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## Road Traffic Noise - Factors modifying its relation to annoyance and cardiovascular disease

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# Road Traffic Noise

Factors modifying its relation to annoyance and  
cardiovascular disease

Theo Bodin



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# Contents

Abstract	1
Populärvetenskaplig sammanfattning	3
List of papers	5
List of Abbreviations	7
1 Introduction	9
1.1 Environmental Noise	9
1.2 Annoyance and sleep	11
1.3 Cardiovascular disease	13
2 Aims	17
3 Materials and Methods	19
3.1 Study Populations	19
3.1.1 Skåne Public Health Survey 2004 and 2008	19
3.1.2 Residential Environment and Health Survey 2007	20
3.1.3 Skåne Public Health Survey Cohort 1999-2010	20
3.2 Exposure Assessments	21
3.2.1 Three Different Noise Exposure Models	22
3.2.2 Air pollution	24
3.2.3 Assessment of quiet side	24
3.3 Assessment of Outcomes	25
3.4 Study Design and Statistical Approach	26
4 Results	29
4.1 General findings	29
Annoyance, sleep and concentration problems	29
Cardiovascular disease	29
4.2 Exposure-related factors modifying the effect of noise	30
Combined exposure to road traffic and railway noise	30
Combined exposure to road traffic noise and air-pollution	31
4.3 Residential factors modifying the effect of noise	31

Quiet Side	31
Years in the same residence	33
Owned or rented	33
4.4 Demographic factors modifying the effect of noise	34
Age	35
Sex	36
Education, Financial stress and Socio-economy	37
4.5 Individual and contextual factors modifying the effect of noise	38
Noise sensitivity	38
Survey context and question wording	39
5 Discussion	40
5.1 General Discussion	41
5.1.1 Combined exposure from different noise sources	41
5.1.2 Combined exposure to road traffic noise and air-pollution	41
5.1.3 Quiet side and time spent in residence	43
5.1.4 Demographic factors modifying the effect of noise	44
5.1.5 Individual and contextual factors modifying the effect of noise	45
5.2 Methodological Discussion	47
5.2.1 Exposure assessment	47
5.2.2 Selection bias	48
5.2.3 Limitations	50
5.2.4 Statistical considerations	50
5.2.5 Assessment of outcomes	51
6 Conclusions	55
Implications for Policy	56
7 Future Research	59
8 References	61
9 Acknowledgments	67

*To: Emma and Omar*



# Abstract

Traffic noise causes annoyance and sleep disturbance and has been linked with several other adverse effects on life quality and health, including increased risk of hypertension and myocardial infarction. Conservative estimates assume that at least one million healthy life years are lost every year from traffic related noise in the western part of Europe. We know from earlier studies that the adverse effects of environmental noise may be modified by social, demographic and individual factors. However, there is a need to better evaluate exposure-response in susceptible groups. The aim of this thesis was to test a number of factors hypothesized to modify the association between road traffic noise, annoyance and cardiovascular disease. Papers I-III are cross-sectional, while paper IV is a cohort study. The four different study populations in this thesis were selected through stratified random sampling of men and women aged 18-80 years old in the county of Skåne and its major city Malmö in southern Sweden. Exposures of road traffic and railway noise as well as air pollution were modelled using geographic information system (GIS) for the survey participants' residential addresses. Possible confounding and modifying factors were mainly drawn from survey responses while outcomes were based on both self-reporting and inpatient registers. We were not able to show a relation between current and medium-term noise exposure to road traffic noise and incident myocardial infarction or ischemic heart disease in the general population. Air-pollution at low levels did not modify this effect. An association was however found between road traffic noise and hypertension in a cross-sectional study  $>60\text{dB(A)}$ . We also found strong and positive relations between road traffic noise and annoyance. Railway noise was found to be less annoying at intermediate levels, but not  $>55\text{dB(A)}$ . Access to quiet side had a protective effect and decreased the risk of annoyance, sleep and concentration problems equal to a  $5\text{dB(A)}$  decrease in noise exposure. Generally middle-aged persons were found to be more susceptible to noise. Higher socioeconomic status and educational level were related to noise annoyance. With regard to sex, findings were less consistent. We also found that results in our studies might be biased due to selective participation, that noise sensitive individuals were likely to have a higher response rate and that inter-study comparison may be difficult since different annoyance scales can produce very different results. In conclusion, the health effects of noise are modified by noise source, co-exposures, environmental and socio-demographic factors (as well as personal traits) and research methodology. To develop better policies for residential noise environment, future research should focus on combined exposures and stressors as well as further explaining age differences and developing better ways to account for social class.





# Populärvetenskaplig sammanfattning

Minst en miljon friska levnadsår går förlorade varje år på grund av trafikbuller i Västeuropa. Buller stör vardagsaktiviteter och sömn, samt har kopplats samman med flera andra dåliga effekter på livskvalitet och hälsa, bland annat ökad risk för högt blodtryck och hjärtinfarkt. Vi vet från tidigare forskning att de dåliga effekterna av trafikbuller kan ändras av sociala, befolkningsmässiga och personliga egenskaper. Men det finns fortfarande ett behov av att hitta och förstå bullrets påverkan på känsliga grupper. Syftet med studierna i denna avhandling var att undersöka ett antal saker som vi trodde ändrar sambandet mellan vägtrafikbuller, störning och hjärt-kärlsjukdom, till exempel kön, ålder och klass men också hur bostäder är utformade.

Män och kvinnor i åldern 18-80 år bostatta i Skåne valdes ut med hjälp av slumpen. Utsattheten för vägtrafikbuller, järnvägsbuller och luftföroreningar i deltagarnas hem räknades ut med hjälp av ett datorprogram som kan sätta ihop luft- och trafikmätningar med information om vägar, byggnader och omgivningar. Alla som var med i studierna fick svara på ett frågeformulär. Detta gav oss information om sjukdomar och störning, men också möjligheten att ta hänsyn till viktig information om deltagarna, till exempel ålder, kön, utbildningsnivå, vikt, rök- och motionsvanor m.m. I en studie kopplade vi också ihop deltagarna med Socialstyrelsens register för att få veta vilka sjukdomar de hade. Vi kunde visa ett samband mellan vägbuller och högt blodtryck. Men när vi följde deltagarna över tid fann vi inget samband mellan buller och hjärtinfarkt. Luftföroreningar påverkade inte förhållandet, men halterna i luften var låga. Vi fann också starka samband mellan trafikbuller och störning. Det visade sig att järnvägsbuller var mindre störande än vägbuller vid mellanhöga, men inte vid höga bullernivåer. Tillgång till tyst sida i bostaden hade en skyddande effekt och minskade risken för störning, sömn- och koncentrationsproblem. Generellt sett såg vi att medelålders personer var mer känsliga för buller. De med högre status i samhället och högre utbildningsnivå var mer störda än arbetarklass och lågutbildade. När det gäller kön, såg vi inget tydligt mönster. Vi fann också att resultaten kunde vara snedvridna för att bullerkänsliga individer troligen skickade in sina svar oftare än andra, kanske för att de är mer angelägna. Hur man ställde frågor om bullerstörning påverkade också resultaten.

För att utveckla bättre sätt att skapa goda boendemiljöer, avseende buller, bör framtida forskning fokusera på kombinationen av olika buller- och luftföroreningskällor och ta hänsyn till andra stressfaktorer. Man bör också försöka förklara och ta hänsyn till ålders- och klasskillnader i framtida forskning.

The thesis and it's included papers at a glance.

Aim/Hypothesis	Type of study/ Study population	Primary outcomes and method of analysis	Main findings and conclusions
Paper I Does noise sensitivity and question wording affect annoyance reporting?	Comparative cross- sectional. Stratified random sample in the city of Malmö	Self-reported annoyance. Logistic regression.	Number of alternatives in noise annoyance scale affects reporting. Some evidence of participation bias among noise sensitive individuals
Paper II Does quiet side affect annoyance, sleep and concentration? Is there a difference in annoyance related to noise source?	Comparative cross- sectional. Stratified random sample in the city of Malmö	Self-reported annoyance, sleep and concentration problems. Logistic regression.	Access to quiet side associated to less annoyance and concentration problems.
Paper III Is there an association between road traffic noise and hypertension?	Comparative cross- sectional. Stratified random sample in the county of Skåne.	Self-reported hypertension. Logistic regression.	Road traffic noise at levels $L_{AEQ24h} > 60\text{dB(A)}$ associated to higher risk of hypertension
Paper IV Is there a relation between road traffic noise, air pollution and myocardial infarction	Prospective cohort. Stratified random sample in the county of Skåne.	MI and IHD in National inpatient registry. Poisson regression.	No increased incidence rate ratio of MI in relation to road traffic noise or air pollution.

# List of papers

- I. **Bodin T**, Björk J, Öhrström E, Ardö J, Albin M. Survey context and question wording affects self reported annoyance due to road traffic noise: a comparison between two cross-sectional studies. *Environ Health* 2012; **11**(1): 14.
- II. **Bodin T**, Bjork J, Öhrström E, Ardö J, Albin M. Annoyance, sleep and concentration problems due to traffic noise from different sources and the benefit of quiet side – results from a cross-sectional study in Sweden (Manuscript)
- III. **Bodin T**, Albin M, Ardö J, Stroh E, Östergren PO, Bjork J. Road traffic noise and hypertension: results from a cross-sectional public health survey in southern Sweden. *Environ Health* 2009; **8**: 38.
- IV. **Bodin T**, Björk J, Bottai M, Mattisson K, Rittner R, Jakobsson K, Gustavsson P, Östergren P-O, Albin M. Road traffic noise and cardio-vascular disease – a prospective cohort study (Manuscript)



# List of Abbreviations

BMI	Body Mass Index
CI	Confidence interval (95% if not stated otherwise)
DALY	Disability-adjusted life year
dB(A)	A-weighted decibel
EEA	European Environment Agency
EEG	Electroencephalogram
END	Environmental noise directive (2002/49/EC)
EU	European Union
GIS	Geographical Information Systems
ICBEN	International Commission on Biological Effects of Noise
ICD-9	International Statistical Classification of Diseases and Related Health Problems, ninth revision
ICD-10	International Statistical Classification of Diseases and Related Health Problems, tenth revision
IHD	Ischaemic Heart Disease
IRR	Incidence Rate Ratio
LAeq(t)h	A-weighted equivalent sound pressure level over (t) hours
Lden	Day-evening-night equivalent sound level
Lnight	Night equivalent sound level
MI	Myocardial Infarction
OR	Odds ratio
WHO	World Health Organization



# 1 Introduction

## 1.1 Environmental Noise

Road traffic noise is a growing hazard in the urbanized world. Conservative estimates assume that at least one million healthy life years are lost every year from traffic related noise in the western part of Europe [2]. Although Sweden is a fairly quiet country compared to continental Europe, aircraft, railway and road traffic density, especially heavy road traffic, has increased over the years and grows faster than the population. The latest available estimate from 2006 found that 1,73 million swedes were exposed to noise levels above the current guideline value for average noise exposure - 55dB(A) at the façade of the buildings they live in. Fewer were exposed to railway and aircraft noise (225 000 and 13 000 respectively) [3]. Since 2006, estimates are produced regularly in accordance to the European Noise Directive. However these updates only cover cities with more than 100 000 inhabitants and for those living close to major highways, railways or airports.

Environmental noise is a policy-relevant area of research, since a fifth of the population in Sweden is exposed to levels exceeding the current Swedish guidelines. Reaching the European Environmental Agency target level of  $L_{den} 50dB(A)$  for everyone would mean an unprecedented reduction of road traffic or new, revolutionizing ways of reducing noise at its source. Going in the opposite direction, the Swedish government recently proposed policy changes, allowing for new buildings to be constructed in environments with up to  $L_{DEN} 65dB(A)$  if there is access to a sheltered side. This is 32 times higher than the EEA average noise target, since decibel is a logarithmic measure.

Traffic noise causes annoyance and sleep disturbance and has been linked to several other adverse effects on life quality and health, including cardiovascular disease and diabetes [4-7]. There is a developed framework for how to calculate disability-adjusted life years (DALYs) for most of the effects discussed in this thesis, including annoyance due to traffic noise, sleep disturbance, hypertension and myocardial infarction [8]. Conservative estimates for DALYs lost due to environmental noise are 61 000 years for ischaemic heart disease, 45 000 years for cognitive impairment of children, 903 000 years for sleep disturbance, 22 000 years for tinnitus and 654 000 years for annoyance [2]. The societal costs related to road traffic noise, also including loss of production, reduction in house prizes etc. are most likely very high. In the EU 22, the social cost of road traffic noise is



estimated to be at least €38 (30 - 46) billion per year, which is approximately 0.4% of total GDP and approximately one third of the societal costs for traffic related accidents [9].

We know from earlier studies that the adverse effects of environmental noise may be modified by social and demographic factors. Children, people with low socio-economic status and various other groups have been proposed as vulnerable or more susceptible to noise. However, we still don't know enough about which groups are at risk and there is a need to increase knowledge regarding exposure-response in high-risk groups, in order to support better protective policies[8].

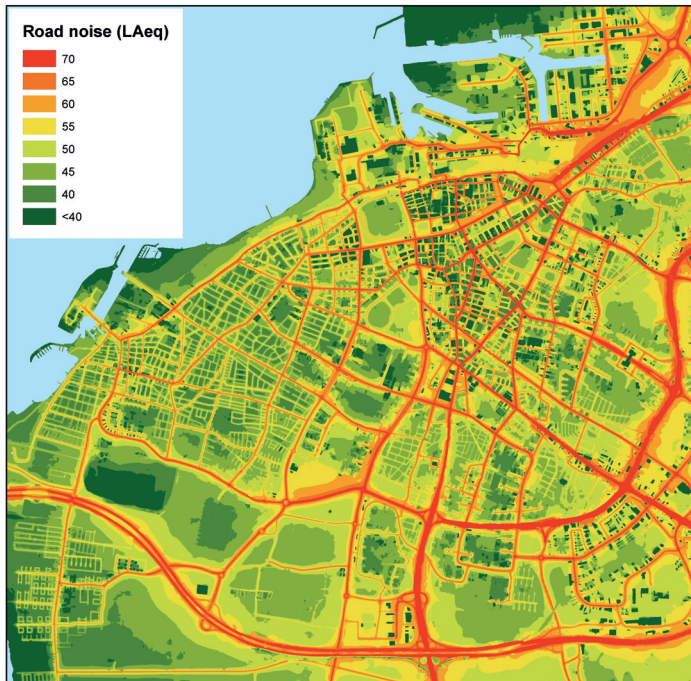


Figure 1: A road traffic noise map of Malmö, modelled using Geographical Information Systems (GIS)  
Credits: Emilie Stroh

## 1.2 Annoyance and sleep

"SOME CONSIDERATIONS CONCERNING CITY NOISES."

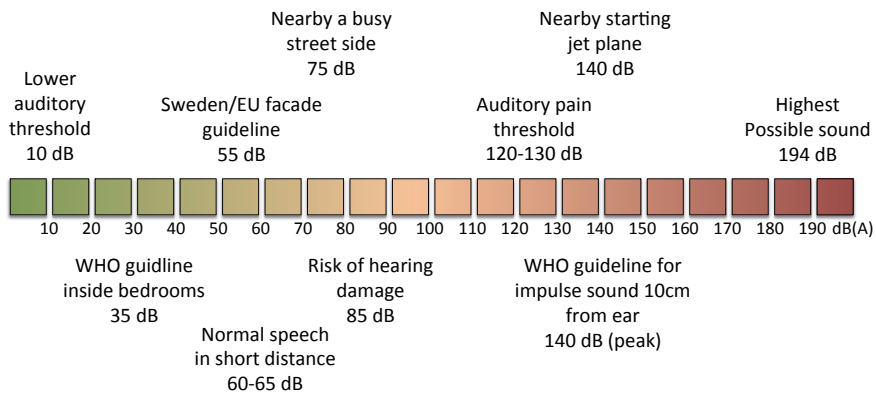
BY PROF. JAMES J. PUTNAM., BOSTON.

American journal of public hygiene, 1905

"In studying the problem of noise with such data as my experience and general information has furnished, I have been forcibly struck at finding two classes of acts, which seem to stand in contrast with each other. Thus, we find, on the one hand, persons who suffer acutely from noises, especially noises of certain sorts, and many whose sensitiveness thereto seems to increase rather than diminish as time goes on; while, on the other hand, there are persons also who seem to get not only relatively but absolutely habituated to noise, or, to speak perhaps more correctly, whose power of concentration makes them oblivious to the disturbances of every sort by-which they may be surrounded[1]."...

As noted, over a hundred years ago, annoyance to the noises of a city show great inter-individual variation and might be subject to habituation. Annoyance is defined as "a feeling of displeasure associated with any agent or condition, known or believed by an individual or group to adversely affect them". However, apart from "annoyance", people may feel a variety of negative emotions when exposed to community noise, e.g. anger, dissatisfaction, helplessness, anxiety, agitation etc. [10]. Annoyance in this thesis is always self-reported "annoyance" ("störning" in Swedish).

On a population level there are few demographic factors that can explain these differences in annoyance. A large meta-analysis from 1993 including 136 studies, mainly on aircraft noise, concluded that there was no support for differences in annoyance based on age, sex, education or income although there were some studies supporting a modifying effect of socio-economy, where high-status residents are more annoyed [11], and that children are less annoyed than their parents, at least to aircraft noise [12]. This meta-analysis was not able to gather evidence supporting an effect of time spent at home, years living in the same residence, home ownership or individual benefits related to the noise source, e.g. being employed by an airline while living close to the runway [11].



**Figure 2:** The decibel scale, including some current guideline values and thresholds (adapted from Eriksson C. 2012)

Instead, there are other factors that matter more, mainly related to the configuration of the residential building and individual attitudes. Starting with the first, it has long been known that insulation of buildings, like installing double and triple glazing lowers the degree of annoyance [11]. In recent years, the effect of quiet side, sheltered from noise, has become an increasingly interesting area of study, and a few studies have been published in recent years. Quiet side has been defined both in absolute and relative terms. In a Swedish study quiet side was defined as <45dB(A) [13], while in a Dutch study quiet side was defined as a difference between the exposed and sheltered side greater than 10dB(A) [14]. These studies have shown that annoyance due to road traffic noise decreases with access to a quiet side of one's dwelling, approximately equal to a 5-10 dB(A) decrease in average noise exposure at the most exposed façade [13-16].

Disturbed sleep due to noise from air, rail and road traffic has been shown in laboratory settings as well as in field studies [17, 18]. Traffic noise affects several aspects of sleep quality. The time it takes to fall asleep is prolonged in relation to noise exposure. Traffic noise also affects subjective sleep quality and is associated with the notion of not being totally rested after a whole night's sleep. Awakenings during the night and premature awakening in the morning have been shown in short-term studies but it is concluded that substantial habituating effects exist [19]. However, habituation has not been observed with regard to arousal measured by increased heart rate or EEG-patterns [18, 20].

Noise from different traffic sources have different characteristics and have been shown to have different impact on sleep at equal nocturnal noise exposure levels. A review on this topic, with pooled data from 24 different studies, found that noise from aircraft was associated with more sleep disturbance than road traffic noise, which subsequently was found to be associated with more sleep disturbance than railway noise [21]. This pattern has resulted in so called "railway bonus", often of 5dB(A), which has been implemented

in noise legislation in a number of European countries. In recent years this bonus has started to be questioned, especially at noise levels above 55dB(A) [22].



Figure 3: The concept of quiet side, where one side is sheltered from traffic noise

It has been shown that those who had difficulties going to sleep because of noise more often reported "concentration problems" [23]. Among participants in a study in Skåne who reported annoyance from road traffic noise, the average road noise level was associated with concentration problems [24]. Noise has also been found to impair cognitive performance in children. A linear dose-response relation has been shown between impairment of children's reading comprehension and aircraft noise close to schools, stable for adjustment for socio-economic differences [25]. A negative relation between road traffic noise and reading ability has been found at home [26], at school [25]

There are also other sources of noise, which can cause annoyance in the residential setting. Noise from ventilation installations is common, and annoyance due to noise from neighbours is more common than annoyance from railway and aircraft, at least in Skåne [27].

### 1.3 Cardiovascular disease

Cardiovascular disease is a class of diseases that involve the heart, the blood vessels (arteries, capillaries, and veins) or both. Most commonly known diagnoses are arterial ischaemic diseases where arteries become partially or totally occluded by atherosclerotic plaques that build up in the arterial wall or by embolus which usually origin from the heart and occlude smaller vessels further downstream. Among these are ischaemic stroke, myocardial infarction, angina pectoris and intermittent claudication. Most studies on noise and cardiovascular disease have focused on ischaemic heart disease and hypertension, with a few recent studies on stroke. Evidence suggests a number of socio-

demographic and individual risk factors for coronary heart disease: Non-modifiable are advancing age, male sex, heredity and ethnicity. Major modifiable risks are high blood pressure, hyperlipidaemia, diabetes mellitus, tobacco smoking, obesity and lack of physical activity. Other modifiable risks are low socioeconomic status, psychosocial stress, mental illness, alcohol use, and certain medications [28].

From late 80's and through the 90's it was quiet unclear whether road traffic noise was associated with hypertension in adults [29], although the association to occupational and aircraft noise was rather well-established[30]. Up until today, there are still very few studies investigating railway noise and hypertension, but they have found an association to measured blood pressure [31] and borderline significant association to self-reported hypertension [32]. In 2009, when paper III was published a few recent studies had provided evidence for associations between traffic noise and hypertension[24, 33-35], although they were heterogeneous with respect to effect size [35], differential effects by sex [24, 33] and age [34]. Since then, even more studies have been presented and the latest meta-analysis from 2012 calculated an hypertension odds ratio (OR) of 1.034 [95% confidence interval (CI) 1.011–1.056] per 5 dB(A) increase of the 16 h average road traffic noise level (LAeq16hr) [range 45–75 dB(A)] [36].

The first longitudinal studies on road traffic noise and cardiovascular disease emerged in the late 90's and found a moderate effect of road traffic noise on MI and a possible increased risk among those with high exposure [37] and long-term exposure [38, 39]. Later on, this has been confirmed by others [4, 40]. The most recent pooled estimate of the relative risk of coronary heart disease was 1.08 (95% confidence interval: 1.04, 1.13) per increase of the weighted day-night noise level  $L_{DN}$  of 10 dB (A) [41].

The biological mechanisms linking noise to cardiovascular disease is thought to be mediated through stress response to noise, with subsequent acute and sub-acute changes autonomous regulation, leading to increased vascular tension [42], decreased heart variability [20], and activation of the HPA-axis with an increased cortisol release [43]. The hypothesis is that long-term exposure to noise could result in lasting metabolic and cardiovascular changes such as atherosclerosis, and increase cardiovascular risk [44] as well as hypertension [29] (Figure 4).

The other major environmental hazard related to road traffic is air pollution. There is an increased risk of MI associated with short-term exposure to all major air pollutants, with the exception of ozone, which was shown in a recent meta-analysis [45]. Long-term exposure to black smoke from traffic has a strong correlation to coronary heart disease [46], and recent evidence show a relation also to long-term PM<sub>2.5</sub>/NO<sub>2</sub> [47]. A number of possible mechanisms for the associations have been suggested (figure 4). The most important ones are the inflammation pathway with increased levels of inflammatory markers such as C-reactive protein in relation to exposure to air pollution [48]. Further,

abnormal regulation of the cardiac autonomic system including increased heart rate [49] and decreased heart rate variability [50]. The third possible mechanism is an increase in blood viscosity as a result of air pollution [51] (Figure 4).

Hence, both road traffic noise and air pollution have been linked to cardiovascular disease and there are biological mechanisms supporting both exposures as causal to cardiovascular disease. However, there are few prospective epidemiological studies available where both road traffic noise and air pollution have been analysed simultaneously and they show conflicting results [4, 40, 52, 53], in some cases due to difficulties of separating the two, since they stem from the same source. To separate noise and air pollution derived from road traffic is crucial to obtain correct estimates of the burden of disease related road traffic, in order for policymakers propose correct measurements to protect citizens. Also, effects of noise may differ between susceptible groups. A recent study analysed a subgroup of elderly, aged above 65 years of age and found an increased risk of myocardial infarction in relation to noise exposure [53]. Other studies indicated no effect modification by age in relation to MI [4]. One study indicated a stronger effect of traffic noise on cardiovascular disease among men [38], whereas others have indicated no sex differences [4, 54].

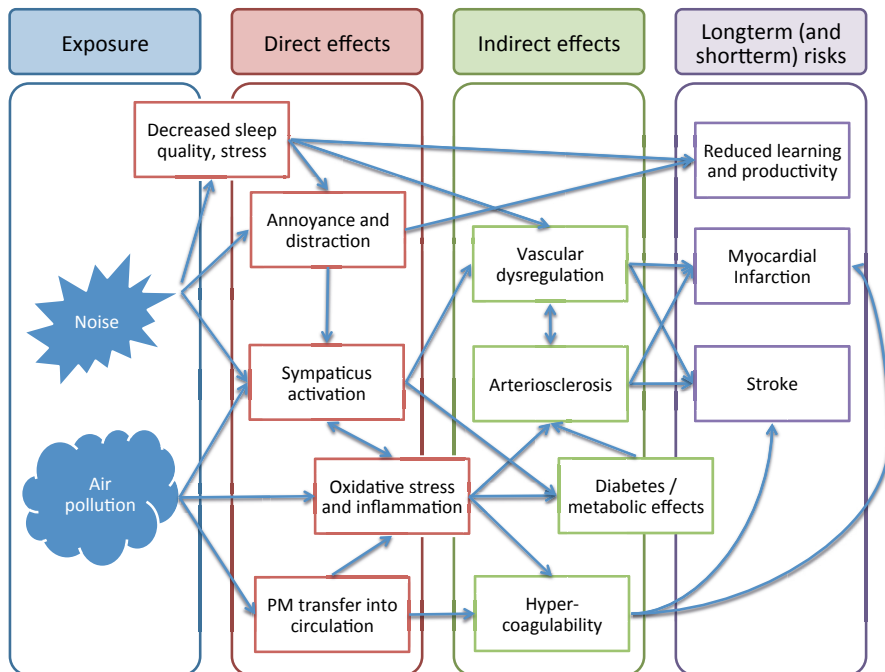


Figure 4: Mechanisms of noise and air pollution exposure effects. (adapted from Brook 2010 [55] and Hammer 2014 [56])

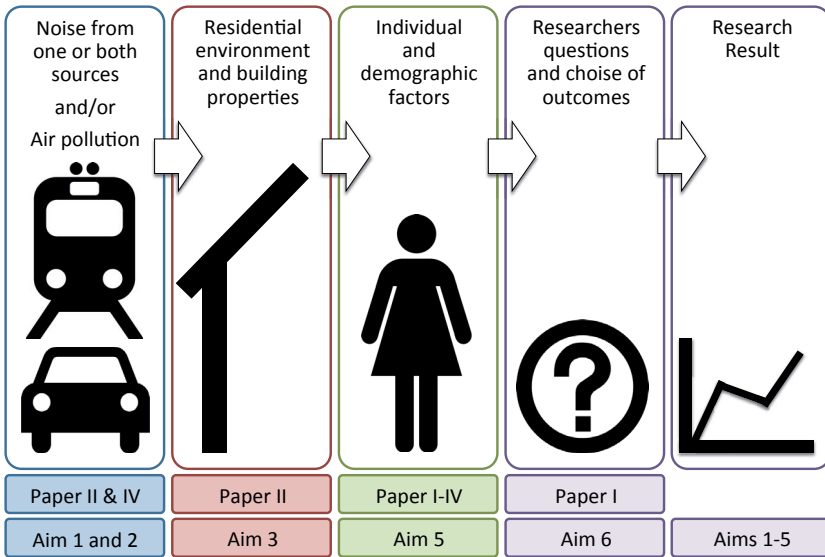


Figure 5: Graphical presentation of the thesis outline and aims.

## 2 Aims

1. Is there an association between road traffic noise and i) hypertension ii) myocardial infarction iii) Ischemic heart disease?
2. Is current and medium term exposure to road traffic noise and air pollution independent risk factors for incident myocardial infarction and is there an additive effect of the two exposures?
3. Is there a difference in self-reported annoyance, sleep quality and concentration problems between those exposed to road traffic noise, railway noise and the two sources combined?
4. Is there a beneficial effect on annoyance, sleep and concentration from access to quiet side in one's residence?
5. Are the above-mentioned associations between noise and adverse effects modified by socio-demographic differences, especially age, sex and socio-economic factors
6. Does survey context and question wording have an impact on the reporting of annoyance from noise in surveys?





# 3 Materials and Methods

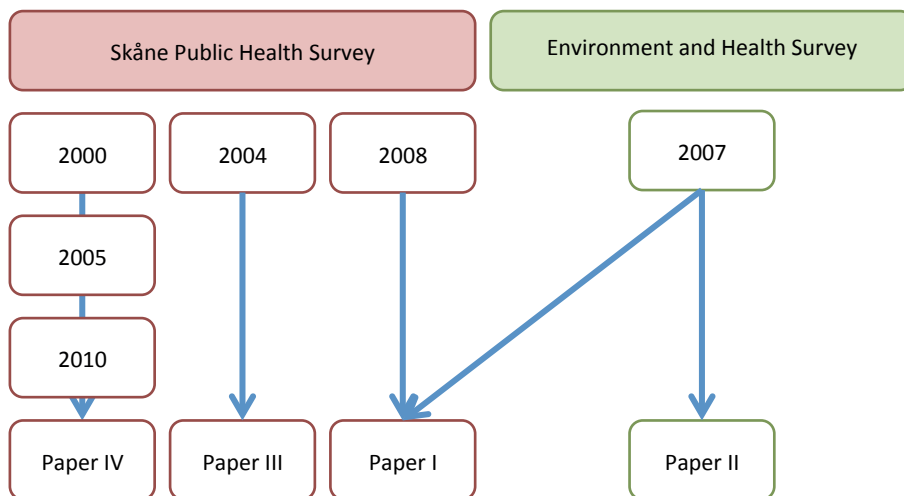


Figure 6: Study populations and surveys in the different papers

## 3.1 Study Populations

### 3.1.1 Skåne Public Health Survey 2004 and 2008

These two, very similar, surveys were both extensive public health surveys (130/134 questions) sent out to inhabitants in the county of Skåne in southern Sweden. All persons 18 - 80 years old, living in this county the year of the survey, constituted the study population (N in 2004 / 2008 = 855 599 / 899 923). Both years, the population was stratified by sex and geographical area, resulting in  $2 \times 62 = 124$  different strata in 2004 and 142 strata in 2008. Samples were randomly selected from the population registry such that an approximately equal number of individuals were contacted in each stratum. In total, the 2004 survey was sent by mail to 46 200 persons, while 2 800 were randomly

selected to answer the questionnaire by telephone interview. In 2008 all questionnaires were sent by mail to 53600 persons. Answers were obtained from 59% in 2004 and 54% in 2008. The participation rate was higher among females, elderly, persons born in Sweden, and among persons with high education or income [57, 58].

Both surveys consisted of detailed questions regarding self-reported illness, health and well-being, life-style habits such as smoking, alcohol consumption, physical exercise and diet, social relations, treatment with drugs, healthcare use, occupation and work environment, financial situation, educational level, ethnic background and residential environment.

### **3.1.2 Residential Environment and Health Survey 2007**

“Undersökning om boendemiljö och hälsa” (“Survey regarding residential environment and health”) was sent to 5600 individuals aged 18-79 residing in Malmö, the main city in Skåne, on April 12, 2007 (N = 207 781). Answers were collected during the period June-August 2007. The selection was made through a random sampling of 800 individuals from six different strata based on road traffic and railway noise exposure levels using a simplified version of the Nordic prediction model.[59, 60] The six strata were based on three levels of road traffic noise (<40dB(A); 40-60dB(A) and >60dB(A)) with or without modelled levels of railway noise exposure. One extra stratum consisting of an additional 800 individuals was added based on those living nearby construction sites related to a major railway tunnel project (Citytunneln). These persons were however not included in this study. The response rate was 54.3%.

### **3.1.3 Skåne Public Health Survey Cohort 1999-2010**

The Skåne Public Health Cohort was established in 1999/2000 and followed up in 2005 and 2010. At baseline a postal questionnaire, which was the predecessor to the 2004 and 2008 public health surveys mentioned above, was sent out to a stratified random sample of 25000 men and women born between 1919 and 1981 in Skåne (N ~820 000). These individuals were randomly selected from the population register so that equal representation was achieved from all 33 municipalities in the region and from the defined city areas in the largest municipalities.

The response rate was 59 % (n = 13604). All of those who responded at baseline were invited to follow-up after five and ten years. The response rate at those follow-ups was about 80-90% giving 10 475 responses in 2005 and 9 031 in 2010. At baseline we were able to find residential coordinates for 13 512 out of 13 604 (99.3%). The reduction in size between the surveys was due to deaths, emigration out of the region and

unwillingness to respond to the follow-up surveys. The questionnaire contained over 200 items, covering self-rated general health, mental health, functional impairments, medication, sickness absence, educational level and occupation, parents' educational level, early childhood conditions, country of birth of both the index person and parents, employment status, financial stress, health related life-styles, psychosocial working conditions, stressors in the family sphere, social relations and social capital. The questionnaires used at all three assessments of the cohort were almost identical, i.e. information from three points in time exists for almost all individuals.

Table 1: Population at baseline and reduction based on age, sex, road traffic noise at baseline and onwards

Year	2000	2005	2010
Original sample	25 000		
Responders to survey	13 604	10475	9 031
Alive and available exposure assessments	13 512	12504	11 652
Dead or emigrated (cumulative)	0	1008	1860
Median Age (5-95 percentile)	49 (22-76)	53 (27-80)	56 (33-83)
Sex (male)	45%	44%	43%
mean L <sub>DEN</sub> (5-95 percentile)	50 (41-61)	51 (41-65)	51 (41-66)
mean NO <sub>x</sub> (5-95 percentile)	13 (6-33)	11 (5-25)	9 (5-21)

Median with (5-95 percentiles) if nothing else is stated

### 3.2 Exposure Assessments

Our research group has developed GIS modelling over the last six years. The basic input has been roughly the same, but advancements in skill and computing power have made the modelling better and more accurate. All modelling was based on the survey participant's residential addresses at the year(s) of interest. These addresses were geocoded and layers of data regarding road traffic, railways, industries, topography, buildings, noise sheltering etc. created a virtual scenery where noise and air pollution exposure could be modelled for each residential building linked to a participating individual.

Original road traffic data from the whole region included road segments administrated by the Swedish Road Administration, and by local municipalities. The databases has constantly been updated over the years that have passed.

### 3.2.1 Three Different Noise Exposure Models

	Average noise level presented as:	GIS model input
Paper II	$L_{AEQ24h}$	Roads, railways, buildings, elevation data, ground types, noise protection installations
Paper I & III	$L_{AEQ24h}$	Roads, ground type
Paper IV	$L_{DEN}$	Roads, railways, buildings, elevation data, ground types, noise protection installations

Using the road traffic data, we used a simplified version of the Nordic Prediction Model for road traffic noise in paper I and paper II to estimate noise exposure at the residential locations of the participants. In paper III a complete version of the Nordic Prediction Model was used, while paper IV included even more in-data. In all studies, we modelled the levels at the highest exposed façade and used this as our exposure level.

In short, the Nordic prediction method first calculates the unattenuated noise level 10 meters from the road centre using the number of light and heavy vehicles and the speed limit of each road segment. Corrections were then calculated for (i) the distance between the source (the road) and receptor, for which the noise levels decrease by 3 dB(A) with a doubling of the distance, (ii) attenuation due to ground surface type and noise barriers [the attenuation of noise depends on surface type with less attenuation for hard surfaces (asphalt, water, concrete) and more attenuation for soft surfaces (vegetation, grass, etc.)], and (iii) additional corrections for special cases (including very steep topography, reflection from buildings, etc.). [See the reports by Lyse Nielsen [59] and Jonasson et al [61] for a complete description]

In paper I and paper III, we had to simplify the Nordic prediction method by using corrections for distance and surface type only. We were not able to correct for noise barriers and the additional special cases already mentioned, as no such data was available. We assumed flat ground in all cases and soft surfaces between the residence and the road for the participants living in the countryside, while a hard surface was assumed for the participants living in more densely populated areas. We had no data indicating the floor of the apartment building on which the residences were located, and we therefore estimated the noise level on the ground floor for all of the residences. The number of vehicles was available for 82% of the road segments. Speed limits were available for >95% of the segments. For road segments without traffic data, mean values were assigned to each segment on the basis of existing data for the included road type [62]. A validation of this simplified model was carried out and is presented in the methodological discussion section.

Railway noise exposure was estimated according to the Nordic Prediction method for railroad Noise [60] using a level of detail comparable to the estimation of road noise, see Liljewalch-Fogelmark, 2006 for details [63].

Paper II took advantage of the EU directive regarding assessment and management of environmental noise [64] which, in order to comply to, the city of Malmö contracted the consultant firm ÅF-Ingemansson AB to do an inventory and assessment of the environmental noise in Malmö in 2007 [65]. Data used for the assessment included geometries of roads, buildings, elevation data, ground types, noise protection installations such as noise barriers, and railways. Road traffic included number of standard and heavy vehicles and their diurnal distribution. Railway traffic data included number and type of trains, train length and velocity (see [65] for details). Calculations were performed according to the standard Nordic prediction model [59, 60, 66, 67] for assessment of noise from road traffic and railway traffic, using SoundPLAN version 6.4 (Braunstein + Berndt GmbH, Germany). Road traffic noise, and railway noise were modelled separately and combined. When comparing adverse effects of noise from different sources we applied a concept of dominant source, i. e. if there was a difference of 3dB(A) or more between railway and road traffic noise the source with higher levels was considered the dominant one.

In paper IV, road traffic noise was calculated based on the Nordic Prediction Method, implemented in the software SoundPLAN [59, 67] There is an on-going strategic mapping of noise in Europe [64] and National Swedish instructions and evaluations acted as a basis for the method used in this study [68, 69]. Roads, with information about average daily traffic, speed, distribution of light and heavy vehicles and diurnal distribution of traffic acted as sources of the noise in the model. These included both governmental and municipality roads, generally with better information regarding traffic intensity on the larger the roads [70]. Topography and buildings acted as screens in the model, information about topography were obtained from satellite data with 30 m resolution. Base areas for buildings were known and height addressed according to type of building [69]. The noise was allowed to reflect two times and ground softness assigned from satellite land use data affected how much of the noise that was reflected [71]. For each façade of residential buildings the noise was calculated in the centroid of the façade. All roads within 2000 m from each façade point were included in the calculation. The façade with the highest noise level was then used as representative for the whole building, due to lack of knowledge of where people were living in the building. Noise was modelled three times 2000, 2005 and 2010. Based on this every person was assigned a yearly exposure from that year's residential address (2000: 2000-2002, 2005: 2003-2007, 2010: 2008-2010). A more detailed description of the method exists in Swedish [72]. Railway noise and aircraft noise was not modelled for this study.

### 3.2.2 Air pollution

An emission database (EDB) was built covering the southernmost county of Sweden, Skåne [70]. The EDB contains approximately 24 000 sources, mainly line sources corresponding to road traffic and shipping but also point sources for industries and large scale energy producers. There are also area sources, such as small-scale heating, light machinery etc. Emissions from Denmark were also added as well as a background level of 2.5 microgram/m<sup>3</sup> accounting for long-range transportation of pollutants. The original EDB version had base year 2001 and as used for exposure assessment 2000-2006. A minor revision was made in 2008 and which was used to calculate the exposure for 2006-2008. In 2009 and 2010 the values for 2008 were used as proxy.

Modules of the software ENIVMAN from OPSIS AB (2006) were used for database management. In another module a Gaussian dispersion model based upon AERMOD from the US EPA was implemented [73]. This implementation made it possible to make calculations of modelled air pollution concentration with a temporal resolution of 1 hour and either to specific geographical points or as a grid of specified coverage and cell size. These calculations were based on either measured true meteorological data or a statistical meteorology from a set of characteristic conditions.

In the present study NO<sub>x</sub> was modelled as a cell grid with 500\*500 m resolution. The levels were aggregated to annual means for each year. Each person was then assigned the annual mean NO<sub>x</sub> level at the centroid of his or her residential real estate at the end of each year.

### 3.2.3 Assessment of quiet side

In Paper II we assessed access to quiet side using 1) objective and 2) subjective, self-assessment of quiet side in the survey:

Windows facing a yard, garden, water or green space.

Q1a: "Does your dwelling have windows facing directly towards..." "Large street or road", "small street", "railway", "industrial area or industry", "a yard, garden, water or green space", "something else..."

Q1b: There was also a question with identical alternatives, asking specifically for bedroom window direction, i.e. "*Does your bedroom window directly face...*".

Access to quiet indoor space.

Q2: Do you have access to a quiet indoor space in your dwelling where you are not disturbed by noise?" "Yes"/"No"

### 3.3 Assessment of Outcomes

Assessment of outcomes was based on self-reports in paper I-II, and based on routinely collected data in national registers in Paper IV.

Paper I - Annoyance: Since the aim of the survey was to compare studies with similar questions in different contexts we used two such studies available to us. The two studies included some identical questions and some questions that were similar to each other. The main result is based on questions regarding noise annoyance frequency, where the 5-point scale in Env&Health07 included the alternatives: "every day", "Several times a week", "Once or twice a week", "Once or twice a month or less often" and "Never". The broader public health survey (PHSurvey08) had a 4-point scale with the alternatives "At least once a day", "At least once per week", "Less often" and "Never"

Paper II - Adverse effects of noise exposure were assessed through self-report. Annoyance was assessed using a Swedish translation of a 5-point ISO/TS 15666 verbal scale for assessment of noise annoyance by means of social and socio-acoustic surveys [23]. "During the last 12 months, how disturbed have you been because of traffic noise [total/rail/road/air traffic] at home?" (1="Not at all annoyed", 2="Slightly annoyed", 3="Moderately annoyed", 4="Very annoyed", and 5="Extremely annoyed"). Sleep and concentration problems were assessed through the following questions, unrelated to noise: "How do you usually sleep?" (5-point scale) 1="Very poorly", 2="Poorly", 3="Not very good", 4="Pretty good", 5="Very good"; "Do you usually have difficulties concentrating on what you want to do?" (4-point scale) 1="Rarely/Never", 2="A few times per month", 3="A few times per week" and 4="Every day".

Paper III – Hypertension: A subject was defined as hypertensive if an affirmative answer was given to any of the following two survey questions: 1) "Do you have the following health problem /.../ Hypertension?", 2) "Have you, during the last three months, used any drug or preparation against hypertension".

Paper IV - Diagnoses of myocardial infarction and ischemic heart disease were collected between 1986 and 2010 on an individual basis for every person who responded to the first survey in 2000 through the Swedish National Inpatient Registry in which more than 99% of all somatic (including surgery) and psychiatric hospital discharges and visits to specialized outpatient care are registered [74]. We also used the Swedish Causes of Death Registry (2000-2010), which includes all deaths of Swedish residents. The primary endpoint was diagnosed myocardial infarction (MI), or complication to MI (ICD 10: I20-23 1996-2010 and ICD 9: 410 1986-1995) in inpatient or outpatient specialist setting, or as one of the underlying causes of death. We analysed the incidence rate ratio (IRR) for first-time MI by excluding everyone with a diagnosed MI 1986-1999, and



analysed the incident cases (visit/hospitalization/death) of MI between 2000 and 2010. Secondary outcome was acute ischemic heart disease (IHD) (ICD 10: I20-24 1996-2010 and ICD 9: 410-414 1986-1995), using the same method as for MI to obtain first-time diagnoses.

### 3.4 Study Design and Statistical Approach

Main results in paper I-III are presented as odds ratios (OR) with 95% confidence intervals (CI) obtained through logistic regression models. Adjusted models included factors considered a priori as relevant in relation to the outcomes investigated in each study (Table 2). P-values below 0.05 were regarded as statistically significant.

In paper IV we used Poisson regression to model the yearly incidence rate ratio (IRR) of MI because it allowed modelling the association with time-varying covariates including age. Since the exact birthday was not available, an offset was not included. The standard errors of the regression coefficients were estimated by the robust sandwich estimator taking the potential intra-individual correlation into account. The analyses were carried out in Stata version 13 (StataCorp, College Station, TX, USA).

Odds Ratio (OR), Relative Risk (RR) and Incidence Rate Ratio (IRR)

	Diseased	Healthy	Total	Person years
Exposed	$D_E$	$H_E$	$N_E$	$Y_E$
Not Exposed	$D_{NE}$	$H_{NE}$	$N_{NE}$	$Y_{NE}$

$$RR = \frac{D_E/N_E}{D_{NE}/N_{NE}} \quad OR = \frac{D_E/H_E}{D_{NE}/H_{NE}} \quad IRR = \frac{D_E/Y_E}{D_{NE}/Y_{NE}}$$

In all analyses noise exposure has been defined as  $L_{Aeq24h}$  road, rail or both combined. Average noise exposure ( $L_{Aeq,24h}$  or  $L_{den}$ ) was entered as a continuous 1dB(A)-step or categorical variable in 5 dB(A)-intervals. In all regression models, the reference category  $L_{Aeq24h} < 40$  dB(A) or  $< 45$ dB(A) includes all values below this level. In the categorical analysis the highest noise category was usually a merger of a span wider than 5 dB(A).

In paper IV which had a longitudinal design, exposure to traffic noise, exposure to NOx and age, were available for every year. Sex and country of birth did not change. BMI was

entered only at baseline due to a substantial number of optical misreading of length and weight, which had to be manually corrected using data from 2005 and 2010. The remaining confounders were taken from survey answers in 2000, 2005, and 2010. The values for the intervening years were assumed to be equal to the latest observed value. In a separate analysis we also considered 3-year average exposures to road traffic noise and to NOx. Due to lack of exposure earlier than 2000, we assigned the same-year and 2-year average for this variable in 2000 and 2001.

**Table 2:** Overview of included papers and their main exposures, outcomes and included confounders

	Included confounders	Main outcome as	Noise	Lower range	Higher range
Paper I	age, sex, educational level and country of origin	Odds Ratio (Annoyance)	Road LAeq,24h	<40	>60 (60-68)
Paper II	sex, age and BMI, physical exercise, education, economy, country of birth, civil status, smoking, hearing impairment	Odds Ratio (Annoyance, sleep quality, concentration)	Road, Railway, Combined LAeq,24h	<40	>60 (60-66)
Paper III	sex, age and BMI, physical exercise, education, alcohol consumption, smoking and socioeconomic status	Odds Ratio (Hypertension)	Road, Railway LAeq,24h	<45	>65 (65-71)
Paper IV	sex, age and BMI, physical exercise, education, economy, country of birth, civil status, smoking, alcohol,	Incidence Rate Ratio (Myocardial infarction)	Road Lden	<45	>65 (65-81)

All regression models were gradually loaded with covariates, and models are presented as crude, partially adjusted, and fully adjusted in all papers. Sensitivity analysis was carried

out to various extent in all studies. This included adding possible confounding factors into logistic regression models for evaluation of robustness of our estimates for exposure and testing for interaction. Interaction between covariates was investigated in paper II-III by adding a multiplicative interactive term ( $a \times b$ ). Paper II tested interaction between road traffic noise exposure (a; 5dB(A) intervals) and windows facing a green space (b; categorical, yes/no). Paper III tested interaction based on road noise exposure (a; continuous) and several categorical interaction terms (b) defined according to sex, age, years in residence, country of birth (Sweden or abroad), strained economy and disturbed sleep.

Stratified analysis for differential effects, especially between demographic groups, has been a key part in our research.

# 4 Results

## 4.1 General findings

### **Annoyance, sleep and concentration problems**

In all papers we tested and found a strong positive relation between road traffic noise and annoyance irrespectively of noise annoyance scale. In paper II poor sleep and concentration problems showed a higher prevalence among those exposed to high levels of noise compared to those with lower levels of exposure. Overall, there was a positive relation between combined noise exposure and self-reported poor sleep quality, OR(95% CI) 1.26 (1.16-1.38) for each 5 dB(A) increase (Table 3). Also, there was a positive relation between combined noise exposure and reported concentration problems, OR (95% CI) 1.14 (1.05-1.23) for each 5 dB(A) increase (Table 3).

Table 3. Estimated effects of noise (un-adjusted and adjusted) and estimated effects of all included confounding factors (mutually adjusted) OR (95% CI)

	Annoyance	Poor sleep quality	Concentration problems
Crude			
$L_{Aeq24h}$ Combined 5dB(A)	2.03 (1.86-2.22)	1.26 (1.16-1.38)	1.14 (1.05-1.23)
Adjusted*			
$L_{Aeq24h}$ Combined 5dB(A)	2.10 (1.91-2.30)	1.20 (1.10-1.31)	1.09 (1.01-1.19)

\* Age, Sex, BMI, Smoking, Education, Country of birth, Financial stress, Hearing impairment

### **Cardiovascular disease**

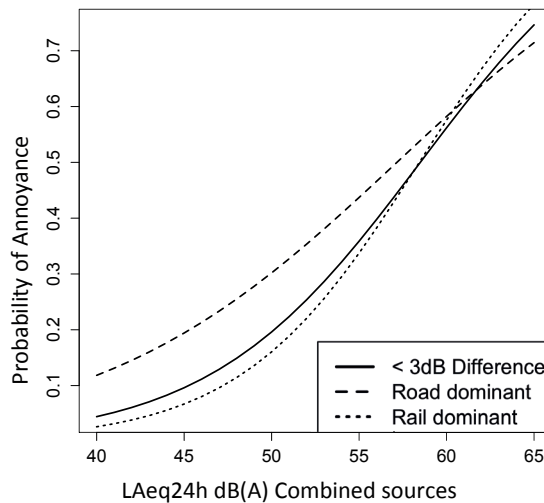
With regard to hypertension (paper III), modest exposure effects of noise (OR  $\approx$  1.1) were noted for the four intermediate exposure categories (45-49, 50-54, 55-59, 60-64 dB(A)). The effect was more pronounced in the highest exposure category > 64 dB(A); OR(95%CI) 1.52 (1.09-2.11) when adjusting for age, sex and BMI. The OR for 10dB(A) increase in average noise level was 1.06 (1.00-1.13) for the total sample in the fully adjusted model. Investigating MI and IHD in paper IV, we did not find an

increased incidence rate ratio for neither one in relation to road traffic noise, nor air pollution (in terms of NO<sub>x</sub>). The IRR for MI in relation to a 10dB(A) increase in average road traffic noise (same year) was 0.99 (0.86-1.14) in the fully adjusted model. For a 10 µg/m<sup>3</sup> increase in NO<sub>x</sub> levels (same year), the IRR for IHD was 1.02 (0.86-1.21). For the 3-year average exposures the IRRs were 0.99 (0.86-1.14) and 1.03 (0.87-1.21) for LDEN and NO<sub>x</sub> respectively in the fully adjusted model (paper IV, table 6).

## 4.2 Exposure-related factors modifying the effect of noise

### Combined exposure to road traffic and railway noise

Annoyance when railway noise was the dominant source was significantly lower compared to equal levels of road traffic noise and noise from combined sources at noise levels 45-49dB(A) and 50-54dB(A)  $p < 0.01$  in both comparisons. No significant difference in annoyance was found  $< 45$  dB(A) or  $\geq 55$  dB(A) ( $p \geq 0.1$ ; paper II, Figure 4A). Three different logistic models were carried out stratified on dominant source (Figure 7). Adjusting for median age (46) and sex (0.5) did not change the shape of the curves.



**Figure 7:** Predicted probabilities of annoyance in relation to traffic noise where either source is dominant

## Combined exposure to road traffic noise and air-pollution

In paper IV we analysed the combined effect of road traffic noise and air pollution. As shown in table 4, combined exposure of  $L_{DEN} < 55$  dB(A) and  $NO_x > 20$   $\mu\text{g}/\text{m}^3$  and  $L_{DEN} > 55$  dB(A) and  $NO_x > 20$   $\mu\text{g}/\text{m}^3$  was related to non-significant increased IRR for MI. 1.20 (0.84-1.71) and 1.21 (0.90-1.64), respectively compared to low noise – low air pollution.

Table 4: Estimated incidence rate ratios for Myocardial Infarction in relation to combined exposure to  $L_{DEN}$  and  $NO_x$  combined

$L_{DEN}$ (current)	$NO_x$ (current)	Unadjusted	Adjusted for age, sex, BMI, smoking	Fully adjusted
<55	<20	Ref	Ref	Ref
>55	<20	1.05 (0.86-1.27)	0.97 (0.79-1.17)	0.97 (0.78-1.20)
<55	>20	1.03 (0.74-1.42)	1.12 (0.81-1.56)	1.20 (0.84-1.71)
>55	>20	1.08 (0.83-1.39)	1.19 (0.92-1.56)	1.21 (0.90-1.64)

$L_{DEN}$ (3-year)	$NO_x$ (3-year)	Unadjusted	Adjusted for age, sex, BMI, smoking	Fully adjusted
<55	<20	Ref	Ref	Ref
>55	<20	1.15 (0.95-1.39)	1.06 (0.87-1.29)	1.07 (0.86-1.32)
<55	>20	0.91 (0.66-1.27)	0.99 (0.71-1.37)	1.10 (0.77-1.56)
>55	>20	1.07 (0.83-1.37)	1.16 (0.90-1.51)	1.18 (0.88-1.59)

Exponentiated coefficients; 95% confidence intervals in brackets

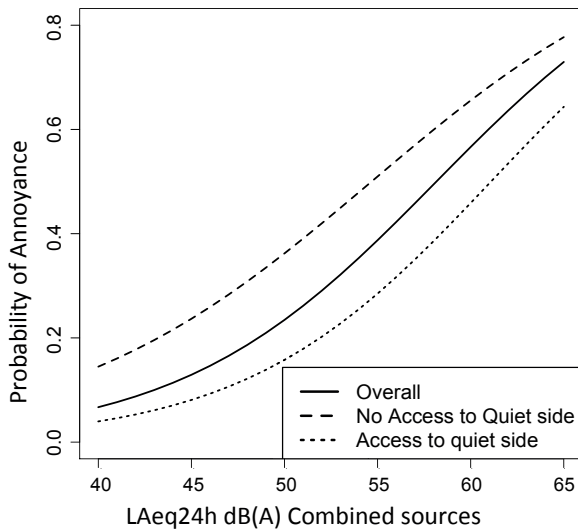
## 4.3 Residential factors modifying the effect of noise

### Quiet Side

The proportion reporting having access to a quiet indoor space or a window facing green space, as well as the proportion having their bedroom window facing a green space decreased with higher modelled levels of noise from combined sources (Paper II, Table 3). The overall proportion annoyed due to traffic noise from combined sources was lower in the group having access to a quiet side, irrespective of which of the three questions that

were used to assess quietness in the dwelling (Paper II, Table 4A). Approximately 50 % of those lacking quiet side (all three questions alike) were annoyed at average noise levels ranging 50-54dB(A) while those who had windows facing a green space did not reach that proportion annoyed until  $\geq 60$ dB(A). However, the relative benefit of having bedroom window facing green space decreased with increasing noise levels, and was not significant at  $\geq 60$  dB(A) ( $p < 0.05$  in all noise categories except  $\geq 60$ dB(A) where  $p = 0.06$ ) (Figure 8 and paper II, table 4A) .

Window facing green space was associated with significantly less annoyance due to combined traffic noise, OR(95% CI) 0.47 (0.38-0.59) (Paper II, Table 5). With access to quite side in the regression model the estimate for noise exposure decreased only marginally from 2.10 to 2.06 per 5dB(A) increase in the noise level from combined sources. Figure 8 graphs three logistic models with the probability of annoyance related to  $L_{Aeq24h}$  dB(A) from combined sources split by access/no access to quiet side, and the overall estimate, the slope of the three curves this similar curve angle, but with different intercepts. There was no significant interaction between noise level and quiet side, irrespectively if noise was entered as a continuous or categorical variable ( $p = 0.87$ ). The estimate for quiet side did not change when adjusting for other confounders stated in Table 3.



**Figure 8:** Predicted probabilities of annoyance in relation to traffic noise whether there is access to quiet side or not.

Poor sleep and concentration problems showed a higher prevalence among those exposed to high levels of noise compared to those with lower levels of exposure (Paper II, Table 4B/C). The overall proportion experiencing the same problems were lower in the group having access to a quiet side, irrespective of which of the three questions that were used to assess quietness in the dwelling (Paper II, Table 4B/C). Overall, there was a positive relation between combined noise exposure and self-reported poor sleep quality, OR(95% CI) 1.26 (1.16-1.38) for each 5 dB(A) increase (Table 3). Having the bedroom towards green space was associated to a lower risk of poor sleep quality; 0.78 (0.64-1.00),  $p=0.048$ . The benefit of having windows facing green space in relation to sleep disturbance was however not significant OR 0.86 (0.68-1.09).

Overall, there was a positive relation between combined noise exposure and reported concentration problems, OR (95% CI) 1.14 (1.05-1.23) for each 5 dB(A) increase (Table 3). There was a clear benefit on concentration problems of generally having windows facing green space (OR 0.76; 0.61-0.95), and also more specifically having the bedroom window facing a green space (OR 0.77; 0.63-0.96). There was no significant interaction between noise exposure and quiet side,  $p$ -value for interaction  $>0.6$  in all aspects of disturbance (annoyance, sleep and concentration).

### **Years in the same residence**

In paper III, we also tested the possible effect modification for years living in the same residence, which showed a similar, bell-shaped pattern as for age ( $p$  for interaction = 0.054). However, age and years in residence were interrelated and the effect modification by years in residence did not remain ( $p$  for interaction = 0.29) when adjustment for effect modification by age was included in the same model. Basically the same was found when reanalysing annoyance using the data used in paper II, The OR for annoyance for living more than 10 years in the same residence was 0.62 (0.27-1.42)( $p$  for interaction = 0.344)



## Owned or rented

We re-analysed data from the public health survey in 2004 and Residential Environmental Health 2007 based on the idea that residential ownership or type might modify the annoyance level. Stratified analysis in Figure 9 shows that the odds ratio of annoyance in relation to a 5dB(A) increase in road traffic noise was higher among those living in houses compared to apartments, even though rented dwelling was associated to higher exposure and a higher annoyance prevalence than for owned dwellings. Rented vs. owned apartments: 38% vs. 24% annoyed, houses: 17% vs. 11% annoyed.

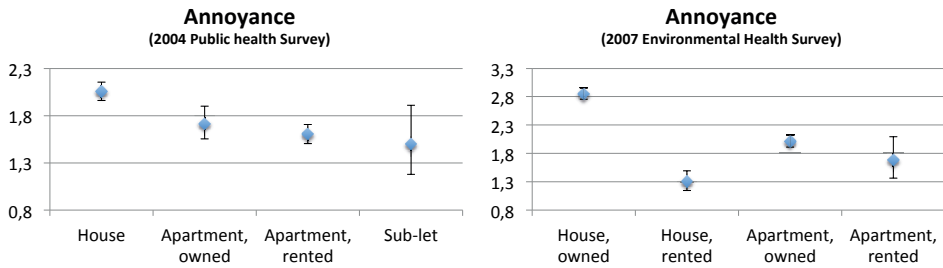


Figure 9: Odds ratio for annoyance, in relation to a 5dB(A) increase in road traffic noise

## 4.4 Demographic factors modifying the effect of noise

In all studies data on non-responders was available regarding age and sex. The survey used in Paper III and one of the surveys in paper I (PHSurvey08) also supplied data on income, ethnicity, educational level and socio-economy for non-responders.

The response rate breakdown in the public health survey used in paper III shows that women were more likely to respond to the survey than men. The same was true for older compared to younger, richer vs. poorer, highly educated vs. others and Swedes vs. immigrants (Table 5). This pattern is also true for the rest of the surveys used in the other papers as far as we know.

**Table 5:** Distribution of demographic factors in the total population of Skåne and response rate to the 2004 Skåne Public Health Survey (used in paper III) stratified by the same demographic factors

		Total distribution (%)	Population Response rate (%)
Sex	Male	50	52
	Female	50	62
Age	18-34	29	49
	35-44	19	53
	45-54	17	58
	55-64	18	64
	65-80	18	66
Country of birth	Sweden	83	60
	Other Nordic country	3	54
	Other European country	8	47
	Rest of the World	6	34
Civil status	Married	46	63
	Others	54	52
Yearly income	0-149 kSEK	40	50
	150-299 kSEK	45	61
	300+ kSEK	15	66
Education	<High School	30	51
	High School	42	57
	>High School	28	65

Adapted from Rosvall et al 2004 [57]

## Age

In paper III investigating road traffic noise and hypertension, a departure from a common relative effect model was noted for age ( $p$  for interaction = 0.018). An exposure effect of road traffic noise was indicated in the youngest age group (18 - 39 years old) at exposure levels 60 - 64 dB(A) OR(95%CI) 1.47 (1.01-2.14), whereas the estimated effect at higher exposure levels was imprecise (Paper III, Table 3). Among middle-aged (40 - 59 years old), effects of road noise exposures were seen in the 60-64 and >64 dB(A) categories with ORs(95%CI) 1.30 (1.05-1.61), and 2.03 (1.28-3.24), respectively (adjusted for age, sex and BMI). A finer stratification of age indicated that significant exposure effects were present only in the age span 30 - 49 years old. There was no clear association between road traffic noise and prevalence of hypertension in the oldest age group (60 - 80 years old), but the effect estimate for the highest exposure category (> 64 dB(A)) was again

imprecise OR(95%CI) 1.10 (0.64-1.89). Re-analysis of the 2004 survey shows bell-shaped relation between age and risk for annoyance, sleep disturbance and hypertension in relation to a 5 dB(A) increase in road traffic noise (Figure 10) In paper IV, stratified analysis was carried out based on age as well. We did not find any increased incidence rate ratios in any of the age groups.

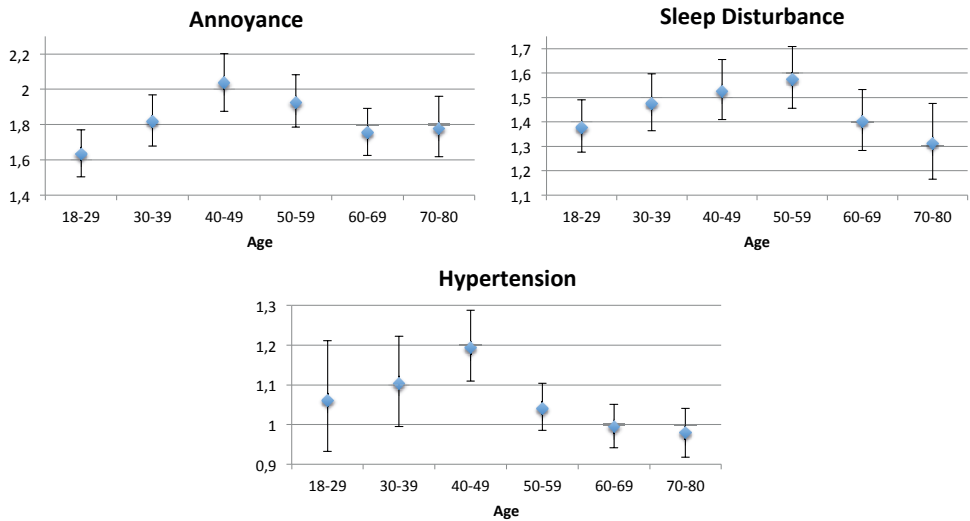


Figure 10 Odds ratio for annoyance, sleep disturbance and hypertension, in relation to a 5dB(A) increase in road traffic noise (The 2004 Public Health Survey)

## Sex

Sex has not shown a clear pattern and it is not clear as to whether sex is an important modifier. In paper II we found that men were less likely to report annoyance due to combined noise exposure OR(95% CI) 0.79 (0.64-0.97). As noted above women reported to be more frequently noise-sensitive. However, in paper III, investigating the association between road traffic noise and hypertension, we found no apparent difference in effect between the sexes when performing stratified analysis (paper III, figure 3). Re-analysing the data used in paper III we found a, close to significant, difference between men and women regarding disturbed sleep in relation to a 5dB(A) increase in average noise exposure: OR men 1.38(1.31-1.46) vs. women 1.51(1.44-1.58). No such difference was found in the aspect of general annoyance (Figure 11).

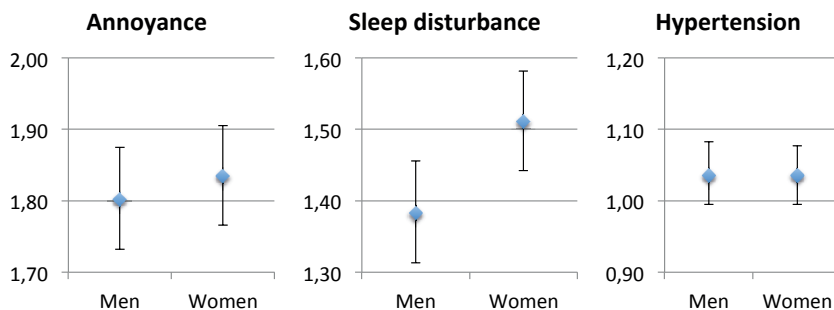


Figure 11: Odds ratio for annoyance, sleep disturbance and hypertension, in relation to a 5dB(A) increase in road traffic noise (The 2004 Public Health Survey)

## Education, Financial stress and Socio-economy

In paper II we could show that strained economy, in this case defined as not being able to pay one's bills on time, was associated with greater annoyance to traffic noise, OR(95%CI) 1.88 (1.33-2.66). Also, unrelated to noise, the odds ratio of reporting sleep and concentration problems in relation to strained economy was 3.04 (2.18-4.25) and 3.31 (2.39-4.59) respectively in the fully adjusted model (Paper II, Table 5).

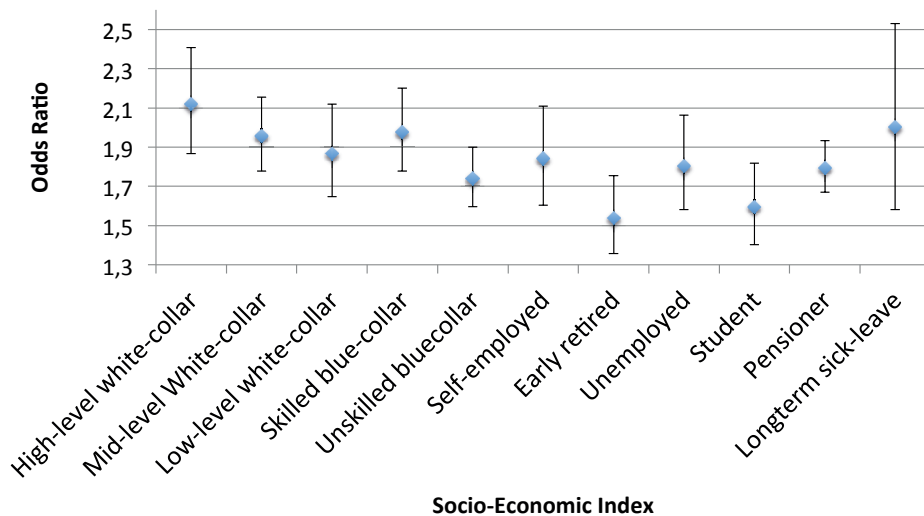


Figure 12: Risk of Annoyance in relation to an increase of 5dB(A) road traffic noise (adjusted for age, sex, BMI)

Also in paper II we found that single or divorced were less likely to report annoyance due to combined traffic noise compared to co-living or married OR (95%CI) 0.87 (0.70-1.08). University education was associated to a higher risk of annoyance compared to low level of education. OR (95%CI) 1.73 (1.27-2.35)

Reanalysing data from 2004 (Figure 12) we found no differential effects of annoyance due to road traffic noise when stratifying for Socioeconomic Index. However, visually there seemed to be a trend of lower effect estimates with declining socio-economic status.

## 4.5 Individual and contextual factors modifying the effect of noise

### **Noise sensitivity**

In Env&Health07, annoyance due to road traffic noise was higher among persons who described themselves as "quite sensitive" or "very sensitive" to noise compared to non-sensitive individuals ("not so sensitive" and "not sensitive at all"). Respondents who characterised themselves as "noise sensitive" were found to be more likely to readily reply than non-sensitive individuals, OR (95%CI) 1.25 (1.04-1.49) in a fully adjusted model. No data was available regarding noise sensitivity in the PHSurvey08, and therefore we could not conclude whether noise-sensitive individuals were more likely to respond to a noise-survey than a broader one. However, we can conclude, based on the assumption that readily reply is a good proxy for response rate, that persons who characterize themselves as noise-sensitive are more likely than others to respond to a survey including questions about noise. Given that this holds, we can conclude that self-reported annoyance through mail surveys most likely overestimate annoyance, or at least do not underestimate true annoyance

Considering one-self as quiet or very sensitive to noise is rather common, and varies in our Env&Health07 Survey between 26-44% depending on socio-demographic factors. In figure 13 the prevalence of noise sensitivity stratified by a number of demographic variables are presented. The data is from Env&Health07 and shows that noise sensitivity is more common among women compared to men, those having difficulties paying one's bills compared to those who didn't, immigrants vs. native Swedes, University educated vs. those with 9 years or less in school, as well as the characteristic inversed U-shape for age. ( $p < 0.01$  for all) Hearing impairment, civil status and time living in the same residence was not associated to self-reported noise sensitivity.

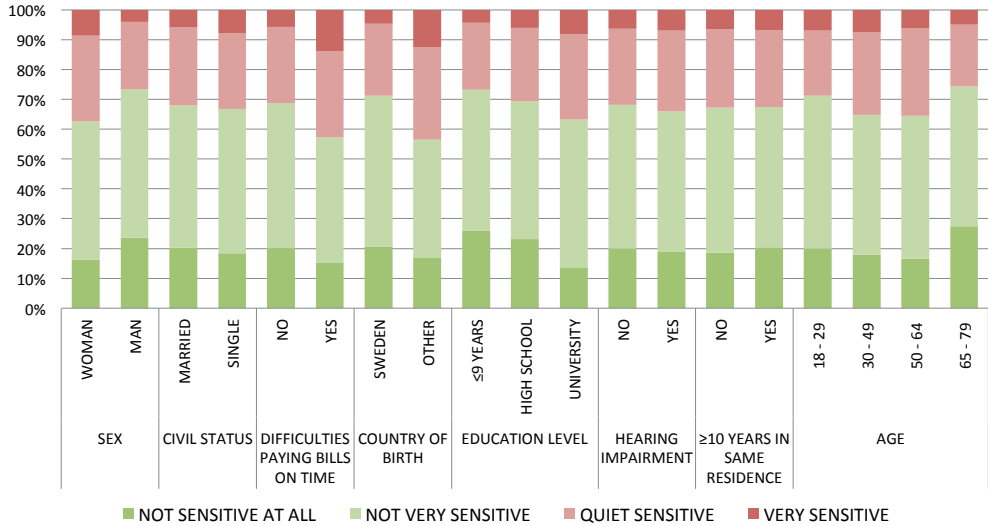


Figure 13 Noise sensitivity between different socio-demographic groups

## Survey context and question wording

In paper II the modelled combined noise levels at the most exposed façade in 5dB(A) categories and annoyance (5-point ISO/TS scale) from the total traffic noise was positively correlated (Spearman's rank correlation coefficient  $r=0.40$ ,  $p<0.01$ ). For road traffic noise the correlation was even better ( $r=0.51$ ,  $p=0.015$ ). In paper II we asked about frequency of disturbance. The 4-point scale used in the public health survey had a correlation coefficient of  $r=0.30$ ,  $p=0.015$  but a 5 point frequency scale which could be found in Env&Health07 performed just as well as the ISO/TS 5-point degree of annoyance scale in the same survey ( $p=0.51$ ,  $p=0.016$ ).

In paper I, baseline prevalence of annoyance at least once per week was the same in both studies up to LAeq,24h 40-44 dB(A). However, at noise levels exceeding 45dB(A), participants in the study explicitly investigating the relation between traffic noise and health (Env&Health07), were more likely to report annoyance more than once per week due to road traffic noise, compared to those participating in the broadly aimed public health survey (PHSurvey08), also when taking differences in railway noise exposure into account. Differences between Env&Health07 and PHSurvey08 with 95% confidence intervals were 10% (4-16), 11% (2-20) and 5% (-3-15 (n.s)) respectively for the highest exposure stratum. However, no apparent difference was found when comparing the proportion of respondents being annoyed every day or among those never being annoyed.



# 5 Discussion

## 5.1 General Discussion

### 5.1.1 Combined exposure from different noise sources

We found a clear and positive relation between traffic noise from road, railway and the two sources combined and self-reported annoyance, sleep and concentration problems. Railway noise was less annoying at intermediate (45-54dB(A)) levels compared to equal levels of road traffic noise (Figure 7). However, no significant difference in self reported annoyance was found at other equal noise levels. This effect was consistent when adjusting for age and sex. The European union standards for calculating traffic noise day-night average ( $L_{DEN}$ ) includes a “railway bonus” of 5 dB irrespective of noise levels, since it has been proposed to be less annoying than road traffic noise [21, 75]. This study finds support for a railway bonus at intermediate noise levels, but we cannot conclude that this bonus is justified at levels exceeding  $L_{Aeq24h}$  55dB(A). This is similar to the findings in the study in Lerum [76]

There are also other possible combinations of noise sources, which we did not investigate in this thesis. A combination of high levels of road traffic noise and occupational noise has been found to have a possible additive effect on the risk of Myocardial infarction in a recent Swedish study [77]. Air craft noise is a known risk factor for hypertension [78]. Road traffic noise has also been studied in the same studies as aircraft noise showing that both are individual risk factors for hypertension [79].

### 5.1.2 Combined exposure to road traffic noise and air-pollution

In our study on road traffic noise, air pollution and Myocardial infarction (Paper IV) we were not able to find an association between road traffic noise, air pollution and cardiovascular disease in the whole study population aged 19-81 years at baseline. Stratified analysis did not show any increased risk among women or men, young or elderly. Combined exposure of  $L_{DEN} < 55$  dB(A) and  $NO_x > 20$   $\mu\text{g}/\text{m}^3$  as well as  $L_{DEN} > 55$  dB(A) and  $NO_x > 20$   $\mu\text{g}/\text{m}^3$  was however related to a non-significant increase in IRR for MI.



De Kluizenaar et al recently presented a study with similar design and size as the present one, although looking at the risk of IHD and cerebrovascular disease (CVD) combined [53]. Like us, they did not find an increased risk of hospital admissions for IHD and CVD, neither in relation to road traffic noise, nor air pollution. Among those without previous history of cardiovascular disease, relative risks (RRs) for a 5th to 95th percentile interval increase were 0.97 (0.78-1.21) for  $L_{DEN}$  and 1.01 (0.99-1.02) for nitrogen dioxide (NO<sub>2</sub>) in their fully adjusted model, which is within the same margin of error as in our study. They also analysed a subgroup of elderly, aged >65 years of age and found RRs 1.02 (0.99-1.04) for  $L_{DEN}$  and 1.01 (0.72-1.42) for NO<sub>2</sub> comparing 5<sup>th</sup> and 95<sup>th</sup> percentile of exposure. We were not able to find such an association for MI although we did find similar results for IHD (not presented in results).

Selander et al 2009 found that exposure to road traffic noise of  $L_{DEN}$  50 dB(A) or more was associated to a 12% (95% CI: -5% to 33%) higher risk for myocardial infarction [4]. This is similar to Sorensen et al, who found a 12% increased risk of MI per 10-dB(A) increase in road traffic noise in a Danish cohort study [40]. Both studies found a positive dose-response relation, which we were not able to confirm in paper IV.

Selander also found a stronger association when excluding exposure from other sources such as railway noise. This was not found in the study by Sorensen, where similar risks were found among persons exposed to over and under  $L_{DEN}$  60 dB of railway noise. We were unfortunately not able to adjust for railway noise in this study, however railway noise is not a very common exposure in paper IV, only 3.8% of the population lived within 200m of a major railway and 7% within 200m from a minor railway. We believe that there is a low risk of misclassification, given that when re-analysing data from Env&Health07 we did not find that exposure to one source was associated to an increased risk of annoyance by the other.

Sorensen found that adjustment for NO<sub>x</sub> only resulted in small changes in estimates: 1.10 (95% CI: 1.03–1.19) before and 1.12 (95% CI: 1.02–1.22) per 10 dB higher  $L_{DEN}$  at diagnosis, which is the same as in this study. Neither did they find a significant association between NO<sub>x</sub> and MI, which is the same as our findings.

The relation between air pollution and myocardial infarction has been extensively studied. Both long-term [80] and current [81] exposure of air pollution has been found to cause myocardial infarction. Some studies have investigated the combined effect of road traffic noise and air pollution on ischemic heart disease. Beelen et al [54] found an increased risk of cardiovascular disease at road traffic noise levels above  $L_{DEN}$  65dB(A) OR 1.25 (1.01-1.53),, which did not sustain when adjusting for air pollution OR 1.17 (0.94-1.45) . The present study found no association between NO<sub>x</sub> and ischemic heart disease, using almost the same definition (ICD10: I.20-I.24 compared to ICD10: I.20-I.25 in that study). This might be due to differences in air pollution definitions. NO<sub>x</sub> was used in the present

study vs. black smoke based on traffic intensity by Beelen et al. They then adjusted for traffic intensity, which might have caused over adjustment.

In one study by Huss et al in 2010 [52], aircraft noise was associated to an increased risk of dying from myocardial infarction OR 1.5 (1.0–2.2), comparing  $\geq 60$  dB(A) with  $< 45$  dB(A) at least 15 years. They did not find an association between background levels of PM10 and MI, while living close to a major road increased the risk. These three variables had quiet low correlations and were included simultaneously, like in paper IV, without changing effect estimates of aircraft noise.

Other outcomes associated to noise, such as cognitive problems in children, does not seem to be modified by air pollution [82].

### 5.1.3 Quiet side and time spent in residence

Results in paper II give clear evidence of several benefits of having access to a quiet side of one's dwelling. Having at least one window facing a yard, garden, water or green space was associated with less annoyance and less concentration problems. Bedroom window facing the same environment was associated to lower risk of poor sleep quality. Our study's results are in line with earlier studies within this field [13-15, 83]. Öhrström et al studied the impact of quiet side using modelled noise levels for both the most and least exposed façade, defining a quiet side in *absolute terms* as average noise levels  $< 45$  dB(A). They found that access to a quiet side reduced noise annoyance and other disturbances by an average of 30–50% equal to a reduction in sound levels of  $L_{Aeq24h}$  5 dB(A) at the most exposed side, which is very similar findings as in paper II, both in absolute and relative terms.

Three Dutch studies have investigated the effect of *relatively quiet* façade. The first, by de Kluizenaar et al. in 2011 found that those living in dwellings with relatively quiet facades, defined as greater difference than 10dB between the most and least exposed façade, were less likely to report annoyance than those living in dwellings where the difference was less than 10dB [14]. They also found that the effect of relatively quiet side possibly increased with higher noise levels. This is opposite to the findings in our study. The results may be influenced by the predominant structure of blocks, i.e. “open” blocks with straight buildings along a road which are not part of a block structure sheltering from all sides, while “closed” blocks have such a sheltering effect. There is anecdotal evidence that “open blocks” are more frequent in Malmö compared to most Dutch cities, which could explain this difference. Van Rentergem and Botteldooren found that lack of access to a relatively quiet side was associated to a higher degree of annoyance [83]. They also found that the effect seemed to be most prominent among people who were noise sensitive. However, we

could not find such difference in our study. In a recent study by de Kluizenaar et al. from 2013 they further investigated the effect of relatively quiet side and found roughly the same results as in the earlier studies, i. e. a benefit of quiet side equalling approximately a 5dB reduction of the most exposed side if one were to lack access to a quiet side. This 5dB shift seems to be relatively stable throughout the other studies. In our study we found a benefit of access to a quiet side corresponding to a 10dB decrease in exposure at dwellings lacking windows facing a supposedly quiet environment and approximately 5dB compared to the total study population.

None of our studies have been able to consider residential noise protection installations which is common in Sweden. The government pays for or subsidies noise protection installations when indoor average noise is  $>40\text{dB(A)}$  or exceeds  $55\text{dB(A)}$  more than 5 times per night. In paper II, table 4A-C show quite clearly that although annoyance due to road traffic noise increases with noise exposure, sleep and concentration problems reaches a plateau or even decreases (sic) from  $55\text{--}59\text{dB(A)}$  to  $\geq 60\text{dB(A)}$ . Noise protection installations that can not be accounted for in the GIS models are therefore a source of systematic confounding, likely leading to an underestimation of the effects of road traffic noise at higher levels.

In one study by Huss et al in 2010 [52], aircraft noise was associated to an increased risk of dying from myocardial infarction OR 1.5 (1.0–2.2), comparing at least 15 years of exposure to  $\geq 60\text{ dB(A)}$  with  $<45\text{ dB(A)}$ . There are other studies that have found increased risk of cardiovascular diseases in relation to long-term exposure to noise (for example [4, 7]). It is however not likely that time in the same residence has a modifying effect in it self, as found in cross-sectional studies. It correlates with age and since current exposure is highly correlated to past exposure, selecting those that have lived for a long time in a residence with high current exposure probably also mirrors past exposure.

#### **5.1.4 Demographic factors modifying the effect of noise**

Although a stronger association between road traffic noise and hypertension have been reported among females compared to males [24], results are far from consistent [33, 34]. In recent studies on cardiovascular disease, one study indicated a stronger effect of traffic noise on cardiovascular disease among men [38], whereas others have indicated no sex differences [4, 54]. Large differences in effects of noise on cardiovascular disease between males and females could be ruled out with high statistical precision both of our studies.

Earlier studies do not indicate that annoyance due to road traffic noise differs between men and women [11]. In our paper II, men were less likely to report annoyance, poor sleep quality and concentration problems than women. We also present findings in this

thesis indicating that women experience more sleep disturbance in relation to road traffic noise and that they are significantly more often noise sensitive, adjusted for noise exposure (figure 13).

Findings suggesting differences in effect across age groups may have several possible explanations. One explanation for the absence of effect among the elderly could be that the effect of noise may become less important, or harder to detect, relative to other risk factors with increasing age. Another explanation could be that noise annoyance varies with age. A recent meta-analysis showed that the association between age and noise annoyance was bell-shaped [84], and others have found that the risk of cerebro-vascular disease was highest among elderly. Paper III identified the strongest relation between noise and hypertension in middle aged subjects. Earlier onset of disease rather than increased life-time risk is another possible explanation yet to be explored.

A possible explanation for the bell-shape found for annoyance, hypertension and sleep problems, might be due to the transition from pre- to postmenopausal status. This transition is associated to a significant increase in sleep disturbance in women without hormone replacement therapy [85]. It has been found that women with sleep related problems have higher systolic and diastolic blood pressures and greater waist:hip ratios.

Regarding Socio-economy there is still doubt how this modifies the effect of noise. Socio-economic index and education on an individual level have shown inconsistent results, while we can show that financial stress seems to contribute to the observed associations, although this is more of an exposure than a feasible way to identify susceptible subgroups in the population. One possible way of adjusting for this might be home ownership as briefly introduced in this thesis. Another way would be to use area-level aggregated socio-economic score, which has been shown to correlate well with long-term survival after myocardial infarction [86], and the risk of stroke [87].

### **5.1.5 Individual and contextual factors modifying the effect of noise**

Noise sensitivity can be defined as a personal trait, but is also influenced by the context in which the individual is exposed or in which way he or she is asked.

Noise sensitive persons are those who has an increased adverse reaction to noise in general. Whether people are aware of their of their increased sensitivity or not, is an open question. One example of this is the lack of congruency between physiological response to noise during sleep and self-reported noise sensitivity [17]. Self-reported noise sensitivity has been show to have a strong genetic component, 40% was estimated to be attributable

to genetic factors in a Finnish twin-study [88]. Sensitivity can also be caused or modified by somatic or psychiatric illnesses [89].

Noise can also be a lesser or greater problem depending on location and in what context people move about the area. A place is "noise-sensitive" if noise interferes with normal activities associated with the area's use. Examples of noise-sensitive areas include residential, educational, health, and religious structures and sites, and parks, recreational areas (including areas with wilderness characteristics), wildlife refuges, and cultural and historical sites where a quiet setting is a generally recognized feature or attribute [90].

Taking these individual and contextual factors into consideration we can begin to identify high-risk groups, with a higher-than-expected risk for developing an adverse reaction in relation to noise.

In paper I, noise sensitivity was associated with readily reply (within two weeks) to the Env&Health07. Readily response have been investigated by others as a predictor for participation bias and it has been found that late responders are more similar to non-responders [91]. This is also supported by the findings in this study, that women respond more readily and have a higher response rate than men. The same was found when considering response time and rate in relation to age. Noise sensitive individuals report, as we know, more annoyance compared to non-sensitive (paper I, Table 4 and [11]) Since we lacked information concerning noise sensitivity from the other study (PHSurvey08) this bias could not be quantified, but it is reasonable to assume that noise sensitive individuals are more likely to respond to a survey that includes questions about noise annoyance, and that this differential participation could lead to an over-estimation when estimating annoyance prevalence for total populations.

Noise sensitivity and trait anxiety scores have been shown to be related to reports of annoyance due to road traffic noise and noise from neighbours as well as other environmental exposures [92]. This suggests caution when using annoyance reports as surrogate for environmental exposure, which happens less often nowadays, but is still frequent in developing countries where noise mapping based on traffic data is unavailable. Also this has implications when studying the moderating effects of annoyance on health outcomes such as the association between road traffic noise annoyance and hypertension. [93].

## 5.2 Methodological Discussion

### 5.2.1 Exposure assessment

The quality of our noise exposure data has generally been detailed and of high quality based on actual measurements of traffic intensity for a majority of the road segments. We were able to combine data on vehicles for road segments belonging to the government and local municipalities. In all studies, we observed a clear correlation between modelled exposure and self-reported annoyance from road traffic noise, indicating a reasonable ranking of current exposure across study subjects.

Some of the limitations were the same in all three noise models. We did not have information regarding the individual buildings such as window glassing, insulation, and on which floor people lived. Noise levels were connected to individual exposure via the residential building closest to the centroid of the real estate. Some study participants might therefore be assigned to the wrong residential building. This problem is expected to be largest in rural areas and areas with large buildings. We also did not know where in the building the study participants were living, which means that there might be an overestimation of the noise for some study participants, due to that the facade with the highest level of noise was used as representative for the whole building.

In paper I and III we were only able to separate between urban (hard surface) and rural (soft surface) areas while topography and buildings were included in the modelling used in paper II and IV. Comparing models in urban setting, we found that the simplified Nordic prediction model (see methods section) overestimated the exposure compared to the END mapping used in paper II. The median difference was +1dB(A); Quartiles: -3, 7 dB(A); 2.5-97.5 percentiles: -10, 18 dB(A) (n = 2,966) with a slight trend towards larger over-estimations at higher noise levels. The END digital noise maps used in paper II have been validated and have been found to have a good precision [94].

The precision error is of classical type. [95] All above mentioned flaws in the simplified model are most likely to lead to an underestimation of our results and might have implications on lower noise levels. Reassuringly, effects on the categorical analysis should be marginal, whereas the continuous analysis might suffer more from the precision error. On the other hand, we observed a clear correlation between modelled exposure and self-reported annoyance from road traffic noise in all studies, indicating a reasonable ranking of current exposure across study subjects.

None of the studies take other noise sources, e.g. noise from neighbours, air traffic, ventilation or work exposure, into consideration. Nor were we able to adjust for hearing impairment, which we found had a strong impact on annoyance in paper II. Also,

Selander et al. 2009 found that adjusting for other noise exposures and hearing impairment increased the effect estimates of noise in relation to myocardial infarction from OR 1.12(0.95-1.33) to 1.38(1.11-1.17), thus we might have underestimated the effects of noise in paper III and IV. This might have led to an underestimation of our results in paper III and IV.

The emission database used for modelling NO<sub>x</sub> has been validated against measured values. In paper IV a yearly average was used and it has been shown that, when reducing the temporal resolution, the choice of coarser spatial resolution did not considerably deteriorate the accuracy of the modelled NO<sub>x</sub> values. Further they concluded that for urban areas a spatial resolution of 200–400m was suitable; and for rural areas the spatial resolution could be coarser (1600 m). In paper IV 500x500m grids are used, which is good for rural areas, but could possibly be less satisfactory in urban areas[96].

NO<sub>x</sub> and L<sub>DEN</sub> showed a clear relation as illustrated in Paper IV, figure 2A although the adjusted R<sup>2</sup> was only 0.15. The rather low correlation is mainly due to differences in how road traffic noise and air pollution propagate in an urban setting, where air pollution dispersion is less affected by buildings and topography compared to noise. This made it possible to analyse the effects of road traffic noise and NO<sub>x</sub> separately and combined.

### **5.2.2 Selection bias**

All papers are based on large random samples including all ages except children and the very oldest. Random error bias is therefore unlikely to affect the results in any of the included papers. The response rates in all surveys used in this thesis have been 53-59% and this may be a source of selection bias. In the cross-sectional surveys we knew the differences between responders and non-responders, and found quite large differences in response rate with regard to basic demographic descriptive data such as age, sex, income, civil status and education, all obtained through registers (Table 5). In the Residential Environment and Health survey 2007, we also knew the exposure level for non-responders and in the public health survey 2004 education and income was available for non-responders. Throughout all of the studies women had a higher response rate than men. There were also differences between different age groups, where elderly were more likely to respond than younger people. In the study where noise levels were available for non-responders (Paper I), the response rate was lower in areas with high noise exposure levels compared to areas with lower exposure.

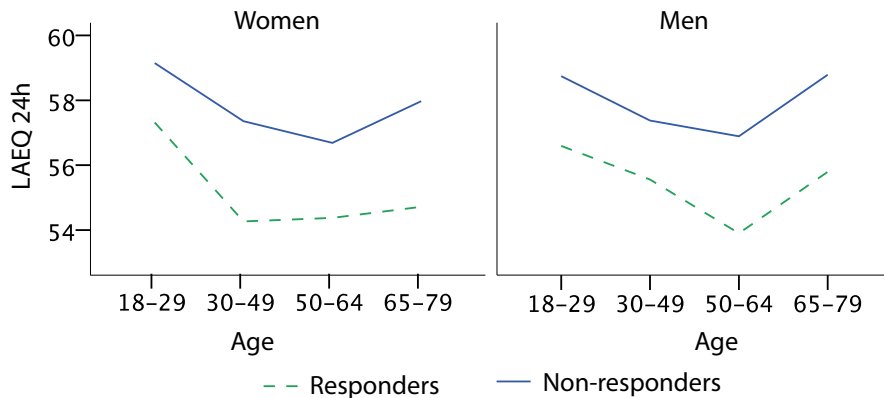


Figure 14 Responders and non-responders to the Env&Health07 survey

Over-estimation of the effect of noise would occur if there was an over-sampling of highly exposed cases, direct or indirect. In the case of hypertension this could be true if known risk factors such as male sex and higher age were associated to higher exposure levels. The relation between age, sex and noise is presented in figure 14, showing a U-shaped/slight inverse relation between age and exposure (which is also true for the public health survey used in paper III), and no obvious sex differences. There is also an undifferential lower level of road traffic noise exposure among respondents compared to non-responders. Based on this, it is most likely an underestimation of the association between road traffic noise and hypertension, as well as the prevalence of hypertension at the population level. The latter is also supported by a major prevalence study [97]. With regard to paper IV we found that the incidence of myocardial infarction was approximately 25% lower in our study population than in the general age standardized population [98].

Several factors influence the respondent's interest in participating. The leverage-saliency theory of survey participation describes how different factors such as cash and other rewards, community involvement, identity of the sender, and personal interest in the survey's topic affect response rates. [99] Personal interest in the survey topic has been shown to increase the response rate with as much as 14%. [100] Recent studies within social science have shown that the differences between responders and non-responders are negligible regarding many commonly asked questions, however demographic items such as income and education, have been skewed, like in the surveys used in our papers [101, 102] The information to respondents to the public health surveys (paper I, IIIb and IV) consisted of general information, nowhere stating specific aims included in this thesis. We believe that this may possibly decreased selection and information bias in those papers, although our own results do not permit a firm opinion, as concluded in paper II. In paper



IV the lower than expected incidence of MI indicates that participation at base-line may have been selective with regard to health-status.

### **5.2.3 Limitations**

There are many limitations in the papers presented in this thesis.

Paper I-III are cross-sectional, with its many limitations, especially regarding causal relations. Paper IV has a longitudinal design, however follow up time was short (7-10 years) and past exposure unavailable. This led to the use of current and 3-year accumulated noise exposure. However, we found that current and past noise exposure were highly correlated and there was very little change on the estimates when comparing the two types of noise exposure.

Socio-economic index (SEI) has been obtained from registers (paper III) or through self-reporting (Paper IV) was not available for Paper I-II. In paper III we included SEI into the analysis. However, when revising the analysis plan for paper IV it became obvious that since “retired” included all pensioners irrespectively of socioeconomic level earlier in life, we would lack a meaningful classification for subjects in the age-group generating most cases, thus risking to over adjust for age, while gaining little extra information. Finding that SEI did not affect the effect estimates for noise, we believe that excluding SEI in paper IV was correct.

### **5.2.4 Statistical considerations**

The strengths of all of our studies are that we worked with large random population samples including all ages except children and the very oldest. In paper III and IV both urban and countryside population are included and we have been able to adjust for a large number of potential individual risk factors. In paper IV we were also able to take changes in individual confounders into account every fifth year and also had access to residential address histories for all individuals who responded to the survey except 77 persons (99.3%). As noted earlier, information on outcomes have also been of generally good or excellent quality.

Despite these excellent data resources, we have been working with relatively low levels of road traffic noise and air pollution levels. This is certainly positive for the population in Skåne, but has caused statistical power problems when estimating risks at high exposure levels, and difficulties in obtaining robust dose-response relations, where we assume we could have found such. E.g. in paper III, the elevated risk for hypertension associated to road traffic noise turns significant at levels >60dB(A) where our modelled levels reach their peak. On the other hand, we have had many observations in the medium-range (45-

60dB(A)) which is the focus for knowledge gaps and controversy on good residential sound environment.

In paper I-III we present Odds Ratios as a measure of association. This is widely used in epidemiologic research, and this is the case also in most papers referred to in this thesis. Odds Ratios have, in this thesis, been used in this thesis whether the outcome have been rare or common, despite that Odds Ratios are similar to Risk Ratios only when outcomes are uncommon like Myocardial Infarction, and therefore become difficult to interpret when outcomes are common, such as in the case of annoyance (see equations in methods section for explanation). As pointed out by Cheung [103], “one major reason for its popularity is the ready availability of software for fitting logistic regression models but not for fitting log-binomial or binomial regression models. The log-binomial and binomial regression models estimate the risk ratio and the risk difference, respectively. Now that many commercially available statistical packages have the capacity to fit log-binomial and binomial regression models, “there is no longer any good justification for fitting logistic regression models and estimating odds ratios” when the odds ratio is not of scientific interest ([104], p. 199).”

An assessment of interaction on an additive scale is often more meaningful than interaction on a multiplicative scale. In epidemiology a positive departure from an additive effect implies synergistic effects, which can be of great interest even though there is a lack of statistical interaction on a multiplicative scale. Having used logistic regression as main tool of analysis in the cross sectional studies interaction has been tested multiplicatively ( $a \times b$ ). To obtain the relative excess risk due to interaction (RERI), i.e. departure from an additive effect on a relative risk scale, we would have had to reversely transform the parameters to probability scale. This has to be done with caution, and no packages have been available for SPSS.

### **5.2.5 Assessment of outcomes**

Self-reporting has been the basis for outcomes in paper I-II while we used registers in paper IV.

#### **Cardiovascular disease**

When it comes to self-reported cardiovascular outcomes, information bias must be considered. Our definition of hypertension in paper III may have many implications. We did not measure the blood pressure ourselves and rely solely on self-reporting. One study concluded that as many as two-thirds of the hypertension cases were missed using self-reporting [105] although other studies have shown a sensitivity of 71% [106] However, self-reported doctor diagnosis of hypertension has been shown to have high specificity (96.4% and 91% respectively in the two studies). The first study also showed that

sensitivity varied. The likelihood of correct reporting increased as age increased and females were almost twice more likely to accurately report hypertension when present than men [105]. The overall proportion of coherent answers between the two questions used to assess hypertension in paper III was 93%.

Many patients may also go undiagnosed. Even though there are well-known definitions of hypertension used in Sweden, one could expect that the actual diagnostic threshold varies between physicians and over time. A study from 2003 reported hypertension prevalence in Sweden being approximately twice as high as in our study [97]. Under-diagnostics may be differential in regard to socioeconomy, age, sex or other important demographic factors. This is known to be common in low and middle income countries [107], while there are no current investigations from Sweden on this topic.

In a study from the Netherlands, somewhat lower effect estimates associated with road noise exposure were seen when self-reported antihypertensive treatment was used rather than actual blood pressure measurements and pharmacy reports [34].

In Paper IV we switched to register-based outcomes obtained from the Swedish national patient registries in which more than 99% of all somatic (including surgery) and psychiatric hospital discharges are registered. A previous validation of the IPR by the National Board of Health and Welfare showed that 85-95% of all diagnoses in the IPR are valid for MI [74].

### **Annoyance, sleep quality and concentration difficulties**

As pointed out earlier we found that different annoyance scales produced different results. Paper II used the 5-point ISO/TS annoyance intensity scale, which has been validated before. Although two different annoyance frequency scales were used for comparison in paper I, we did not find any evidence that a 5-point frequency scale performs worse than the 5-point ISO/TS annoyance intensity scale in the population investigated.

4-point and 5-point scales did however produce different annoyance prevalence. This has earlier been proposed in data supplied by Rohrmann to the ICBEN [108], and also shown in a study by Yano in 1997 with results consistent with ours suggesting that the extreme alternatives showed better alignment between scales than dichotomized variables. [109] As illustrated in paper I, figure 1, no difference was found between the two studies at low noise exposure levels. These findings also suggest that the number of alternatives could matter more at high exposure levels. Despite this, today's dose-response curves have translated different scales based on the assumption that a set of annoyance categories divides the range from 0-100 in equally spaced categories [75].

The question regarding sleep quality (“How do you usually sleep”) has been used by Öhrström et al earlier, however the scale has not been validated although it is somewhat

similar to the Basic Nordic Sleep Questionnaire “During the last three months, how well have you usually slept?” – “well, rather well, neither well nor badly, rather badly, badly” [110].

The question “Do you usually have difficulties concentrating on what you want to do?” with an attached 4-point scale has, to the best of our knowledge, not been validated. There are several other questions that could have been used such items from MADRS [111] GHQ-12 [112] or other.

Overall, using binominal outcomes in all studies, and since we have not found reason to doubt that misclassification of outcomes is non-differential with respect to road noise exposure, results are most likely biased towards the null.



# 6 Conclusions

This thesis set out to contribute to the growing evidence of cardio-vascular effects of road traffic noise. We also wanted to investigate factors modifying this relation, both combined exposures and differential effects between groups in society. We also wanted to investigate factors modifying annoyance, sleep disturbance and concentration problems associated to traffic noise. Below, we present the aims stated in the beginning of this thesis, and our conclusions.

1. Is there an association between road traffic noise and 1) hypertension 2) myocardial infarction 3) Ischemic heart disease?
  - a. We found an association between road traffic noise and hypertension at high average levels ( $> 60$  dB(A))
  - b. We did not find an increased risk for IHD or MI in relation to road traffic noise.
2. Is current and medium term exposure to road traffic noise and air pollution independent and/or joint risk factors for incident myocardial infarction?
  - a. We were not able to show a relation between current and medium-term noise exposure and incident myocardial infarction or ischemic heart disease in the general population. The most recent pooled estimate of coronary heart disease in relation to road traffic noise is OR 1.08/10dB(A), based mostly on studies with non-significant trends, and in specific age-groups [41]. With the result from our study, the question is still open to weather there is an increased risk of coronary heart disease in the general west-European population or if this only holds true for specific parts of the population based on demographic indicators, but more likely individual susceptibility.
  - b. Regarding the relation between Air-pollution derived from road traffic, we believe that due to generally low exposure levels of NO<sub>x</sub> ( $<40$   $\mu\text{g}/\text{m}^3$ ), the non-positive result should be interpreted with caution.
  - c. Since individual effects of noise and air pollution were not found, an additive effect was difficult to assess. Our findings do not support an additive effect of road traffic noise and low levels of NO<sub>x</sub>.
3. Is there a difference in self-reported annoyance, sleep quality and concentration problems between those exposed to road traffic noise, railway noise and the two sources combined?

- a. Railway noise was found to be less annoying than road traffic noise at lower average noise levels, but we found no support for this at levels exceeding  $L_{Aeq24h}$  55dB(A). Scientific support for a railway bonus at higher levels is challenged by other recent studies.
- 4. Is there a beneficial effect on annoyance, sleep and concentration from access to quiet side in one's residence?
  - a. Having at least one window facing a green space was associated with substantially less annoyance and concentration problems. If this window was the bedroom window, this was also true for sleeping problems. To protect most people (80%) from experiencing annoyance, the sound levels from road traffic should not exceed  $L_{Aeq24h}$  50 dB at the most exposed facade, even if the dwelling faces a quiet side. If there is access to a perceived quiet indoor space this level could be raised to 55dB.
  - b. Although noise sensitive persons are more annoyed to noise, they were not found to have a greater relative benefit from access to quiet side than non-sensitive individuals.
- 5. Are the above-mentioned associations between noise and adverse effects modified by socio-demographic differences, especially age, sex and socio-economic factors?
  - a. We found a stronger association between road traffic noise and hypertension, annoyance and bad sleep quality in middle-aged persons
  - b. Results were inconsistent with regard to sex.
  - c. Higher socioeconomic status and educational level seems to be related to noise annoyance. However, other stressors related to low socioeconomic status such as financial stress, country of birth and job-strain tend to be related to higher degree of annoyance. Participation is also biased with regard to socio-economic factors and there is need for better evaluation of this area.
- 6. Does survey context and question wording have an impact on response to noise surveys
  - a. The wording and number of alternatives on the annoyance reporting was found to produce different results when comparing the two studies.
  - b. It is likely, but cannot be definitely concluded from our study,, that noise sensitive individuals are more prone to answer a questionnaire including questions about noise.

## Implications for Policy

Quiet side of dwellings have lately become a possible solution for regulators wishing to build in noisier environments. In Sweden a recent governmental report suggests that houses should be allowed to be constructed in areas exceeding  $L_{Aeq24h}$  55 dB(A) at the most exposed façade, if at least half of the windows face a relatively quiet side [113]. A 5dB benefit of a quiet side would in that case allow for construction in areas with up to 60dB(A) at the most exposed façade. However the authors of that report want to go further, claiming that modern buildings, due to improved insulation, allows for even higher noise levels. In this study we asked about access to quiet indoor spaces where one did not notice traffic noise. The question was excluded from the analysis (except in paper II, table 4A-C) due to its obvious risk for reversed causality, where those less annoyed are more likely to report access to perceived quietness. This question is very unlikely to underestimate the benefit of quiet side and could therefore be relevant for current proposed policy changes, which relies heavily on the benefits of quiet side and that newer buildings isolate better for noise. Firstly: Even with access to indoor spaces that were perceived as quiet, there was still a clear dose-response between annoyance and noise levels at the most exposed façade. Secondly, annoyance levels in the group with access to quiet indoor spaces (paper II, table 4A) were shifted approximately 5 dB compared to the average annoyance. This suggest that access to quiet indoor spaces would make it possible to build in environments more noisy than today, but only up to 60dB(A) at the most exposed façade. Possibly even more important, this study found that, even though one has access to a quiet indoor space, the annoyance prevalence is still 27% at levels 55-59dB(A) and 41% at levels exceeding 60dB(A) which hardly can be considered as acceptable and shows that indoor noise levels are far from the only thing to consider when it comes to environmental noise protection in the residential setting.

Railway noise was found to be less annoying than road traffic noise at lower average noise levels, but we found no support for this at levels exceeding  $L_{Aeq24h}$  55dB(A). This effect was consistent when adjusting for age and sex. The European union standards for calculating traffic noise day-night average ( $L_{DEN}$ ) includes a “railway bonus” of 5 dB irrespective of noise levels, since it has been proposed to be less annoying than road traffic noise [21, 75]. This study finds support for a railway bonus at low noise levels, but we cannot conclude that this bonus is justified at levels exceeding  $L_{Aeq24h}$  55dB(A). This is similar to the findings in the study in Lerum [76]





# 7 Future Research

- Combined exposures: As stated earlier it is still unknown what the individual and joint effects are from different sources of noise and air pollution. Noise and air pollution at work and transit as well as residential noise and air pollution exposure from road traffic and noise from railway aircraft, neighbours, and wind turbines could all be hypothesized to have a synergistic effect.
- Multiple stressors, unrelated to noise and air-pollution should be further investigated in the future. New results indicate that a combination of Job-strain, psycho-social and financial stress might modify the effect of noise. Moreover, noise may impair restitution from other stressors and thereby reduce the coping capacity, e.g. from work stress. This should be further investigated.
- Better way to assess social class as effect modifier. It has been difficult to find a winning strategy to assess the modifying effect of social class. Socio-economic index and education have shown inconsistent results. One possible way of adjusting for this might be home ownership as briefly introduced in this thesis or by using area-level adjustments
- Newer buildings have been proposed to insulate better for sound. As this is true when the building is new, it might change over time as the structure erodes. Although indoor environment might be better, it is still unknown whether this can compensate for out-door environment. Does "quiet building" have a similar positive effect as "quiet side"?
- New outcomes, such as diabetes, metabolic diseases, stroke and mental illness should be further investigated and might lead to new insights of casual pathways and outcomes.
- Intervention studies: It is clear that noise, especially night-time noise, causes sleep disturbance, which might be the single most important aspect of annoyance and a possible gateway to much of the ill-health caused by noise. Night-time prohibition of driving in certain city centres is not unheard of in Sweden, and when implemented, it should be evaluated from a noise disturbance point of view.



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