

Sound Reactions?

Modelling the influence of socioeconomic status, noise annoyance, noise sensitivity and sleeping problems on subjective health complaints and cardiovascular disease.

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"Diseases of the soul are more dangerous and more numerous than those of the body."

Cicero

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Oslo, August 2011

Aslak Fyhri

Summary

1.5 million people in Norway (1/3 of the population) are exposed to transport noise levels exceeding recommended values. How do people react to such noise? How do environmental characteristics and socio-economic factors contribute in explaining exposure to and annoyance from road traffic noise? What is the role of personal factors such as noise sensitivity? And finally, are there any negative health consequences? The aim of this thesis was to investigate these research questions.

The current thesis belongs to the field of Psychology; more specifically to Environmental Psychology. Environmental Psychology emphasizes that persons and environments, even if they are separate entities, are continually involved in a series of interactions, both being mutually shaped by the encounter with the other. This focus on *interactionalism* implies an increased awareness about the causal relationship between contextual background variables and the outcome variables under scrutiny. In the current thesis, Structural Equation Models (SEM) are chosen to investigate the interrelationships between variables. By forcing the researcher to make more explicit assumptions about cause and effect, SEM helps to elucidate the quantitative expression of a given theoretical model.

The thesis used data from two major data sets. Data set 1 (applied in articles I-IV) stems from 17 local environmental surveys carried out between 1987 and 2001, comprising a total of 19 000 respondents from the cities of Oslo and Drammen. The studies were conducted in 50 different subareas. Data set 2 (applied in article V) derives from a socio-acoustic survey of 3262 persons in Oslo. Response rates were in the range 40-50% in data set 1, and 60% in data set 2. In both data sets noise levels inside and outside each participant's dwelling were assessed using the Nordic Prediction Method for road traffic noise using digitalised terrain data on buildings and noise screens in three dimensions. The precision of the estimated noise exposure values is deemed to hold a higher quality than what is normally associated with noise mapping software.

General relationships between noise exposure levels and annoyance from road traffic in Norway were established in paper I. Half of the population find road traffic noise highly annoying at 70 dB and somewhat annoying at 58 dB. These curves indicate that even if the respondents react somewhat more strongly to a given noise level than do respondents surveyed in other European studies, the results fits well with previous results on noise-annoyance relationships.

Noise level explains only about 20% of the variance in noise annoyance. Hence, there are a range of other variables that might potentially contribute to explaining why some people find noise bothersome, and others not. In paper II we were interested in the impacts of having an adverse neighbourhood soundscape. We therefore used the highest equivalent noise level attained within a radius of 75 meters of the apartment, in order to calculate a neighbourhood maximum difference indicator, $L_{\text{diff.max}}$. The $L_{\text{diff.max}}$ indicator explains a considerable amount of noise annoyance in addition to exposure at the most exposed facade, the worst cases can add upwards to 7 dB the exposure level.

In paper III we investigated whether income may influence annoyance levels directly, by high SES residents having better resources for dealing with a given noise level, or indirectly, by giving high SES residents a choice to live in less noisy areas. The SEM model that was developed helped to illustrate the dynamics of how noise annoyance is produced and socially distributed in a community. Income was only (indirectly) related to noise exposure in a medium-sized city. In a larger metropolitan area, other factors related to residential quality seem to override any potential relationship between income level and noise exposure. In line with previous results no (direct) relationship was found between noise annoyance and income.

The models were further elaborated in papers IV and V. These models were instrumental in establishing relationships between noise, sleep disturbances, subjective health complaints and cardiovascular disease. No relationship was found between noise exposure or annoyance and cardiovascular disease. The close ties between noise sensitivity and subjective health complaints were used as an argument for paying close attention to the role of general vulnerability in future studies of noise health relationships. Sleeping problems due to road traffic noise have been suggested as a major contributor to stress-related negative health outcomes. We show that road traffic noise is only a moderate contributor to overall sleeping problems, and that subjective health complaints are linked to both sleeping problems and noise experience.

In line with core theoretical principles of environmental psychology the results of these papers point to the importance of looking at the noise health relationship in a broader environmental and psychological context. Future research should combine large-scale community studies with good quality individual exposure assessments. Alongside the pursuit of further knowledge of potential health effects of noise, we should therefore strive to gain further understanding of the causal mechanisms, with particular focus on the psychological and behavioural effects of noise.

List of papers

1. Klæboe, Amundsen, Fyhri and Solberg (2004) Road traffic noise - the relationship between noise exposure and noise annoyance in Norway. *Applied Acoustics*, 65(9):893-912
2. Klæboe, Kolbenstvedt, Fyhri and Solberg (2005) The impact of an adverse neighbourhood soundscape on road traffic noise annoyance. *Acta Acustica united with Acustica*, 91(6):1039-1050
3. Fyhri and Klæboe (2007) Direct and indirect influences of income on road traffic noise annoyance. *Journal of Environmental Psychology*, 26(1):27-37
4. Fyhri and Klæboe (2009) Road traffic noise, sensitivity, annoyance and self-reported health - A structural equation model exercise. *Environmental International*, 35(1):91-97
5. Fyhri and Aasvang (2010) Noise, sleep and poor health: modeling the relationship between road traffic noise and cardiovascular problems. *Science of the Total Environment*, 408(21):4935-4942

Introduction

The origin of the word *noise* is uncertain. Some suggest it derives from the Latin word *nausea* (“disgust, nausea”), others that it comes from another Latin word, *noxia*, meaning “hurt, harm, damage, injury”. This difference reflects an important schism in current community noise research, where noise is either treated as a problematic experience, something bothersome and nauseating, or rather the focus is on the harmful long term effects of noise, on negative health outcomes to be precise.

The current thesis accounts for both these understandings of noise. Firstly, it examines the everyday role of road traffic noise as a cause of disturbance and annoyance in people’s lives, and how these experiences are related to other environmental and welfare issues. Secondly, it examines if and how noise might have a negative influence on people’s health. Some might argue that the differences between these two perspectives are quite subtle; we are after all talking about the same issue, the effects of noise on humans. But the vantage point we choose still has a certain influence on both our choice of methodology and on the general approach of our research. According to a Chinese proverb, “There are many paths to the top of the mountain, but the view is always the same”. Rephrasing this, one could say that depending on which road we choose to follow, the views to the valley below will differ considerably, at least while we are en route.

General background

Combining the words “road traffic” with “noise” on Google gives 323,000 hits. Combining “road traffic” with “pollution” gives 1.15 million hits, with “congestion” gives 1.43 million hits, and with “accidents”, gives 6.42 million hits. Even combining “road traffic” with “cows” gives more hits (516,000) than noise!

Empirical studies focusing on residential quality invariably state / imply / assume that road traffic is the major challenge to a satisfactory local environment, the main explanation being noise pollution (Kolbenstvedt & Fyhri, 2004). Indeed, when people are asked to name the source of noise they are most bothered by, road traffic is most often given (Kolbenstvedt & Fyhri, 2004). 1.5 million people in Norway (1/3 of the population) are exposed to transport noise levels exceeding recommended values (Engelien, Haakonsen, & Steinnes, 2004), which is comparable to the 30% of European citizens estimated to be exposed to noise levels above those deemed acceptable by the WHO (European Environmental Agency, 2003). On average we spend 15 hours every day in the home environment (Vaage, 2002). In Norway the average

household spends 38 % of its income on housing (Statistics Norway, 2004). The quality of the residential environment is of great importance to our welfare. So even though noise as a topic does not receive much attention in the media and in general discourse, road traffic noise is a major factor in peoples everyday lives and potentially has a great impact on our well-being.

An interactional approach to the environment

Epistemologically the study of people's reactions to noise can be said to belong to several disciplines: psychology, epidemiology, acoustics, audiology, physiology, sociology etc. This is well illustrated by the broad range of backgrounds that can be found among the participants of any research conference on the topic.

The current thesis belongs to the field of Psychology; more specifically it belongs to the field of Environmental Psychology. Environmental psychology is "the study of transactions between individuals and their physical settings" (Gifford, 2007, p. 1). Given such a definition it could be argued that *all* studies of noise experience are about Environmental Psychology. Within the noise research community the term "noise experience" is typically dealt with under the headlines of "community noise", "noise and health", "soundscape", "psychoacoustics" or "environmental acoustics" (which are all headlines of topics sampled from Internoise and ICA conferences in the last few years). All these fields are of a rather interdisciplinary nature. Still, the researchers' background to a large extent governs the precise issues that are dealt with and how the topic is approached. Even if the distinction between different disciplines often becomes blurred and scientists often find themselves grappling with issues not belonging to their "home discipline", most researchers have some sense of "where they come from". A claim that Environmental Psychology should adopt the whole topic of noise experience would seem out of place and alienating to many fellow scientists, and will not be suggested here. Rather I would like to stress the fact that noise as a topic belongs well inside the fold of Environmental Psychology, even if this field just like the public discourse has tended to neglect this important topic in favour of more "sexy" topics such as "landscape aesthetics" "place identity" and "pro-environmental behaviour". In the following an attempt will be made to study noise from an Environmental Psychological perspective.

Studies of how people experience noise are most often conducted as applied research. As such, the field is atheoretical in character; focus is most often on empirical rather than theoretical developments, a concern that has been raised a number of times (Cohen, Evans, Stokols, & Krantz, 1986; Lercher, 1996)

There is no single theory that fully applies to all topics covered in environmental psychology. Attempting to cover the broad range of theories, Gifford (2007) outlines seven different theoretical approaches: stimulation theories, control theories, behaviour setting theory decision making theories, integral theories, the operant approach and ecopsychology. Within these approaches a number of more specific theories can be found. It should be noted that even if these theories are described as approaches to environmental psychology, most of them do not belong exclusively to this field, but may originate from other fields of psychology or indeed other disciplines. Stimulation theories in general, and in particular *stress theory* which is covered below, have been quite influential for noise research

Earlier approaches to man-environment studies were rather deterministic: human behaviour could be attributed to *either* the environment *or* to the person. *Interactionalism* implies that persons and environments, even if they are separate entities, are continually involved in a series of interactions, both being mutually shaped by the encounter with the other. A point is made of distinguishing between interactionism and *transactionism*, where the latter takes the interactions one step further and claims persons and environments to be part of “one whole”. Although both approaches probably render a truthful description of man-environment relationships, the reality of normal research methods rarely allows for them to be followed in full (Gifford, 2007). Still, it is clear that the transactional element inherent in these two approaches, and indeed in environmental psychology as a whole, can be quite fruitful for gaining a further understanding of how noise is experienced.

An ecological perspective

Winkel et al. (2009) outline what they call an *ecological perspective* to environmental psychology, offering six fundamental principles that in turn lead to 11 useful guidelines for carrying out research in environmental psychology. The approach may not qualify as a theory in the classical sense, the outlining of the principles is somewhat lacking in analytical clarity, and the distinction between each of the principles is not clear. Still, in discussing a range of central research findings and topics the authors present some of the fundamental challenges for the field of environmental psychology. Of particular relevance to the current thesis is the attention given to how individual agents’ actions and experiences are embedded in a *context*, a context that can be described as *economic, physical* or *social*. Often these different contextual factors are conflated, i.e. due attention is not given to their distinct effects. Such simplifications might often make sense for the individual researcher, who is not interested in learning much about the context as such but in how a certain phenomenon, e.g. noise

experience, is influenced by the context. Indeed in applied research there is little room for developing such conceptual differences. However, in order to gain a deeper understanding of the mechanisms involved, attention should be given to the unique contributions of each factor. Following on from this, Winkel et al. (2009) see a need for careful modelling of the processes by which the physical environment operates on individual outcomes, and draw particular attention to the difference between *moderating* and *mediating* variables (Baron & Kenny, 1986). Such processes are often neglected, and little attention is given to this very important distinction.

Besides the sampling issues that apply to all social scientific research, there are some particular challenges that need to be addressed specifically within the field of environmental psychology. Not only do we need to make sure that the population sample is representative, but also that we attend to certain aspects of the *environmental variables*. For one thing, sufficient *range of variance* (Brunswick, 1956) should be sampled in order to produce differences in outcome. As an example, studies looking at the relationship between feelings of insecurity and choice of transport mode have had problems finding any such correlation (Backer-Grøndahl, Fyhri, Ulleberg, & Amundsen, 2009). One explanation given for this is the lack of exposure of the study population to sufficiently threatening environments, in what was a typically safe Northern European city (Fyhri, Hof, Simoniva, & de Jong, 2010). Studying the same phenomenon in Bogotá or Lagos might have produced different results.

Another commonly neglected issue with particular relevance for noise research is that of *exposure estimation*. Acousticians pay much attention to the physical properties of the actual estimation, i.e. the calculation procedures, the units of measurement etc. That is after all what acoustics is about. Some of the specifics related to noise exposure will be covered later. However, as is exemplified by Winkel et al. (2009), less attention has hitherto been paid to how exposure is influenced by the way in which people typically move around both between and within buildings, how they vary their mode of transport and how they vary in their general activity patterns. This is perhaps not surprising given that acousticians by far outnumber the environmental psychologists of the world, in particular those concerned with noise. Still, for people's actual experience of a certain noise, it is likely that the end result of the interaction between the temporal and spatial distribution of that noise and people's behavioural adaptations to it are just as important as the frequency spectrums, loudness assessments etc. that acousticians use to characterize noise.

Related to the topic of interactionism mentioned above, *self selection into environments* (Winkel, et al., 2009) is a basic property of ecological systems, and raises some

fundamental methodological challenges. To what extent is the outcome we are studying, e.g cardiovascular disease, a result of the particular environmental qualities (noise) that we are studying, and to what extent is it a function of differential residential selection among people with differing levels of socioeconomic status? Adding to this, people's tolerance or vulnerability related to the environment may also play a role in their environmental selection. Hence, individuals of high noise sensitivity might opt away from noise-exposed residential areas, thus deflating potential effects of noise on well-being and health.

Noise and its measurement

A quite common definition of noise is "unwanted sound". Such a definition attempts to turn a rather precise and objective concept from physics ("sound") into something subjective and psychological (goals, desires, needs etc). Intriguingly enough, the apparently objective concept of "sound" already contains a major psychological component: in order to describe the physical magnitude of a sound -- its *sound pressure level* (L_p) -- the objective measurements have to be transformed into a scale that is comparable with human perception, the *decibel* (dB) scale. The decibel scale is a logarithmic scale, accounting for the fact that the human ear can tackle an immense difference in sound pressure levels: the ratio between the energy of lowest detectable sound and a sound that will cause permanent damage is one to one trillion (1: 1000 0000 000 000).

In addition, sound measurement has also to account for that fact that the human ear is not equally sensitive to all frequencies: the A-weighting scale which is used for environmental noise measurement, gives stronger weight to sounds in the frequency range 2 to 4 kHz, which also happens to be the normal frequency range for the human voice. Road traffic noise varies considerably throughout the day and throughout the week as well. The sound energy level is therefore averaged over a given time period. The most common measure for studies of environmental noise has been 24 hour equivalent A-weighted sound pressure level. ($L_{p,A,eq,24}$). As noise exposure at evening and nighttime is more annoying than at daytime, the EU Directive on Environmental Noise (Directive 2002/49/EC) specifies the day-evening-night equivalent noise level (LDEN), which gives higher weight to noise emitted at evening and nighttime (European Commission, 2002). This measure is increasingly often used to predict community response to road traffic noise.

Effects of noise

The adverse effects of noise have been studied extensively, both in laboratories and in field studies. The terms *community noise* or *environmental noise* are used to denote the study of noise from industry, road traffic etc. These sources rarely reach levels that are harmful to hearing. Hence, in community noise studies it is the *non-auditory effects* that are the focus of interest. The most immediate and apparent effects of noise are interference with communication, disturbance of concentration and sleep/relaxation disturbance (Berglund, Lindvall, & Schwela, 1999). Behavioural effects, which can be considered to be our secondary responses to the primary effects of noise, may include closing of windows, not using balconies or outdoor areas and moving the bedroom to the least exposed façade of the dwelling (Berglund, et al., 1999).

Annoyance

“Annoyance” is by far the most studied subjective response to noise (Guski, Schuemer, & Felscher-Suhr, 1999). In the current thesis the Norwegian word “plage” has been used as the Norwegian equivalent to annoyance. The word “plaget” has the same Latin origin, *plaga* = blow or wound as the English term *plagued*. The definition of the term captures more of the suffering part, and less of the “being irritated” part than the English term “annoyed”. The fact that studies in different countries use a word in their own language which is assumed to translate directly into a common phrase such as annoyance has caused some concern among researchers (Klæboe & Fyhri, 1997); can we be sure we are measuring the same thing?

Guski et al. (1999) conducted a cross-cultural study aimed at clarifying the content of the notion of annoyance. According to this study the main components are the same in the studied countries, although there were some national differences. Factorisation of the concept of annoyance showed a three-factor solution. When someone says they are annoyed, they are expressing two things: (1) they are disturbed in an intended activity and (2) they evaluate the noise source in negative terms (displeasure, anger, irritation). The evaluative or emotional component also points to the way in which the subject copes with the situation (tension, helplessness) (Guski et al., 1999). However, it can be argued that the latter is a third, separate aspect of noise annoyance.

A study looking at Norwegian lay peoples’ conceptualisations of noise annoyance indicate this (Klæboe & Fyhri, 1997). According to this study there is a gender difference: males tend to react with more anger whereas females feel more powerless or frightened. However, the main finding was that even though *irritated* (“irritert”) correlates better with

each of the noise reaction indicators *frustrated* (“frustrert”), *stressed* (“stresset”) or *depressed* (“deprimert”) than it does with “plage”, all the concepts seem to be measuring different facets of one single factor.

These results show that annoyance is a multifaceted concept, and that it consists of a series of experiences or emotions that are interdependent and exist both in parallel and as sequences. Hence, it could be argued that questionnaire studies would benefit from using more than one item in order to tap negative reactions such as annoyance. However, for all practical considerations, and since we still are talking about one factor not several, the use of annoyance or “plage” such as is the case in this thesis captures quite well the many negative effects of noise. This is supported by several reviews showing clear and consistent relationships between noise exposure and annoyance (Fields, 1993; Miedema & Vos, 1998).

Noise sensitivity

Contrary to what some people might believe, noise sensitivity is *not* an effect of noise exposure. In other words, people living in noisy residential areas are not more sensitive than other people. Rather, sensitivity to noise is a strong predictor of noise annoyance, and moderates the effect of noise exposure on annoyance (Stansfeld, 1992). Noise sensitivity can be defined as a personality trait that makes certain individuals report more annoyance than their neighbours when exposed to a given noise level (Griffiths & Langdon, 1968). As such, it is the strongest predictor of noise annoyance, apart from the noise level itself (Miedema & Vos, 1998).

The role of noise sensitivity in a noise-health model is not fully understood, and is a rather unexplored avenue. Noise sensitivity has been associated with both subjective health complaints, medical conditions and behavioural risk factors for disease such as stress, smoking and hostility (Heinonen-Guzejev, et al., 2004).

Stansfeld (1992) argues that increased sensitivity to noise might be an indicator of increased vulnerability to minor psychiatric disorders, and also links sensitivity to *negative affectivity*, which is further covered later.

Noise and health

Ever since its foundation in 1948 the World Health Organization adopted a quite ambitious definition of *health*: "a state of complete physical, mental, and social well-being and not merely the absence of disease or infirmity". The negative effects of community noise

mentioned above would easily qualify as health problems following such a definition, as would almost any negative experience we encounter. Among researchers and practitioners there has been an increasing concern that community noise may have negative health impacts even following a stricter definition of health (Babisch, 2008). For many years there has been quite clear evidence from occupational studies that industrial noise has negative health outcomes (Welch, 1979), including cardiac morbidity (Capellini & Maroni, 1974) and hypertension (Stansfeld & Matheson, 2003). Could the same be the case for noise in the residential environment?

Several studies have identified increased levels of cardiac problems and hypertension in areas with high exposure to aircraft noise (Aydin & Kaltenbach, 2007; Jarup, et al., 2008). Studies have also found links between road traffic noise and cardiovascular problems (Bluhm, Berglind, Nordling, & Rosenlund, 2007; de Kluizenaar, Gansevoort, Miedema, & de Jong, 2007).

However, there is possibly / probably a publication bias and that studies looking at these issues do not take fully into account the high correlation between socioeconomic status levels and noise levels (Cohen, et al., 1986). A meta-analysis of 43 epidemiologic studies found only an effect of occupational noise and air traffic noise (military) on hypertension, and no effect from road traffic noise (van Kempen, et al., 2001).

The noise-stress-health model

Most studies looking at the potential negative health effects of noise suggest the same kind of physiological mechanism for the relationship between noise exposure and detrimental health effects: that noise induces a number of negative outcomes (sleep disturbance, disturbance of daily activities and rest, concentration problems) that results in the chronic activation of the sympathetic nervous and endocrine systems, and elevated levels of physiological risk factors (hypertension, blood lipid levels) that over time give rise to serious health disorders such as cardiovascular disease (Babisch, 2005).

However, an important element of the model as described by Babisch deviates from the psychological theories of stress from which it originates (Cohen, et al., 1986; Levine, Ursin, Brown, Koob, & Rivier, 1991): *annoyance* is described as a psychological side-effect, as an indicator of the negative impact of noise, and not as the causal agent for the negative health effects. According to these theories it is the individual's conscious and cognitive assessment of the stressor (e.g. noise) and its outcomes that is crucial for the stress response. In other words, the potential health effects of noise via stress would have to be mediated by

annoyance or some other measure of appraisal. At the core of this distinction lies a fundamental question concerning the mechanism for the causal pathway from noise to cardiovascular disease: is it physiological or psychological? Can we say that however strong or long-lasting the noise is, if it is not causing any annoyance it will not lead to any cardiovascular problems? A number of empirical community studies support this: annoyance, rather than actual noise levels, is the factor that has the closest association with cardiovascular diseases (Babisch, 2006). Still, this issue is not resolved. As will be discussed later, sleep studies indicate that there are physiological responses to noise about which the individual is not conscious; in other words there is a pathway that bypasses the suggested psychological route to poor health. That is why authors tend to suggest that both mechanisms are at play (Cohen, et al., 1986; van Kempen, et al., 2002).

Negative affectivity and subjective health complaints

Negative affectivity (NA) can be defined as "...a general dimension of subjective distress and unpleasurable engagement that subsumes a variety of aversive mood states, including anger, contempt, disgust, guilt, fear and nervousness..." (Watson, Clark, & Tellegen, 1988, p. 1063). Alongside the factor *positive affectivity*, NA represents two central and dominant affective state dimensions, both recognized as universal. The affective state of negative affectivity roughly corresponds to the personality trait of anxiety/neuroticism, whereas positive affectivity is reflected in the personality trait of extraversion (Watson & Pennebaker, 1989).

A common assumption, particularly in early models of health psychology, was that stress adversely affects physical health. A range of predictors were empirically linked to poor health outcomes, e.g. minor daily hassles (DeLongis, Coyne, Dakof, Folkman, & Lazarus, 1982) and Type A behaviour patterns (Matthews, 1982). Early research, based on the *Big Five* personality traits, (McCrae & Costa, 1987) started questioning these results. According to these findings, the personality trait *neuroticism* was highly correlated with subjective health complaints, but not with objective measures of poor health, among them coronary heart disease (Costa & McCrae, 1987). This suggests that many of the correlations previously found between stress and negative somatic health may be spurious in situations where both stress and health variables are measured using self reports, and that this spurious relationship may be attributed to neuroticism or its correlate negative affectivity. In a study aimed at testing this assumption Watson and Pennebaker (1989) found that NA was strongly correlated to both self report measures of stress and health, but it was not correlated to biological markers of somatic health, thus confirming the hypothesis.

Sleep disturbances

Sleep disturbances are regarded as one of the most serious effects of environmental noise and a main reason for noise complaints (Guski, 1977). Sleep is a fundamental need of human beings, as it is for all mammals and insects (at least those that have been studied). On the face of it, the reason for *why* we sleep might seem obvious: we sleep in order to avoid feeling sleepy. But sleepiness is just a symptom. The *real* reason why we sleep is actually something scientists are still grappling with, but studies of sleep deprivation have identified some of the functions that are dependent on good quality sleep, including memory functions, mood and cognitive performance (Dinges, et al., 1997).

Sleep deprivation has also been shown to have negative effects on some metabolic, hormonal, and immunological variables (Irwin, et al., 1996; Spiegel, Leproult, & Van Cauter, 1999) and it may have serious long-term health effects (Ferrara & De Gennaro, 2001). Noise-induced awakenings tend to habituate, i.e. people experience less awakenings over time. Autonomous, or physiological, responses on the other hand do not tend to habituate (Carter, 1996; Griefahn, Brode, Marks, & Basner, 2008; Öhrström, Björkman, & Rylander, 1990). Based on this, sleep disturbances have been proposed as an important mediator of the impact of noise on health (Carter, 1996; Griefahn, et al., 2008; Jarup, et al., 2008; Muzet, 2007). However, the potential impact of long-term exposure to nocturnal noise on cardiovascular endpoints has rarely been studied. In order to gain further insight into these processes we first need to have a better understanding of the mechanisms involved in nighttime noise exposure and its effect on sleep. As will be discussed later, the exploration of such mechanisms places quite strong demands on the analytical tools that are utilised.

Socioeconomic status and health

Socioeconomic status (SES) is seen as one of the most influential variables to explain differences in community health (Elstad, 2000; Taylor, Repetti, & Seeman, 1997). However, within noise research there is rarely any discussion about the relevance of SES for the impacts of noise, or about the possible mechanisms involved in producing differences in annoyance, even though most researchers would acknowledge that SES is potentially an important effect modifier between noise and poor health. Systematic SES differences between high noise and low noise areas have been documented for some time, especially in large scale community samples (Cohen, et al., 1986). There are data documenting relations between a number of environmental risk factors (among them noise exposure) and SES (Evans & Kantrowitz,

2002). Some studies on the relationship between aircraft noise and *school performance* have indicated that such relationships disappear when SES is controlled for (Haines, Stansfeld, Head, & Job, 2002).

The term socioeconomic status can be defined as “access to goods that defines an individuals place in the social stratification” (Østerud, Goldmann, & Pedersen, 1997). SES is most often operationalised as income, education or occupational status. More recent theories within health research will contend that people’s *lifestyles* and *behaviours* emerge as a consequence of the social positions they occupy, and that these behaviours and lifestyles (coping styles) again to a varying degree produce good health (Elstad, 2000). Such an explanation will to a greater degree than the structuralist/materialist explanation of *segregation*, highlight individual and social agency (Elstad, 2000).

In line with this, people of higher socioeconomic status also have more resources to enable them to take more effective action than can be accomplished by people in lower SES groups. Pulles et al. (1990) distinguish between three different coping styles for noise:

- Taking action
- Developing comforting cognitions
- Denial or avoidance (mentally) of stressful situation

Whitfield (2003) found the number of complaints about air traffic noise from residents in an affluent community was greater than that from residents in more deprived areas. This finding could be due to increased sensitivity among people of high status. It has been argued that people with high incomes have more expensive houses, and hence have a higher vested interest in the quality of their home environment. However, a more likely interpretation is that it is an expression of an increased ability to take action among high SES groups, as suggested by Pulles et al. (1990).

Thus, there are several processes by which income might influence noise annoyance. Income can influence noise annoyance through two pathways, either indirectly, by the mechanism of high income groups buying themselves free from noise exposure, or directly, by way of different types of coping or handling mechanisms for a given level of noise.

The local environment, what is it?

An issue that is often neglected in the study of people’s experience of their local environment is the definition of the scope or unit of study. The size of the object has to reflect in some sense what people themselves see as a meaningful unit or *Gestalt*.

In community studies we are interested in how noise impacts us in the *home environment* as opposed to other types of environments (the occupational environment in most cases). As such the term community is a bit misleading, as studies rarely involve the whole community or neighbourhood, but only focus on the dwelling. Noise exposures are in almost every case calculated for the most exposed facade of the building, and questions are posed about the experience “at home”. Such delimitation makes sense, as the home is the place where we spend most time, and also the place where important restorative activities and sleeping take place. Also, using the home as a study unit serves definitional purposes. It simplifies the task of noise calculations and provides a concrete frame of reference for the questionnaire. A large scale study involving a range of different places for each respondent would not be feasible practically.

So the home environment can be said to be distinguished from other environments by *time spent* and *activities*. However, assumptions about these variables are rarely discussed and are often taken for granted. In a classic study from 1944 it was discovered that people walking in a park spent nearly all the time gazing between 0.3 and 1 meter ahead of them (Brunswick, 1944). However, people’s recollection of such a trip would normally involve people they have met, and in some cases striking environmental features that they have passed. Hence, it is clear that the time spent on perceiving an object is not necessarily equal to the impact the object has on you. For noise perception this is to a certain degree accounted for by the use of different measures of noise, for instance giving more weight to nighttime noise (DENL) or by measures taking number of events into account. It can still be questioned whether such adjusted measures are fully capable of capturing all the significant noise impact situations.

It can also be discussed whether it is possible for people to confine their environmental experiences to a delimited study unit like the home in the way we would expect. It is likely that people’s perceptions of the home environment are to a certain degree “contaminated” by the experiences they encounter on daily trips to work, in the neighbourhood, and in other places in the city.

Causal modelling

At the core of the current thesis is the use of Structural Equation Models (SEM) to investigate the interrelationships between variables. The use of such models is more than just a practical choice of analytical tools for investigating the data. SEM models are also particularly suited for dealing with causal relationships.

The issue of *causality* has a long history of fierce philosophical and scientific debate. It could in fact be said that the issue has been the most important topic for philosophical discussion (maybe just surpassed by “the existence of God”). One of the most significant figures in this debate, the Scottish philosopher David Hume (1711-1776) advocated a stark form of empiricism that has had a strong influence on the debate to this day. According to Hume we cannot infer from the co-existence of two phenomena that one of them *causes* the other. This line of reasoning eventually led Karl Pearson to aim at formulating a new language for scientific endeavour wherein the word “causation” is completely eradicated, thus laying the foundation of modern statistics at the same time. Or as anyone will have been taught quite early on in a statistics class: “*Correlation does not imply causation*”. Following from this we now have a situation where most researchers shun the use of the word “cause”, or any of its derivations, in their scientific publications. It is considered to be something like a “relic of bygone age” according to Bertrand Russell (Russell, 1913).

In the last few decades, the almost obsessive fear of discussing causality among scientists has been challenged, most prominently by the computer scientist and statistician Judea Pearl. As Pearl describes in his book “Causality – models reasoning and interference” (Pearl, 2009), even in the field of physics researchers avoid using the word. As an example he uses Newton’s second law $F=ma$. This is popularly expressed as “force is caused by mass times acceleration”. Following algebraic rules (and laws of physics) this could also be expressed as $m=f/a$, but we would not go on to say that mass is caused by the ratio of force over acceleration. In other words, physicists might replace “cause” with “equation” when formulating laws of physics, but as Judea Pearl states they “...continue[d] to write equations in the office and talk cause and effect in the cafeteria” (Pearl, 2009, p. 408). This discrepancy illustrates the point made by Sloman (2005) about the central role causality plays for human reasoning. A fact recognized even by David Hume, who admitted that it is in our nature to make such causal attributions, unjustified as they might be.

This fear of expressing causation has also entered the world of SEM, which originally was developed with clear intentions about predicting causality. According to Pearl (2001) the founders, Wright (1921) and Haavelmo (1943), were explicit in their assumptions that it is a model’s *structure* (i.e. the qualitative assumptions that are based on prior knowledge about causal relations) that renders causality, not the statistical relationships between any of the variables included (the equations). Even if SEM is not a method for *testing* causal models, it is nonetheless a method for “testing a tiny fraction of the premises that make up a causal model” (Pearl, 2009, p 149)

By forcing the researcher to make more explicit assumptions about cause and effect, SEM helps to elucidate the quantitative expression of a given theoretical model, and in doing this it emphasises the importance of clarifying the implicit theoretical premises that are assumed in empirical research (Pearl, 2009). In other words the vivid and precise expression of the premises of a graphical model forces the researcher to be conscious and explicit about the causal relations between the variables under scrutiny.

Aims and objectives

The main aim of the current thesis is to achieve further understanding of the consequences for health and well-being of road transportation noise. To help achieve this it was seen as important to develop a model framework of the interrelationships between a range of variables all hypothesized to be either predictors of or predicted by noise annoyance. More specifically, the thesis aims to explore if and how road traffic noise might have negative health outcomes.

The objectives of the individual studies included in the thesis were:

- To establish general relationships between noise exposure levels and annoyance from road traffic in Norway
- To examine how noise characteristics of the neighbourhood area influence the experience of residential road traffic noise
- To examine how socioeconomic variables help explain exposure to and annoyance from road traffic noise
- To establish a model framework for the interrelationships between noise experience related variables
- To examine the role of sleeping problems in the noise-health relationship
- To investigate if increased noise exposure or annoyance leads to cardiovascular disease

Methods

This thesis is based on two sets of data, dataset 1 which was collected by the Institute of Transport Economics from 1987 to 2001, and dataset 2 which was collected by Norwegian Institute of Public Health in 2000.

Data set 1

Sample and study areas

Seventeen local environmental surveys were carried out by the Institute of Transport Economics between 1987 and 2001, comprising a total of 19000 respondents from the cities of Oslo and Drammen. The studies were conducted in 50 different subareas. The sampling units in each area were households drawn from telephone directories. The person who last had birthday and was above 15 years of age was asked to participate in the interview.

All of these studies followed the same questionnaire template, although with some variations between each study. The studies were intended for use in relation to large scale road system changes, and would normally function as before and after studies of these projects. The surveys were designed as epidemiological cross-sectional studies, providing a snapshot of the situation at time of investigation (Clench-Aas, Bartonova, Klæboe, & Kolbenstvedt, 2000). In addition to the survey data, exposure estimates for noise, air pollution or vibrations were calculated for about 8000 of the respondents. These exposure indicators are of higher quality than those traditionally used in community health surveys and also offer a good spread of values, making them particularly suitable for the analyses carried out in the current thesis. The data set from these surveys is used for papers I-IV.

The Oslo East studies

Oslo is the capital of Norway. The population of the municipality of Oslo is 600 000, but the metropolitan area of Oslo has a population of 1.4 million people, of whom 900 000 live in the contiguous conurbation. The four Oslo studies were undertaken in the autumns of 1987, 1994, 1996 and 2001. The first three of these surveys functioned as before and after studies of two separate tunnel projects alleviating a centrally located urban area in Oslo of through-traffic. In 1987 personal interviewing took place in eight sub-areas. In 1994 and 1996 telephone interviews were undertaken in 14 areas, including the original eight. The response rate was approximately 50% in the three surveys (resulting n=1028, 1140, 1097). The sub-areas were

selected systematically to reflect areas experiencing traffic increases, decreases and unaltered traffic situations, and not necessarily to obtain a representative sample of the inhabitants of the area. Within each sub-area probability sampling was used.

The Drammen studies

Drammen is a city of 63 000 inhabitants and is located some 40 kilometres southwest of Oslo. The city centre lies at the end of a valley, on both sides of the river Drammenselva, where the river meets the Drammen fjord. In Drammen the first socio-acoustic survey was undertaken in June 1998, obtaining answers from 1215 respondents. The purpose of the survey was to describe the environmental situation before a major rerouting of the traffic through the city. In addition to the purposive selection of sub-areas along major roads, a random sample was selected from the whole city area. To enhance the coverage of the areas most affected by the road construction package planned for Drammen, 376 additional interviews were obtained in June 1999. Non-response was higher in the Drammen studies (61%) than in the previous three Oslo studies (50%). This increase in non-response over the decade has also been observed in other surveys undertaken during the same period (Klæboe, Amundsen, & Fyhri, 2008).

Questionnaire

All of the surveys were introduced as a general community study of neighbourhood quality. In the initial questions the respondents were invited to freely comment on any aspect of environmental quality or environmental problems associated with their neighbourhood. They were then asked more specifically about environmental annoyances.

Noise annoyance

There were slight changes in how the noise annoyance questions were posed in the different surveys. In 1987 people's annoyance with road traffic noise was measured by first asking:

Can you hear noise from road traffic when right outside the house in the yard, on the lawn, on the balcony, etc? (Yes, No and Not applicable).

In the rest of the surveys the first question was shortened to

Can you hear noise from road traffic when you are right outside the apartment?

In 1987 noise indoors was measured as

Do you hear road traffic noise (when) in your dwelling?(Yes, No, Not applicable, and Do not know).

In the rest of the surveys respondents were asked:

Do you hear road traffic noise (when) inside your dwelling?

In all cases those who responded yes were then asked:

Is this noise highly, somewhat or not annoying?

Noise sensitivity

Noise sensitivity was measured by a single question using a 3-point scale: “Would you say you are highly, somewhat or not sensitive to noise”. The survey questions on noise sensitivity were not asked in the 1998 Drammen survey.

Subjective health questions

Subjective health complaints were measured using a battery of questions based on the SHC inventory (Eriksen et al., 1999). The original version of SHC consists of 29 questions concerning severity and duration of subjective somatic and psychological complaints. In these series of environmental studies health status was measured using simple yes/no responses to questions concerning the presence of 15 such complaints in the last six months. Further we recorded presence of five chronic conditions (no time limitation).

Noise exposure calculations

The 24 h equivalent noise levels at the dwellings most exposed side, LAeq,24h, were calculated using the Nordic prediction method (Nordic Council of Ministers, 1996). This method adds 3 dB due to reflection from the façade. In most cases the noise was calculated from one or two dominating streets. For dwellings in Ekebergåsen, a high-rise area affected by noise emissions from a larger number of streets, a terrain model had to be applied to obtain exposure values with the required precision. The calculated noise value is for each of the surveys within ± 4 dB of the true level, with the exception of a small number of observations in the Drammen study, which have errors of up to ± 7 dB. When the calculated noise exposure levels, LAeq,24h, were less than 50 dB, they were set to 50 dB. This was done to be on the conservative side. Because there might be possible contributions from numerous distant noise sources not taken into account by the calculation model, results calculated at below 50 dB would tend to underestimate the real noise exposure level.

The Nordic prediction method (NPM) was revised during the time period. Prior to pooling all data sets into one matrix, all calculations were thus converted to the 1987 version of NPM. To make it easier to compare the results with those produced internationally, the values have summarily been converted to A-weighted Lden values by detracting 1.4 dB from

the 1987 version LAeq,24h values. (The Lden-values are lower than the LAeq,24h-values in spite of the evening and nighttime weighting because of the deduction of 3 dB in order to arrive at free field values).

In the Oslo East area about 300 road segments were defined for the 2 km² study area. In addition to the information drawn from the public road administrations traffic database for the streets in Oslo, custom traffic counts were undertaken at several important road segments and crossroads in the study area. Their purpose was to improve the vehicular air pollution emission database and the road traffic noise emission data.

For each respondent, the outdoor noise was calculated outside of the most exposed facade. This location was determined from the survey questions about which streets different rooms of the dwelling faced. The choice between the possible resulting locations was determined after several tests of consistency.

Noise calculations in Drammen were obtained from the County Road Authority. As their original database focused on dwellings exposed to higher noise levels, a special effort was made to supplement their database with dwellings exposed to intermediate and lower noise levels. The data were quality assured by a noise calculation expert and adjusted to allow the data to be pooled together with the Oslo East studies. As a result of the quality assurance process noise calculations for 507 of the respondents were excluded.

Data set 2

The data set for paper V derives from a socio-acoustic survey carried out by the Norwegian Institute of Public Health (NIPH) during the autumn of 2000. The aim of the survey was partially to compare the impact of rail and road traffic noise on sleep disturbances, and partially to compare the predictive values of different noise exposure measures onto noise disturbance measures.

Sample

The study included inhabitants living in Oslo. Data on residential addresses were obtained from the Norwegian National Rail Administration in connection with their ongoing work on noise mapping. Selection of the study areas was based on traffic density maps and crude data on noise levels outside of the most exposed façade of the residential buildings. From the home addresses, an age- and gender-stratified sample of 5390 persons in Oslo was selected using the central Norwegian person registry (49% female and 51% male > 18 years). A self-administered questionnaire together with an introductory letter was mailed to the population

sample in October 2000. To avoid a possible bias in responses to the noise questions, the study was presented in the introductory letter as a general investigation of health and quality of life, with no specific focus on noise. In total, 3262 respondents (60.5 %) answered and returned the questionnaire.

Questionnaire

The questionnaire consisted of items concerning perceived sleep quality and sleep disturbances, sleep problems due to external noise, orientation of the bedroom (towards noise source or garden/backyard), and personal characteristics such as year of birth, gender, total income, education, duration of residence and noise sensitivity. The general sleep questions were adopted from the Basic Nordic Sleep Questionnaire (Partinen & Gislason, 1995). Additional details regarding these questionnaire items can be found in another article utilising the same data set (Aasvang, Moum, & Engdahl, 2008).

Annoyance questions

The annoyance questions differed from those in study 1. In compliance with recommendations of ISO (ISO/Tc43, 2003), no filtering questions were asked, and a five point categorical scale was used (extremely, very, moderately, slightly, not at all). The nighttime noise annoyance questions were introduced with the following instructions:

If you think about the last three months, when at home, how annoyed are you by noise at nighttime from the sources that are mentioned below.

A shorter time frame than what is commonly used was chosen to comply with the standardized time frame for the sleep quality and sleep disturbance questions.

Noise sensitivity

The last question of Weinstein's noise sensitivity scale (Weinstein, 1978) was used to assess noise sensitivity: "*I am sensitive to noise*". This statement was presented with a six-point scale of response options ranging from "disagree strongly" to "agree strongly".

Health items

Subjective health complaints were measured by using the SHC inventory (Eriksen et al., 1999). The original version of SHC consists of 29 questions concerning severity and duration of subjective somatic and psychological complaints. 27 of these items were used (two questions concerning sleeping problems were omitted, as more specific questions on sleeping

problems were asked elsewhere in the questionnaire). Severity was scored on a four-point scale, from 0 – no complaints to 3 – severe complaints. Information on duration was also collected, but was not used in the analysis, as tests indicated that this did not add to the information provided by severity.

In the end it was decided that only one SHC factor was to be included in the analysis. As pseudoneurological complaints previously has shown to have the highest correlation with sleeping problems (Pallesen, et al., 2005) this factor was selected for the final SEM model. The factor *pseudoneurological complaints* consists of the following items: *palpitation, heat flushes, dizziness, anxiety* and *depression*. In the original version of the questionnaire (Ihlebaek, Eriksen, & Ursin, 2002) this factor also consists of the items *sleep problems* and *tiredness*. In order to avoid circularity, these two items were left out of the current questionnaire.

The 25 item Hopkins Symptom Checklist (HSCL) was used to measure psychological distress (Derogatis, 1983). We used the Norwegian version of this well-established measuring instrument, which is aimed at tapping into anxiety and depression. The SCL-25 has proved to have satisfactory validity and reliability as a measure of psychological distress (Derogatis, Lipman, Rickels, Uhlenhuth, & Covi, 1974; Glass, Allan, Uhlenhuth, Kimball, & Borinstein, 1978). Four alternative responses are given to each question, ranging from ‘not at all’ to ‘much.’

Prevalence of cardiovascular problems was measured by three items: previous or existing diagnosis of myocardial infarction, previous or existing diagnosis of angina pectoris and previous or existing diagnosis of hypertension. These three variables are summarized as one dichotomous variable *Cardiovascular problems*.

Noise exposure calculations

As in study 1 the Nordic Prediction Method for road traffic noise (Nordic Council of Ministers, 1996) was used, this time for calculating nighttime equivalent noise levels ($L_{p,A,eq,night}$). Assessment of individual noise exposure was conducted using digital maps and geographical coordinates of the address of each respondent in the survey. The software program CadnaA (DataKustik, 2004) was employed for the noise exposure calculations. CadnaA applies digitalised terrain data, buildings and noise screens in three dimensions. Quantitative data for road traffic in the study areas (traffic counts, % heavy vehicles, speed, diurnal distribution), representative for the survey period, were obtained from the Norwegian Public Roads Administration and the City of Oslo. Additional on-site traffic counts were

conducted on some low trafficked roads for which no data on traffic volume were available. The effects of distance from receiver to the noise source, air absorption, ground properties, topography, and screens were included as major sound propagation parameters.

The nighttime equivalent noise levels were calculated by integrating the sound energy from all noise events over an 8-hour nighttime. The 8-hour nighttime period is defined here as lasting from 23.00 to 07.00. $L_{p,A,eq,night}$ was calculated outside each respondent's dwelling, at the bedroom façade. For each address, we used the information provided on the questionnaire about which side of the dwelling the bedroom faced, and the elevation (floor) of the bedroom. When the bedroom was reported to be oriented towards a major road, the calculation of the noise level representing the most exposed façade was used. In those cases in which the bedroom was reported to be oriented towards a garden or backyard, the calculation points represent the façade with the lowest noise exposure. The outdoor noise levels are given as free-field values.

Analysis with ordinal regression and Structural Equation Modelling (SEM)

Regression models are often used for studying relationships between noise exposure and noise annoyance. Normally, logistic or linear regression is utilised. In order to utilise as much as possible of the information collected by the questionnaire items, together with the information from the continuous traffic noise exposure variable, ordinal logit models were used in papers I and II, rather than normal binary logit models that are often used for such analyses. In ordinal models every degree of annoyance is accounted for, whereas in logistic models the annoyance variable has to be truncated into a binary variable in order to be analysed.

However, regression models (even ordinal ones) only take into account the direct impacts of noise exposure on health, and thus neglect the indirect effects. Structural Equation Models (SEM) are more powerful alternatives to multiple regression analysis, as the method deals with both latent variables (through statistical elimination of measurement error) and measured variables at the same time. Further, in SEM any exogenous variable can be regressed on, hence functioning both as independent and dependent variable in the same model. Thus, the analysis allows for better handling simultaneously of a chain of causal events or the interrelationships between a set of independent variables. The models can be used for both confirmatory (theory testing) and exploratory (theory development) purposes. These models are used in paper III to V.

There are a number of ways of assessing model fit for structural models. The first and simplest is to look at the probability level (p). Using the simple probability level as measure

of fit has been much debated, especially for models based upon large samples (Jöreskog, 1969), as is the case here. The goodness-of-fit index (GFI) and the adjusted root mean square error of approximation (RMSEA) are more appropriate in such instances. A simpler alternative, that is often used, is the chi-squared criterion (Hu, Bentler, & Hoyle, 1995). The χ^2 to degrees of freedom ratio has no exact interpretation, but it has been suggested that ratios of 2 and below (the lower the ratio, the better the fit) are indicative of an acceptable fit between the hypothetical model and the sample data (Byrne, 1989) .

Main results

Paper I

This study examined the relationships between the level of road traffic noise at the most exposed side of a dwelling's facade and the residents' reactions to road traffic noise. Estimates of the size of the exposure–response relationship were calculated. The data came from data set 1. Simple tabulations of the proportion of residents that experience different degrees of annoyance as a function of noise exposure indicated a relationship that followed sigmoidal curves, thus suggesting the use of logit models for further analysis. Simple tabulations also showed that people express less annoyance indoors than when right outside their apartment.

An indicator of window quality was constructed as a combined indicator of the quality of the bedroom and living room window, and introduced into the model as an independent variable along with other modifying factors. This indicator gave significant contributions to explaining noise annoyance.

Based on the parameter estimates for the noise exposure indicator (L_{den}) we learned that 50% of the respondents find road traffic noise highly annoying at 70 dB, 50% at least somewhat annoying at 58 dB and that 50% of the respondents report that they can hear noise at 46 dB (extrapolated) when right outside their dwelling. The estimated odds for reporting a higher degree of annoyance increases with 13% as the result of a 1 dB increase in the noise exposure indicator L_{den} . The equivalent odds figure for noise annoyance indoors is 13%, and the noise level at which 50% are highly annoyed is 76dB. Comparison of these results with those from a study aimed at summarizing international results (Miedema & Oudshoorn, 2001) indicates that Norwegians react more strongly to road traffic noise than people of other nationalities.

Paper II

Data set 1 was used for this study. In this paper we were interested in the impacts of having an adverse neighbourhood soundscape. In addition to the 24-h equivalent noise levels at the apartments most exposed side, we therefore used the highest equivalent noise level attained within a radius of 75 meters of the apartment, $L_{neigh,max}$, to indicate the noisiness of the neighbourhood soundscape of an apartment. A neighbourhood maximum difference indicator, $L_{diff,max}$, was constructed. This indicator is simply the number of decibels that the

neighbourhood soundscape noisiness indicator $L_{\text{neigh.max}}$ exceeds the noise exposure level at the most exposed facade of the dwelling. The largest variation in the relative neighbourhood soundscape noisiness values $L_{\text{diff.max}}$ is found among the apartments and dwellings exposed to lower noise exposure values.

Log-likelihood Ratio tests for the inclusion of the neighbourhood maximum difference indicator $L_{\text{diff.max}}$ was performed for indoor and outdoor noise annoyance. The result of these tests revealed that the neighbourhood maximum difference indicator provides considerable additional explanatory power to that of noise exposure at the most exposed facade. The estimated effective size of the neighbourhood maximum difference indicator for annoyance right outside the apartment (0.074) is about 40% that of the noise level at the most exposed facade (0.172). This implies that a resident with a noise level at the facade of 55 dB, and with a maximum noise level in the immediate neighbourhood of 62 dB, is just as annoyed (outside of their dwelling) as someone living in a dwelling with 60 dB at the facade (and no higher noise levels in vicinity).

Paper III

Data set 1 was used for this study. By the use of SEM two models outlining the relationship between noise exposure, socioeconomic status and noise experience were formulated. The first model contained data from the studies carried out on stratified samples in urban areas (five out of six studies). This analysis found no relationship between socioeconomic status and noise exposure. The second model used data from one of the studies conducted in the city of Drammen. This study was conducted as random sample of residents from the whole of the city. In this model a relationship between noise exposure and income was found. In none of the models were there any significant direct effects of socioeconomic status on annoyance. As data on noise sensitivity and education could not be obtained for the randomised sample, a test was made of the stratified sample to see if omission of these variables could influence the results. This test revealed that these omitted variables did not contribute to create any difference between the models

The study suggests that geographical scale (i.e. the size of the city) and accessibility to the city centre is of importance for how an environmental indicator like noise is distributed within a community sample.

Paper IV

The data set used in this study is a subset of data set 1. This subset consisted of 1842 respondents reporting on their subjective health complaints and their sensitivity to noise. The study explores the relationship between road traffic noise and health. More specifically the relationships between noise complaints, noise sensitivity and subjectively reported hypertension and heart problems were investigated.

By use of SEM we found that there were no direct relationships between noise exposure and any of the self-reported health indicators. The embedded model suggests that there are significant, but small relationships between increased noise annoyance on the one side and the variables sleeping problems, nervousness, tiredness, sore throat and headaches on the other. The model suggests that there are no relationships between high blood pressure or heart pain and noise annoyance/noise level. It suggests fairly strong relationships between noise sensitivity and all of the subjective health complaints.

The test of model complexity indicated that information on the neighbourhood soundscape and air pollution were important modifiers and that they served to explain an important part of the variability that was not captured by the simplified model.

Paper V

In paper V the relationship between noise-related sleeping problems, subjective health and cardiovascular health problems are examined. Data set 2 was utilised.

Questionnaire data from a subsample of the respondents (N=2786) were combined with nighttime noise levels calculated from outside each respondents dwelling, at the bedroom façade. The results of the SEM analysis showed significant relationships between noise annoyance at night and sleeping problems. However, the analysis showed that quite a number of respondents were annoyed without being interrupted in their sleep, and quite a number of respondents had sleeping problems without being annoyed by noise. The inclusion of information on subjective health problems gives a significant contribution to the model. Without these variables in the model, noise annoyance seemed to be a very strong predictor of sleeping problems. When information on pseudoneurological complaints was included, the *health problems* factor became the strongest predictor of sleeping problems, in place of noise annoyance.

When all variables are considered together, age, gender and pseudoneurological problems are the most important predictors of cardiovascular problems. No relationship was detected between either noise exposure or response to noise and cardiovascular problems.

Discussion

The results of the studies are discussed in detail in the five individual papers. In the following a broader discussion of these results is presented where the individual findings are considered in light of each other, and in light of a broader theoretical framework. Secondly, some methodological issues of particular relevance to the thesis as a whole is raised, and finally implications of these results for noise abatement measures and directions for future research are discussed.

Noise experience in Norway

Paper 1 serves an important methodological purpose within the context of this thesis. As mentioned in the introduction the Norwegian word “plage” has less to do with irritation than the English phrase “annoyance”. It could thus be speculated that the use of this phrase would influence the validity of the studies relative to English language counterparts. However, as was shown in paper 1, the amount of variance explained by the regression models is no less than that explained by models based on data from other countries, thus indicating that differences in validity is not a major issue for the subsequent studies using this data set.

The neighbourhood soundscape

In line with Winkel et al.’s (2009) call for a stronger focus on *exposure estimation* in environmental psychology, paper II attempts to refine the residential measure of noise exposure by including information on noise levels in the immediate neighbourhood. By doing so we cater for the fact that studying noise exposure and experience in the field is quite different from studying it in the laboratory. In a laboratory environment people are restricted to being exposed to the level of noise that the experimenter has defined. In real life, people move about, and quite importantly they bring with them impressions left in one physical setting to another setting. As we have found, respondents who are exposed to higher noise levels in the neighbourhood than “at home”, are more annoyed than those who have equal or lower noise levels in their neighbourhood. A fundamental assumption for environmental psychology, and for this thesis, is that people live in interaction with their environment: they accommodate. A typical way of accommodating would be to avoid using the noisiest parts of your neighbourhood. However, if people could accommodate fully we would not have found a neighbourhood effect. They would have levelled out the differences by adjusting their

behaviour. The fact that people are in fact influenced by noise levels in the immediate vicinity of their house, serves as a warning to anyone studying man-environment relationships: even if people have the ability to adjust their behaviour, such adjustments rarely counterbalance completely for an adverse environment.

Conceptually, the neighbourhood maximum difference indicator $L_{\text{diff,max}}$ is thought of as an improvement to existing noise exposure measures. However, it can be argued that the problem lies not with the exposure assessments but with our subjective measures of experience, i.e. with the annoyance measure. In data set 1 we asked people about their experience of noise, and specified the location as *in your dwelling* or *when you are right outside the apartment*. By doing this we hoped that people's responses would be related to their experiences in those two rather specific settings. This clearly turned out not to be the case. We find that people also think about the neighbourhood, or are at least influenced by it at a subconscious level. Theoretically, we could have asked people to consider their noise experience *when you are right outside the apartment, but not when you walk outside your gate or into the playfield behind your house or onto the rooftop veranda of your apartment block etc....* This would be a tedious enterprise both for interviewer and interviewee and within the context of a postal or telephone interview practically impossible. More importantly, we still could not be sure that people would be able to make such discriminate assessments.

In data set 2 we have used the ISO standardised and now internationally established *when at home*. It is quite obvious that this formulation is even more vulnerable to individual differences in interpretation concerning the extent of the physical setting in question than those used in data set 1. However, we have no calculations of neighbourhood noise levels for this data set, and were therefore not able to conduct the same analysis using these formulations.

Causal mechanisms

Papers III to V all make use of SEM models to study relationships between noise exposure and several outcome variables. Behind this work there lies a considerable "silent" effort in formulating the nature of the causal relationships between all these variables, in describing the causal chains so to speak. By doing so, we have significantly enhanced our understanding of how noise produces negative outcomes, and of how individuals cope with the presence of an adverse environment. Even if this is one of the main achievements of this thesis, and a lot of intellectual effort and time was used to deal with these issues, we have not been able to elaborate much on the topic of causality in the individual papers. There are few examples of

previous attempts at formulating causal paths in noise experience research (Job, 1996; Lercher, 1996). As an example, Stallen (1999) outlined a theoretical model for noise annoyance. This was however done on secondary data, and did not involve the use of SEM or other empirical analyses to support the model.

Stating that certain background variables, such as age and gender, are at the start of a causal model and that others, such as cardiovascular disease, are at the end is quite unproblematic. However, any attempt at causal descriptions is challenging, and is as mentioned often avoided even by researchers working with SEM. To illustrate this and to push the realm of noise research one step forward in terms of making causal mechanisms more explicit, two such casual chains are discussed further in the following.

Socioeconomic status and noise

In paper III we find that socioeconomic status does not influence noise experience, but that it might influence noise exposure in a small city or town. This latter finding could be discussed in light of Winkel et al.'s (2009) focus on selection of appropriate level of analysis in order to cater for the reciprocal relationship between the individual and the environment. In fact we could suggest that the direction of causality is totally dependent on our unit of analysis. If we use the individual resident as the unit, the most likely causal relationship is that your socioeconomic status influences the resources you have for selecting appropriate residential quality. This in turn will influence the amount of noise you are exposed to (figure 1). On the other hand if we use a certain geographical area, like a neighbourhood, as the study unit the causal direction is exactly the opposite: the noise level is one part of the sum of factors constituting residential quality and improving the residential quality in an area will eventually attract affluent people who will replace those who can no longer afford to stay there (figure 2). The latter phenomenon is described as gentrification in paper III, and is a typical feature of modern western cities.

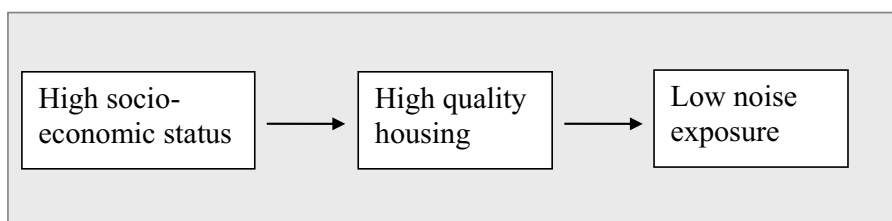


Figure 1: The relationship between socioeconomic status and noise at the individual level

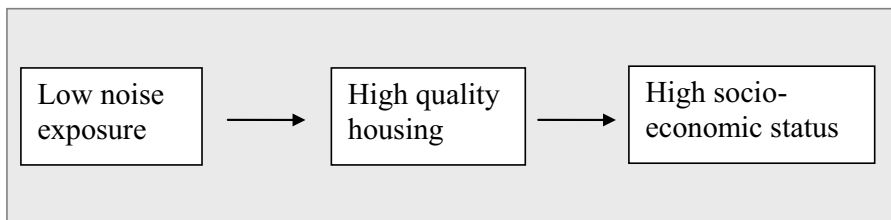


Figure 2: The relationship between socioeconomic status and noise at the neighbourhood level

Sleep and noise

In paper V a causal model is suggested in which noise exposure leads to “sleep disturbances from traffic noise”, which in turn leads to nighttime noise annoyance, which in turn influences the latent variable “sleeping problems”. In this model sleep disturbances related to traffic are seen as quite different from other, more general sleeping problems, and no direct causal path is suggested (empirically) between these. Rather, the causal path goes via nighttime annoyance to general sleeping problems. This fits well with the general understanding of annoyance in which disturbances are seen as one major component of annoyance (Guski, et al., 1999), and hence as being positioned earlier in the causal chain.

However, it could be argued that general sleeping problems lead to increased nighttime noise annoyance rather than the opposite. This would make sense, as one has to be awake in order to be able to experience the noise and subsequently be annoyed by it. It is more normal for people to be kept awake by other causes such as personal troubles, illnesses, crying children etc. than by traffic (Aasvang, et al., 2008). A typical scenario would thus be that you are woken by something, e.g worries about your work, and that while trying to fall asleep you hear occasional cars passing by, and feel annoyed. This might potentially be a more plausible causal mechanism than the proposed one, wherein noise disturbs people’s sleep and those that find this disturbance annoying are more prone to having general sleeping problems than others. It is hard to disentangle these causal directions, and the cross-sectional data, such as are available in the current analysis cannot provide a definite answer as to which solution is closest to reality.

Annoyance and sensitivity

In paper IV the causal relationship between sensitivity annoyance and health problems is discussed. In the analysis *all* of the subjective health complaints were correlated with noise sensitivity, i.e. not just those outcomes most likely associated with noise experience. Based on

this, it is suggested that another variable, termed *vulnerability*, leads to increased sensitivity and to increased health problems. It is speculated that the existence of such a variable could explain the relationship between noise and ill-health, that this relationship is in fact spurious and can be explained by certain individuals' disposition to be more vulnerable to any hazard they encounter, be it physical or psychological. In paper V the main aim was to look at the role of sleep in a noise – health relationship. Hence, even if sensitivity was included along with subjective health measures, some of the less relevant health measures were excluded in order to avoid a too complex model. Thus it was not possible to test the hypothesis put forward in paper IV with this analysis. However, as suggested in the article, some pilot tests were carried out with the use of all SHC variables. According to these pilot tests sensitivity is associated with the omitted SHC variables, albeit to a lesser extent than in paper IV.

In most studies where noise sensitivity is included it comes out as a strong predictor of noise annoyance (Miedema & Vos, 2003; Stansfeld, 1992; van Kamp, Job, Stansfeld, Hatfield, & Haines, 2002). In all of the papers in the current thesis, information on noise sensitivity is included. In papers I-IV, sensitivity has strong correlation with annoyance. In paper V sensitivity was a significant predictor, but the relationship was not very strong. This difference in results cannot be attributed to variables such as sleeping problems and health complaints “taking over” for sensitivity, since these variables are also present in the model in paper IV.

The major difference between papers IV and V in this respect is that in paper V annoyance is measured as annoyance from road traffic noise *during nighttime*, whereas in paper IV it was measured as annoyance at any time of day.

If the nighttime annoyance question is replaced by a more general road traffic annoyance question, the relationship with noise sensitivity increases to 0.16, which is more in line with previous results. In other words, as road traffic noise at nighttime is generally seen as more annoying than at day time, the “distinguishing power” of sensitivity is reduced in the nighttime situation. This finding points to an interesting feature of noise sensitivity: in situations where “everyone” is annoyed, sensitivity plays a smaller role than in situations with low exposure. Instinctive as it may seem, this phenomenon has been suggested in a few previous studies on aircraft noise (Aasvang & Engdahl, 2004; Tarnopolsky, Barker, Wiggins, & McLean, 1978) but is not known from previous literature on road traffic noise, and has not been related to nighttime noise exposure.

Annoyance without disturbance?

In the SEM model in paper V we have placed nighttime annoyance after sleep disturbances due to traffic in the causal chain. This corresponds well with the typical understanding of the concept of annoyance, that it is strongly related to *disturbance*. According to Guski et al. (1999) annoyance also includes an affective component, an emotional reaction to the aversive sound stimulus. In other words, *the sound itself* may to a certain degree be considered to be displeasing to the listener, regardless of activity disturbances. It seems quite likely that the latter component of annoyance is less relevant for studies of noise in the natural environment, such as road traffic noise in residential areas which is the topic of the current thesis. The sounds from road traffic, though they may vary in character and loudness, rarely reach levels that are actually *unpleasant* for people. Although this distinction is rarely discussed, it is implicitly expressed in the definition of noise annoyance by the European Commission Noise Team: “*Annoyance is the scientific expression for the non-specific disturbance by noise, as reported in field surveys” (European Commission, 2000)*

In community noise studies the focus thus tends to be on the disturbing properties of noise. But what is disturbed? Typically, we think of concrete external activities, or rather *behavioural goals* (Cohen, et al., 1986) such as reading, watching TV, sleeping, having a conversation etc. However, it is clear that also more “internal” activities like thinking or contemplating can be interfered with.

An underlying theme in this discussion is the level of consciousness associated with the noise experience. Can the noise be annoying without entering our awareness? And may it be harmful without entering our consciousness? The mechanisms proposed in the literature (Babisch, 2005) and the empirical model we have followed here assumes a conscious processing of the noise stimulus. However, we can not rule out that noise has harmful effects that go unnoticed by the observer (the respondent), via e.g. continuous low level stress activation or subconscious affective states. Experimental sleep studies on humans (Di Nisi, Muzet, Ehrhart, & Libert, 1990) and on animals (Flynn, Dengerink, & Wright, 1988) have suggested that noise need not be consciously processed in order to create cardiovascular responses.

Sensitivity –an additive or multiplicative variable?

Van Kamp et al. (2002) and Miedema and Vos (2003) discuss the role sensitivity plays in a causal relationship and finds that the effect size of noise exposure on annoyance does not depend on the degree of sensitivity, in other words an increase of 1 dB means the same for a

sensitive and non-sensitive person and it is only the level of annoyance that is different. Based on this they conclude that the effect of sensitivity on annoyance is additive, not multiplicative. Other studies (Babisch, 2010) have found indications of a multiplicative effect of sensitivity on *cardiovascular disease*. According to our data there was no interaction effect between sensitivity and annoyance, but in paper V we find that the impact of noise sensitivity was far smaller during nighttime than found for daytime annoyance in paper IV. We conclude that this implies that noise sensitivity does not mean the same regardless of noise situation. This finding is important for several reasons. First of all, it functions as a sort of delimitation of the “truism” concerning the prevalent role of sensitivity as the major subjective factor to explain noise annoyance: in situations where “everyone” is annoyed, introducing noise sensitivity into an explanatory model is of limited value. This limitation is quite obvious when we speak about differences in *noise levels*: anyone would be annoyed (not to say frightened!) if a jet plane passed 100 meters above their head, whether they were sensitive or not. As we have suggested, the limitation also applies to different situations in which the noise is experienced, i.e. to the *context* within which the noise is experienced.

Secondly, the result might help explain why some researchers suggest a multiplicative effect of noise sensitivity. The situation which we are focusing on in our study seems to alter the relative contribution of noise sensitivity. Thus, it might be that studies suggesting a multiplicative effect in reality have looked at sensitivity in different *contexts* rather than at different *noise levels*.

Sensitivity, general vulnerability and health

The results of paper IV have received some attention since publication. In the paper a hypothesis is put forward: that noise sensitivity is an indicator of a “general vulnerability” and that this vulnerability is the causal agent for increased health problems and for increased noise annoyance (via sensitivity). Hence it is proposed that there is no causal link, only a spurious relationship, between increased noise annoyance and health problems. One paper at the InterNoise conference 2010 addresses the issue directly by reanalysing previous data on noise and cardiovascular disease, and in so doing *refutes* the proposed hypothesis (Babisch, 2010). According to this study, the proposed link between noise sensitivity and health can only be found in *retrospective* studies (studies where the health outcome is measured prior to or alongside with the noise related questions). In *prospective* studies, where the health outcome is measured after the noise related questions, the relationship between sensitivity and poor health is either slightly negative or non-existent. Further the results indicate an *interaction*

effect in the retrospective studies, i.e. that the risk of cardiovascular disease due to noise exposure increases with increasing levels of noise sensitivity. Based on this it is suggested that sensitivity and self-reported health problems are closely associated because noise sensitivity is an expression of *negative affectivity*.

One objection to Babisch's (2010) logical reasoning from the proposed hypothesis to its rejection is that it is arguable since negative affectivity should not have any influence on noise exposure levels. This objection does in fact point to an important limitation with the proposed hypothesis. The hypothesis put forward in paper IV functions to explain a potential link between *annoyance* and poor health. As there is no reason to assume that sensitivity is correlated with exposure (a fact that has been proven a number of times), it would not function to explain a potentially proven link between noise *exposure* and poor health.

The proposed link between sensitivity and negative affectivity warrants a comment. In earlier studies looking at sensitivity and psychiatric disorders (Stansfeld, 1992; Öhrström & Björkman, 1988) such a relationship is shown. Later studies have found no link between sensitivity and negative affectivity (Miedema & Vos, 2003). A recent study (Schreckenber, Meis, Kahl, Peschel, & Eikmann, 2010) finds that even if noise sensitivity to a certain degree explains other environmental nuisances it is mostly source specific, and hence is not an expression of negative affectivity. In this study sensitivity was not correlated with mental health, as has previously been found, but with physical health. It should here be noted that none of these studies have actually measured negative affectivity directly, by the use of acknowledged psychometric measures of negative affectivity such as PANAS (Watson, et al., 1988). One study, cited by Smith (Smith, 2003) reportedly used such a measure, and found that the link between noise sensitivity and poor health disappeared when control was made for negative affectivity.

In sum these findings points to some stable disposition (sensitivity, negative affectivity, "vulnerability", neuroticism) that predicts noise annoyance. These dispositions vary in their degree of specificity, from noise sensitivity, which is fairly source directed, to neuroticism, which is a rather general trait. Further, these dispositions have proven links with negative health outcomes, both psychological and physical. The interrelationship between these variables is still unresolved, and further research is needed in order to disentangle the unique contribution of each variable on negative health outcomes in general and on cardiovascular diseases in particular. In particular prospective studies combining measures of objective health with carefully selected measures of psychological constructs such as neuroticism or negative affectivity are called for.

It should be noted that the suggestion that affectivity explains health problems does not change the fact that there is no (bivariate) association between noise exposure and cardiovascular disease or between annoyance and cardiovascular disease according to our data. The concept of negative affectivity is often used as a warning against *inflated* causal relationships with health outcomes, not against *deflated* relationships, as could have been the case here.

Noise and its health effects

In papers IV and V we find no effect of noise or noise annoyance from road traffic on occurrence of cardiovascular disease. This is in line with several previous studies, including one using meta-analysis (van Kempen, et al., 2002). Some studies of aircraft noise have indicated significant effects (Huss, Spoerri, Egger, Roosli, & Swiss Natl Cohort Study, 2010). Selander et al. (2009) found an association between level of the stress hormone cortisol and level of aircraft noise, but not road traffic noise.

As researchers we are obliged to ask ourselves why such differences in results occur. Theoretically, increasing levels of noise should lead to increasing levels of stress, and subsequently increasing amounts of health problems, herein cardiovascular disease. The biological plausibility of all the mechanisms involved in such an explanation have been proven through numbers of lab studies (Ising, Dienel, Gunther, & Markert, 1980; Miki, Kawamorita, Araga, Musha, & Sudo, 1998; Peterson, Augenstein, Tanis, & Augenstein, 1981), and has been suggested in several field studies (Babisch, et al., 1990; Knipschild & Salle, 1979; Lercher & Kofler, 1996). How can it then be that road traffic noise exposure does not lead to cardiovascular disease in the community?

It may be suggested that the relationship is in fact source specific, but then the question arises to “Why?” Why should it be that aircraft noise leads to increased risk of cardiovascular disease but road traffic does not? Intermittent noises from transportation are more disturbing than continuous noises at the same levels, and also produce more sleep disturbances (Carter, 1996; Öhrström & Rylander, 1982). Thus it could be that aircraft noise, which is of a more intermittent nature than road traffic noise, could be more detrimental to physical health, and studies of *general annoyance* have found that aircraft noise is considered to be more annoying at a given level than road traffic noise (Miedema & Vos, 1998). Aircraft noise also produces more self-reported sleep disturbances at a given noise level than road traffic does (Miedema & Vos, 2003).

Bodin (2009) argues that the reason for diverging results is that studies are normally conducted in normal urban environments where average noise levels are typically too weak to produce an effect on health. Such an explanation would be in line with Winkel et al's (2009) emphasis on the importance of achieving sufficient range of variance. Thus, it might be that the demands on the data are stronger in terms of noise levels for road traffic epidemiological studies than for air traffic studies. We have to ask ourselves if the exposure levels encountered in the current data are too low to produce the hypothetical stress reactions involved in a noise stress health model. In both data set 1 and data set 2 respondents with more than 70 dBA equivalent noise levels are well represented, and are most probably over-represented compared with the normal population, due to stratified sampling. In data set 1, 35% percent of respondents were exposed to noise levels at 65 dB LA,eq,24h or above, which according to some studies is the level where noise has an effect on cardiovascular disease (WHO, 2009).

One important premise of the noise-stress-health model is that it is the recurring events of stress reactions that eventually will be manifest as increased risk of cardiovascular disease. Short-term exposure of typical community noise levels should not lead to increased health risk. Another question we should ask is therefore whether the detrimental effects of noise on health are diluted by too many respondents who have only had short-term exposure? According to one study (Babisch, Beule, Schust, Kersten, & Ising, 2005) the increased risk of cardiovascular disease only occurred after 10 years of residence. In the current data 69 percent of the residents had lived at the address for more than 5 years (paper V).

In the data analysis of both papers IV and V, length of residence was tested as an independent variable in the models, and separate models were also tested on subgroups of the population who had lived at the address for more than five years. These results were not reported, as they yielded no significant effects. However, the subgroups became quite small following such a partitioning of the data set. We can thus not rule out the possibility that purposive sampling of long time residents with high exposure levels would have provided different results.

Methodological considerations

Sampling and validity

The data sets used in the current thesis are cross-sectional. In most cases we have used stratified (purposive) sampling in order to achieve a sufficient range of variance in noise exposure levels. In one study we used random sampling. These two choices of sampling

techniques have different implications for the validity of the study. By using stratified sampling we increase the proportion of highly exposed in the sample and hereby improve the *conclusion validity* of the study, i.e. we are better equipped to make statistically valid conclusions about the relationships between noise exposure and certain outcome variables. As mentioned, it has been argued that the noise levels encountered in normal urban residential areas might be too low to produce the proposed negative health effects (Bodin, et al., 2009). Randomized sampling would therefore require very large samples in order to achieve significant effects.

There are however several problems with using stratified sampling. The first is that *external validity* is reduced, i.e. we can not generalize the results to a broader population. This is not a major challenge, as it is only the *levels* (of exposure or annoyance or health problems) that are not representative of the general population.

However, stratified sampling may also place some constraints on the *internal validity* of the study, i.e. our ability to make conclusions about *causal* relationships between variables. In paper III we found no relationship between socioeconomic status and noise exposure in the stratified samples from Oslo and Drammen. We did find such an effect in the random sample of residents from Drammen. The explanation we have put forward is that geographical scale (i.e. the size of the city) and accessibility to the city centre is of importance for how an environmental indicator like noise is distributed within a community sample. In this case a confounding variable that has to do with the general attractiveness of a geographical area might interact in rather complex ways with our measured variables, noise and socioeconomic status. If this is the case the only way to avoid a compromised internal validity is by the use of randomized sampling.

The conclusion to be drawn from this is that the choice of sampling procedure is not just a matter of generalisability or not, but also a choice that should be made with close regard to the proposed mechanisms involved in the topic of study.

Noise sensitivity

Noise sensitivity plays a central role in this thesis, both because it is normally assumed to be a major predictor of noise annoyance and because of its close conceptual association with subjective health and psychological distress. In all of the surveys sensitivity was measured by a single question, scored on either 3 categories (papers I to IV) or a 6-point scale (paper V).

In paper V we argue that the reason for the rather weak predictive power of noise sensitivity is because annoyance was measured as annoyance from road traffic noise *during*

nighttime, as opposed to paper IV where it was measured as annoyance at any time of day. As road traffic noise at nighttime is generally seen as more annoying than at day time, the “distinguishing power” of sensitivity is reduced in the nighttime situation.

It could be speculated that the another reason for the difference in the role played by noise sensitivity in studies I-IV vs. study V is the slightly altered wording for this question between the different surveys: the Oslo/Drammen studies use the phrase “ømfintlig” (touchy, sensitive) and a three-point scale, whereas the Norwegian Institute of Public Health (NIPH) survey use the phrase “følsom” (delicate, tender, sensitive) and a six-point scale. However, even though these two words cover slightly different nuances of sensitivity, it is not likely that they are interpreted very differently when seen in the context of noise experience. The use of a six-point vs. a three-point scale could potentially introduce a difference, as the former is a more accurate and sensitive measure. The most likely result of this would have been a difference in explanatory power, rather than a difference in parameter estimates as is the case here, and with the poorer correlation, in the NIPH study, having most power.

Annoyance questions

In papers I to IV filter questions are used. The respondents are asked to state whether they “can hear road traffic noise indoors”. Those who answer yes are then asked about their degree of annoyance. By splitting a question into two distinct parts filter questions may reduce the cognitive load of answering. In situations where many respondents are not affected, they also may help reducing the time spent responding. However, concerns have been raised concerning the use of such filter questions in conjunction with the perception of sound/noise. The question may be seen as double-barrelled in that it asks about the audibility of a sound while also requiring that it be assessed as unwanted—that is: as noise. The ISO technical specification (ISO/Tc43, 2003) does not therefore recommend the use of filter questions. The questions used in paper V follows the ISO recommendations in that no filtering questions were asked. It could be argued that the use of filter questions in paper IV also could be the reason for the different role (see above) of noise sensitivity in the two models: if annoyance is measured with a poorer measure in paper IV than in paper V, sensitivity might have “taken on” some of the predictive power that ideally should have been attributed to annoyance. However, as we conclude in paper I when the response characteristics of the two filter questions are combined (“do not hear noise” is coded as the lowest annoyance category along with “not annoyed”) they behave quite comparably with the ISO-recommended

question, a finding that is supported by another study, looking at annoyance from vibrations (Klæboe, Öhrström, Turunen-Rise, Bendtsen, & Nykänen, 2003).

Measures of socioeconomic status

In papers III to V socioeconomic status (SES) is included as a modifying variable. In paper III SES is operationalised as income, education and employment status. As we were interested in examining the influence of each of these variables individually and in particular in focusing on the effect of income, we did not attempt to make a composite SES variable. In papers IV and V, SES is operationalised as education. The reason for using only one variable in the latter papers was the need for keeping the models simple. Education was selected partly because the “best” model in paper III indicated that this was the only of the two variables that had any significant influence on any of the outcome variables (noise sensitivity). Another study utilising the same data set as that in paper V (Aasvang, et al., 2008) found effects neither for education nor income on noise induced sleep disturbances.

A further justification for the choice of education rather than income was that previous research comparing the two (Winkleby, Jatulis, Frank, & Fortmann, 1992) have indicated that education is a better predictor of cardiovascular disease than income. A longitudinal study from the USA concluded that education had the closest link with the *onset* of poor health, whereas income was more predictive of the *progression* of health problems (Herd, Goesling, & House, 2007). According to the authors higher education gave better access to psychosocial resources such as self-efficacy and social support, and higher incomes had more to do with having the material resources available for expensive health care such as the costly medicine involved in chronic diseases. Norway has a system of free health care, a system that is particularly geared towards avoiding such effects of differences in economic resources. It could thus be argued that the choice of education above income is further justified. Still, some studies show that socioeconomic differences in Norway have increased over time (Rognerud & Zahl, 2006). Data from Sweden and Germany were inconclusive on the magnitude of effect from education and income on MI, and concluded that income influences some specific health outcomes more than education and vice versa (Geyer, Hemstrom, Peter, & Vagero, 2006). In the two data sets utilised in papers III to V we see that the correlation between education and income is significant, but is not so large that they can be treated interchangeably, a finding supported by several studies (Geyer & Peter, 2000) (Herd, et al., 2007).

There is no clear evidence of whether education or income would have been the better predictor for the SEM models. Most of the evidence leans towards education. However, the

models are complex and the two variables might potentially have had a differential effect on different parts of the model structure. Theoretically, the best solution would have been to use both variables. In practice, the inclusion of the variable income in addition to education would most likely not have had much effect on the main results of the two papers.

Measures of health

Self-report data are used in papers IV and V to assess the occurrence of cardiovascular diseases (myocardial infarction, hypertension and angina pectoris). As is discussed in paper V, previous research and the rather similar prevalence of cardiovascular diseases with national data indicates that the use of self-report measures should not have a strong influence on the main conclusions concerning the link between noise exposure and cardiovascular disease. Based on the discussion about the relationship between negative affectivity and noise sensitivity (see above) it could be argued that the proposed link between noise sensitivity and cardiovascular disease is affected, in the sense that there is an over-reporting of cardiovascular problems among those of high noise sensitivity. In paper V there is no direct observed correlation between sensitivity and cardiovascular problems. There is a weak link (unstandardised parameter estimate 0.05) between cardiovascular problems and Subjective Health Complaints which is in turn linked to noise sensitivity via the “psychological distress” (HSCL) variable. These links are not strong enough to produce any significant indirect effect from sensitivity to cardiovascular disease, and there is no bivariate relationship between these two variables.

The measures of subjective health complaints that were utilised in papers IV and V have previously been shown to be associated with the trait anxiety (Ihlebaek, et al., 2002), as has noise sensitivity (Stansfeld, 1992). Nivison and Endresen (1993) found an association between noise sensitivity and scores on the SHC checklist. It could therefore be argued that a measure of neuroticism should have been included in order to account for the potential confounding effect of this personality trait. However, in paper V, the Hopkins Symptom Checklist was included as a measure of psychological distress, and thus a considerable amount of what could be termed “psychological vulnerability” is accounted for.

SEM analyses

In papers III to V data are analysed by the use of SEM models. SEM analysis offers flexibility and the ability to analyze complex relationships between continuous and discrete variables, both measured and latent. However, the SEM procedure places some demands on data. First,

in principle SEM assumes multivariate normality. As discussed in the papers this assumption is violated by the models obtained. This is not unusual for this type of data. The issue of non-normality can be handled in various ways. One common method is transformations. For all models attempts at transformations were made, but did not lead to satisfactory results as normal distribution was not achieved. Since some variables, such as cardiovascular disease, are not expected to be normally distributed, and since normal distribution often cannot be achieved even after transformations, there are estimation techniques that can deal with non-normal distribution. Several tests have been made of the performance of these techniques (Bentler & Yuan, 1999; Hu, et al., 1995), and the Maximum Likelihood (ML) estimator that was utilised in papers III to V is shown to function quite well with sample sizes above 2500 (Hu, Bentler, & Kano, 1992). In papers III and V the sample sizes were above this threshold, whereas in paper IV it was somewhat lower (1842). Ideally, this model should have been subject to procedures that can better handle non-normal distribution with such a sample size, e.g. Bayesian estimation or bootstrapping. In paper V bootstrapping was utilised together with a logistic regression of the variables included in the model to test the robustness of the results. Such a procedure could have been utilised in paper IV to confirm the results achieved in the model. However, the same data set is analysed both by use of SEM (paper III) and regression analysis (papers I and II), providing quite similar effect sizes for all important variables. This may function as a validation of the results and an indication that the relationships obtained are robust. Such a test would therefore most probably have led to similar results as those presented in paper V.

Another limitation with SEM is that the procedure assumes linear relationships. Previous research (Miedema & Vos, 1999) suggests a non-linear relationship between age and noise annoyance, which is confirmed in paper I where the youngest and the oldest are the least annoyed. In paper III, dummy variables were used to test if the curvilinear nature of the relationship could influence the results of the model, but no difference in results was found.

One of the main findings in this thesis is that there is no relationship between noise (either exposure or annoyance) and cardiovascular disease. In the previous sections the argument has been that even if the assumptions of SEM are not completely followed the analysis and the results are valid, an argument that is supported by the fact that all papers have passed thorough review processes in high-ranking journals. It is quite unlikely that different analysis techniques would have provided different results. In other words, the data simply does not contain any relationship between noise and cardiovascular disease, as is shown by the simple bivariate analysis. We have also argued that the data quality *in sum* is of a higher

standard than what is normally found in other relevant publications. Still, we cannot rule out that larger data samples or other analysis techniques could have produced a relationship between noise and cardiovascular disease. In other words a type II error might have occurred. As scientists we are normally more concerned about avoiding type I errors (claiming a non-existent relationship) than type II errors, but as will be discussed later type I errors can also be the source of major concern in certain cases.

Implications of findings and future research

When it comes to potential negative health consequences of road traffic noise the results of these papers present us with an ethical dilemma. As mentioned there is a certain risk that we make a type II error when it comes to the negative health consequences of road traffic noise. Some researchers (Berglund, et al., 1999) have claimed that *the precautionary principle* could be applied to this situation. In other words: since the potential harm (cardiovascular problems) from this activity (road traffic) is so severe and the scientific knowledge is still uncertain it is better to assume that there is a relationship than that there is not. The use of the precautionary principle in this situation deserves some further discussion.

First of all, the principle is in itself more specific than just telling us to disregard the possibility for type II errors. Rather it states that if an action or policy has a suspected risk of causing harm to the public or to the environment, and in the absence of scientific consensus that the action or policy is harmful, the burden of proof that it is *not* harmful falls on those taking the action (Goldstein & Carruth, 2004; Grandjean, et al., 2004). Hence, it has more to do with *leaving responsibility* than with being cautious about scientific results. Thus, one apparent consequence of following this principle would be that transportation authorities around the world should allocate more funding for research into noise and health relationships, and that this research should be of a high enough academic standard to give scientifically rigorous evidence about causes and effects.

Secondly, the principle is normally applied to certain specific domains of policy, such as global warming, extinction of species and introduction of new products. The principle is applied either when something new is introduced or when consequences are grave. Neither description fits very well with the potential risk of cardiovascular disease from road traffic noise. The researchers of the world everyday identify potential risks of similar or greater magnitude to that of road traffic noise and cardiovascular diseases. If policy makers were to follow the precautionary principle for each and every such risk, they would have difficulty finding something that they actually could allow. In order for the precautionary principle to

fulfil its potential as a powerful tool for us scientists (Goldstein & Carruth, 2004), we should not fall into the temptation of misusing it.

Following from this, the possible fact that there is no relationship between noise exposure and cardiovascular disease leads to important discussion concerning the concepts health and well-being. According to the WHO *Annoyance* is in itself an adverse health effect (Berglund, Lindvall, & Lindvall, 1995). This is in line with the general definition of health according to WHO: "...a state of complete physical, mental and social well-being and not merely the absence of disease or infirmity". Although this definition has received some criticism, partly because of its lacking distinction between "health" and "happiness" (Saracci, 1997), it is still legitimate to state that the "community reaction" to noise may be regarded as a health effect (Job, 1996). The evidence for annoyance from road traffic noise is both strong and indisputable, as opposed to the evidence of a cardiovascular effect. Hence, it might be argued that using these subjective noise effects as leverage for noise policy development is a more fruitful approach. Focusing too much on "hard" medical outcomes such as cardiovascular problems might lead to a depreciation of the importance of "soft" outcomes, such as annoyance, mental health problems and disturbances (Lercher, 1996). The importance of good quality *restorative environments* to maintain health and well-being, particularly for vulnerable groups, has been mentioned as an important argument for policy initiatives towards noise even at sub-pathological levels (Pedersen & Waye, 2007).

It can be argued that only when we establish a proven relationship between increased noise and somatic health outcomes (cardiovascular diseases) can we hope that this important issue receives the public attention it deserves. As mentioned in the introduction noise is not among the top ranking road traffic issues published on the web. However, we cannot place all our eggs in the cardiovascular basket. The adverse effects of noise on well-being are plentiful and well proven. Even without having proven evidence of a somatic health effect, ambitious policies have in the last decades been adopted to reduce noise exposure. Admittedly, these policies have to a varying degree been effective, mostly due to ever increasing traffic volumes, both in the industrial world and in developing countries. Still, most governments and international governing bodies recognise noise as a major environmental challenge that should be dealt with, and call for the development of further noise abatement policies and noise reducing technology. Alongside the pursuit of further knowledge of potential health effects of noise, we should therefore strive to gain further understanding of the causal mechanisms, with particular focus on the psychological and behavioural effects of noise.

We can put forward the allegation that there is a tendency for those studies finding an effect of noise on cardiovascular diseases to have good quality health data but poorer quality noise data; and conversely studies that find no effect have good quality noise data, but more questionable health data. Future research should aim at combining large-scale community studies with good quality individual exposure assessments. The use of standardised instruments for assessing relevant psychological constructs such as noise sensitivity, subjective health and coping behaviour is warranted.

Previous research has found little evidence of a general habituation to noise exposure over time. In this current thesis, no relationship was found between noise annoyance and income, but some associations were found between income and noise levels, thus indicating some kind of self-selection into environments. It might be that the dynamics of the selection into and out of residential environments for different groups might influence results from cross-sectional studies looking at community noise experience. In this respect, research looking at the role noise plays in people's selection of residential environments would be very useful; are people living in noisy environments more concerned with assessing the noise situation when picking a new home?

Combining high quality exposure assessment and psychological instruments will take us some way towards definitive answers to questions regarding noise health relationships. Using longitudinal studies will be an essential asset in our pursuit of further knowledge on this issue. Doing so with empirical models that dutifully outline causal relationships based on solid theoretical assumptions will bring us, if not the whole way, pretty much closer to the top of the mountain. At any rate, from here the view of the valley below can be both breathtaking and salubrious.

Conclusion

In the present work general relationships between noise exposure levels and annoyance from road traffic in Norway has been established based on results from several socioeconomic studies. These curves indicate that even if the respondents react somewhat more strongly to a given noise level than do respondents surveyed in other European studies, the results fits well with previous results on noise-annoyance relationships. By examining how one environmental characteristic (the neighbourhood noise level) and one socioeconomic variable (income) contribute to explaining exposure to and annoyance from road traffic noise, we lay the foundation for more complex modelling of the relationship between noise exposure and its

detrimental effects. A person who experiences that the noise situation is better in the neighbourhood than at home is less likely to be annoyed at a given noise level than someone who experiences increased noise levels in the neighbourhood as they move about in their immediate neighbourhood area.

The SEM model that was developed in paper III helped to illustrate the dynamics of how noise annoyance is produced and socially distributed in a community. Income was only related to noise exposure in a medium-sized city. In a larger metropolitan area, other factors related to residential quality seem to override any potential relationship between income level and noise exposure. In line with previous results no relationship was found between noise annoyance and income.

The models were further elaborated in papers IV and V. These models were instrumental in establishing relationships between noise, sleep disturbances, subjective health complaints and cardiovascular disease. No relationship was found between noise exposure or annoyance and cardiovascular disease. The close ties between noise sensitivity and subjective health complaints were used as an argument for paying close attention to the role of general vulnerability in future studies of noise health relationships. Sleeping problems due to road traffic noise have been suggested as a major contributor to stress-related negative health outcomes. We show that road traffic noise is only a moderate contributor to overall sleeping problems, and that subjective health complaints are linked to both sleeping problems and noise experience. In line with core theoretical principles of environmental psychology the results of these papers in sum point to the importance of looking at the noise health relationship in a broader environmental and psychological context. A general conclusion that can be drawn from this work is that the use of SEM models have forced us as researchers to clarify and be explicit about the implicit theoretical causal assumptions underlying previous empirical research on noise and its effects on humans.

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The Impact of an Adverse Neighbourhood Soundscape on Road Traffic Noise Annoyance

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Summary

As a predictor of noise annoyance from road traffic, noise exposure is most often calculated at the most exposed side of the dwelling or apartment. This paper investigates whether an adverse neighbourhood soundscape – noisy areas along roads in the immediate neighbourhood of the dwelling – contributes to residential noise annoyance. The research hypothesis is that people react more strongly to noise when road traffic noise levels in the neighbourhood exceed the noise level at the most exposed façade of the dwelling. Such is the case for people living in apartments facing side streets and backyards or in second row dwellings that are shielded from a main road by intervening building structures. When these residents leave their dwellings to shop, walk, or wait for public transport, they usually encounter the high noise levels along the main street. Five socio-acoustical surveys featuring 3950 respondents were used to test the hypothesis. Results indicate that an adverse neighbourhood soundscape has a substantial impact on residential noise annoyance. Exposure–effect relationships ignoring neighbourhood soundscape information are misleading. In particular, annoyance reductions due to shielding apartments are likely to be overestimated, while the impacts of noise reduction at the source are likely to be underestimated.

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1. Introduction

European city areas have experienced an increase in the number of vehicles and increased traffic in the last 30–40 years. New connecting streets force their way through former residential areas, resulting in high traffic volumes quite close to the building façades. Before the new member states joined the EU it was estimated that about 80 million people were exposed to residential noise levels above 65 dB (black areas) while as many as 170 million were exposed to noise levels between 55 dB and 65 dB (grey areas) [1]. With the addition of the new member states, these numbers have increased. Most of the noise problems are associated with road traffic noise and occur in built-up regions in city areas. Many people in the urban “grey areas” exposed to intermediary road traffic noise levels live in second row dwellings, or along side streets bordering on the black areas along major streets. While these dwellings profit from being shielded from the main road, people living in them are exposed to high noise levels along the main roads in the immediate vicinity. Such high noise levels in the neighbourhood may be experienced as stressful and reduce an individual’s capacity for tolerating noise when at home. They may affect residents’ general attitudes to-

wards road traffic and road traffic noise and may diminish the sales value of their dwellings. It is therefore reasonable to investigate whether the noisiness of the neighbourhood soundscape also has an adverse impact on peoples’ reactions to noise at their dwelling.

Research on community annoyance is usually epidemiological, correlating exposures with responses. While we capture one aspect of the neighbourhood soundscape, its noisiness evaluated by traditional acoustic measures, there are other aspects that remain unexplored. We lack information on psycho-acoustic characteristics of the soundscape [2, 3]. There are contextual aspects and meaning and their relationship to attitudes and cognitions as well as qualitative assessments and the eventfulness of soundscapes we know little about [4, 5, 6, 7]. Important aspects of the road environment are also vibrations [8, 9] and air pollution [10, 11]. There is usually little information on the influence of road traffic on insecurity and the aesthetic aspects of everyday urban life [12, 13]. It is our view that in order to obtain fully viable models, it is necessary to delve into each aspect of the Environmentscape, Soundscape and Psychscape research areas, to follow the categorisation of Job and Hatfield [14]. Ideally these research “worlds” should be explored in parallel and in an integrated fashion [15], with a charting also of the inner body, sensitivity, stress or cognitive pathways. This means more co-operation between researchers familiar with the different worlds and methodologies, who can integrate the different results and

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approaches, as well as larger, more integrated research programmes. In the meantime, we have to settle for partial relationships. Important partial relationships form part of a puzzle that over time will allow additional pieces to be added. They identify areas for further exploration, and indicate where to target field and laboratory research.

2. Study areas and sampling

Three studies in Oslo East in 1987, 1994 and 1996 [16] and a study in Drammen consisting of two surveys undertaken in 1998 and 1999 respectively [17] were used for analysing the main research questions. With the exception of the 1987 Oslo East Survey, the surveys utilised a sampling scheme that under-represents larger households [18]. After quality assurance, there were 3913 respondents available for analyses of exposure–effect relationships between road traffic noise and road traffic outdoor annoyance, and 3940 for analyses of indoor annoyance.

2.1. The Oslo East studies

The three Oslo studies functioned as ‘before and after’ studies of two separate tunnel projects alleviating a centrally located urban area in Oslo of through-traffic. In 1987 personal interviewing took place in 8 sub-areas. In 1994 and 1996 telephone interviews were undertaken in 14 areas, including the original 8. The response rate was approximately 50% in the three surveys (resulting in $n=1028$, 1140, 1097). The sub-areas were selected systematically to reflect areas experiencing traffic increases, traffic decreases, and unaltered traffic situations. Within each sub-area, probability sampling was used to obtain a representative sample of the inhabitants.

2.2. The Drammen studies

In Drammen the first socio-acoustic survey was undertaken in June 1998 obtaining answers from 1215 respondents. The purpose of the survey was to describe the environmental situation before a major re-routing of the traffic through the city. In addition to the purposive selection of sub-areas along major roads, a random sample was selected from the whole city area. To enhance the coverage of the areas most affected by the planned road construction scheme for Drammen, 376 additional interviews were obtained in June 1999. Non-response was higher in the Drammen study (61%) than in the previous three Oslo studies (50%). This increase in non-response over the decade has also been observed in other environmental surveys undertaken at the Institute of Transport Economics. The main reason for non-response is a refusal to participate.

2.3. Additional Oslo West study

As a separate project, a small socio-acoustic survey [19] was undertaken in an Oslo West city area. This study featured 400 respondents after a non-response of 62%. The purpose of this separate study was to establish a direct link between what is deemed an adverse neighbourhood soundscape according to our calculations and the residents’ self-reported annoyance in the neighbourhood. This would pro-

vide direct evidence that a noisy neighbourhood, according to our definition and calculations, is also *perceived* by residents to be noisy.

3. Questionnaire

3.1. Annoyance questions

There were slight changes in the wording of the noise annoyance questions between the different surveys. In 1987, people’s annoyance by road traffic noise was measured by first inquiring: “Can you hear noise from road traffic when right outside the house in the yard, on the lawn, on the balcony etc?” (The answers were “Yes”, “No” and “Not applicable”). People were thereafter asked: “Is the noise highly, somewhat, or not annoying?”¹ In 1994 and 1996, the first question was shortened to “Can you hear noise from road traffic when you are right outside the apartment” while the second question was the same as in 1987 except that “for you” was added at the end of the question.

With respect to annoyance indoors the question in 1987 was: Do you hear road traffic noise (when) in your dwelling? (The answers were “Yes”, “No” and “Not applicable”, and “Do not know”). If yes: “Is this noise highly, somewhat, or not annoying?”

In the rest of the surveys “in” your dwelling was replaced with “inside” and “for you” was added to the annoyance part to emphasize that it was the respondents opinion that was of interest, not what other persons might think. The resulting question was: Do you hear road traffic noise (when) **inside** your dwelling? (The answers were “Yes”, “No” and “Not applicable”, and “Do not know”). If yes: “Is this noise highly, somewhat or not annoying **for you**”. The questions in the Drammen study were the same for both indoor and outdoor noise annoyance, as in the Oslo studies of 1994 and 1996.

The question on noise annoyance in the neighbourhood posed in the Oslo West study was as follows: How annoyed are you by traffic noise when in the immediate neighbourhood? The alternatives were “extremely”, “highly”, “moderately”, “a little” and “not annoyed”. If the respondent inquired about what area constituted the neighbourhood, the interviewers were told to specify within 75 meters of the dwelling.

3.2. Modifying factors

Noise sensitivity was measured by a single question using a 3-point scale: “Would you say you are highly, somewhat, or not sensitive to noise”. Respondents’ reported ages were recorded and re-coded into age groups. The survey questions on noise sensitivity were only posed in the 1999 Drammen survey and the 1998 Drammen data are therefore not utilized in analyses featuring noise sensitivity as an independent variable.

¹ The number of response categories was chosen in the late 1980’s for the first of the surveys. For comparison purposes, the number of categories were kept the same in the following surveys, otherwise a 5-point annoyance scale would more likely have been used.

4. Noise calculations

The 24-h equivalent noise levels at the apartments most exposed side, $L_{Aeq,24h}$, were calculated using the Nordic calculation method [20]. This method includes a 3 dB reflection from the façade. Detailed information on the location of each apartment was available (entrance, floor, which roads the residents overlooked from their living room and bedroom windows). Apartments where the information was ambiguous were excluded from the survey. The precision of the estimated noise exposure values is thus deemed to hold a higher quality than what is normally associated with noise mapping software. The calculated noise values for each of the surveys are deemed to be within ± 4 dB of the true level, with the exception of a small number of observations in the Drammen study that are within ± 7 dB. When the calculated noise exposure levels, $L_{Aeq,24h}$, were less than 50 dB, they were set to 50 dB. This was done to be on the conservative side, and because there might be possible contributions from numerous distant noise sources not taken into account by the calculation model.

As the Nordic calculation method was revised during the time period, all calculations were converted to the 1987 version, in order for the data sets to be pooled. To make it easier to compare the results with those produced internationally, the values have summarily been converted to A-weighted L_{den} -values. This was accomplished by subtracting 1.4 dB from the 1987 version $L_{Aeq,24h}$ -values. (The $L_{den,façade}$ -values are lower than the $L_{Aeq,24h}$ -values, in spite of the evening and night time weighting, because of the deduction of 3 dB in order to arrive at free field values).

4.1. The concept of the neighbourhood soundscape

The soundscape is any acoustic field of study. We can isolate an acoustic environment as a field of study just as we can study the characteristics of a given landscape.

R. Schafer Murray [21]

The study areas are continental built-up city areas where main streets run through residential areas. The neighbourhood soundscape of both front row and second row apartments will often be dominated by the noise levels along the main streets. These streets connect the local city area with the city centre and with neighbouring city areas. They are often used for public transport. Shops or businesses may be located along the street. We are thus talking of urban neighbourhoods that are in use. Norwegian environmental studies have shown that about 20% of the residents in such areas make daily trips in their neighbourhood while 55–75% make a trip in the neighbourhood at least once a week.

We have coined the term *neighbourhood soundscape* to denote the spatial distribution of noise levels in the immediate neighbourhood of apartments (or dwellings) in these types of urban areas. Each apartment thus has its own associated neighbourhood soundscape, and there are as many

neighbourhood soundscapes as apartment/dwelling locations. Road traffic noise is often the major contributor to the acoustic soundscape in city areas, and we have therefore initially focussed on the road traffic noise levels in the neighbourhood of a dwelling. The study areas were also purposively chosen so that there would be no other major noise sources “disturbing” the relationships between road traffic noise and road traffic noise annoyance. In this paper, we focus on the impacts of having an adverse neighbourhood soundscape. To indicate the noisiness of the neighbourhood soundscape of an apartment we use the highest equivalent noise level attained within a radius of 75 meters of the apartment: $L_{neigh,max}$. The highest noise levels are usually found alongside nearby main streets and the noise levels encountered when the residents use the pavement and recreational areas along these streets are those that usually dominate the neighbourhood soundscape.

4.2. Second row apartments have a relatively adverse soundscape

An apartment shielded by intervening building structures, or that is situated up a side street from a main road with heavy traffic, can be exposed to quite low road traffic noise levels even when the noise affecting the neighbouring apartments facing the main street is quite high. In Figure 1 the shielded apartment B has a calculated road traffic noise level $L_{den,façade}$ in front of the most exposed façade of 60 dB, the same as apartment C located further up the side street. The beneficial effect of intervening building structures and distance from the noise source means that both apartments are exposed to substantially lower $L_{den,façade}$ -values than apartment A facing the main street.

However, the residents in apartments A, B, and C use the same main street for public transport, walking, cycling, and making trips to neighbours and shops. The neighbourhood soundscape noisiness (due to our focus on the highest attained road traffic noise level within a given radius from each apartment) is the same: 75 dB. The increase in noise levels between the apartment and the immediate neighbourhood (often along the main street), the neighbourhood maximum difference ($L_{diff,max}$), is as large as 15 dB for apartments B and C while it is only 3 dB for apartment A.

4.3. Front row apartments have a relatively benign soundscape

Figure 2 shows apartment D in a front row building facing a main street with less traffic than apartment A in Figure 1. As a result of the lesser traffic along the main street, the noise level in front of the most exposed façade of apartment D, $L_{den,façade}$, is only 60 dB. When the residents of this apartment use their main road for walking, cycling or taking public transport, they are often exposed to only slightly higher noise levels than in front of the most exposed façade of their apartment. The difference between the noise level along the main street and that in front of the most exposed façade is 3 dB.

For predicting road traffic noise annoyance, the exposure situations for apartments B, C and D are treated

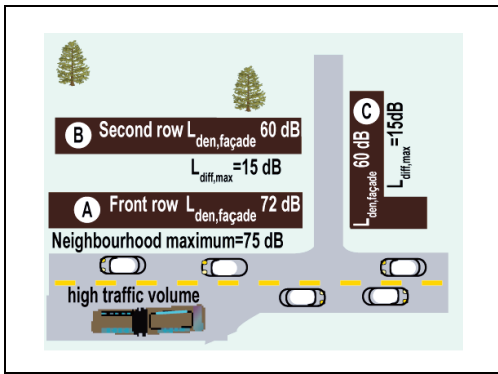


Figure 1. Apartments A, B and C have the same neighbourhood soundscape: 75 dB – the road traffic noise level the residents encounter when walking, taking the buss etc. along the main street. The neighbourhood maximum difference $L_{diff,max}$ for apartment B that is partially shielded and C that is located in a side street is 75 dB – 60 dB = 15 dB.

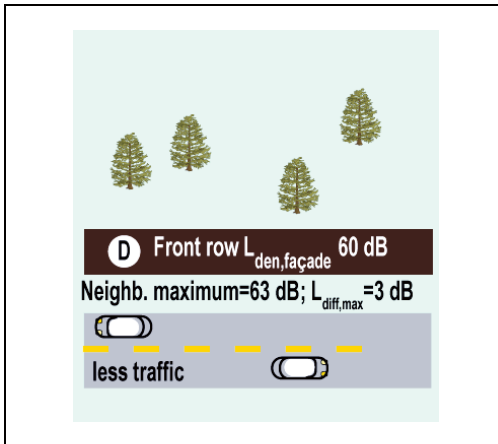


Figure 2. Apartment D is located facing a main street with much less traffic than the main street portrayed in Figure 1. The neighbourhood maximum difference $L_{diff,max}$ for apartments D is 63 dB – 60 dB = 3 dB.

as equivalent. All apartments are exposed to the same level of road traffic noise, $L_{den,façade}=60$ dB. However, the neighbourhood soundscape noisiness of apartment D is not much worse ($L_{diff,max}=3$ dB) than at the apartment itself, while the neighbourhood soundscape of apartments B and C are much worse ($L_{diff,max}=15$ dB). With respect to residential noise annoyance our contention is that while locations B and C are preferable to location A, location D is to be preferred over locations B and C.

4.4. Neighbourhood noisiness versus silent sides

Our research has focussed on neighbourhood noisiness while other research initiatives such as in the Mistra

project [22] have focussed on analysing the impacts of quiet sides of buildings, and the advantage of e.g. locating the bed rooms away from traffic [23]. Noisy neighbourhoods have the potential to increase residential noise annoyance, primarily for apartments exposed to low residential noise levels, whereas quiet neighbourhood areas have the potential to reduce noise annoyance the most at intermediate and high residential noise levels. A follow up study assessing the respective contribution of localized noisy and silent areas on residential noise annoyance has been reported [24]. The results from this follow-up study indicate that localized quiet and noisy areas in the neighbourhood have separate impacts on residential noise annoyance. In this paper, we focus on the impacts of having an adverse soundscape.

4.5. Neighbourhood noisiness calculations in the Oslo studies

To obtain a simple indicator of the noisiness of the neighbourhood soundscape we initially focus on obtaining an indicator $L_{neigh,max}$ defined as the highest of the A-weighted equivalent noise levels encountered within 75 meter of an apartment. The radius of 75 meters was chosen to capture the adverse impact of the noise levels encountered along significant nearby streets, while maintaining a high probability of the street actually being used by the respondents. More sophisticated indicators could weight the noise levels encountered in the neighbourhood with the inverse distance from the apartment, take into account actual behavioural patterns of each respondent etc. However, for this study the simpler approach was chosen.

In the Oslo studies the neighbourhood noisiness indicators were derived and calculated after the noise exposure calculations were completed. The original data on noise emissions along main streets and other input used for these calculations were therefore no longer easily available. The neighbourhood soundscape noisiness indicator for each respondent, $L_{neigh,max}$, was therefore derived indirectly from the information provided by the noise exposure calculations for other respondents living in the neighbourhood of each respondent.

The location of the most exposed façade of each apartment/dwelling was first geographically coded with better than 5 meters resolution using a geographical information system (GIS) and a high quality digital map of the study area. Algorithms were developed that made use of the spatial routines of the GIS package to determine which other survey respondents lived within 75 meters of the apartment location of a given respondent. Thereafter, the highest of the $L_{den,façade}$ exposure values these “neighbours” were exposed to, was chosen as an indicator of the neighbourhood soundscape noisiness: $L_{neigh,max}$. These calculations were performed for all respondents. (Respondents living at the same address were excluded as “neighbours”). In the Oslo studies, almost all residents living within densely populated sub-areas were contacted and asked to participate in the study. All respondents were therefore surrounded by other respondents participating in

the study and the quality of the neighbourhood soundscape indicator should therefore be reasonably good. Following the procedure used in the Oslo studies, apartments B and C in Figure 1 would be assigned 72 dB as their neighbourhood soundscape noisiness level² as apartment A lies within a 75 meter radius from each of the apartments. Apartment A would be assigned a neighbourhood soundscape noisiness level of 72 dB, the same as the apartment was exposed to.

4.6. Neighbourhood noisiness calculations in the Drammen and Oslo West studies

In the Drammen studies, where a sub-sample was drawn randomly from the whole municipality, the respondents' dwellings were in many cases located far from each other. The spatial GIS-based procedure applied for the Oslo studies would therefore not work. There would simply be too few other respondents living in the neighbourhood of each respondent to obtain a reliable $L_{\text{neigh,max}}$ -value – in many cases none. However, the original input data to the noise calculations were available for the Drammen studies. It was therefore possible to use this information for obtaining an indicator of the $L_{\text{neigh,max}}$ -value for each apartment. The road-side noise emission level 10 meters from the centre line of nearby main streets, would most often also indicate the noise exposure levels of pavement and recreational areas along the main street and be employed directly as the $L_{\text{neigh,max}}$ -value. (When the most significant noise contributions were from distant streets the highest noise exposure value within the neighbourhood was calculated).

According to the Drammen method the noise emission value of 75 dB on the pavement in front of apartment A in Figure 1 was used as the neighbourhood soundscape noisiness indicator $L_{\text{neigh,max}}$ of apartments A, B and C. (Streets that could or would not be utilised by residents were excluded from the calculations).

4.7. Construction of the neighbourhood maximum difference indicator $L_{\text{diff,max}}$

Before pooling the Drammen and Oslo East data, the GIS-based calculations and the Drammen method were compared using a subset of dwellings in the Oslo Studies. This analysis indicated that the neighbourhood noise levels on the average were underestimated by 2 dB by the GIS-method employed in the Oslo studies. The neighbourhood noisiness indicator values in Oslo East were therefore increased by 2 dB before pooling the data.

To clearly differentiate in the statistical analyses between the impact of the noise level at the most exposed façade of an apartment, $L_{\text{den,façade}}$ and the road traffic noise load in the neighbourhood $L_{\text{neigh,max}}$, a neighbourhood maximum difference indicator

$$L_{\text{diff,max}} = L_{\text{neigh,max}} - L_{\text{den,façade}}$$

was constructed. This indicator is simply the number of decibels that the neighbourhood soundscape noisiness indicator, $L_{\text{neigh,max}}$, exceeds the noise exposure level, $L_{\text{den,façade}}$ at the most exposed façade of the dwelling. It is thus an indicator of the **relative** neighbourhood soundscape noisiness given the noise level at the apartment. An important advantage of forming the neighbourhood maximum difference, $L_{\text{diff,max}}$, is that this indicator is not positively correlated with attributes of the main street such as road traffic volumes, air pollution indicators or aesthetics. This makes it easier to rule out potentially confounding factors in the statistical analyses. Possible multi collinearity problems associated with using both $L_{\text{den,façade}}$ and $L_{\text{neigh,max}}$ as predictors of road traffic noise annoyance are also reduced.

In Figure 1 the apartments A, B and C have the same neighbourhood soundscape $L_{\text{neigh,max}} = 75$ dB. The neighbourhood maximum difference indicator, $L_{\text{diff,max}}$, is 3 dB for apartment A and 15 dB for apartments B and C. For apartment D in Figure 2 the neighbourhood maximum difference, $L_{\text{diff,max}}$, is 3 dB, the same as for apartment A.

5. Statistical models and procedures

5.1. Statistical models for describing exposure–effect relationships

Most environmental research measuring people's adverse reactions to environmental exposures, feature dependent variables that are ordinal and categorical [25]. Degrees of annoyance, degrees of disturbance, how often people awaken (nightly, weekly, monthly), the severity of subjective health complaints symptoms etc. are examples of such variables.

The relationship between a continuous exposure variable and annoyance responses often display the characteristic sigmoid (S-shaped) relationships that pose problems for linear regression models, but are a natural part of logistic regression and ordinal logit models. An advantage of the ordinal logit model and the grouped regression model employed by Miedema and Oudshoorn [26] over the simpler logistic regression models for each separate degree of annoyance is that they provide politicians and the authorities with a broader picture about the full range and size of annoyance effects, without compromising the accuracy of the estimated relationships. The models produce exposure–effect relationships for each separate degree of annoyance using all the available data, which also results in narrower statistical confidence intervals than when estimating partial relationships.

5.2. Statistical procedures

The main purpose of the analyses was to test whether an adverse neighbourhood soundscape quality indicated by a high value of $L_{\text{diff,max}}$ contributes to road traffic noise annoyance. As a departure point, models for road traffic noise annoyance when right outside the apartment and when indoors were estimated. These were ordinal logit models featuring $L_{\text{den,façade}}$ as sole explanatory variable.

² Provided Figure 1 contains all relevant information: i.e. no other apartments outside the "picture" frame.

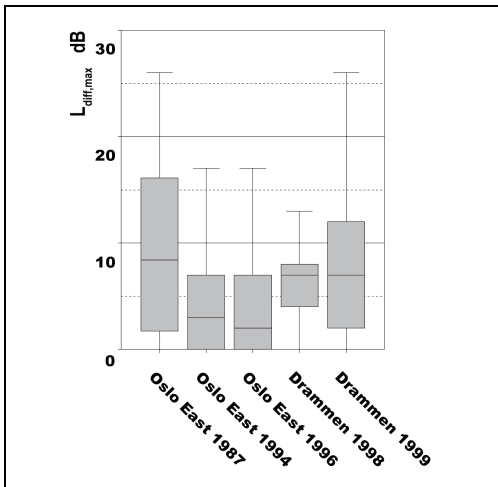


Figure 3. The frequency distribution of the neighbourhood maximum difference $L_{diff,max}$. Box plots. Five socio-acoustic surveys. $N=3950$.

Thereafter, the neighbourhood maximum difference indicator $L_{diff,max}$ was introduced into each of the models as a second explanatory variable. The log-likelihood of each of the models was obtained from the maximum likelihood estimation. The expanded models were thereafter tested against the simpler ones by means of log-likelihood ratio tests. These tests determine whether the inclusion of the additional variable provides relevant new information, or whether the simpler model is adequate. After the log-likelihood ratio tests, the exposure-effect relationships of the expanded models were estimated.

To check whether individual variables such as noise sensitivity, age group and environmental variables, such as air pollution, modified the estimated relationships, a model also featuring these variables was formulated. These are variables that are usually not available when applying the relationships to predict the impacts of road traffic noise changes in residential areas. The purpose of this model was therefore simply to check that the significance and relative sizes of the estimated parameter values did not change too much. As the 1998 Drammen study had no information on noise sensitivity, the associated survey data were automatically excluded from this analysis. The estimation results of this additional expanded model are therefore derived from the remaining four surveys – see Appendix.

When traffic along dominating streets with high traffic volumes, such as the main street in Figure 1, is reduced, it no longer has much higher noise levels than other streets in the vicinity and distant road traffic noise sources play a larger role. As a result the neighbourhood soundscape becomes more homogenous and the relative neighbourhood soundscape noisiness differences $L_{diff,max}$ become smaller. This could provide part of an explanation of the

phenomena of “overreaction” to traffic changes. A simple stacked bar chart is employed to show the changes in $L_{diff,max}$, as a function of $L_{den,façade}$, in 1987 before and, in 1994 and 1996, after traffic reductions in Oslo East.

For the separate Oslo West study, an ordinal logit model was utilised to model the relationship between the residents’ degree of annoyance by traffic noise in their neighbourhood as a function of its calculated neighbourhood soundscape noisiness, $L_{neigh,max}$. The model compensated statistically for noise sensitivity and age group.

6. Results

6.1. Frequency distributions

The $L_{diff,max}$ -values vary mainly between 0 and 17 dB in the five socio-acoustic surveys (see Figure 3). The 1987 Oslo survey was undertaken in a situation where the E6 ran through a densely populated city area, with many second row dwellings bordering on to the associated road network system. The high noise levels associated with the main road, and the significant shielding effect of the intervening buildings contributes to the steep noise gradients in the immediate neighbourhood of the main roads. The neighbourhood maximum differences for many of the second row and shielded apartments are therefore large.

In addition to purposive sampling in sub-areas, a large number of dwellings were sampled randomly from the municipality of Drammen. This is reflected in a narrower range of noise exposure values. The smaller 1999 Drammen study on the other hand was again undertaken with purposive sampling with many second row apartments along streets with high traffic volumes. In spite of the smaller sample, $L_{diff,max}$ takes on a wider range of values.

In Figure 1 we demonstrated that the relative neighbourhood soundscape noisiness indicated by $L_{diff,max}$ could vary a lot between apartments being exposed to the same noise level in front of the most exposed façade, indicated by $L_{den,façade}$. While apartments B, C and D were all exposed to a façade noise level, $L_{den,façade}$, of 60 dB, apartments B, C had relative neighbourhood soundscape noisiness, $L_{diff,max}$, of 15 dB, while apartment D had 3 dB. This type of variation in the $L_{diff,max}$ indicator is illustrated using a simple box plot that shows the variation in the $L_{diff,max}$ -indicator for apartments exposed to the same noise level outside the most exposed façade (5 dB intervals of $L_{den,façade}$) – see Figure 4.

The largest variation in the relative neighbourhood soundscape noisiness values $L_{diff,max}$ is, of course, found among the apartments and dwellings exposed to lower noise exposure values.

6.2. Estimation results and illustration of the baseline results

The parameter estimates for the baseline model for road traffic noise annoyance, when right outside the apartment and when indoors, are presented in Table I. (The table is

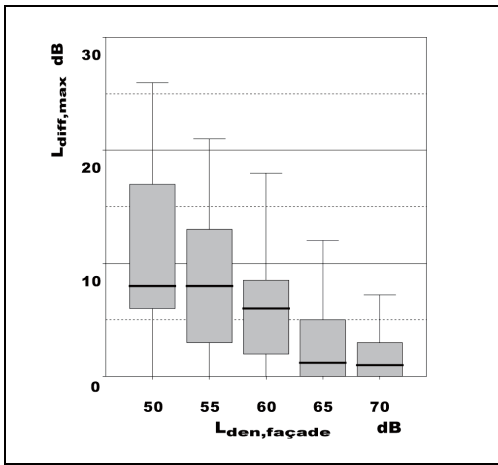


Figure 4. The frequency distribution of the neighbourhood maximum difference $L_{diff,max}$ for each 5 dB interval of the residential road traffic noise exposure indicator $L_{den,façade}$. Box Plots. Five socio-acoustic surveys. N=3950.

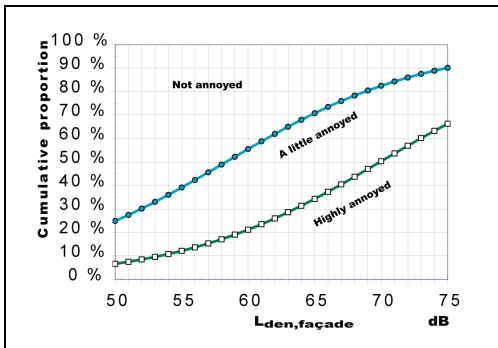


Figure 5. Simple exposure-effect relationships for the degrees of road traffic noise annoyance when right outside the apartment as a function of the noise exposure in front of the most exposed façade, $L_{den,façade}$. Five Socio-acoustic surveys. N=3957.

a slightly edited version of the output from the ordinal regression model PLUM in the statistical package SPSS version 11.5).

The probability of people reporting a higher degree of annoyance (from *Not annoyed* to *A little annoyed* or from *A little annoyed* to *Highly annoyed*) as a result of changes in the variables can be derived directly from the parameter estimates by exponentiating the parameter estimate times the change in dB [27]. For example, a parameter estimate of 0.133 means that a 1 dB increase in the noise exposure results in an increase of 14% (as $e^{0.133} = 1.14$) in the probability that a person reports a higher degree of annoyance e.g. from not annoyed to a little annoyed or from a little annoyed to highly annoyed.

For indoor annoyance we find that the parameter estimate in front of $L_{den,façade}$ is 0.120 and a 1 dB increase

Table I. Parameter estimates for an exposure-effect model featuring the degrees of road traffic noise annoyance when *right outside* one's dwelling as dependent variable, and the noise level $L_{den,façade}$ outside the most exposed façade as single independent variable. Socio-acoustic surveys. N=3957. b : Estimate, σ : Standard error, Sig.: significance. A.l.a.: A little annoyed, H.a.: Highly annoyed.

Annoyance right outside		b	σ	Sig.	e^b
Threshold	A.l.a.	7.740	0.2907	0.0%	
	H.a.	9.276	0.3030	0.0%	
Location	$L_{den,façade}$	0.133	0.0049	0.0%	1.14

Table II. Parameter estimates for an exposure-effect model featuring the degrees of road traffic *indoor* noise annoyance as dependent variable, and the noise level $L_{den,façade}$ outside the most exposed façade as single independent variable. Five Socio-acoustic surveys. N=3957. b : Estimate, σ : Standard error, Sig.: significance. A.l.a.: A little annoyed, H.a.: Highly annoyed.

Indoor annoyance		b	σ	Sig.	e^b
Threshold	A.l.a.	7.462	0.3001	0.0%	
	H.a.	9.021	0.3115	0.0%	
Location	$L_{den,façade}$	0.120	0.0050	0.0%	1.13

in the noise exposure is therefore estimated to result in a 13% increase in the probability of a person choosing the next higher annoyance category – see Table II.

For road traffic noise annoyance right outside the apartment the estimated exposure-effect relationships are illustrated in Figure 5.

6.3. Tests of the relative soundscape quality indicator $L_{diff,max}$

To test whether the neighbourhood maximum difference indicator $L_{diff,max}$ improves the explanatory power relative to the baseline model, this was estimated using ordinal logit models with both $L_{den,façade}$ and $L_{diff,max}$ as explanatory variables. Log-likelihood Ratio tests for the inclusion of the neighbourhood maximum difference indicator $L_{diff,max}$ were performed for each of the relationships. The result of these tests revealed that the neighbourhood maximum difference indicator provides considerable additional explanatory power. The simpler models (only $L_{den,façade}$ as explanatory variable) were firmly rejected for both annoyance right outside the apartment and when indoors ($p < 0.0\%$).

When $L_{den,façade}$ increases by 1 dB, the probability of obtaining a higher degree of annoyance right outside is 1.19, as $e^{0.172} = 1.19$, or in other words the probability of a more adverse response increases by 19%. This means that taking the severity of the neighbourhood soundscape into account, the estimated impact of a change in noise level for front row apartments, and other apartments where the neighbourhood maximum difference $L_{diff,max}$ is constant, is larger than simple statistical relationships indicate.

When the $L_{diff,max}$ indicator increases by 1 dB the probability for obtaining a higher degree of annoyance

Table III. Parameter estimates from an ordinal logit model for annoyance by road traffic noise when *right outside* one’s dwelling, as a function of the residential noise exposure at the most exposed façade $L_{den,façade}$ and of the neighbourhood maximum difference $L_{diff,max}$. Five Socio-acoustic surveys. N=3913. b : Estimate, σ : Standard error, Sig.: significance. A.l.a.: A little annoyed, H.a.: Highly annoyed.

Annoyance right outside		b	σ	Sig.	e^b
Threshold	A.l.a.	10.491	0.404	0.0%	
	H.a.	13.059	0.416	0.0%	
Location	$L_{den,façade}$	0.172	0.006	0.0%	1.19
	$L_{diff,max}$	0.074	0.007	0.0%	1.08

Table IV. Parameter estimates from an ordinal logit model for *indoor* annoyance by road traffic noise, as a function of the residential noise exposure at the most exposed façade $L_{den,façade}$ and of the neighbourhood maximum difference $L_{diff,max}$. Five socio-acoustic surveys. N=3940. b : Estimate, σ : Standard error, Sig.: significance. A.l.a.: A little annoyed, H.a.: Highly annoyed.

Indoor annoyance		b	σ	Sig.	e^b
Threshold	A.l.a.	9.529	0.415	0.0%	
	H.a.	11.100	0.425	0.0%	
Location	$L_{den,façade}$	0.149	0.006	0.0%	1.16
	$L_{diff,max}$	0.057	0.007	0.0%	1.06

is 1.08, or an increase of 8%. The estimated effective size of the neighbourhood maximum difference indicator $L_{diff,max}$ for annoyance right outside the apartment (0.074) is about 40% that of the noise level at the most exposed façade, $L_{den,façade}$, (0.172) – See Table III. This implies that a dwelling exposed to $L_{den,façade}=55$ dB, with $L_{diff,max}=12$ dB, is estimated to induce about the same degrees of annoyance right outside the apartment as a dwelling exposed to $L_{den,façade}=60$ dB and $L_{diff,max}=0$ dB.

The estimated effective size of the neighbourhood maximum difference indicator $L_{diff,max}$ for road traffic noise annoyance when indoors is 0.057, also about 40% that of the residential noise level, $L_{den,façade}$, (0.149) – see Table IV.

6.4. Illustration of the impact of an adverse neighbourhood soundscape

The results from the statistical tests imply that we should distinguish between the impacts of road traffic noise in situations where the neighbourhood soundscape is adverse, and where the noise levels are similar to those the apartment itself is exposed to. Exposure–effect relationships for two idealised opposite situations are therefore calculated to illustrate this: One where all apartments are affected by a main street with a constant high neighbourhood noise level $L_{neigh,max}$ of 75 dB. (The neighbourhood maximum difference indicator $L_{diff,max}$ is thus 25 dB at $L_{den,façade}=50$ dB, and decreases linearly to 0 dB at $L_{den,façade}=75$ dB). The other is the simpler front row

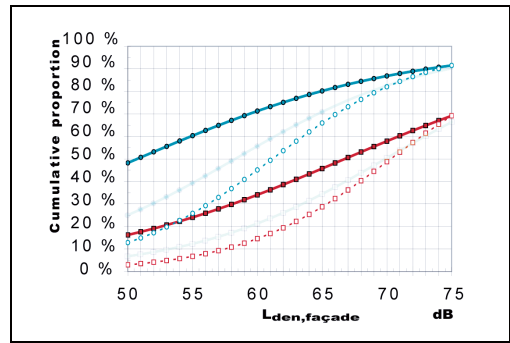


Figure 6. Estimated exposure-effect relationships for outdoor annoyance for a situation where the neighbourhood noise is the same as at the dwelling (Hollow markers $L_{neigh,max} = L_{den,façade}$) and for a situation where the neighbourhood noise is adverse (Filled markers $L_{neigh,max}=75$ dB). Five Socio-acoustic surveys. N=3913. (Curves from Figure 5 in grey).

situation where the neighbourhood soundscape is similar to the noise situation at the most exposed façade of the apartment ($L_{neigh,max} = L_{den,façade}$ for all values of $L_{den,façade}$) – See Figure 6.

An implication of obtaining two different sets of curves is that ordinary exposure–effect relationships not taking the neighbourhood maximum difference into account must be understood as a weighted average of these quite different curves. This is also evident from the relationship between the two sets of curves in Figure 6 and those from Figure 5. To facilitate the comparison of the two sets of curves, a greyed out version of the exposure–effect curves in Figure 5 has been inserted into the background of Figure 6.

6.5. Changes in the neighbourhood soundscape after traffic changes

When traffic along the main street in Figure 1 is reduced, it no longer has much higher noise levels than other streets in the vicinity, and distant road traffic noise sources play a larger role in the noise exposure in front of the most exposed façade of second row buildings. As a result, the noise exposure levels for apartments B and C are no longer dominated by the noise emissions from the former main street, and the neighbourhood soundscape becomes more homogenous. Consequently, traffic reductions along this type of main street not only result in lower noise levels, but also that the neighbourhood maximum differences $L_{diff,max}$ in the study area, for a given level of noise exposure, becomes smaller – See Figure 7.

The opposite takes place when there are traffic increases along a main street of this type: both the noise levels and the relative neighbourhood maximum differences $L_{diff,max}$ associated with a given noise exposure level increase. This phenomenon contributes to what we have dubbed an “area-effect” [11, 28], explaining “over-reactions” to traffic changes. The term “over-reaction” de-

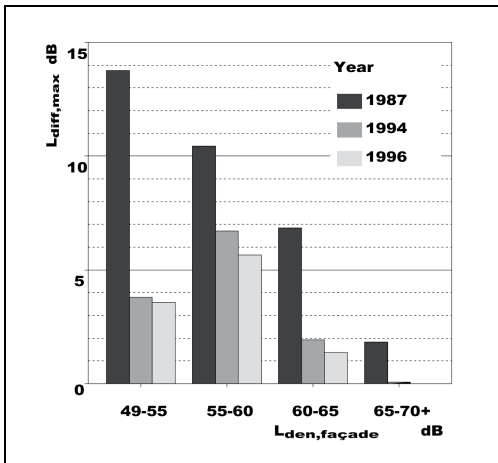


Figure 7. The average size of the relative neighbourhood soundscape noisiness indicator, $L_{diff,max}$, before and after traffic reductions. Oslo East surveys sub-areas 2–8. $N=1744$.

scribes the phenomena that people tend to react with more annoyance after traffic increases and less annoyance after traffic decreases than predicted by simple exposure–effect relationships that do not take the neighbourhood soundscape into account [29, 30, 31]. We are here talking about long-term and not short-term effects. In the short-term expectations, resistance against deterioration of the environment and other psychological and societal influences may distort relationships.

6.6. Results for the separate Oslo West study

Many of the apartments in the Oslo West study were exposed to high road traffic noise levels in the neighbourhood. In spite of a relatively small range of values for the $L_{neigh,max}$ -indicator in the small Oslo West study, the results of the analysis was still that the more noise there was in the neighbourhood as indicated by $L_{neigh,max}$, the more the noise in the neighbourhood was also considered to be annoying by the residents. The relationship was significant at the 5% level (one-sided test).

Perhaps more significant is the fact that most of the residents (over 61%) announced that they were *highly annoyed* by road traffic noise in the neighbourhood. We have thus succeeded in establishing a link between the noisiness of the neighbourhood as we have defined it, and people's perception of it in the form of noise annoyance.

7. Discussion

7.1. Possible noise calculation errors

The Nordic noise calculation method was developed to calculate high noise levels at the most exposed part of a façade and not the more difficult low noise situations in back yards and where there may be noise imissions over

the roof from several distant noise sources. By applying an innovative urban landscape model, Kihlman, Kropp, and Ögren have concluded that the Nordic noise calculation methods may be erroneous for low noise levels [32, 33]. As this is the calculation method used in all surveys, too low $L_{den,façade}$ -values for shielded conditions could possibly affect our conclusions. Depending on the mixture of situations that would be applicable to the apartments in our surveys, it could in the worst case mean that the effect we attribute to an adverse neighbourhood soundscape only reflects the failure of the calculation method to estimate the noise exposure $L_{den,façade}$ correctly at the apartment itself.

However, as input to the analyses, we have applied a conservative approach. All calculated values below $L_{den,façade}^3=49$ dB were set to 49 dB. This leaves little room for this type of error to manifest itself. In the first of the socio-acoustic surveys in 1987, a number of control measurements were also undertaken to ensure the quality of, and possibly improve on, the Nordic noise calculation procedures. The comparison in shielded situations of calculated and measured values at that time did not indicate any systematic bias. We therefore conclude that this potential source of error is not an issue in our analyses.

7.2. Possible errors associated with utilising equivalent noise levels as exposure measure

When viewing noise contour maps, it is evident that the road network affects the areas along major roads the most. The pavement and recreational areas that are used by people are important parts of their daily lives and, according to our research, are important for residential noise annoyance. However, we must also consider alternative explanations. The frequency spectrum, the number of noise events, and the maximum noise levels of the noise emissions from the associated main street will be affected by the shielding provided by intervening buildings or by the added distance from the main street. However, it is not clear what impact this would have on annoyance. There are some smaller laboratory studies that can shed some light on the importance of noise frequency: Versfeld and Vos report from an experiment where listeners were asked to judge the annoyance caused by the sounds from a continuous stream of vehicles, assuming they were exposed to it at home on a regular basis [34]. Results showed that in such conditions, the annoyance is virtually independent of the proportion of heavy vehicles. The number of pass-by events and the A-weighted equivalent sound levels were kept constant. Ishiyama reports from a test on how people reacted to noise from direct noise emissions, compared to noise in a shielded situation [35]. This study concluded that the high frequency components (over 4000 Hz) contributed positively to the annoyance. Neither of these studies offers any evidence that changes in the quality of the noise is to blame for the increased annoyance for second row dwellings. However, being located in the vicinity of a

³ Original criteria was that $L_{Aeq,24h} + 3 \geq 50$; see Klæboe et al. 2004.

larger street might also mean that these dwellings are exposed to somewhat more night-time traffic that we are not taking properly into account. From our knowledge of the streets this should not be an important factor. In a small study, Berglund and Nilsson compared loudness ratings and noise measurements on the silent and noisy side of a few buildings [36]. They found that the loudness was higher outdoors on the shielded side than the measured noise levels would lead one to believe. The opposite was true for the indoor situation. There are also other aspects of the noise situations, context etc. that can differ, but none that we have information about. However, these factors are not likely to cause such large systematic effects as we have uncovered through the analyses presented in this paper.

7.3. Possible “response-side” contributions to the neighbourhood soundscape effect

The Norwegian annoyance questions distinguish between indoor and outdoor road traffic noise annoyance. For most respondents their noise annoyance when outside their apartment will be dominated by the noise situation at the most exposed façade. For the relatively few situations where an apartment in a building block is located such that it is wholly facing a back yard, some of the respondents may interpret “right outside the apartment” as also covering the area in front of the building, even though the apartment itself lies towards the back yard. If this should prove to be the case, a minor part of the effect attributed to the neighbourhood severity could be because only a part of the “neighbourhood” is considered when this sub-sample of respondents offer their annoyance response. For the indoor situation, this possible contributing aspect of the neighbourhood soundscape effect does not exist.

7.4. Possible influence of noise sensitivity

Noise sensitivity has a large impact on noise annoyance. However noise sensitivity is virtually uncorrelated with $L_{\text{den,façade}}$ and $L_{\text{diff,max}}$. The correlation coefficients (Pearson) are 0.07 and -0.03 respectively.

The results presented in the Appendix, statistically controlled for noise sensitivity, air pollution levels and survey differences, show that the main results from the estimated exposure relationships remain the same: the relative neighbourhood soundscape noisiness indicator contributes about 34% to road traffic noise annoyance when right outside ones apartment.

8. Conclusion

We have shown that simple exposure–effect relationships ignoring neighbourhood soundscape quality as indicated by $L_{\text{diff,max}}$ are rejected. Both the road traffic noise exposure at the most exposed façade ($L_{\text{den,façade}}$) and how much the noise level in the immediate neighbourhood exceeds this noise level ($L_{\text{diff,max}}$) are needed in order to predict road traffic noise annoyance. Living in a relatively adverse neighbourhood soundscape, indicated by a high $L_{\text{diff,max}}$ -value, means that annoyance by road traffic noise also increases when at home.

9. Implication of the results for noise abatement measures and policies

Using traditional exposure–effect relationships ignoring neighbourhood soundscape quality has the following consequences:

- (a) The population annoyance in situations where the neighbourhood soundscape is not worse than at the dwelling itself (front row houses) is overestimated
- (b) The population annoyance in situations where the neighbourhood soundscape is adverse (more noisy than at apartment) is underestimated
- (c) The effect on noise annoyance of reducing / increasing noise in front row houses is underestimated (follows from the often steeper exposure–effect curves that are applicable to these situations)
- (d) The effect on annoyance of reducing / increasing noise at the dwelling in cases where the neighbourhood is adverse is usually overestimated (follows from the smaller annoyance changes due to the “flatter” exposure–effect curve for this situation)

According to our calculations, noise reductions at the source along main streets, such as speed reductions, porous road surfaces or traffic reductions, have a significantly larger impact on noise annoyance than indicated by simple exposure–effect relationships that ignore soundscape information. Measures only affecting a single building or dwelling, such as a noise screen (or for indoor noise, façade insulation), leave the neighbourhood noise the same, or even relatively more adverse ($L_{\text{diff,max}}$ becomes larger). These noise abatement measures could therefore easily fail to deliver the amount of noise reduction “promised” by traditional exposure–effect relationships that do not consider the neighbourhood soundscape.

For cost benefit analyses, the real changes in annoyance due to altering the noise situations are of interest. It is therefore the dynamic exposure–effect relationships and not static averages that supply information on the benefits of the noise reductions. For such analyses it is therefore important to distinguish between the efficacy of different noise measures depending on the exposure situation as defined by both the residential noise level $L_{\text{den,façade}}$ and the neighbourhood soundscape as indicated by $L_{\text{diff,max}}$.

To facilitate the use of the results and to allow researchers using their own exposure–effect relationships or those from meta-analysis, such as that of Miedema and Oudshoorn [26], the methodology has been developed further – See [37].

Appendix

The estimation results of the expanded ordinal logit model for road traffic noise annoyance right outside the apartment are displayed in Table A1. This expanded model controls for noise sensitivity, survey, and age group. It features the noise level in front of the most exposed façade, $L_{\text{den,façade}}$, the relative neighbourhood noisiness indicator, $L_{\text{diff,max}}$, as well as an indicator of 3-month periodic average levels of NO_2 air pollution as exposure variables.

Table A1. Parameter estimates of an ordinal logit model for annoyance by road traffic noise *right outside the apartment* as a function of the residential noise level $L_{den, facade}$, the neighbourhood maximum difference $L_{diff, max}$, the 3-month periodic mean of NO_2 , survey, age-group and noise sensitivity. Four socio-acoustic surveys. N=3181.

Annoyance right outside apartment				95% Confidence Interval		
		<i>b</i>	Standard error	Sig.	Lower bound	Upper bound
Threshold	A little annoyed	9.143	0.564	0%	8.038	10.248
	Highly annoyed	10.858	0.574	0%	9.733	11.963
Noise exposure	$L_{den, facade}$	0.144	0.009	0%	0.126	0.161
Neigh. max. Difference	$L_{diff, max}$	0.049	0.009	0%	0.032	0.067
Air pollution	NO_2	0.034	0.006	0%	0.023	0.045
Survey indicators	Oslo East 87	-0.137	0.163	40%	-0.457	0.182
	Oslo East 94	-0.415	0.150	1%	-0.709	-0.121
	Oslo East 96	-0.219	0.150	14%	-0.513	0.074
	Drammen 89	0			Reference group	
Age group	16–19	0.165	0.129	20%	-0.088	0.418
	20–29	0.627	0.135	0%	0.361	0.892
	30–39	0.472	0.153	0%	0.172	0.773
	40–49	0.033	0.169	84%	-0.299	0.365
	60–69	0.129	0.173	46%	-0.210	0.467
	70+	0			Reference group	
Noise sensivity	Not sensitive	-1.539	0.126	0%	-1.786	-1.293
	A little sensitive	-0.619	0.123	0%	-0.860	-0.379
	Highly sensitive	0			Reference group	

All variables, if not all levels of the categorical variables, contribute substantially to the relationship (significant relationships are indicated by significance levels below 10% for one-sided tests, 5% for two-sided tests). The three environmental indicators, $L_{den, facade}$, $L_{diff, max}$, and NO_2 are all highly significant and substantial. The variation in exposure–effect relationships between the four surveys is about ± 2.5 dB. The 20–39 age group have a somewhat stronger annoyance reaction, while people who are not highly sensitive to noise react less strongly. This is as expected. The most important environmental exposure indicator predicting road traffic noise annoyance is the noise level in front of the most exposed façade $L_{den, facade}$, as in the simpler models. The effective size of the neighbourhood maximum difference is 34% of that of the residential noise level – somewhat less than the 40%-Figure derived from the simpler models. For more information on the air pollution modelling in Oslo see [38]. For a description of the similar procedures in the Drammen studies–please contact the first author.

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