences between the variances of the differences, the Greenhouse-Geisser correction was used for the result. Multiple comparisons were done with paired samples t-test and Wilcoxon signed-rank test, for the repeated measures ANOVA and Friedman test, respectively. For all the statistically significant results, the Benjamini-Hochberg procedure was applied to control the false discovery rate in all the pairwise comparisons of individual variables with three levels. In addition, the χ^2 -test was used to analyse the question of the obtrusiveness of the noise environments in the rooms. An alpha level of 0.05 was used throughout the analyses. All statistical analyses were performed using IBM SPSS Statistics version 20.

3. Results

3.1 Objectively Measured Primary Effects of Nocturnal Traffic Noise

The means of the PSG variables were compared between the LF Room, HF Room and Q Room, and the means and the standard deviations of these variables are shown in Table 2. The only statistically significant difference was found in the overall duration of SWS ($F(2) = 5.29$, $p = .01$). In both the LF Room ($t(20) = -2.97$, $p = .02$) and HF Room ($t(20) = -2.64$, $p = .02$), the participants slept less SWS compared with Q Room. Low frequency and high frequency noise conditions did not differ from each other in the overall duration of SWS ($p = .52$). Thus, being exposed to traffic noise seemed to influence the overall duration of SWS when compared with sleeping in quiet condition. Being exposed to traffic noise of either kind did not influence any other PSG variables.

Table 2.

Means and Standard Deviations of PSG variables Compared Between Each Room

	LF Room	HF Room	Q Room	
Variable	*M (SD)*	*M (SD)*	*M (SD)*	*p-value*
Time in bed (h)	8.00	8.00	8.00	
Total sleep time	7 h 28 min (16.81)	7 h 29 min (16.99)	7 h 33 min (21.78)	.43
Sleep latency (min)	13.86 (12.30)	13.26 (9.56)	12.50 (10.55)	.55
N1 (min)	29.36 (13.97)	31.62 (16.49)	27.00 (12.47)	.80
N2 (min)	228.26 (27.92)	224.67 (27.77)	218.21 (42.10)	.31[a]
SWS (min)	86.48 (30.19)	88.83 (25.04)	97.07 (26.38)	.01[a]
REM (min)	104.10 (24.44)	104.35 (23.29)	110.57 (26.75)	.50[a]
Arousals	49.38 (22.69)	54.43 (23.89)	47.33 (24.03)	.16
WASO (min)	18.64 (15.25)	17.79 (12.61)	15.23 (16.26)	.55

LF Room = low frequency noise room, HF Room = high frequency noise room, Q Room = quiet room, N1 = total time in stage N1 sleep, N2 = total time in stage N2 sleep, SWS = total time in slow-wave sleep REM = total time in REM sleep, WASO = wake after sleep onset, M = mean, SD = standard deviation

[a] = parametric test (repeated measures ANOVA) was used

3.2 Subjectively Measured Primary Effects of Nocturnal Traffic Noise

In the final evening questionnaire on Friday, the participants were asked about the obtrusiveness of the traffic noise in different rooms. As shown in Figure 2, the majority of the participants replied that the HF Room had the most obtrusive noise environment. There was a statistically significant difference in the obtrusiveness of the noise environments, when these data were compared with a situation, in which these different noise environments would have been equally obtrusive (χ^2 (2) = 22.57, p < .001). As shown in Figure 2, the high frequency noise condition differed from both the low frequency noise condition and the quiet condition in its evaluated obtrusiveness.

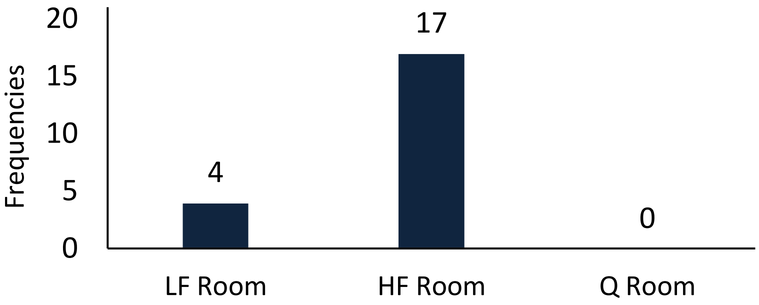

Figure 2. The frequency of participants choosing each room, when asked after the experiment, which of the rooms had the most obtrusive noise environment.
LF = low frequency noise, HF = high frequency noise, Q = quiet.

When asked, how much different environmental factors had interfered with participants' sleep on the previous night, the only difference found between the rooms was the interference of traffic noise (F_R = 24.91, p < .001). In Figure 3, it is shown how participants evaluated the interference of traffic noise on average. Traffic noise was considered more interfering in both the LF Room (Z = -3.714, p < .001) and HF Room (Z = -3.714, p < .001), when compared with Q Room. The low frequency and high frequency noise conditions did not differ in the interference of traffic noise (p = .29). No differences between any of the rooms were found in the interference of other environmental factors (silence, cold, hotness, registration equipment, quality of the bed, darkness of the room, sleeping in an unfamiliar place and monitoring camera) (p > .05; data not shown; range of means 1–1.62). This result was expected, as the rooms were presumed to be similar to each other in terms of these other environmental factors.

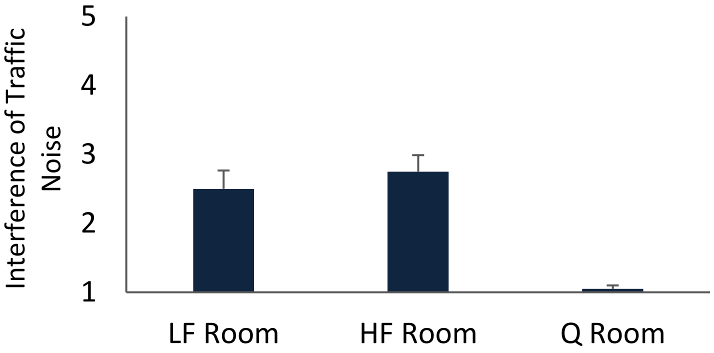

Figure 3. Means and standard errors for participants' evaluations on how much traffic noise interfered with their sleep in the LF Room, the HF Room and the Q Room.
1 = Not at all; 2 = Only a little; 3 = A little bit; 4 = A lot; 5 = Very much.
LF = low frequency noise, HF = high frequency noise, Q = quiet.

There was a difference between the rooms on how satisfied the participants were with their sleep (F_R (2) = 7.90, p = .02). The means for participants' answers are shown in Figure 4. Participants were more satisfied with their sleep in Q Room compared with the LF Room (Z = -2.63, p = .03), and HF Room (Z = -2.51, p =.02). There was no difference in satisfaction with sleep between low frequency and high-frequency noise conditions (p = .37).

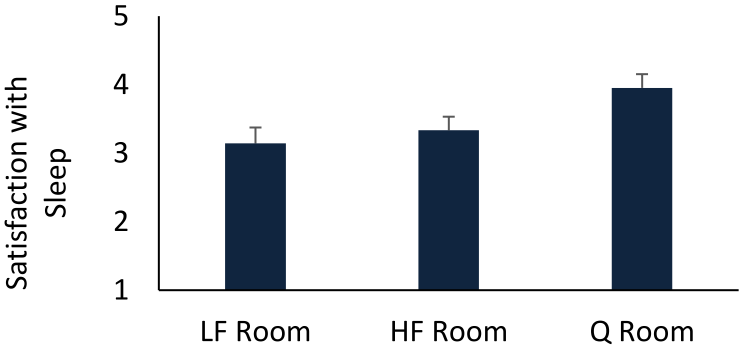

Figure 4. Means and standard errors for participants' satisfaction with sleep in LF Room, HF Room and Q Room.
1 = Very dissatisfied; 2 = Dissatisfied; 3 = Neither satisfied nor dissatisfied; 4 = Satisfied; 5 = Very satisfied.
LF = low frequency noise, HF = high frequency noise, Q = quiet.

Every morning, participants had to evaluate how different claims corresponded to their experience of previous night. Mean and standard errors of participants' answers are shown in Table 3. There was a difference between the rooms in participants' subjective difficulties in falling asleep ($F_R(2)= 7.81$, $p = .02$) and subjective sleep latency ($F_R(2)= 10.10$, $p = .01$). Participants reported more difficulties in the LF Room (falling asleep $Z = -2.59$, $p = .03$; sleep latency Z = -2.81, p = .01) and HF Room (falling asleep $Z = -2.39$, $p = .03$; sleep latency Z = -2.17, p = .05) than in the Q Room. There was no difference between the two noise conditions (falling asleep $p > .58$; subjective sleep latency $p > .19$). In the LF Room and HF Room, participants reported on average *"Only a little"* difficulties falling asleep and *"Not at all"* in the Q Room. There was a difference between the rooms in experienced difficulties staying asleep, but after using the Benjamini-Hochberg procedure, no differences were found between the rooms in multiple comparisons. No other differences were found between the rooms in the claims from morning questionnaire.

Table 3.

Means and standard deviations of how participants answered to different claims from morning questionnaire

	LF Room	HF Room	Q Room	
Variable	*M (SD)*	*M (SD)*	*M (SD)*	*p-value*
"I had difficulties falling asleep"	2.19 (.93)	2.10 (.94)	1.57 (.75)	.02
"Falling asleep took longer than usually"	2.14 (1.01)	1.90 (1.04)	1.48 (.81)	.01
"My sleeping was discontinuous, and I had difficulties staying asleep"	2.24 (.10)	2.10 (1.04)	1.57 (.98)	.01
"I tossed and turned many times during the night"	2.38 (1.07)	2.19 (.75)	1.95 (.97)	.10
"I recovered well from the previous day's strain during the night"	3.24 (.94)	3.19 (.87)	3.48 (1.12)	.29
"I woke up feeling energetic"	2.67 (.86)	2.81 (.68)	3.05 (1.12)	.16

LF Room = low frequency noise room, HF Room = high frequency noise room, Q Room = quiet room, *M* = mean, *SD* = standard deviation

1. Not at all; 2. Only a little; 3. A little bit; 4. A lot; 5.Very much

There was a difference between the rooms in how many times participants' evaluated having woken up during the night ($F_R(2) = 8.04$, p =. 02). Percentages for participants' evaluations are shown in Figure 5. According to participants' evaluations, they had woken up less often in the Q Room, than in the LF Room ($Z = -2.35$, $p = .03$) or HF Room ($Z = -2.49$, $p = .04$). No difference was found between sleeping under the low frequency or high frequency noise condition ($p = .81$).

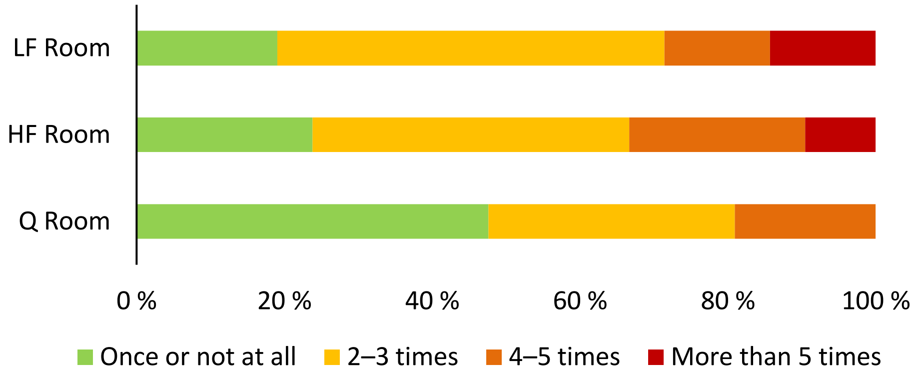

Figure 5. Percentage of each answer option chosen, when participants evaluated how many times they had woken up during the night when sleeping in low frequency noise (the LF Room), high frequency noise (the HF Room), and quiet (the Q Room).

3.3 Objectively Measured Secondary Effects of Nocturnal Traffic Noise

Vigilance was measured in the mornings with PVT, and no differences were found between any of the rooms in any of the measured variables, i.e. RTs ($p = .21$), number of lapses ($p = .39$), or number of anticipations ($p = .25$). The mean RT's were 300.86 ms ($SD = 31.86$) for the LF Room, 296.65 ms ($SD = 36.75$) for the HF Room and 301.22 ms ($SD = 38.25$) for the Q Room. The mean number of lapses in the morning were 2.71 ($SD = 5.52$) for the LF Room, 3.10 ($SD = 4.67$) for the HF Room and 3.57 ($SD = 5.27$) for the Q Room. For the number of anticipations in the morning, the means were 12.48 ($SD = 8.06$) for the LF Room, 15.95 ($SD = 12.11$) for the HF Room and 15.48 ($SD = 11.73$) for the Q Room.

Participants' performance in the PVT in the mornings after research nights was compared with their performance in the previous evenings. This was done with 3 x 2 ANOVA (Room x Time). No interactions in any variables were found between the rooms and the times of measuring. A main effect was found for the RTs ($p < .001$). In all rooms, reaction times were faster in the mornings than in the evenings.

The perceived workload of PVT was measured with the NASA-TLX Index. Participants' answers varied on a range of 76–463. The means for this index were 232.57 (*SD* = 89.52) for the LF Room, 213.33 (*SD* = 81.29) for the HF Room and 217.81 (*SD* = 96.29) for the Q Room. No difference between the rooms was found on this index ($p = .53$).

3.4 Subjectively Measured Secondary Effects of Nocturnal Traffic Noise

Subjective secondary effects of traffic noise were measured with questionnaires both in the morning and in the evening of the following day after sleeping in each room. Means and standard deviations for these variables are shown in Table 4. There were no differences between the rooms either in the morning or in the evening in any of the subjectively measured secondary effects, i.e. sleepiness, strain and tiredness.

Table 4.

Means and standard deviations for variables that measured secondary effects of traffic noise

	LF Room	HF Room	Q Room	
Variable	*M(SD)*	*M(SD)*	*M(SD)*	*p-value*
Sleepiness, morning	5.76 (1.67)	5.38 (1.66)	5.24 (2.36)	.41
Strain, morning	2.33 (1.11)	2.33 (.86)	2.19 (1.03)	.52
Sleepiness, evening	4.67 (1.56)	5.38 (1.66)	4.76 (2.17)	.74
Tiredness compared	3.33 (1.02)	3.43 (.93)	3.10 (1.04)	.52
Strain, evening	2.05 (.97)	2.43 (1.12)	2.14 (1.20)	.11

LF Room = low frequency noise room, HF Room = high frequency noise room, Q Room = quiet room, *M* = mean, *SD* = standard deviation

4. Discussion

The aim of this study was to assess whether there are differences in the effects of traffic noises with different audio frequencies on sleep. The low frequency noise and the high frequency noise conditions were compared with each other and the quiet condition. The participants rated the high frequency noise condition as the most obtrusive noise environment for sleep. However, the low frequency and the high frequency noise condition did not differ from each other on any variable when primary and secondary effects of noise were subjectively and objectively assessed. When the two noise conditions were compared to the quiet condition, it was observed that the participants slept less SWS, were less satisfied with their sleep, experienced more difficulties in falling asleep and evaluated having woken up more often in the noise conditions. Being exposed to traffic noise during the night did not have statistically significant secondary effects, that is to say, participants were as sleepy and as strained during the next morning, day and evening regardless of the room they had slept in the preceding night. In addition, nocturnal traffic noise did not affect participants' vigilance in the morning.

4.1 Being Exposed to Traffic Noise Affects Sleep Quality

4.1.1 Primary Effects of Nocturnal Traffic Noise

Less SWS was slept during both nights with traffic noise exposure compared with the quiet night. The total time spent in SWS was on average about 10 minutes shorter in the LF Room and about 8 minutes shorter in the HF Room than in the Q Room. This result is supported by previous studies (Eberhardt et al., 1987; Griefahn et al., 2006). The decrease in SWS has thought to result from a general elevation of the organism's arousal level caused by the acute effects of noise on sleep, that is to say arousals, awakenings and body movements. These acute effects increase the time spent in wakefulness and stage N1 sleep at the expense of REM sleep and SWS. In this study, however, no alterations to the time spent in other sleep stages were found. In future research, it would be interesting to analyse the sleep stage modifications in relation to individual noise events. Nights with traffic noise should then be analysed in shorter epochs to see, if the sleep stage modifications are occurring especially during certain parts of the night, for example in the first third of the night, when SWS dominates. While SWS is considered important for humans, the exact functions and nature of it are still uncertain (Roth, 2009). SWS is thought to be important for memory functions and especially for the memory consolidation during sleep (Rasch & Born, 2013). In future research, it could be valuable to study whether memory functioning is affected by reduced amount of SWS that is caused by nocturnal noise.

As time spent in SWS was possibly reduced due to an elevation of arousal level caused by nocturnal noise, it could be hypothesized that more arousals occurred during the nights with traffic noise. This was, however, not the case in this study. The number of arousals, the abrupt changes in the pattern of brain wave activity, was not affected by nocturnal traffic noise. Furthermore, less arousals were found occurring during the night than normally, as on average 83 arousals have been found to occur in an eight-hour sleep of healthy young subjects (aged 21–30) (Bonnet & Arand, 2007). In this study, the number of arousals was on average 49.38 for LF Room, 54.43 for HF Room and 47.33 for Q Room. This raises the question of whether all the arousals were detected during the scoring of polysomnogram.

Being exposed to nocturnal traffic noise did not affect sleep latency in this study. Although exposure to nocturnal traffic noise has been associated with objectively measured increase in time to fall asleep (Muzet, 2007; Pirrera et al., 2010), many studies have not found increases in sleep latency during nights with traffic noise (Griefahn et al., 2006; Marks & Griefahn, 2007). Results of this study support the view that traffic noise of this noise level does not increase time to fall asleep. In this study, playing of the noise was started 15 minutes before the lights were turned off, so that participants could habituate to the noise. The noise profile of traffic noises used in this study was made to resemble a normal weekday night with the number of noise events decreasing for the night and increasing again during the morning hours. This kind of noise profile was also used in the study of Griefahn et al. (2006). The noise arrangements in this study might have contributed so that no increases in sleep latency were found.

According to self-evaluations, falling asleep was a bit harder in the two rooms with traffic noises than in the quiet room. There is, thus, a discrepancy between the objective and subjective evaluations of falling asleep in this study. Previously, self-evaluations of sleep latency have been found to be slightly overestimated compared to objectively measured sleep latency (Silva et al., 2007). In their study, however, participants evaluated, how long (in minutes) it took them to fall asleep and these self-evaluations were then compared to objectively measured sleep latency. Because in this study, falling asleep was subjectively assessed with claims *"I had difficulties falling asleep"* and *"Falling asleep took longer than usually"*, comparison between subjectively and objectively assessed sleep latency is more difficult. Even so, participants may have overestimated the difficulties they had in falling asleep. However, the discrepancy between the objective and subjective evaluations of falling asleep is fairly small, as the claims corresponded to participants' experiences of the room with traffic noises on average *"Only a little"*. These results suggest that traffic noise affected participants' evaluations on falling asleep, but the difficulties in falling asleep were not considerable.

Along with sleep latency, also the duration of wake after sleep onset (WASO) affects total sleep time. As these variables did not increase during the nights with traffic noise, neither was total sleep time affected by nocturnal noise. As for WASO, the results of this study are in contradiction with those of Griefahn et al. (2006). They found an increase in WASO with a noise level of 39 dB, which is close to the noise levels used in this study (38 dB). They found WASO to be on average 36.5 min (SD = 17.1), while in this study WASO was on average 18.64 min (SD = 15.25) under the low frequency noise condition, and 17.79 min (SD = 12.61) under the high frequency noise condition. The small a difference in the noise levels is unlikely to explain the discrepancy between these results. Griefahn et al. (2006) used road, rail and traffic noise, and no distinction as to the type of noise was made when this noise levels was analysed. Noises from different means of transport may differ in their effects on sleep, which might explain this discrepancy. In addition, with relatively low noise levels, awakenings might not be a sensitive enough a measurement for sleep disturbances, as the noise levels of single events may not be high enough to cause an awakening.

Subjective sleep quality was partly affected during the nights with traffic noise. Participants were less satisfied with their sleep and evaluated having woken up more often when they were exposed to traffic noise. Participants' evaluations of their satisfaction with sleep during the nights with traffic noise were on average closest to *"Neither satisfied nor dissatisfied"*. Evaluations of the claims from the morning questionnaire indicated that falling asleep was more difficult in the two rooms with noise exposure, although this claim applied to these rooms on average only a little. According to these results, the effects of traffic noise on subjective sleep quality were significant, but not substantial in their size. Although decreases in subjective sleep quality have previously been found (for example Öhrström & Skånberg, 2004), comparisons to previous studies are complicated, as there are differences in how participants are asked to evaluate their sleep. One of the main reasons for this problem is that no clear definition for sleep quality exists, and various operational definitions are used in different studies (Pirrera et al., 2010).

4.1.2 Secondary Effects of Nocturnal Traffic Noise

No secondary effects of noise, either objective or subjective, were found in this study. Being exposed to traffic noise during the night did not have an effect on how sleepy or strained the participants felt in the morning and in the following evening. No effect on tiredness during the following day after nocturnal noise was found, unlike the significant differences in tiredness found by Öhrström (1995). The discrepancy between these results might be due to somewhat higher maximum levels of 45 dB for noise events in Öhrström's study, compared to the noise level of 38 dB used in this study. The participants studied by Öhrström were also rather or very sensitive to noise, which may explain a greater impact of noise on tiredness.

Participants' performance, in relation to reaction times, lapses and anticipations in the PVT, was not altered in the mornings after traffic noise exposure. There is some evidence that nocturnal noise might slow down reaction times on performance test in the morning (Öhrström, 1995, Marks & Griefahn, 2007), but these data do not support this claim. Performance deficits have been found to correlate with tiredness in the morning (Öhrström, 1995), which might suggest that more sleep disturbances need to occur to have an effect on performance in the morning. Indeed, longer periods of partial sleep deprivation result in more lapses in PVT (Van Dongen, Maislin, Mullington, & Dinges, 2003). Nocturnal traffic noise in this study did not seem to cause significant sleep deprivation.

Healthy young adults were enrolled in this study, which has been the case for most of the studies assessing the effects of traffic noise on sleep (Muzet, 2007). This group is hardly among the most vulnerable groups for sleep disturbances due to nocturnal traffic noise. This might partly explain why only few primary effects and no secondary effects of nocturnal traffic noise were found in this study. All participants also lived along some busy road or nearby, so they might be used to sleeping in noisy conditions. Furthermore, noise sensitivity was not an inclusion criterion in this study as it was not of interest to study participants particularly sensitive to noise. Some studies have enrolled people who are rather or very sensitive to noise (e.g. Öhrström & Rylander, 1990; Öhrström, 1995), and generalization of those findings to general population should be made with caution. For instance, noise sensitivity has been found to affect subjective evaluations of sleep (Marks & Griefahn, 2007).

4.2 Traffic Noises with Different Audio Frequencies Compared

The room with the high frequency noise condition had the most obtrusive noise environment for sleep according to two thirds of the participants. This result indicates that high frequency noise is experienced as more disturbing for sleep than low frequency noise. However, there were no differences between these two noise conditions in any of the variables that measured objective and subjective sleep quality or vigilance. The effects of traffic noise on sleep seemed to be as great regardless of the audio frequency range of the noise. For example, there were no differences between the two noise conditions in how much the traffic noise interfered with sleep according to participants’ evaluations.

Low frequency noise is especially problematic as it can travel long distances and through many structures with little attenuation (Waye, 2004). For this reason, the effects of low frequency (ventilation) noises have been of interest in some studies (Waye et al., 2003; Waye et al., 2004; Öhrström & Skånberg, 2004). This was the first study to compare the effects of low frequency traffic noise and high frequency traffic noise on sleep quality. Low frequency traffic noise affected both objective and subjective sleep quality in some respects, but so did the high frequency traffic noise. Hence, the findings from this study do not accentuate either low frequency or high frequency traffic noise as more disturbing for sleep than the other. On the basis of this study, it cannot be said with certainty that traffic noises with different audio frequencies do not differ in their effects on sleep, as this was only the first study to examine this hypothesis. Frequency spectrum is rarely reported for the intermittent noises used to study the effects of traffic noise on sleep, as commonly only the sound pressure level is referred to (Waye, 2004). It is suggested that, in future studies, it would be useful to announce also the audio frequency range of the traffic noises that are used, so more information on the effects of audio frequencies on sleep would be gained.

4.3 Strengths and Limitations

As this research was done in laboratory settings, it was possible to control many of the intervening variables and the whole experimental environment. The laboratory environment was made as homelike as possible with a common room, decoration and comfortable beds. The importance of homelike environment in laboratory has been discussed previously by Skånberg and Öhrström (2006). Participants slept in all three rooms and the order of the rooms was counterbalanced to reduce order effects. In some studies, only the order of the nights with noise has been counterbalanced, and the quiet reference night has been first for all the participants (Öhrström, 1995; Öhrström & Skånberg, 2004). In this study, it was seen important that the order of all the rooms, including the quiet room, would be counterbalanced.

Also the traffic noise used in this study was well controlled. Traffic noises were recorded on a normal weekday night, and thus, the noise profile was assumed to reflect the noise occurrences of a normal night. Audio tape was edited so that all noises that were not the main interest of this study were deleted. The comparison of results from laboratory and field settings is often complicated as the precise individual indoor levels are not known in many field studies or control of these levels is lacking (Öhrström, 2000). Indoor noise levels are usually derived from outdoor measurements, and as the façade reductions vary, the evaluations of indoor noise levels might be imprecise. In this study, the exact noise levels were known, and verifying measurements were carried out every night to ensure the noise levels were correct.

Laboratory setting also made it possible to use PSG as the objective method for measuring sleep disturbances. Because of PSG, it was possible to acquire information about subtle physiological changes and sleep structure during the nights with nocturnal traffic noise. With other available objective methods, such as wrist-actigraphs, it would not have been possible to assess sleep depth reliably. Currently, PSG is the most reliable and standardized method to objectively measure the effects of nocturnal traffic noise on sleep. Considering that polysomnography as physiological measurement of sleep is costly and laborious, it is easier for field studies and studies with large samples to use subjective evaluations of sleep. The variety of measurement techniques used by different researchers complicate the comparison of results from different studies.

Sample size of this study was fairly small, which has possibly lowered the statistical power. It has been suggested by Basner et al. (2012) that as PSG is a somewhat disruptive method, it might decrease participation rates. Furthermore, the arrangements of this study were quite demanding for the participants as they had to sleep for four consecutive nights in laboratory conditions. These conditions may have decreased the number of volunteers who participated in this study. Only a few men volunteered for participation, which resulted in a sample consisting mainly of women. It was not, thus, possible to examine whether there are gender differences in the effects of traffic noise on sleep. The individuals who volunteered for this study were possibly “good sleepers”, as individuals who usually sleep poorly are unlikely to participate in a sleep study in which their sleep might be disturbed.

Sleep quality was not explicitly defined in this study even though both objective and subjective methods were used to measure it. Acquiring a clear definition for sleep quality could have eased the comparisons with the previous studies especially in regard to subjective sleep quality. Some of the questions that measured subjective sleep quality in this study were ambiguous, which complicated the interpretation of the results. More precise questions, such as “*How many minutes do you think it took you to fall asleep last night?*”, would have been useful. These questions could also have enabled the comparison between the objective and subjective evaluations of sleep quality, which was not possible with the questions that were chosen for measurement of subjective sleep quality.

A standard measurement technique for the effects of nocturnal traffic noise is missing, and it would be important to know whether subjective evaluations validly reflect the physiological changes in sleep due to traffic noise. Subjective evaluations of this study might have been affected by the expectations the participants had about noise and its effects on sleep. The information given to the participants about the noise was, therefore, kept as low as possible. Participants may have, nevertheless, evaluated their sleeping during nocturnal noise worse than in the quiet conditions, as they knew that the aim of this study was to assess the effects of traffic noise on sleep. For example, they may have evaluated that falling asleep took longer than usually when the noise was played, although in the light of objective evaluations, participants fell asleep as quickly in all the rooms. The reliability of objective methods can also be questioned. Electrodes and their leads may have disturbed participants and, therefore, influenced their sleep. Although sleep stage classification and scoring of the arousals was done by trained personnel, they might be subject to human errors.

Extrapolation of these findings into sleeping in home environment has to be made with caution as is usually the case for sleep studies done in laboratory. Thus, one can question the ecological validity of this study. According to some reviews, fewer awakening reactions have been found in field settings than in laboratory studies (Pearsons, Barber, Tabachnick & Fidell, 1995; Öhrström, 2000). However, these comparisons between results from field and laboratory settings are uncertain and their commensurability can be questioned, as slightly different methods and noise sources have been used in field and laboratory settings and, as exact indoor noise levels are rarely known in field settings. When the same subjects were exposed to equal levels of traffic noise both in a laboratory and in their homes, no significant differences were found in the sleep quality that was assessed with wrist-actigraphy and questionnaires (Skånberg & Öhrström, 2006). These results indicate that the studies done in a laboratory and the field are comparable when the same methods are used and exact noise levels are known.

4.4 Conclusion

When participants were exposed to nocturnal traffic noise, they slept less SWS, were less satisfied with their sleep, and evaluated having woken up more often and experienced slightly more difficulties in falling asleep. No secondary effects of nocturnal traffic noise were found, including tiredness or performance deficits in the PVT. Although the high frequency noise condition was experienced as the most obtrusive environment for sleep, there were no differences between the low frequency and the high frequency noise conditions in primary and secondary effects of traffic noise on sleep. Results from this study do not highlight that either low frequency noise or high frequency noise is more disturbing for sleep than the other. The possibility that traffic noises with different audio frequencies differ in their effects on sleep cannot be ruled out, as this was the first study to examine this hypothesis.

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