Environmental noise and health

Current knowledge and research needs

C. ERIKSSON, M.E. NILSSON AND
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Förord

Naturvårdsverket samordnar de svenska myndigheternas arbete med omgivningsbuller.

Vår förhoppning är att denna kunskapsöversikt om hälsoeffekter av omgivningsbuller ska ge en vetenskaplig grund och vägledning i det svenska arbetet med omgivningsbuller.

Studien har genomförts av forskare från Institutet för Miljömedicin vid Karolinska Institutet och Psykologiska institutionen vid Stockholms universitet. De har analyserat publicerade studier och syntesrapporter och ställt resultaten i relation till svenska förhållanden. I rapporten pekar de på viktiga kunskapsluckor och sammanfattar också behoven av ytterligare forskning.

Författarna svarar för innehållet i rapporten. Rapportens innehåll har genom Naturvårdsverkets initiativ och hantering granskats och kommenterats av oberoende experter inför färdigställandet. Kontaktpersoner vid Naturvårdsverket har varit Johanna Bengtsson Ryberg, Moa Ek, Marta Misterewicz och Tove Hammarberg.

Studien har finansierats med medel från Naturvårdsverkets miljöforskningsanslag.

Naturvårdsverket, mars 2013

Preface

The Swedish Environmental Protection Agency coordinates the national authorities´ work on environmental noise. Our aim for this review on the health effects of environmental noise is to provide a scientific basis and guidance to this work.

The review was carried out by researchers at the Institute of Environmental Medicine at Karolinska Institutet and the Department of Psychology at Stockholm University. They have reviewed scientific studies and reports and put the results in relation to Swedish conditions. In the report they point to important knowledge gaps and also summarize the needs for further research.

The authors are responsible for the contents of the report. On the initiative and management by the Swedish EPA, the report has been reviewed and commented on by independent experts before completion. Contact persons at the Swedish EPA have been Johanna Bengtsson Ryberg, Moa Ek, Marta Misterewicz and Tove Hammarberg.

The project has been funded by the Swedish EPA's Environmental Research Grant.

The Swedish Environmental Protection Agency, March 2013.

Contents

1 Executive summary

Environmental noise is an inevitable nuisance in the urban community. Despite efforts to restrict the exposure, noise constitutes an increasing problem, primarily as a consequence of continuous urbanization and transportation growth. The major contributor to the overall burden of environmental noise is traffic, primarily road-, railway- and aircraft traffic, but noise from neighbours, construction sites and industrial plants also contribute. Absence of quiet and restorative areas in the society affects our health and well-being. Annoyance, sleep disturbances, impaired communication, cognitive effects and physiological stress reactions are possible health impacts associated with an excess exposure to noise. There is also evidence of a long-term effect of traffic noise on the cardiovascular system, but many issues remain to be resolved in the risk assessment.

With the aim of providing a scientific basis and guidance for future work on noise abatement in Sweden, we conducted a literature review of the current knowledge on health effects related to traffic and industrial noise, including annoyance, sleep disturbance, performance and learning and cardiovascular disease. Certain aspects concerning the exposure assessment techniques used in health risk assessments have also been reviewed. Furthermore, we aimed to identify important gaps in the knowledge and to summarize the main imminent research needs.

Noise exposure can be assessed in different ways, commonly by measurements or modelling. In terms of modelling, national calculation models and indicators are often used, resulting in difficulties to compare the findings internationally. With the implementation of the European Environmental Noise Directive (END; 2002/49/EC), the Member States of the European Union (EU) are obliged to produce strategic noise maps for major roads, railways, airports, agglomerations and industries on a five-year basis. The END also proposed that common assessment methods should be established in order to ensure consistency of noise exposure data across Europe. Such methods are currently developed within the CNOSSOS-EU program and could, when fully developed, be valuable for estimations of population exposure. However, for the purposes of local action planning, urban planning and health risk assessments, the END maps need some refinements. For example, the maps should include noise levels <55 dB L_{den} and 50 dB L_{night} and have a resolution of less than 5 dB. Equally important is to adapt the calculation models to local conditions; in Sweden, primarily with regard to temperature and the use of studded tyres. To assess the impact of noise on health, it is also important to improve the individual assessments of traffic noise exposure. For example, techniques should be developed to take into account noise from multiple sources, varying exposure during the day and exposure modifying factors, in particular acoustic insulation and access to a quiet side.

Traffic noise is clearly related to annoyance. For a given equivalent noise level, aircraft noise generates a higher proportion annoyed residents than road traffic noise, which, in turn, generates a higher proportion annoyed residents than railway noise. For aircraft noise, an upward trend in annoyance has been seen which cannot fully be explained by methodological issues. Also, new findings suggest that annoyance related to railway noise may be higher than expected in areas with intense traffic or simultaneous ground-borne vibrations. These models thus need to be updated. Furthermore, exposure-response models for combined traffic noise are lacking and should be developed. Industrial noise has been found to be similarly or slightly more annoying than road traffic noise. But further studies are needed, in particular for annoyance relating to harbours and rail yards.

Sleep disturbances are one of the most common complaints in noise exposed populations and have several short and long-term health consequences, such as tiredness, irritability and impaired cognitive functioning. Clear exposure-response associations exist between traffic noise and sleep disturbances, but data on industrial noise are lacking. Since the auditory system is always open, noise may activate our alertness system even during sleep, thereby affecting several endocrine, metabolic and immune functions. Physiological effects of noise during sleep, such as increases in blood pressure and heart rate, are seen from 35 dB $L_{Amax,\ inside}$ and awakenings occur from 42 dB $L_{Amax,\ inside}$. However, established threshold levels, defined as sound levels at which certain effects are first observed, are lacking for several effects, including changes in stress hormones. Furthermore, there is a need for large-scale longitudinal studies to demonstrate a causal pathway linking noise and disturbed sleep to long-term cardiovascular and metabolic effects.

Traffic noise may disturb cognitive functioning, that is, how information is processed, retained and recalled, and thereby affect performance and learning. But much is still unknown regarding the mechanistic pathways. Most studies on traffic noise and cognitive functioning have concerned day-time noise at schools among children, showing effects primarily of aircraft noise on reading comprehension, memory and motivation. However, the overall evidence of cognitive effects among children is limited and no reliable studies exist among adults. Further longitudinal studies are therefore needed, for children as well as for adults, preferably differentiating the role of day- and night-time exposures.

A recent review on the long-term effects of traffic noise on the cardiovascular system stated that the weight of evidence clearly supports a causal link. However, it was also concluded that many questions remain to be resolved, in particular with regard to the establishment of threshold levels and source-specific exposure-response associations. To some extent, the inconclusiveness is due to methodological problems, such as a lack of large-scale longitudinal studies and imprecise exposure characterisation. Efforts are also needed to disentangle the effects of noise and air pollution as well as to identify particularly vulnerable groups. Furthermore, there are also plausible biological pathways between traffic noise and metabolic outcomes which have not yet been investigated systematically and therefore warrant further attention.

This review has identified a number of important gaps in the knowledge on health effects of environmental noise. To protect populations from harmful health effects of excess exposure to noise, further research in this area is urgently needed. Of particular interest is to study the long-term consequences of traffic noise-induced sleep loss and chronic stress on cardiovascular as well as metabolic outcomes. Synergistic effects between noise and air pollution should be prioritized. Additional studies are also needed on health effects of railway and industrial noise, as well as on combined exposures. Furthermore, identification and definition of particularly vulnerable individuals may assist in targeting preventive measures.

2 Sammanfattning på svenska

Omgivningsbuller är den vanligaste miljöstörningen i vårt samhälle. Trots insatser för att minska exponeringen så utgör buller ett allt större problem, framför allt beroende på en ökad urbanisering och tillväxt av transportsektorn. De främsta källorna till omgivningsbuller är trafik, det vill säga buller från vägar, järnvägar och flyg, även om ljud från grannar, byggarbetsplatser och industrier också bidrar. I och med att de tysta områdena i vårt samhälle blir allt färre påverkas både hälsa och välbefinnande. Exempel på hälsoeffekter som kan uppkomma till följd av buller är allmän störning, sömnstörning, försämrad kommunikation, kognitiva effekter och fysiologiska stressreaktioner. Långtidsexponering för trafikbuller har även visat sig kunna öka risken för hjärt- och kärlsjukdom, men mer forskning behövs som underlag för hälsoriskbedömningen.

Syftet med den föreliggande rapporten är att sammanfatta kunskapsläget om trafik- respektive industribuller och hälsa, inklusive allmän störning, sömnstörning, inlärning och prestation samt hjärt- och kärlsjukdom, och därigenom skapa en vetenskaplig grund och ge vägledning för det framtida bullerarbetet i Sverige. Vi har även granskat de metoder som används för att kartlägga buller och som ligger till grund för hälsoriskbedömningar. Målet var även att identifiera viktiga kunskapsluckor och att sammanfatta de huvudsakliga behoven av forskning.

Metoderna för att kartlägga buller varierar, vanligtvis används mätningar eller modellering. Vid modellering används ofta nationella beräkningsmodeller och indikatorer vilket lett till svårigheter att jämföra resultaten internationellt. I och med att det Europeiska Bullerdirektivet (2002/49/EC) infördes ålades alla medlemsstater inom Europeiska Unionen (EU) att kartlägga bullret vid större vägar, järnvägar, flygplatser, samhällen och industrier vart femte år. För att göra kartorna jämförbara föreslogs även att gemensamma kartläggningsmetoder ska införas. Dessa är nu under utveckling inom programmet CNOSSOS-EU och kan, när de är fullt utvecklade, användas för att bestämma bullerexponering på populationsnivå. För att kartorna ska kunna användas som underlag för lokala åtgärdsprogram, stadsbyggnadsplanering eller hälsoriskbedömningar behöver de dock göras mer detaljerade. De bör till exempel inkludera bullernivåer <55 dB L_{den} och 50 dB L_{night} och ha en bättre upplösning än 5 dB. Lika viktigt är anpassningen till lokala förutsättningar, i Sverige framför allt när det gäller temperatur och dubbdäcksanvändning. För att kunna bedöma effekter av buller på hälsan är det även viktigt att förbättra de individuella exponeringsskattningarna. Detta kan till exempel göras genom att utveckla metoder som tar hänsyn till buller från mer än en källa, varierande exponering över dygnet samt faktorer som modifierar bullerexponeringen, särskilt ljudisolering och tillgång till tyst sida.

Allmän störning är tydligt relaterat till trafikbuller. Vid samma ekvivalenta ljudnivå genererar flygbuller en större andel bullerstörda än vägtrafik, som i sin tur genererar en större andel bullerstörda än spårbuller. För flygbuller tycks det finnas en uppåtgående trend i störningskurvan som inte kan förklaras fullt ut av metodologiska förändringar. Nya resultat visar även att spårbuller kan vara mer störande än förväntat i områden med intensiv trafik eller samtidiga markvibrationer. Uppdateringar av dessa samband kan därför behövas. Det saknas även exponering-responssamband för kombinerat trafikbuller. Industribuller har funnits lika eller något mer störande än vägtrafikbuller. Fler studier behövs dock, speciellt är det gäller störningsgrad i förhållande till hamnar och bangårdar.

Sömnstörningar är ett av de vanligaste klagomålen i bullerexponerade populationer och har flera kort- och långtidseffekter på hälsan, till exempel trötthet, irritation och försämrad kognitiv förmåga. För trafikbuller och sömnstörning finns det tydliga exponering-responssamband, men för industribuller saknas data. Hörselsinnet är alltid öppet och buller kan därför aktivera våra vakenhetssystem även när vi sover, och i och med det påverka en rad endokrina, metabola och immunologiska funktioner. Fysiologiska effekter av buller under sömnen, till exempel ökningar i blodtryck och hjärtfrekvens, har observerats från 35 dB $L_{Amax,\ inomhus}$ och uppvaknanden sker från 42 dB $L_{Amax,\ inomhus}$. Etablerade tröskelvärden, dvs. bullernivåer där hälsoeffekter först uppträder, saknas dock för flertalet effekter, tillexempel vad gäller förändringar i stresshormonnivåer. Vidare behövs även fler longitudinella studier för att kartläggga sambanden mellan trafikbuller, sömn och långtidseffekter på hjärt- och kärlsystemet samt på det metabola systemet.

Trafikbuller kan störa kognitiva funktioner, dvs. hur information bearbetas, bibehålls och återkallas, och därigenom påverka inlärning och prestation. Mycket är dock fortfarande oklart när det gäller biologiska mekanismer. Merparten av de studier som gjorts hittills har undersökt effekter av trafikbuller dagtid på barn i skolmiljö. I synnerhet flygbuller har visat sig inverka negativt på barns läsförståelse, minne och motivation. Vi vet dock fortfarande relativt lite om hur buller påverkar barns inlärning och prestation, och för vuxna saknas helt tillförlitliga data. Fler longitudinella studier behövs därför, på barn såväl som på vuxna, och som helst bör helst separera effekterna av exponering dag- respektive nattetid.

I en nyligen genomförd granskning av forskningen på trafikbuller och hjärt-kärlsjukdom gjordes bedömningen att det samlade underlaget talar för ett orsakssamband. Dock påpekades vissa brister i kunskapen, framförallt när det gäller tröskelvärden och källspecifika exponering-responssamband. Till viss del kan dessa brister härledas till metodologiska begränsningar, som avsaknad av större longitudinella studier och oprecisa exponeringsbedömningar. Satsningar behövs också för att särskilja effekterna av buller och luftföroreningar, samt att identifiera särskilt känsliga individer. Ett ytterligare behov är studier på metabola utfall. Trots att det finns tydliga biologiska mekanismer för hur buller kan inverka på det metabola systemet har detta ännu inte undersökts systematiskt i epidemiologiska studier.

Denna granskning har identifierat ett antal viktiga kunskapsluckor i forskningen kring buller och hälsa. För att skydda befolkningen från att utsättas för hälsoskadliga bullernivåer är det angeläget att vidareutveckla forskningen inom detta område. Framför allt behöver vi veta mer om hur bullerrelaterade sömnstörningar och kronisk stress påverkar risken för hjärt- och kärlsjukdom och metabola komplikationer. I dessa studier bör man även reda ut samverkanseffekterna av buller och luftföroreningar. Fler studier behövs även kring hälsoeffekter av spår- och industribuller, samt om riskerna med att vara utsatt för buller från mer än en källa. För att kunna genomföra målinriktade preventiva åtgärder är det dessutom av betydelse att förbättra kunskapen om särskilt känsliga individer i befolkningen.

3 Introduction

The Institute of Environmental Medicine at Karolinska Institutet has been assigned by the Swedish Environmental Protection Agency to produce a comprehensive review of recent research on non-auditory health effect of exposure to environmental noise. The review focuses on traffic noise, that is, road, railway and aircraft noise, and industrial noise, defined as noise from stationary sources, including industrial plants, shunting yards, and harbours. Noise from other sources, for example boats and snowmobiles, are not reviewed here since health-data for these sources are lacking. However, wind turbine noise has been reviewed in a previous report [1].

The project was funded by a research grant from the Swedish Environmental Protection Agency and aimed at providing a scientific basis and guidance for future work on noise abatement in Sweden. The review summarizes current knowledge on health effects related to traffic and industrial noise, including annoyance, sleep disturbance, performance and learning and cardiovascular disease, and also examines certain aspects concerning the exposure assessment techniques used in the health risk assessments. We also aimed to identify important gaps in the knowledge and to summarize the main imminent research needs.

Several previous reviews on non-auditory health effects of environmental noise have been undertaken. In 2000 the World Health Organization's (WHO) "Guidelines for Community Noise" addressed outcomes such as communication, sleep disturbance, cardiovascular and physiological effects, mental health, performance as well as behaviour and annoyance [2]. Since then, the evidence of non-auditory effects of environmental noise has expanded, primarily in the area of cardiovascular and physiological effects.

Two more recent WHO compilations are the "Night Noise Guidelines for Europe" from 2009 [3] and the "Burden of disease from environmental noise, Quantification of healthy life years lost in Europe", published in 2011 [4]. The Night Noise Guidelines were initiated by the WHO regional office for Europe and can be viewed as a continuation of the Guidelines for Community Noise. In order to provide scientific advice to the Member States of the European Union (EU) for development of legislation and policy actions, the report reviewed the available scientific evidence on health effects of night noise and derived health-based guideline values. A threshold of 40 dB $L_{night,outside}$ was set as a target to protect the public, including vulnerable groups such as children, chronically ill and elderly, from harmful effects of noise. In the Burden of disease report, an attempt was made to quantify the burden of disease from environmental noise through calculations of the number of healthy life years lost in Europe. Based on existing exposure-response relationships, exposure distributions, background prevalence's of disease and disability weights of the outcome, the number of disability-adjusted life years (DALYs) was calculated for each of five specific outcomes: cardiovascular disease, cognitive impairment in children, sleep disturbance, tinnitus and annoyance.

An important step towards harmonizing the work on noise around Europe was initiated through the European Environmental Noise Directive (END; 2002/49/EC) [5]. The purpose of the END was to

> *"Define a common approach intended to avoid, prevent or reduce on a prioritized basis the harmful effects, including annoyance, due to the exposure to environmental noise".*

To achieve this, all Member States were required to perform noise mappings in order to determine the exposure to environmental noise, adopt action plans based on the noise mapping results and to ensure that the information was made available to the public. The first round of the mappings was reported to the European Commission (EC) in 2007. However, an analysis of the implementation of the directive revealed that improvements are still necessary, in particular concerning standardization of the mapping methods [6]. The second round of mappings was due December 31st 2012 but have not yet been analysed with regard to methods. Activities are, however, on-going to increase the harmonization with the goal of having standardized procedures implemented in all EU Member States until the third round of mappings, foreseen in 2017 [7].

The above mentioned WHO and EU documents serve as a starting point for the current report, which concentrates on findings published since then, using original research articles, reviews and meta-analyses as primary sources. The included studies had to be published in a peer reviewed journal and written in English. Conference proceedings and similar literature have generally not been included.

Original research articles and reviews were identified through searches in the medical databases:

- Medline/PubMed held by the National Centre for Biotechnology Information, http://www.ncbi.nlm.nih.gov/pubmed/
- Science Citation Index by Thomas Reuters http://thomsonreuters.com/products_services/science/science_products/a-z/web_of_science/, and
- PsycINFO by the American Psychology Association (http://www.apa.org/pubs/databases/psycinfo/index.aspx)

Additional reports and documents, for example from the WHO and the EC, have been identified via searches on the internet and contacts with experts in the field. Furthermore, a number of work-shop reports from recent EU-projects on noise have been scanned. In particular, we examined the conclusions of the European Network on Noise and Health (ENNAH), funded by the European Union's Seventh Framework Program (2007–2013), www.ennah.eu. The ENNAH-network was coordinated by Queen Mary University of London and brought together noise experts from 33 European research centres in order to establish future research directions and policy needs for noise and health in Europe. An important task of the network was to identify gaps in noise and health research and to assess, prioritize and integrate the future research into policy development. Furthermore, the network aimed to develop connections between air pollution and noise researchers in order to exchange views on how the pollutants can be further studied jointly.

4 Background

Environmental noise is an inevitable nuisance in the urban community. Despite efforts to restrict the exposure, noise pollution is an increasing problem, primarily as a consequence of the continuous urbanization and growth of the transport sector [8]. The major contributor to the overall burden of environmental noise is traffic, primarily road, railway and aircraft traffic. However, noise from neighbours, construction sites and industrial plants also contribute.

According to the first round of the strategic noise mappings of the END, approximately 65 million people who live in agglomerations with more than 250 000 inhabitants are exposed to noise levels exceeding 55 dB L_{den}, the EU benchmark for excessive noise [6]. Road traffic is the dominating source with 55.8 million exposed, followed by railway and aircraft traffic with 6.3 million and 3.3 million exposed, respectively. Additionally, among people living outside of agglomerations, approximately 40 million people are exposed to noise levels exceeding 55 dB L_{den} from major roads, railways and airports (34, 5 and 1 million for each source, respectively). Based on figures on the total number of inhabitants in EU, which amounts to approximately 500 million [9], more than 20% of the population is thus exposed to traffic noise levels ≥55 dB L_{den}. These numbers are, however, most likely an underestimation of the total number of exposed since the END mappings do not provide a full coverage of the EU. In Sweden, the number of people exposed to traffic noise levels ≥55 dB L_{den} according to the first round of the END mappings were estimated to 1.1 million [10]. Based on a total population of approximately 9 million, this corresponds to 12%. Sweden thus appears to be somewhat better off when it comes to the fraction of exposed in comparison to EU as a whole. However, a more detailed and nationwide analysis of the traffic noise situation for the year 2006 showed that approximately two million people (22%) in Sweden are exposed to traffic noise exceeding 55 dB L_{Aeq24h}: 1 730 000 to road traffic, 225 000 to railway and 13 000 to aircraft noise [11]. Corresponding data for industrial noise exposure is lacking.

Absence of quiet and restorative areas in the society affects our health and well-being. Although environmental noise is not directly damaging to the auditory system, it may influence us in many other ways. A primary response to unwanted sound is general annoyance, which is characterized by a feeling of discomfort or irritation. According to the Swedish National Environmental Health Survey from 2007, 14% of the adult population (18–80 years) were annoyed by noise from any of the traffic noise sources at least once a week [12]. This was an increase with almost 40% compared to a similar survey performed in 1999 [13]. Other effects of excess noise include impaired communication and speech intelligibility, reduced performance and learning, sleep disturbances and physiological stress reactions. Results from the National Environmental Health Survey 2007 indicated a rise in the number of persons reporting disturbed communication due to noise, from 1% in 1999 to 2% in

2007, as well as in sleep disturbances, from 3% to 4%. If the noise exposure persists over an extended period of time, increasing evidence suggests that more severe health consequences, such as cardiovascular diseases, may emerge as a result of prolonged physiological stress [4, 14].

An accurate exposure assessment is vital to research on health effects of noise. However, differences in the noise assessment methods of previous studies make the results difficult to compare. For instance, the studies have often used national calculation models and indicators. Furthermore, the quality of the input data may differ greatly. We therefore begin this review by a brief overview of the on-going harmonization process and the implementation of common noise assessment methods and indicators in the EU.

Although people are often exposed to noise from more than one source at a time, few studies have considered the physiological and psychological effects of noise from multiple sources. Also, the possibilities of taking varying exposures during the day into account (at home, work and during leisure time) have been limited. We therefore summarize what is known so far about the combined effect of noise from varying sources and of fluctuations of noise throughout the day.

Furthermore, knowledge about "exposure modifiers", that is, factors that may modify the noise on its pathway from source to receiver, is important for a correct assessment of noise-induced health effects and may also be crucial to protect individuals from excess noise. Here, we review and discuss what is known regarding the effects of acoustic insulation (including window opening behaviour) and access to a quiet side.

Health effects included in relation to traffic noise in this review are annoyance, sleep disturbance, performance and learning, and cardiovascular disease. Additionally, we highlight possible impacts of noise on the metabolic system, for which there is a clear biological mechanism but very limited epidemiological evidence. In relation to cardiovascular disease, we review the current stat-of-art of the knowledge on the joint effects of noise and air pollution. Noise and air pollution stem from the same source, that is, road traffic, and may therefore be correlated. Also, both exposures have been associated with effects on the cardiovascular system, although through partly different mechanisms. Here, we discuss some possible solutions to investigate both separate and synergistic effects of noise and air pollution.

Few studies have investigated noise related health and well-being among residents living close to industries. These studies only measured noise annoyance or similar self-reported disturbances. Because of the lack of studies on other end-points, the review will be limited to what is known regarding industrial noise exposure and annoyance.

The associations between noise and health are modified by several factors and individuals may therefore be more or less affected by the noise. These so called "effect modifiers" can be demographic factors, for instance age, sex and socioeconomic position, personal or attitudinal factors, such as noise sensitivity and fear of the noise source, or related to the individuals lifestyle and occupation, including physical activity, psychosocial health and job strain. In addition, coping mechanisms, such as use of ear plugs or window opening behaviour, and situational factors, including time of day and type of activity, may modify the effect of exposure (Figure 1). Identification of risk groups, that is, individuals which are particularly vulnerable to noise, is of importance for assessments of public health impact and can serve as a basis for preventive measures. For each specific health outcome, we therefore summarize the available evidence on factors that may modify the effect of noise, and thus the risk of disease.

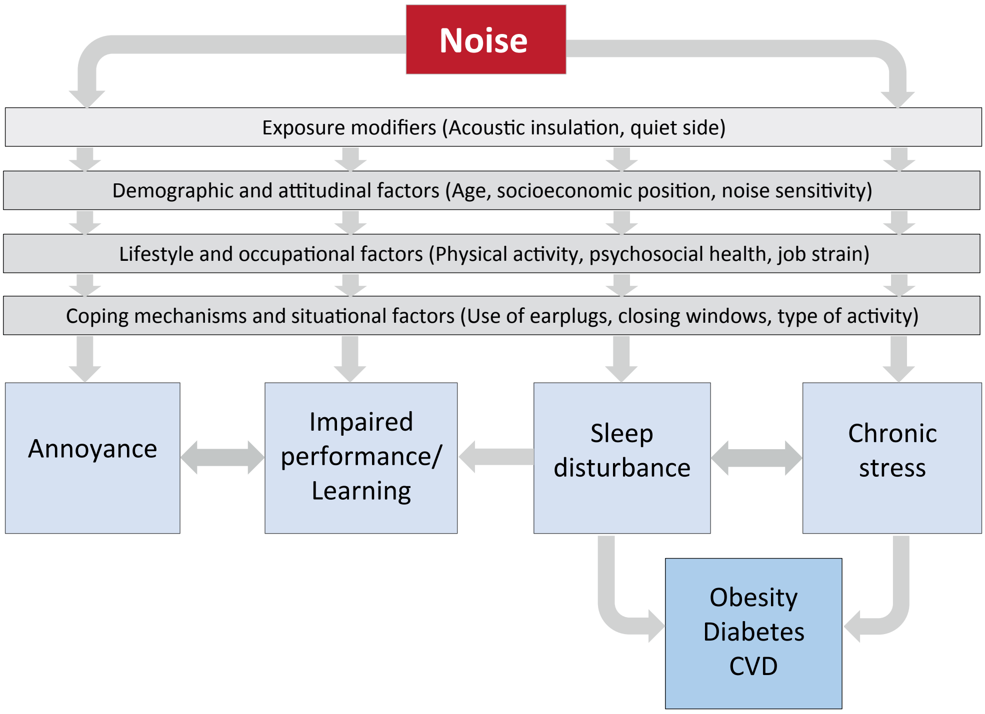


Figure 1. A framework for health effects of noise.

In a final section, we summarize the main research needs regarding health effects of traffic and industrial noise, respectively. The conclusions drawn are based on mechanistic knowledge as well as on epidemiological evidence. Methodological aspects, for example relating to study design and assessment of outcomes and exposures, have also been taken into account. It should be noted that a lack of evidence is not the same as a lack of an effect but merely indicate that no conclusions can be drawn yet since there are no data available, or, that the data at hand are of insufficient quality.

5 Traffic noise

5.1 Exposure

5.1.1 Common noise assessment methods and indicators

Noise and health researchers have assessed noise exposure in different ways [3]. Measurements, self-reported annoyance responses and various modelling techniques have been used to characterize exposure to noise. In terms of modelling, national calculation models and indicators are often used. Also, the quality and accuracy of input traffic data may differ, resulting in difficulties to compare the findings. However, during the last decades, improvements in computer capacity and the development of geographical information systems have greatly facilitated the production of digital noise maps, and thereby estimations of population exposure and health effects [15]. Residential traffic noise exposure assessments are easily made by linking address information (a geographical coordinate) to digital noise maps [16]. However, the accuracy of the estimates depends on the quality of the map, which in turn depends on the accuracy of input data and calculation methods used.

Since June 2007, the EU member states are obliged to produce strategic noise maps for all major roads, railways, airports, agglomerations and industries on a five-year basis. The maps are used to assess the noise exposure situation across the EU and to identify priorities of action planning. Article 6.2 of the END proposed that common assessment methods for the determination of the noise indicators L_{den} and L_{night} should be established in order to ensure consistency of noise exposure data across the EU [5]. Until the common assessment methods are adopted, the Member States are allowed to use national assessment methods and noise indicators, provided that they give equivalent results as the interim methods suggested by the END (paragraph 2.2 of Annex II). However, an analysis of the comparability of the results generated by the different methods for the first round of the strategic mappings (2006–2007) showed that there were significant differences between the methods used [17]. The second round of mappings was reported to the EU by December 31st 2012 but no conclusions have been drawn with regard to methodological aspect so far. Presumably, there is still a great need for harmonization and common noise assessment methods for mappings of road, railway and aircraft traffic as well as industries are currently developed by the CNOSSOS-EU program [7].

The main objective of CNOSSOS-EU is stated as follows:

> *"The process should develop a consistent method of assessment capable of providing comparable results from the strategic noise mapping carried out by MS to fulfil their obligations under the END."*

The first phase (phase A) of CNOSSOS-EU lasted from 2009 to 2012 and aimed at developing a methodological framework for the process. Core activities of this phase have included:

- Development of a quality framework describing the objective and requirements of the common noise exposure assessment methods
- A description of the noise source emission and sound propagation for road traffic, railway, aircraft and industrial noise, respectively
- A description of the methodology chosen for aircraft noise prediction
- Development of a methodology to assign receiver points to the facade of buildings and to assign population data to the receiver points
- Development of "Good practice guidelines" for competent use of CNOSSOS-EU

The development phase is now followed by an implementation phase (phase B), which is intended to take place between 2012 and 2015. The main goal is to have the common noise exposure assessment methods fully implemented to the next round of mappings, foreseen in 2017. Additional activities planned in phase B include the set-up of a common noise exposure database to which the national databases will be transferred, development of a common reference software and development of procedures for validation of the CNOSSOS-EU methodological framework.

The CNOSSOS-EU has been designed to make cost-efficient calculations and it may therefore not be the optimum method for other purposes than the strategic noise mappings. Phase B will therefore also include an extension of the methodological framework to allow for more precise exposure assessments on a local scale. For the purpose of action planning, preservation of quiet green areas and assessment of health effects, it may for example be of importance to map also noise levels below 55 dB L_{den} and 50 dB L_{night} and to use a finer resolution than 5 dB contour bands [18]. Furthermore, the calculations of sound power emissions need to be adapted according to local conditions. For example, the equations for estimating sound power from road traffic are derived to be valid under certain reference conditions: A constant vehicle speed, a flat road, an air temperature of 20°C, a virtual reference road surface (consisting of an average of dense asphalt concrete 0/11 and stone mastic asphalt 0/11, between 2 and 7 years old), a dry road surface, a vehicle fleet corresponding to the European average and no studded tyres [7]. For Swedish conditions, it is of particular importance to make corrections for air temperature and use of studded tyres. The yearly average temperature in Sweden varies greatly, from areas with –8°C in the north to +10°C in the south [19]. Rolling noise emission decreases when air temperature increases and not taking air temperature into account would bias the estimates. Studded tyres are commonly used during the winter months in Sweden. According to data from 2009, 70% of all cars had studded tyres between December to April [20]. However, since certain regions have implemented bans of studded tyres on selected roads, for example in the city of Stockholm, a decline in the use of studded tyres has been noted [21]. Since studded tyres cause a speed dependent increase in the rolling noise, local data on the use of these tyres should be used for the calculations of sound power emissions.

To facilitate comparison with international reporting, use of the common EU-indicators L_{den} and L_{night} are recommended. However, for research purposes, the setting and study objectives will determine the kind of noise assessment (timeframe, indoor or outdoor noise) that is required [22]. Depending on the outcome under study, it is important to apply a reliable noise-dose descriptor, which may not only include the mean noise level but also the maximum noise level or the number of events. For long-term health effects, the $L_{Aeq,24h}$ or the L_{den} are usually the best summary measure of noise, however, for short-term biological effects, such as heart rate or cortisol levels, other measures reflecting the momentary noise exposure should be used. It is also of importance to separate effects occurring during day-time and night-time. As an example, effects on sleep should preferably be estimated using the L_{night} as an indicator of the exposure, while effects on learning and performance in schools should use day-time indoor noise, perhaps measured noise levels in the classroom [23]. Furthermore, the L_{den} is a weighted noise indicator (+5 dB for evening hours and +10 dB for night hours) which may not be the best option for assessing some of the health effects. In principle, non-weighted noise indicators may therefore be preferred [18].

When fully developed, the END maps may provide a valuable tool for estimations of the number of exposed which are comparable across EU, thereby serving as a basis for action planning. Furthermore, with some refinements of the maps, they could also be used on a local scale for urban planning, identification and preservation of quiet areas as well as for assessing health effects in relation to noise in research settings. It is therefore desirable that noise mappings in Sweden should adhere to the CNOSSOS-EU requirements, although some adaptions and refinements are needed.

5.1.2 Noise from multiple sources

Noise from multiple sources refers to the presence of different noise sources at the same time, such as road-, railway- and aircraft traffic or industries. However, it may also refer to noise exposures that are present at different times of the day; traffic noise in the home environment, occupational noise at work, leisure noise during spare time activities or neighbourhood noise during relaxation periods [18].

A number of older studies have assessed annoyance in situations with two or several noise sources. In a review of those studies, published in 1998, Fields concluded that residents' reactions to one source (for example road traffic) are only slightly or not at all reduced by the presence of another noise source (for example aircraft) [24]. There was, however, considerable variation from study to study, so it is of course possible that interactions between sources may exist in some environments but not in others. In a Swedish study from 2007, Öhrström and colleagues investigated annoyance due to single and combined exposure from railway and road traffic in a socio-acoustic survey among 1 953 residents in the municipality of Lerum, Gothenburg [25]. In areas exposed to both railway and road traffic noise, it was found that the proportion of annoyed was significantly higher than in areas with one dominant noise source with the same total noise exposure ($L_{Aeq,24h}$). This indicates an interactive effect between the two exposures which was statistically significant and increased gradually from 59 dB.

Apart from annoyance studies, little evidence is available on the combined effects of noise from multiple sources. Although it has been repeatedly shown that the degree of noise annoyance differs according to the mode of traffic [26], much less is known about the differences in physiological effects between the traffic noise sources. However, in a recent polysomnographic laboratory study, the single and combined effects (double and triple) of road traffic, railway and aircraft noise on sleep and recuperation were assessed among 72 adult subjects [27]. Cumulative effects of double as well as triple exposure nights were observed for sleep continuity variables (frequency of awakenings, arousals and sleep stage changes) as well as for subjective sleep quality (falling asleep, sleep disturbances and recuperation) in comparison to nights with single exposures only. However, no significant cumulative effects were observed for average heart rate, performance or memory consolidation. This study also showed that road traffic, railway and aircraft noise affects the objective and subjective assessment of sleep differentially. For example, it was found that road traffic noise led to the most prominent changes in sleep structure and continuity whereas the subjective assessments of sleep were worse after nights with aircraft or railway noise. These differences could be explained by spectral and temporal compositions of the noise. However, since these are laboratory findings, field studies are needed to confirm and validate the results.

Health effects of cumulative exposure to noise from several sources over the day have not been investigated. One primary reason for this is that the methods for assessing personal noise-doses during the day are inadequately developed. The ENNAH network concluded that accumulating noise energy throughout the day, in terms of a personal dose, is not the best option for assessing effects of combined noise. Rather, the noise levels should be related to specific activities, for example using time-activity patterns in relation to noise exposure [18].

The issue of multiple noise exposure can be extended to include also historical exposure. In longitudinal studies, the exposure to noise must be weighted over an extended period of time. Different studies handle this in different ways; through sensitivity analysis, energy summation or calculations of linear time-weighted average sound levels. Clearly there is a need to standardize these procedures. One approach suggested by the ENNAH network is to calculate person-months of exposure where subjects move from one noise category to another. This approach would enable time-window analyses and studies of the effect of different combinations of source specific noise and length of exposure. This is for example useful to ascertain the induction time of noise on different health effects and to assess effects of long-term and short-term exposure.

5.1.3 Exposure modifying factors

Exposure assessments are not only limited to mappings or measurements but also include assessment of factors that may modify the noise on its path from source to receiver, or in other ways alter the individuals exposure to noise. Not taking these factors into account will lead to incorrect exposure assessments which will result in biased estimates of the true relationship between noise and health. Two main exposure modifiers are discussed in this report, namely acoustic insulation (including window opening behaviour) and quiet facades. Other exposure modifiers, for example use of ear-plugs and height of buildings, may also be of importance but are not further elaborated here.

ACOUSTIC INSULATION

The standardized noise indicators in the END maps refer to outdoor exposures at the most exposed facade of the building. However, for the study of health effects, disturbed sleep in particular, indoor noise levels may be more relevant than outdoor levels. Indoor noise levels are determined by the sound power emission and frequency composition of the outdoor noise sources, the attenuation due to the noise reduction of windows, individual window opening behaviour and, to a lesser degree, facade reduction above the reduction due to windows [18].

With regard to frequency composition of the noise, road traffic noise typically contains high sound pressure levels at low frequencies, especially at frequencies around 60 Hz. In this frequency range, sound insulation is less effective than at higher frequencies. Noise from inter-city and commuter trains, which has less energy in the low-frequency part of the spectrum, is therefore more reduced by windows and facades than road traffic noise.

The degree of attenuation by windows and walls depends on factors such as the type and construction year of the building, type of window glazing and materials used in the walls. The simplest types of facade usually reduce the sound by less than 24 dB while the most elaborate facades have sound reductions of more than 45 dB [3]. Double-glazed windows, which are the most common type of window in central Europe, have an average sound reduction of 30 to 35 dB. Insulation of facades and windows are commonly used measures to reduce noise exposure. The efficacy of acoustic insulation in reducing indoor noise annoyance has been assessed for example in the Norwegian facade insulation study, performed by Amundsen and colleagues, using a before-and-after design [28]. Before insulation, and with an average noise level of 71 dB $L_{Aeq,24h}$ at the most exposed facade, the average indoor noise level was 43 dB $L_{Aeq,24h}$. After the implementation of facade insulation, the indoor noise levels were reduced by an average of 7 dB $L_{Aeq,24h}$. This resulted in a reduction of the percentage of people who were highly annoyed by noise in their homes from 42% to 16%.

Window opening behaviour is also of importance with regard to indoor noise levels. In the National Environmental Health Survey from 2007, almost 13% of the respondents reported that they always sleep with open window and only 17% reported that they never have their windows open during sleep. When windows are slightly open, the outside sound levels are only reduced by 10 to 15 dB [3]. Keeping windows open may thus modify the individuals' exposure to traffic noise substantially. In addition, since the WHO has recommended that people should be able to sleep with their bedroom window open, window opening behaviour should be taken into account in the planning of new buildings.

The Swedish Environmental objective "A good built environment" states that, by the year 2020, buildings and their characteristics shall not be harmful to human health. An overall goal is that all buildings shall fulfill the requirements on noise protection set for new construction works, although deviances of maximum 5 dB can be accepted in exceptional cases. By this goal, 90% of the Swedish residents will experience a satisfactory sound level within their homes. However, in a report from the Swedish National Board of Housing, Building and Planning, which describes the conditions of Swedish real estates with regard to damages, lack of maintenance and technical status [29], it is estimated that sound related efforts are needed in almost one third of the apartment block buildings. Thus, to reach the Environmental Objectives, approximately 50 000 buildings are in need of acoustic insulation measures. The number of people living in these buildings is estimated to 1.2 million.

Clearly, there may be large differences in the buildings' capacity to reduce noise emissions and many people live in buildings with inadequate insulation to noise. However, few epidemiological studies consider acoustic insulation when assessing residential traffic noise exposure.

QUIET SIDE

Another factor that may modify the exposure to traffic noise is access to a quiet side. Effects of road traffic and the benefits of access to quietness have been studied in depth in the Swedish multi-disciplinary research program Soundscape to Support Health [30, 31]. This report defined a 'quiet side' in urban areas as:

> *"a side with $L_{Aeq,24h}$ <45 dB (free field value with the association + 3 dB 2 m from the facade) combining noise from traffic, fans or similar and, if existing, industry. The quiet side shall also be visually, functionally and acoustically attractive to stay in."*

Various other definitions of quiet facades are also used. However, these levels are generally higher than what would be desirable from the view point of preventing harmful effect of noise. In the END, a quiet facade is defined to be at least 20 dB lower than at the most exposed facade [5]. However, if for example the most exposed facade has a noise level of 75 dB, a noise level of 55 dB would be considered as "quiet". In the ongoing EU project QSIDE, aiming at protecting quiet facades and quiet urban areas, ideas are explored to recommend a range of levels rather than a single limit level for quiet facades (and areas) [32]. So far, however, no consensus has been reached in this matter.

One of the main aims of the Swedish Soundscape to Support Health research program was to evaluate how having access to a quiet side of one's dwelling affected the reporting of annoyance, activity interference, sleep disturbance and overall wellbeing [30, 31]. It was found that, to some extent, a quiet side of the building can compensate for high noise levels at the most exposed facade. The results showed a clear difference in the reporting of annoyance between persons living in noise exposed buildings (45–68 dB $L_{Aeq,24h}$) if they had access to a quiet side or not (defined as 35–45 dB $L_{Aeq,24h}$). Among the most highly exposed (63–68 dB $L_{Aeq,24h}$), 57% reported annoyance if they did not have access to a quiet side, compared to 38% among those who did have access to a quiet side. A quiet side reduced the annoyance corresponding to a reduction of the sound level of approximately 5 dB at the most exposed facade. The benefits of having access to a quiet side was also apparent for sleep disturbances, where the number of complaints almost halved among those with access to a quiet side, and stress related symptoms, such as anxiety, irritability and fatigue. This study also concludes that sound levels should not exceed 60 dB $L_{Aeq,24h}$ at the most exposed facade in order to protect most people (80%) from experiencing annoyance or other adverse health effects, even if there is a quiet side of the building (defined as <45 dB $L_{Aeq,24h}$).

Other studies investigating the effects of a relatively quiet facade on annoyance response include the Norwegian facade insulation study [28] and a Dutch study by de Kluizenaar and colleagues from 2011 [33]. In Amundsen and colleagues, the size of the benefit from having a bedroom at the least noisy side of the building was estimated to 6 dB. de Kluizenaar and colleagues defined a quiet facade as a difference of more than 10 dB L_{den} between the most and the least exposed facade. Annoyance was less likely among those with access to a quieter facade, corresponding to a noise reduction of approximately 2.5 dB L_{den}. de Kluizenaar and colleagues also investigated building structures in relation to the facade differences. It was found that typical building structures which result in large differences between the facades are those oriented parallel to the source (for example a road or railway) or those built in a u-shaped formation, creating a noise shielded side. Buildings that are exposed from more than one direction, for instance near cross roads or those oriented with the gable towards the road, often have less than 10 dB differences between the facades.

The current standard methods for assessments of traffic noise exposure do not take acoustic insulation into account. Furthermore, their predictions are less precise for noise shielded sides of buildings and at large distance from the source, for example in quiet areas. Efforts are, however, made to improve the exposure assessments, taking these factors into account. For example, the European project "Quiet City Transport" (QCITY) has suggested an approach for refining the exposure-response functions, taking into account acoustic insulation, quiet facade as well as quiet areas in the neighbourhood [34, 35]. The basic idea of the QCITY approach is that the sound level at the most exposed facade is replaced by an "effective" level that includes contributions from the level at the least-exposed facade and the ambient level in the neighbourhood of the dwelling. In the subsequent QSIDE project, preliminary numerical parameters for the correction terms of quiet facades and areas were determined based on available information [32, 36]. In addition to the refined acoustical model, the QSIDE project also aimed at deriving a human-response model for calculating the beneficial effect of quiet facades and areas. This model is based on existing databases from studies which include relevant information, that is, noise levels at most and least exposed facade of buildings and self-reported annoyance responses of the residents. The noise score rating models for residents are currently further elaborated to include also frequency spectrum and temporal variations of the noise levels in the adjacent European program "Acoustically Green Road Vehicles and City Areas" (CityHush) [37].

In conclusion, the methods to assess traffic noise exposure vary greatly. An attempt is made to harmonise the methods by the CNOSSOS-EU program, although the full efficacy of this program has not yet been seen. It is, however, desirable that the Swedish noise exposure calculation methods are harmonized with European standards. Hopefully, the CNOSSOS-EU will be a useful tool in this process, but some adaptions and refinements of the models are needed. Furthermore, to improve the assessment of individual noise exposure, techniques should be adopted to take multiple and time-varying exposures as well as exposure modifying factors into account.

5.2 Health effects

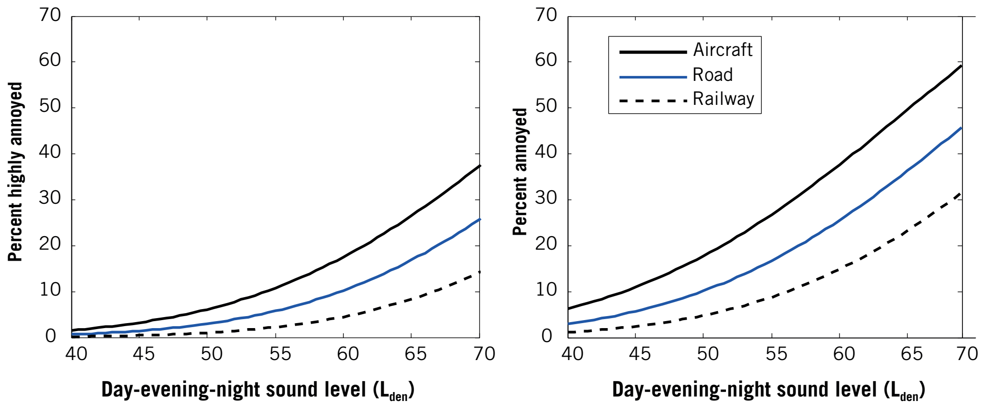
5.2.1 Annoyance

According to the WHO definition of health as "a state of complete physical, mental and social well-being and not merely the absence of disease or infirmity", noise-induced annoyance is an adverse health effect [4]. Noise annoyance is caused by noise related disturbances of the individual's speech communication, concentration and performance of tasks and it is commonly associated with negative emotional reactions, such as feelings of displeasure, anger and disappointment. Furthermore, annoyance may give rise to physiological symptoms, including tiredness, stomach ache and stress symptoms. In fact, noise annoyance is a symptom of stress building up inside as a consequence of signals transmitted from the auditory system to the nervous system, stimulating several reactions in our bodies [38].

Compared to other effects of environmental noise, there is a relatively large amount of data available for noise annoyance in the population. Noise annoyance is assessed in questionnaire studies, and is typically expressed as the percentage of exposed persons reporting annoyance above a pre-defined sound level. A wide variety of response scale has been used in previous research. For comparison across studies, their response scales have therefore to be transformed to a common unit. For example, Miedema and Vos compared data from a large number of studies by recoding the various annoyance scales to a common scale ranging from 0 to 100, and used cut-offs at 50 to define the percentage "annoyed" (%A) and 72 to define the percentage "highly annoyed" (%HA) respondents [26].

The comparability of annoyance studies have increased considerably since 2003, when the International Commission on Biological Effects of Noise and the International Organization for Standardization proposed two standardized scales for annoyance measurements: an 11-point numeric scale and a 5-point category verbal scale [39]. Since then, most annoyance studies have used one or both of these scales.

Synthesis curves for the exposure-response relationships between L_{den} and %HA or %A are presented in the EC "Position paper on dose response relationships between transportation noise and annoyance" [40]. The curves are based on an extensive set of data from 46 studies on traffic noise and annoyance (20 on aircraft, 18 on road traffic and 8 on railway noise) which were performed in Europe, North America and Australia between 1971 and 1993 [26, 41]. Figure 2 present the proportion of highly annoyed and annoyed persons as a function of the L_{den} exposure for each of the traffic noise sources. It is clear that for any given noise level, aircraft noise causes more annoyance than road traffic which in turn causes more annoyance than railway traffic (exact numbers of %HA and %A are presented in Table A1 of the appendix).



Source: Adapted from EC 2002.

Figure 2. The percentage highly annoyed (left panel) and annoyed (right panel) persons as a function of exposure to aircraft, road and railway noise (L_{den}).

There is some evidence that the exposure-response curves for aircraft noise has changed over time [42-45]. Results from the multi-centre study "Hypertension and Exposure to Noise near Airports" (HYENA) showed higher ratings of noise annoyance due to aircraft noise than the EU standard curves, possibly indicating a change in people's attitudes towards the noise [42]. No differences were, however, seen for road traffic noise.

Several explanations for the shift in annoyance have been suggested. In 2011, Janssen and colleagues investigated whether study and sample characteristics could explain the heterogeneity in annoyance response, analysing data from 34 separate airports [44]. The results suggested that several study characteristics can explain the increase in annoyance. Primarily, a shift in the type of annoyance scale, from 4 or 5 point categories to the 11-point scale, may have influenced the reporting of annoyance. Two further study characteristics associated with differences in annoyance are the type of contact, with the now commonly used postal surveys showing higher annoyance ratings than the previously preferred telephone or face-to-face interviews, and the response percentage, with higher annoyance in surveys with lower response percentages. However, this type of methodological explanations cannot explain why a change over time has been observed for aircraft noise annoyance but not for road traffic noise annoyance, which has been measured with the same methodology. Other possible explanations put forward by Janssen and colleagues include changes in the aircraft noise exposure which are not reflected by the noise exposure metrics (increased number of events, but each of lower sound level), shifts in the modelling of exposure (earlier models may have overestimated the exposure, or newer models may have underestimated the exposure) and increases in the rate of expansion of airports, possibly leading to an overreaction in annoyance response. Clearly, many factors predicting noise annoyance due to aircraft noise have changed and an update of the exposure-response relationships for aircraft noise is needed.

Although railway noise is estimated to cause less annoyance than road traffic and aircraft noise at the same noise level, new findings from the Swedish study “Train Vibration And Noise Effects” (TVANE) show that both the number of trains and the presence of ground-borne vibrations are of relevance for how annoying railway noise is perceived [46]. In areas with the most intense railway traffic (481 trains /24h), railway noise generated similar general noise annoyance as road traffic. Furthermore, in the presence of railway-induced ground-borne vibrations, the noise annoyance increased, corresponding to a difference in sound level of about 5 to 7 dB. Additional studies are, however, needed to confirm this, as well as to increase the knowledge on combined effects of railway noise and vibration.

Some groups in the population may be more vulnerable to traffic noise and although the noise-reaction relationship in populations generally show great similarities, the relationship on an individual level is not easy to determine since it has more dimensions than just physically measurable acoustical variables [38]. The differences between individuals in experiencing noise effects may be influenced by several non-acoustical factors, including for example age, sex, education level, occupational status, home-ownership, dependency of the noise source, noise sensitivity and fear of accidents.

In 1999, Miedema and Vos investigated the modifying effects of demographic and attitudinal factors on noise annoyance, based on the database used for deriving the EU exposure-response curves [47]. It was found that those who reported being sensitive to noise or expressed fear of the noise source were significantly more annoyed than those who were less sensitive and did not express fear. The impact of noise sensitivity on annoyance ratings has been confirmed in several studies and noise sensitivity is recognized as the most important individual characteristic for predicting dissatisfaction with road traffic noise [38, 48].

Demographic factors were found to have much less impact on noise annoyance; there were for example no differences between men and women [47]. However, some tendencies were seen. For example, middle aged persons seemed to be more annoyed than young and elderly. This finding was confirmed in a recent Dutch study which investigated how the response in noise annoyance changes across the lifespan [49]. In this study, it appeared that the percentage of highly annoyed subjects followed an inverted U-shaped curve with the highest proportion of annoyed among people in their mid-40s. A possible explanation suggested by the authors is that annoyance is determined by the average level of mental workload or cognitive challenge a person experiences in daily life. When there are limited cognitive resources to adapt to the noise, the annoyance tend to increase. However, this may also just reflect the general tendency of a lower well-being in middle age [50]. A possible explanation for the lower ratings of annoyance in the older ages is hearing acuity which makes people less susceptible to noise stimuli. There are clear exposure-response associations between traffic noise exposure and annoyance also for children. Generally, however, children reported less annoyance at higher noise levels [51]. Other factors related to a higher noise annoyance in the study by Miedema and Vos were high education and homeownership. In contrast, persons who were dependent economically on the activities caused by the noise source and those who used the noise source were found to be less annoyed.

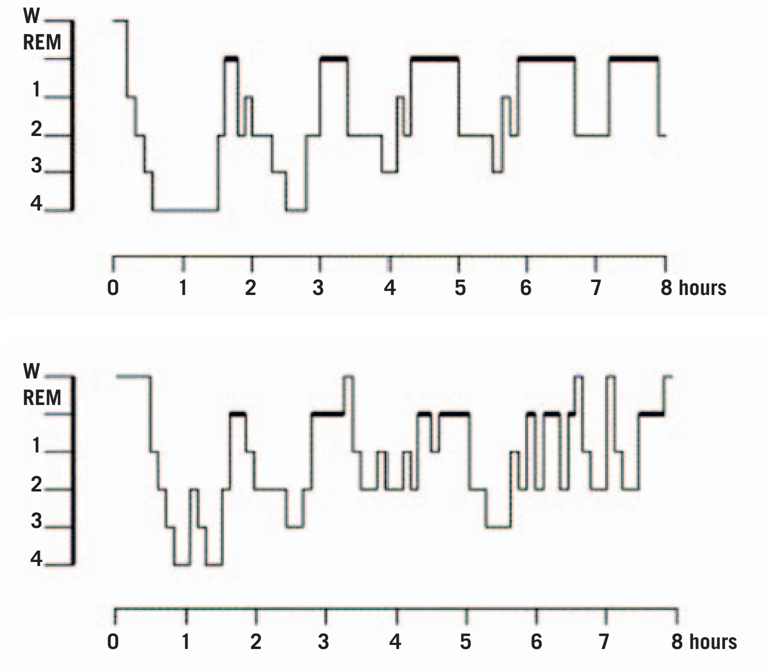
In summary, clear exposure-response associations exist between traffic noise and annoyance on a population level. At the same exposure level, aircraft noise causes the most annoyance, followed by road traffic and railway noise. Recent studies suggest an upward trend in noise annoyance in relation to aircraft noise which cannot fully be explained by methodological issues. New findings also suggest an increased annoyance in relation to railway noise in areas with intense railway traffic or railway-induced ground-born vibrations. These models thus need to be updated. Furthermore, exposure-response models for combinations of noise sources are lacking. On an individual level, there may be large variations in the annoyance response, depending on exposure modifying factors as well as on personal and situational factors. To identify risk groups in the population, more knowledge is needed on how these factors affect the level of annoyance.

5.2.2 Sleep disturbance

One of the most common complaints in noise exposed populations is sleep disturbances. Sleep is a biological necessity for mental and physical health and loss of sleep may have several detrimental health effects. Normal sleep has a clearly defined and stable structure of six different stages (Figure 3). Early in the night, the sleep pressure is high and the body goes into deep sleep (stage 3 and 4), also called short wave sleep [3]. The deep sleep is interrupted by several cycles of REM sleep. REM stands for rapid eye movement and refers to the stage of sleep where dreaming occurs, thus this stage is also called dream sleep. As the night progress, the sleep pressure reduces and we sleep lighter (stage 1 and 2). While the deep sleep appears to be an energy restoration state of the body, the dream sleep seems to be more related to mental and memory processes [52].

Immediate effects of noise on sleep include shortening of the sleep period, increased motility, sleep stage modifications, autonomic responses and awakenings [52]. The total sleep time may be reduced through a delay of the sleep onset, repeated awakenings during the night or a premature awakening in the morning. Motility, or bodily movements, is an important measure of sleep disturbances and have been found to increase with increasing noise level. The threshold of (aircraft) noise-induced onset of motility have been found to be on average 32 dB(A) $L_{Amax,\ inside}$ [53]. Night noise events may also cause transitions from a deep sleep stage to a shallower one, thus reducing the amount of deep sleep and affecting the rhythmicity of the dream sleep. Furthermore, since the auditory system is always open, noise may induce changes in the electric activity of the brain and activate our alertness systems [3]. Activation of the reticular activating, autonomic nervous and endocrine systems give rise to so called "arousals". Arousals are characterized by several physiological and psychological changes, such as increases in the levels stress hormones, heart rate, blood pressure and ventilation, constriction of the blood vessels, sensory alertness, mobility and readiness to respond [54]. The occurrence of acute cardiovascular effects of traffic noise during sleep has been demonstrated in epidemiological studies. For instance, in the multi-centre HYENA-study, aircraft noise during night-time was significantly associated with short-term increases in blood pressure as well as heart rate [55]. The $L_{Amax,\ inside}$ threshold for noise-induced arousals have been found to be about 35 dB(A), assuming a background noise level of 27 dB(A) [3].

If the noise stimulus is intense enough, the arousals may lead to awakenings. The awakening threshold depends on the sleeper's current sleep stage and has been found to be particularly high during deep sleep. In the morning hours, when the dream sleep is dominating and the sleep pressure is lower, awakenings occur more easily. Physical characteristics and signification of the noise may also affect the threshold; intermittent or sharp noise and meaningful sounds (speech) being particularly disturbing. Although arousals and awakenings occur spontaneously during sleep, noise-induced awakenings are more disruptive and require a longer recovery time than spontaneous awakenings and are therefore more often experienced consciously and also remembered afterwards. The threshold for waking up in the night and/or too early in the morning is around 42 dB $L_{Amax\ inside}$.



Source: Muzet 2007.

Figure 3. Hypnogram for normal (upper) and noise-disturbed sleep (lower).

Disturbed sleep, as described above, has several short and long-term consequences on well-being and health. The evidence for these has been summarized by WHO in the Night Noise Guidelines for Europe [3] and are given in the appendix of this report (Table A2-A4). Shortly, in addition to effects on well-being, such as self-reported sleep disturbance, use of sleep medication, tiredness during the day, irritability and impairments of cognitive functions, insufficient sleep may also cause medical conditions related to endocrine, metabolic and immune functions. For example, the cardiac responses that occur as a consequence of noise-induced arousals have been found not to habituate within the night [54, 56]. This indicates a chronic activation of the stress systems, in particular the Hypothalamic-Pituitary-Adrenal axis, which increases the level of stress hormones in the blood, for instance cortisol, which in turn may increase the risk of cardiovascular and metabolic diseases (for further reading, see the section on cardiovascular disease) [57]. Additionally, sleep loss is related to a decrease in the appetite regulating hormone leptin, which increases appetite and reduces energy expenditure, thus predisposing weight gain and impaired glucose tolerance [58-60]. There is also considerable evidence for a relationship between disturbance of sleep, especially deep sleep, and immune function. Sleep loss is related to an increase in C-reactive protein which promotes secretion of inflammatory mediators from the endothelium and contributes to the development of atherosclerotic lesions [61, 62].

Although so called polysomnography, that is, a method for recording the electric activity in the brain, is the gold-standard for measuring and evaluating sleep, the impact of noise on sleep is mostly assessed via self-reporting in environmental surveys. However, the survey questions often vary in type of disturbance (difficulty falling asleep, disturbances during the night, early awakenings) and number of response categories (varies between 2 and 11). In 2007, Miedema and Vos presented exposure-response functions for night-time traffic noise and self-reported sleep disturbance on re-analyses of pooled data from 24 studies [63]. As for annoyance, all sets of response categories were transformed into a 0 to 100 scale, using cut-offs at 72 to characterize individuals "highly sleep disturbed", 50 for "sleep disturbed" and 28 for "(at least) a little sleep disturbed". Also similar to annoyance, it was found that at the same average noise level, aircraft noise was associated with more self-reported sleep disturbance than road traffic, and road traffic caused more disturbances than railways.

There is a lack of data on changes in sleep disturbances due to environmental noise over time. However, as for annoyance, there may have been changes in study design and population characteristics as well as in people's awareness of the impact of noise on sleep that could shift the exposure-response curves upward. An update and reanalyses of the curves are therefore recommendable.

With regard to risk groups, age is an established predictor of disturbed sleep [3]. Old age is often related to poorer sleep quality and frequent awakenings, thus the elderly may be more easily affected by environmental noise. On the other hand, since old age is associated with impaired hearing, some people may also have a reduced risk of being disturbed. Fragmented sleep or insufficient sleep is highly relevant during childhood and children seem to require more time to recuperate from nights with restricted sleep than adults. Although the data is sparse, some clinical and observational studies indicate that inadequate sleep among children results in tiredness, attention deficits, irritability and difficulties in controlling impulses and emotions. There is also evidence of more long-lasting effects, such as impairment of cognitive and memory functions, resulting in reduce academic performance and learning, behaviour problems, reduced mental health, growth impairment and cardiovascular complications. Men seem to have an increased morbidity and mortality related to sleep problems than women although females tend to complain more about to sleep loss. However, there does not seem to be much of a sex difference in polysomnographical parameters; thus, these potential sex differences and their implications for health need further study. Other risk groups may include pregnant women, since pregnancy affects sleep negatively through awakenings and difficulties getting back to sleep, shift-workers, because their sleep period is during day-time when the exposure generally is higher, and persons exposed to other stressors than noise, for example high demands at work or psychosocial problems, which may increase the individuals total stress load.

A recent review summarized the findings on effects of environmental noise on sleep from the past 3 years and identified future research goals [64]. The paper assessed both short-term effects (arousals and awakenings) and long-term health impacts. Key findings from this review includes that 1) noise may induce arousals at relatively low exposure levels and independently of the noise source (traffic, neighbour and indoor noise), 2) new epidemiological studies support previous findings that night-time noise is likely associated with cardiovascular diseases in the elderly, and 3) that nocturnal noise exposure may be more relevant for the genesis of cardiovascular disease than day-time noise. Furthermore, the main issues to be addressed in the field of noise-induced sleep disturbance was found to be 1) studies demonstrating a causal pathway linking noise and disturbed sleep to long-term health, including cardiovascular disease, and 2) quantification of the impact from emerging noise sources, such as high speed rail traffic and wind turbines, on sleep.

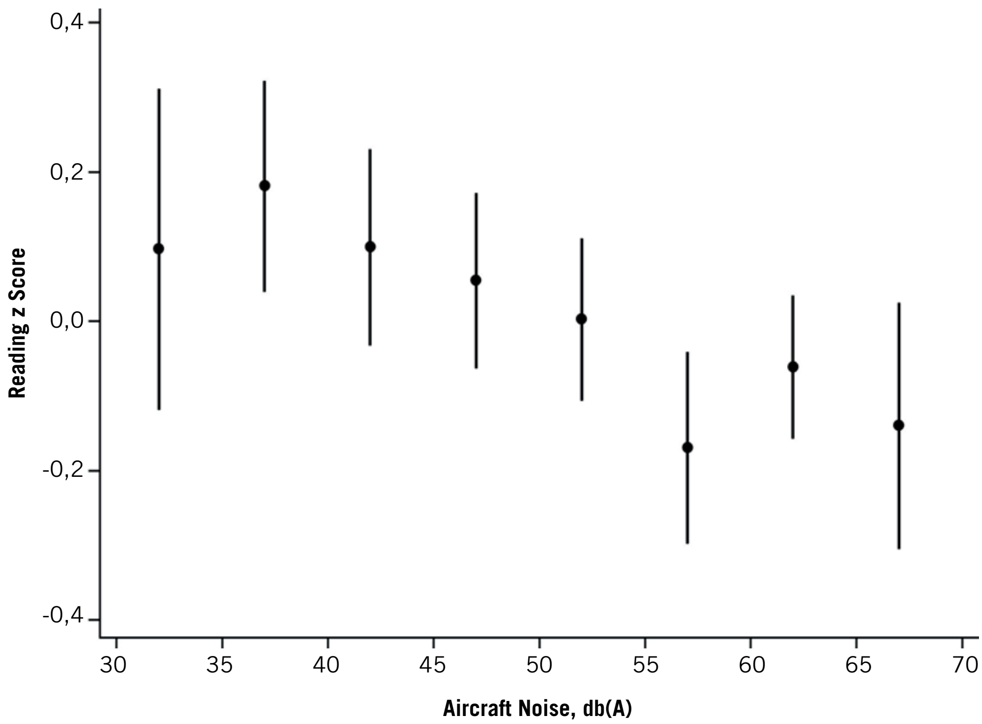
In conclusion, traffic noise is clearly linked to self-reported sleep disturbance in the population. Physiological effects of noise during sleep, such as increases in blood pressure and heart rate, are seen from 35 dB $L_{Amax, inside}$ and awakenings occur from 42 dB $L_{Amax, inside}$. Estimated threshold levels are, however, lacking for several effects, including changes in stress hormone levels. Data on the role of number of events during the night is also lacking. An expansion of the exposure-response models to include somatic stress reactions would provide useful knowledge as to where the harmful effects of noise begin. Furthermore, large-scale longitudinal studies are needed to demonstrate a causal pathway linking noise and disturbed sleep to long-term health effects, including cardiovascular and metabolic outcomes. In order to identify risk groups, these studies should also investigate factors which modify this association.

5.2.3 Performance and learning

Exposure to traffic noise disturb cognitive functioning, for example, how information is processed, retained and recalled, and thereby affect performance and learning. Several pathways for this mechanism have been suggested, including impairments of speech intelligibility, indiscriminate filtering out of noise during cognitive tasks resulting in loss of attention and concentration, increased arousal, noise annoyance and sleep disturbance [65]. Still, however, much is unknown regarding these mechanistic pathways and how they interact.

For cognitive effects of noise, it is important to separate the effect of day- and night-time exposure. While day-time exposure may affect encoding and acquisition of information, night-time exposure is more likely to interfere with storing of the material to be remembered or learnt [3]. However, noise-induced chronic insomnia may lead to day-time effects in terms of fatigue, memory difficulties, concentration problems and slow reaction time, thus resulting in poor work performance and difficulties in learning new things.

So far, most studies on noise and cognitive functioning has concerned day-time noise at schools and effects among children [66-68]. These studies show that traffic noise may affect children in many ways, but that it primarily impairs reading comprehension, memory and motivation. In 2002, Hygge and colleagues studied the effects of aircraft noise on cognitive performance in 326 schoolchildren before the opening of the new Munich International Airport and the termination of the old airport [69]. This was the first study to show prospective impacts of chronic noise on cognitive functioning, in particular long-term memory. Reading and long-term memory effects emerged in children after the new airport was opened and disappeared when the old airport closed, thus providing strong causal evidence for an effect of noise on central language processing, as well as of the reversible nature of the impact. The to-date largest study on noise and cognitive functioning among children, "Road traffic noise and Aircraft Noise exposure and Children's cognition and Health" (RANCH), assessed the effects of exposure to aircraft and road traffic noise on cognitive performance amongst almost 3 000 children in the ages 9–10 years, attending 89 schools near three major European airports [66, 68]. It was found that chronic aircraft noise at school was associated with a significant impairment in reading comprehension, with a 5 dB $L_{Aeq,16h}$ difference in aircraft noise corresponding to 1–2 months of reading delay (Figure 4).



Source: Clark and colleagues 2006.

Figure 4. Adjusted mean reading z scores and 95% confidence intervals for 5-dB(A) bands of aircraft noise among 9–10 year old school children in RANCH.

Aircraft noise was in this study also linearly related to recognition memory, but there were no associations with working memory, prospective memory or sustained attention. Road traffic noise was not associated with reading comprehension or any of the other outcomes. The authors argued that the effects of aircraft noise might be greater because of its intensity, variability and unpredictability, which disrupt the children's concentration and distract them from learning tasks, and that road traffic noise, which has a more constant nature, may allow children to habituate and therefore would be less distracting [66]. A few studies among children have also shown associations between long-term noise exposure in the home-environment and impaired cognitive functions. In a study among fourth-grade school children living in the Tyrol Mountains, long-term exposure to ambient (road and rail) noise above 60 dB L_{dn} was significantly associated with memory deficits (intentional, incidental and recognition memory) [70].

There are no reliable field studies of chronic traffic noise exposure and cognition in adults [71]. Studies of day-time (office) as well as night-time (home) noise exposure on performance and learning among adults are therefore needed. Cognitive effects of traffic noise exposure at home could be mediated via sleep disturbances since lack of restorative sleep is harmful both to the physical and mental health (as described in the previous chapter). So far, no studies are available to quantify to what degree exposure to traffic noise at home impairs day-time performance and learning among adults. However, in a secondary analysis of the RANCH data, and additionally data from the Munich study [69, 72], an attempt was made to differentiate between day- and night-time noise exposure on children's cognition [73]. The results from these studies suggested that night-time aircraft noise exposure did not appear to add any decrement of cognitive performance in addition to what was seen for the day-time exposure. This suggests that day-time noise at school, or at the office, may be more important for performance and learning than night-time noise in the home-environment. However, the studies had methodological problems, such as a high correlation between day- and night-time exposures, which warrant further investigations of this matter. High traffic noise levels at home during evenings may also affect children's preparation of homework, but this has not been investigated.

Although the overall evidence for an effect of traffic noise on children's cognition has increased in recent years and studies have begun to establish exposure-effect thresholds, most studies have been cross-sectional with rather small samples, the natural experiment of the Munich study and the large sample RANCH study being the exceptions. Further longitudinal studies on large-scale samples therefore remain a research priority in order to establish exposure-response functions for cognitive effects of traffic noise among children [65]. Similar exposure-response functions should also be derived for adults, for day-time as well as for night-time noise exposure.

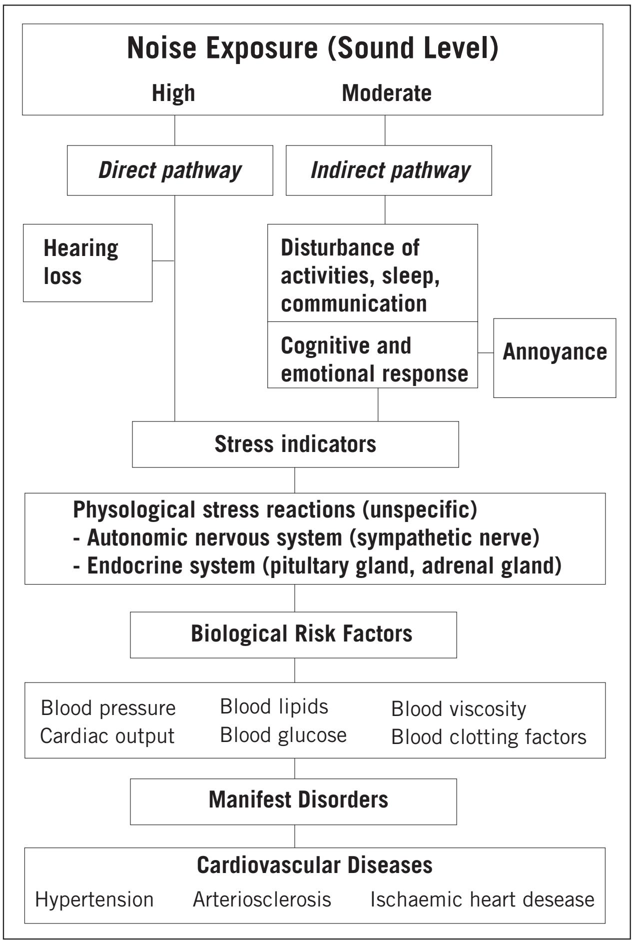
Little is known about modifying factors when it comes to effects on performance and learning of traffic noise. However, children are often pointed out as a particularly vulnerable group since excess noise may interfere with learning at critical stages of their development. Children also have less capacity than adults do to anticipate, understand and cope with the noise [68]. Likewise, the elderly may also be particularly vulnerable. Old age is often associated with a decreased mental capacity and noise may reduce the ability to understand the world around one and what is being said, as well as affect the short-term memory. Other risk-groups may include shift-workers, people with hearing deficits and persons with another mother tongue than the spoken.

To conclude, effects of traffic noise on performance and learning has mostly been studied among school children in cross-sectional settings. Aircraft noise exposure at school has been shown to impair children's reading comprehension, memory and motivation but there are no clear effects of road traffic noise. No reliable studies exist on traffic noise and cognition among adults. To derive exposure-response models on traffic noise and cognition, there is a need for longitudinal studies among children as well as adults; preferably separating between day- and night-time exposures. Further identification and definition of risk groups are also needed.

5.2.4 Cardiovascular disease

A harmful effect of traffic noise on cardiovascular disease has, even if it is small, high public health relevance given the large number of exposed individuals [3]. Cardiovascular diseases are a leading cause of death and include diseases of the heart (for instance myocardial infarction), vascular diseases of the brain (stroke) and diseases of blood vessels (hypertension). In 2008, the WHO estimated that 17.3 million people died from diseases related to the cardiovascular system, thereby accounting for one third of the global mortality. In terms of DALYs, the cardiovascular diseases account for 151 377 million life years lost globally [74]. In addition, cardiovascular diseases are closely related to metabolic diseases such as obesity and Type 2 diabetes. Obesity is rising steadily around the world and in 2008, the WHO estimated that more than 500 million adults (≥20 years) were obese (200 million men and 300 million women) [75]. Type 2 diabetes is also increasing and it has been appraised that more than 300 million people globally have diabetes [76]. The majority of these (90%) have Type 2 diabetes which to a large extent could be prevented by life-style measures, such as improvements of diet, increases in the physical activity and reductions of stress, smoking and alcohol.

The biological mechanisms through which noise may induce harmful cardiovascular effects have been thoroughly described [77-80]. Through subcortical connections, the auditory system is directly linked to the sympathetic branch of the autonomic nervous system as well as to the endocrine system. Exposure to loud noise may thus trigger a stress response, thereby affecting a number of physiological, metabolic and immunological processes (Figure 5). Generally, stress is induced by two different systems: the Sympathetic-Adrenal-Medullary axis and the Hypothalamic-Pituitary-Adrenal axis [81]. The Sympathetic-Adrenal-Medullary axis is primarily triggered during acute stressors and results in the secretion of catecholamines, that is, adrenaline and noradrenaline, from the adrenal medulla. This mechanism prepares the body for "fight-or-flight" by mobilizing energy to the muscles, heart and brain and reducing blood flow to the internal organs. The Hypothalamic-Pituitary-Adrenal axis is more involved in the long-term effects of both acute and chronic stress and is characterized by a "defeat reaction", associated with a lack of control, helplessness and feelings of distress, anxiety and depression. The endocrine response of the Hypothalamic-Pituitary-Adrenal axis stems from hypothalamus which releases various regulatory neuropeptides, for instance corticotrophin releasing hormone. This hormone activates a cascade of releasing hormones from the pituitary gland, amongst these, the adrenocorticotropic hormone. The target organ for adrenocorticotropic hormone, in its turn, is the adrenal cortex and from here, the glucocorticoid hormone cortisol is secreted [82, 83].



Source: Babisch 2002

Figure 5. The noise effects reaction schema according to Babisch 2002.

Over- or under activity in any of these stress systems may be detrimental to health. For example, lasting elevated levels of catecholamines have been shown to contribute to the development of atherosclerosis, thereby increasing the risk for hypertension and ischaemic heart diseases, including myocardial infarction [56]. Additionally, because the Hypothalamic-Pituitary-Adrenal axis may continue to be activated long after the stressor has been removed, it is of special interest for long-term cardiovascular, and also metabolic, effects of traffic noise exposure. Cortisol is an important regulatory hormone of the lipid and glucose metabolism and a prolonged dysfunction of its feedback mechanism may result in several health effects, including hypertension, centralization of body fat, dyslipidemia and insulin resistance [82-88].

Increasing epidemiological evidence suggests a long-term effect of traffic noise on the cardiovascular system [3, 14]. The Night Noise Guidelines present an updated review of sixty epidemiological studies on noise and mean blood pressure, hypertension, ischaemic heart diseases and medication and drug consumption. For mean blood pressure, it was concluded that there is no evidence that community noise increases mean systolic or diastolic blood pressure but that this may be related to methodological issues among the studies, such as insufficient power and narrow exposure ranges. For children it is said that the findings are difficult to interpret with regard to possible health effects later in life. If any, the effects of noise on children's blood pressure are small and are not likely to pose a health hazard during youth but could increase the risk for elevations of blood pressure later in life. With respect to hypertension, studies on aircraft noise consistently show higher risks in higher exposed populations. However, so far, only one cohort study has been performed on aircraft noise and hypertension, showing significant associations between aircraft noise exposure ≥50 dB(A) L_{den} among men but not among women [89]. For road traffic, the overall picture is more heterogeneous. Older studies do not indicate any associations while some of the newly performed investigations do. For ischaemic heart disease, it was found that the risk appears to increase first above 60 dB(A). However, these results were based on studies on road traffic noise only since, at the time, no study had investigated associations between aircraft or railway noise and ischaemic heart disease. The studies on the relationship between the use of medication or purchase of drugs and community noise exposure were found to support the hypothesis of an increase in sleep disturbance and cardiovascular risk in noise-exposed subjects.

In addition to the WHO review, some recent meta-analyses have been carried out to assess quantitative exposure-response relationships between aircraft and road traffic noise, respectively, and hypertension and ischaemic heart diseases [90-92]. In 2009, Babisch and van Kamp made an attempt to derive an exposure-response relationship for the association between aircraft noise and hypertension, based on a meta-analysis of five studies considered reasonably valid [91]. A linear trend coefficient of 1.13 with a 95% confidence interval (CI) of 1.00–1.28 per 10 dB(A) L_{dn} was calculated, however, since there were large methodological differences between the studies, no conclusions regarding possible threshold values could be drawn and the results should be interpreted with caution. Concerning road traffic noise and hypertension, the evidence is not as limited. A meta-analysis from 2012 aggregated data from 24 observational studies in order to derive a quantitative exposure-response association [92]. The results showed a positive and statistically significant association with an odds ratio of hypertension of 1.034 (95% CI 1.011–1.056) per 5 dB(A) $L_{Aeq,16h}$ increase . With regard to ischaemic heart disease, no exposure-response association has been derived for aircraft noise since there are few available studies. However, in 2010, Huss and colleagues reported a significantly increased risk of mortality from myocardial infarction among subjects who had lived 15 years or more in areas exposed to aircraft noise ≥60 dB(A) L_{dn} in comparison to those living in areas with noise levels <45 dB(A); hazard ratio 1.5 (95% CI 1.00–2.2) [93]. This study may, however, suffer from residual confounding since it did not adjust for several important individual life-style characteristics (for example smoking, physical activity and diet). For road traffic, a meta-analysis conducted in 2008, pooling data from two descriptive and five analytical studies, revealed an odds ratio for myocardial infarction of 1.17 (95% CI 0.87.1.57) per 10 dB(A) $L_{Aeq,16h}$ increase. [90]. No exposure-response associations have been derived for railway noise since only a few studies are available [94-96].

Metabolic effects of long-term traffic noise exposure have so far not been investigated systematically. Two cross-sectional studies have considered metabolic parameters in relation to aircraft noise, but with conflicting results [97, 98]. One longitudinal study, performed in Stockholm County, Sweden, between 1992 and 2006, has investigated the long-term effects of aircraft noise on metabolic outcomes [99]. Preliminary findings of this study show statistically significant associations between aircraft noise exposure ≥50 dB(A) L_{den} and increases in waist circumference. Furthermore, a recent Danish cohort-study reported an association between road traffic noise and incidence of diabetes [100]. However, to establish a causal pathway between traffic noise and metabolic outcomes, more evidence is needed. Studies should preferably be of longitudinal design and include assessment of outcomes associated with the metabolic syndrome; for instance, waist circumference, blood lipids, glucose intolerance, insulin resistance and manifest Type 2 diabetes.

Although it until now has not been possible to identify any particular risk groups for the association between traffic noise and cardiovascular disease, some factors have been investigated with regard to effect modification. For example, findings from noise experiments have shown that the physiological reactions controlled by the autonomic nervous system are less pronounced in females than in males [77]. This is supported by findings from several epidemiological studies which indicate an increased risk of noise-induced cardiovascular disease in males but not in females [89, 94, 96, 101, 102]. However, these differences could be explained by methodological shortcomings of the studies. For example, an improper control of confounding by intake of sex hormones may have biased the results. Use of contraceptives and hormone replacement therapy have blood pressure lowering effects and may prevent, or postpone, the development of cardiovascular disease in females [103, 104]. Regarding age, contradictory results are reported. Although some studies report stronger effects among elderly [93, 105], the results are not consistent. For children, there is a lack of data and quantitative assessments can therefore not be made. Additional research is needed to clarify the modifying effects of several potential effect modifiers, including annoyance, noise sensitivity, socioeconomic status, employment (shift work) etcetera.

In addition to personal characteristics or traits, some additional factors have been found to modify the effect of noise on cardiovascular outcomes. These include residence time (subjects with a longer duration of residence in exposed areas seem to have an increased risk in comparison to those with shorter residence time), window-opening behaviour (opening windows appear to increase the risk), bed room position (the risk is smaller if the bed room is located towards a quiet side) and hearing impairment (hearing loss appears protective) [3].

In studies of noise and cardiovascular outcomes, it is also important to study the interactive effects with air pollution. Noise and air pollution mostly stem from the same source, that is, road traffic. Furthermore, the models used to calculate noise and traffic related air pollution concentrations use the same type of input data and the correlation may therefore be high. However, in the most recent review on noise and cardiovascular disease, examining the literature from 2008 to 2011, it is concluded that the correlations between noise and air pollution are not as high as many researchers feared [106]. Some reasons for the lower than expected correlations were suggested, including differences in the actual source and propagation paths, traffic density and meteorological conditions. For example, noise may be shielded by barriers or buildings and air pollution, in its turn, is greatly affected by wind directions and other meteorological conditions [18].

So far, relatively few studies have attempted to disentangle the cardiovascular effects of noise and air pollution [93, 95, 107-110]. Both exposures have, however, been linked to negative effects on the cardiovascular system, although through (partly) different physiological mechanisms. While noise may prompt a physiological stress response, air pollution is believed to induce vascular and systemic inflammation, thereby promoting atherosclerosis and thrombosis [111]. Improved knowledge on the mechanistic pathways, and possible biological interactive effects, are of importance to estimate the separate and synergistic effects of the two exposures. Based on mechanistic knowledge, studies can be enhanced through choices of exposure characterization and outcome specification. Another approach is to separate out effects by including spatial elements in the design of the studies. By investigating the correlation between traffic noise and air pollution, settings or situations can be identified in which the levels of the two exposures differs. Personal exposure measurements could be used to identify environments where the correlation is weak or strong. Some information on this is already available, for example it appears that noise varies less than air pollution over the season as well as on a day to day basis. Furthermore, the correlation between noise and air pollution seems lower in rural areas than in urban. Within cities, the correlation also fluctuates, depending on for example street canyon effects and shielding of buildings [18].

The most recent review on noise and cardiovascular disease, of the literature between 2008 and 2011, stated that “the weight of evidence clearly supports a causal link” [106]. However, it was also concluded that many questions remain to be resolved. Key issues identified were 1) establishment of threshold levels for adverse effects of noise, 2) assessment of how noise and air pollution may interact in disease causation, 3) identification of vulnerable groups, including effects of gender, 4) the effect of exposure modifiers, for instance location of bedrooms, and 5) improvement of epidemiological methodology.

In conclusion, although the evidence of a cardiovascular effect of traffic noise is increasing, in certain areas it is still inconclusive, limited or even lacking. To some extent, this is due to methodological problems. For instance, there is a lack of large-scale longitudinal studies. The key-focus in future studies on noise and cardiovascular outcomes should be on deriving source-specific exposure-response associations. In addition, efforts are needed to disentangle the effects of noise and air pollution as well as to identify particularly vulnerable groups. Furthermore, there are also plausible biological pathways between traffic noise and metabolic outcomes which have not yet been investigated systematically in epidemiological settings and therefore warrant further attention.

5.2.5 Burden of disease

The estimates of burden of disease from environmental noise presented by the WHO in 2011 [4] are based on calculations of DALYs. A brief description on the methods for calculations of DALYs can be found in the appendix of this report; more detailed information is available elsewhere [112-114].

The estimation of burden of disease attributed to noise annoyance was based on the exposure-response functions presented in ECs “Position Paper” on annoyance [40] in combination with the exposure distribution in L_{den} from the first round of mappings of large agglomerations (<250 000 inhabitants) in Europe according to the END [115]. With a conservative estimate of the disability weight related to high annoyance, equal to 0.02, annoyance accounted for 654 000 DALYs lost; by that being the second most important contributor to the burden of disease from environmental noise.

Sleep disturbances accounted for the main burden of DALYS related to traffic noise, with a total of 903 000 life-years lost each year [4]. This calculation was based on a disability weight equal to 0.07, synthesis curves for self-reported sleep disturbance from road traffic, aircraft and railway noise from pooling of 15 original datasets with more than 12 000 individual observations [116] and the exposure distribution in L_{night} from the first round of mappings of large agglomerations (<250 000 inhabitants) in Europe according to the END [115].

Cognitive impairment is not a clinical diagnosis, which makes the derivation of conventional exposure-response associations difficult. To quantify the burden of disease from cognitive impairments caused by environmental noise in children, the WHO used the following definition [4]:

> *"Reduction in cognitive ability in school-age children that occurs while the noise exposure persists and will persist for some time after the cessation of the noise exposure."*

The calculations of DALYs due to noise-induced cognitive impairments in children were based on a very conservative disability weight, equal to 0.006, hypothetical exposure-response curves derived from three epidemiological studies on aircraft and road traffic noise, reading and recall memory [68-70] and percentages of children exposed to various levels of noise (L_{dn}) within the EU population [117]. The number of DALYs attributed to noise-induced cognitive impairments among children amounted to 45 000; by that being the fourth most important contributor to the burden of disease from environmental noise.

For traffic related ischaemic heart disease, the calculation of DALYs was based on exposure-response associations for road traffic and myocardial infarction [90] and the exposure distribution in L_{den} from the first round of mappings of large agglomerations (<250 000 inhabitants) in Europe according to the END [115]. However, since there is a lack of data, several assumptions and "best guesses" have been made and the estimation of DALYs related to ischaemic heart disease should therefore be interpreted with caution. For example, the exposure-response associations were estimated solely from five studies, including males only and with differing sets of confounders. Since no exposure-response associations were available between traffic noise and other ischaemic heart diseases (for instance angina), the associations for myocardial infarction were applied for all ischaemic heart diseases. Furthermore, a lack of studies on aircraft and railway traffic precluded separate estimates for these sources. From the above mentioned data and a disability weight of 0.405, it was appraised that 1.8% of all myocardial infarctions was attributed to road traffic noise. Calculations from 2008 estimated the total burden of ischaemic heart disease in high income European countries to 3 376 000 DALYs, consequently 61 000 of these were attributed to traffic noise (1.8% of 3 376 000 DALYs) [4]. Thus, ischaemic heart disease is the third most important contributor to the burden of disease form environmental noise.

In conclusion, the estimates of burden of disease from environmental noise presented above depend on available information regarding exposure distributions in the population and exposure-response associations for each specific outcome. Also, the choice of disability weight affects the estimates greatly. Since the underlying information regarding these factors to some extent is limited and involve assumptions and "best guesses", the calculations of DALYs are more or less uncertain. The estimates should thus be interpreted with caution, in particular for cognitive effects and ischaemic heart disease where no reliable exposure-response associations are available. However, calculations of this kind may provide valuable information in risk estimation as well as for assessments of economic cost attributed to noise. Updates of the estimates of burden of disease from environmental noise are therefore recommended.

6 Industrial noise

6.1 Exposure

For this review, we will adopt the Swedish guidelines' definition of external industrial noise [118]. These guidelines apply to external noise from new and existing industries, including rail yards and harbours. They do not apply to noise from airports, roads, railways, shooting ranges, motor sport activities and construction sites. However, road and railway traffic at the industrial site, including noise from loading operations, is part of the site's noise exposure. The guidelines do not apply to wind turbine noise, which is regulated in other guidelines [119]. We will therefore not review research on wind turbine noise, but we will present some results for comparison with data from (other) industrial sources.

The characteristics of industrial noise vary considerably depending on type of machinery and activity. For example, rotating and reciprocating machines generate sounds with tonal components. Operations involving mechanical impact, such as shunting, riveting, and unloading of scrap iron, can generate high-level impulse noise, and systems that move air, such as fans and ventilation systems, often generate low-frequency noise [120]. Often, several sources jointly generate the noise from a given industrial plant. This means that a given plant can generate several types of noise, for example low-frequency noise from ventilation systems, impulse noises from operations involving mechanical impact, and sounds with tonal component from rotating components of machinery.

Although it is clear that industrial noise is less wide spread than transportation noise, little data is available on how many residents that are exposed to industrial noise in their homes. According to the first round of the strategic noise mappings of the END, approximately 0.7% of people in large cities were exposed to noise from large industries exceeding 55 dB L_{den}, and about 0.3% were exposed to levels exceeding 60 dB L_{den}. In comparison, more than 50% of people in large cities were exposed to road traffic noise exceeding 55 dB L_{den} [121]. Note, however, that the mapping of industrial noise only included the very largest industrial plants, and no Swedish industry was large enough to be included. It is therefore obvious that the percentage exposed persons would be much larger if smaller industries also had been included in the mapping.

No estimates exist of the number of persons exposed to industrial noise in Sweden. However, survey data can be used to picture the exposure situation. According to the Swedish National Environmental Health Survey from 2007, 2.2% reported that their dwelling had at least one window facing an industry or industrial area [122]. In comparison, 15% reported that their dwelling had a least on window facing a major road or highway and 4.3% that their dwelling was facing a railway line.

The same survey found that 0.7% of the adult Swedish population were annoyed 'at least once a week' by industrial noise. In comparison, 12% were annoyed by road-traffic noise, 2.8% by railway noise, 2.8% by aircraft noise and 2.4% by construction noise. Thus, in terms of number of annoyed residents, industrial noise seems to be less of a problem than noise from any of the main transportation noise sources or noise from construction sites. It must be borne in mind, however, that these data refer to questionnaire responses, which are influenced by the respondent's interpretation of the question. For example, some respondents may not include noise from rail yards or harbours in their definition of industrial noise.

The Swedish National Environmental Health Surveys did not find an increase in the percentage of persons annoyed by industrial noise between the years 1999 and 2007 [122]. Despite this, there are reason to believe that exposure to industrial noise will increase in the future. People continue to move into the large cities, which already are short of undisturbed spaces where to locate new residential areas. Therefore, such areas increasingly often are placed close to industrial areas, including harbours.

6.2 Guideline values

Guideline values for industrial noise are typically defined in terms of equivalent levels. Below is a compilation of Day-evening-night sound levels, L_{den}, from 14 European countries [123]. In this sample of countries, the average guideline value for industrial noise was 52 dB L_{den}, which is lower than for any of the three main transportation noise sources.

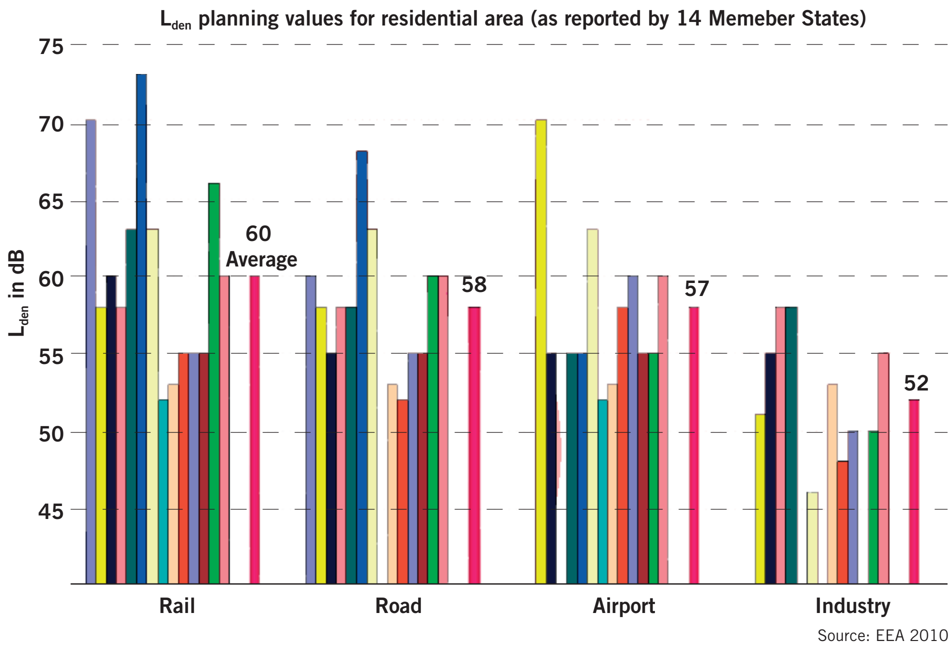


Figure 6. Planning values for industrial noise in residential areas as reported by some member states of the European Union [123].

The Swedish guidelines has separate values for the day (07.00–18.00), the evening (18.00–22.00), and the night (22.00–07.00). For the setting up of new industries, the guideline values are 50 dB L_{Aeq} for the day, 45 dB L_{Aeq} for the evening and 40 dB L_{Aeq} for the night. For existing industries, the values are 5 dB higher [118].

The Swedish guideline values are similar to the L_{den} in the sense that both treat evening noise 5 dB stricter, and night noise 10 dB stricter than day-time noise. A combination of 50 dB day-time noise, 45 dB evening noise, and 40 dB L_{Aeq} night-time noise corresponds to an L_{den} value of 50 dB. However, a guideline value of 50 dB L_{den} would allow an industry to produce 52 dB L_{Aeq} during the day, provided that the industry is quiet during evening and night. In this respect, the Swedish system is stricter than a system based on a single L_{den} value, because the former does not allow a compensation for high exposure during one part of the 24-hours with low levels during another part.

In contrast to most other European countries, Sweden complements equivalent-level guidelines with maximum-level guidelines. For transportation noise, two maximum-level guidelines are defined: 70 dB L_{Amax} and 45 dB L_{Amax} (fast time-weighting for road and rail, slow for aircraft noise). The higher level is intended to protect outdoor areas designated to rest and relaxation and applies outdoor during day and evening. The lower level is intended to protect sleep and applies indoors during night.

Unlike the transportation noise guidelines, the guidelines for industrial noise only define one maximum-level [118]. It is presumably intended to protect sleep indoors, but is defined as an outdoor level, 55 dB $L_{Amax,fast}$ during night (same value for new and existing industries). Assuming a facade and window reduction of 25 dB, this corresponds to an indoor level of 20 dB $L_{Amax,fast}$. With the window slightly opened, the reduction would be around 10 dB, which means an indoor level of about 45 dB $L_{Amax,fast}$.

Industrial noise includes many different noise sources, some of which have particularly annoying characteristics. Therefore, the Swedish guideline values include a 5 dB penalty for industrial noise that contains repeated impulse sounds or tonal components or both [118].

6.3 Health effects

Only a few studies have been published on noise related health and well-being among residents living close to industries. These studies only measured noise annoyance or similar self-reported disturbances. There are no data available on resident's cognitive functioning, learning, or cardiovascular health in relation to industrial noise exposure. This is also true for sleep disturbance, for which the WHO concludes that "For industrial noise there is an almost complete lack of information, although there are some indications [124] that impulse noise may cause considerable disturbance at night." ([3], p. 58, the cited article refers to shooting-range noise).

The lack of studies on other end points means that the following presentation will be limited to noise annoyance. The presentation will rely heavily on a single study, by Miedema and Vos [125], which is the only study on industrial noise published in recent years. However, three studies on wind turbine noise have been published and results from these studies will be used for comparisons with noise annoyance from (other) industrial sources (Swedish policy does not classify wind turbine noise as industrial noise). To our knowledge, studies are lacking on annoyance, or other health effects, caused by harbour noise.

Noise annoyance is a negative attitude or feeling of displeasure evoked by noise from a specific source, as a resident have experienced it during the last several months while at home. Noise annoyance is measured using category scales, with end points typically labelled ‘not at all annoyed’ and ‘extremely annoyed’. Noise annoyance is often expressed as the percentage of noise annoyed residents, that is, the percentage of residents in an area responding above a specific cut-of on the category scale, for instance, above the middle category or above 50 on a scale scored from 0 to 100.

Of particular interest is the relationship between the percentages of noise annoyed residents and their noise exposure, henceforth called exposure-response functions. Such functions can be used to predict the extent of noise annoyance in existing or future residential areas. Exposure-response functions also allow comparison of different noise sources in terms of their annoyance evoking potential. Such comparisons may assist decisions regarding guideline values for specific sources. Below, exposure-response functions for industrial noise will be compared with functions for road traffic noise and wind turbine noise.

Miedema and Vos [125] have published the only recent study on noise annoyance from industrial sources. This study was designed to make it possible to derive exposure-response relationships for industrial noise. Early studies, from the 1980’s, used methods for exposure or annoyances assessment that make them less usable for deriving exposure-response relationships (see review in [125]). For example, Gyr and Grandjean [126] used sound level measurements to assess noise exposure, which also included noise from other sources in the environment. Häberle and colleagues [127] related exposure to number of noise complaints, which is a poor indicator of annoyance, since many noise annoyed residents refrain from lodging complaints.

Miedema and Vos [125] interviewed residents living near nine industrial areas and two shunting yards about noise and other environmental factors. Five of the nine industrial areas consisted of one industry only; the other four consisted of two or three industries. The industries included chemical industries, synthetic fibre industries, paper and carton industries, glass industries, food industries, and one shipyard. The two shunting yards belonged to the Netherlands’ railways. Predicted L_{den} levels showed that most participants, 92%, were exposed to between 46 and 60 dB L_{den}. The remaining participants were exposed to levels below 46 dB, with the exception of two persons with exposure greater than 60 dB L_{den}. Telephone interviews were conducted to obtain responses from totally 1 875 residents, 84–262 residents per site. The response loss was about 35%. Noise annoyance was measured using a scale from 0 to 10, with end points labeled 'not at all annoying' and 'very much annoying'. Statistical analyses suggested that the residents living close to the shunting yards were more annoyed than other residents with similar exposure. Therefore, the shunting yard data was treated separately from the other industrial sites. Analyses also suggested that residents living close to a sugar industry with production only 90 days per year, during beets harvesting season, were considerably less annoyed than other residents and this data was therefore not included in the aggregated analyses of data from the other industrial sites.

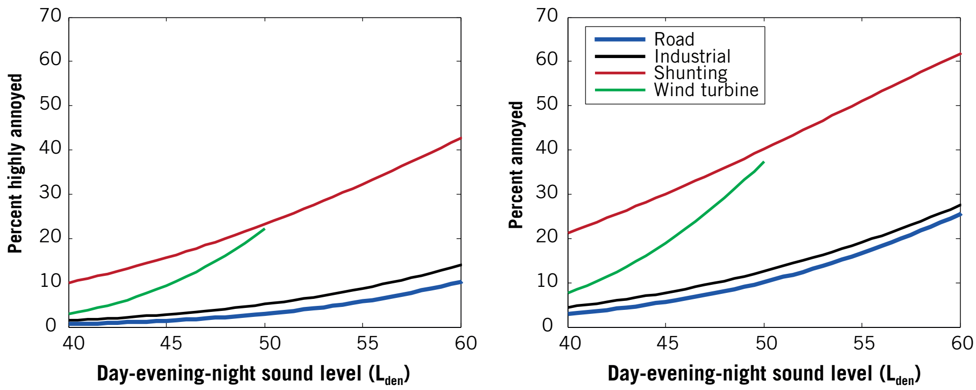


Figure 7. Exposure-response relationships for industrial noise, shunting yards, road traffic noise and wind turbine noise. Curves for industrial noise (black) and shunting yards (red) were taken from [125], curves for road-traffic noise (blue) from [128]. Curves for wind turbine noise (green) were derived from [129], by averaging functions for indoor and outdoor noise annoyance.

Figure 7 shows exposure-response functions derived separately for shunting yards (data from 2 sites and 212 observations) and (other) industrial sites (8 sites and 1 481 observations). We did not include a curve for the seasonal industry, since it was only one site with less than 200 observations (but results can be found in the original article [125]). The left diagram of Figure 7 shows functions for percent highly annoyed (%HA), and the right diagram show functions for percent annoyed (%A). The definition of %HA and %A follows the convention established in previous studies, in which %HA were calculated as the percentage of respondents with a score greater than 72, and %A as the percentage with a score greater than 50 on an annoyance scale scored from 0 to 100 (cf. [128]).

For comparison, exposure-response functions for road traffic noise and wind turbine noise are also included in Figure 7. The road traffic functions were derived from 26 studies with a total of 19 172 observations [128]. The wind turbine functions were derived from a compilation of three studies with a total of 1 820 observations [129]. The three wind turbine studies [130–132] used separate questions for annoyance outdoors and annoyance indoors. Annoyance outdoors is generally rated higher than annoyance indoors [129, 133]. For comparability with Miedema and Vos's study on industrial noise, which did not separate between indoor and outdoor annoyance, we averaged the published indoor and the outdoor exposure-response functions for wind turbine noise [129].

As seen in Figure 7, the exposure-response function for industrial noise (not shunting yard) is located slightly above the function for road traffic noise, suggesting that industrial noise is similarly or slightly more annoying than road traffic noise at the same L_{den}. In contrast, shunting yard noise seems to be considerably more annoying than road traffic noise or ordinary industrial noise at similar L_{den}. Shunting yard noise seems also to be more annoying than wind turbine noise at similar levels.

A way to quantify the difference between the exposure-response curves is to calculate exposure levels (L_{den}) for given percentages of annoyed residents. Table 1 show levels which, according to the exposure-response functions, are associated with 8% highly annoyed residents and 22% annoyed residents. We selected these specific percentages, because they corresponds to a typical guideline value for the most wide spread exposure, road traffic noise (the Swedish guideline value is 55 dB $L_{Aeq,24h}$, which is about 58 dB L_{den} for a typical 24-h-distribution of traffic volumes, cf. [134]). In addition to the industrial sources, we also included calculations for aircraft noise and railway noise in the table.

According to the calculations, the difference between industrial noise and road-traffic noise corresponds to a few decibels, 3 dB for %HA and 1 dB for %A. That is, industrial noise generates the same percentage annoyed residents as road traffic noise at a slightly lower exposure (L_{den}). Industrial noise seems to be less annoying than aircraft noise, and more annoying than railway noise at equal levels of exposure. In contrast, shunting yard noise is much more annoying than any of the three transportation noise sources. For example, 38 dB shunting yard noise generates the same percentage highly annoyed residents as 58 dB L_{den} road traffic noise. This is even worse than for wind turbine noise, which is another noise source that is considerably more annoying than transportation noises at comparable exposure levels.

Table 1. Day-evening-night sound levels (L_{den}) for various sources at equal proportion of annoyed residents, as predicted from published compilations of noise annoyance studies.

Noise source	Number of studies (total number of observations)		L_{den} for a given % annoyed residents (dB): 8% highly annoyed residents (%HA)	22% annoyed residents (%A)
Road traffic	26	(21,228)	58	58
Railway	9	(8,527)	64	64
Aircraft	20	(34,214)	53	53
Industrial noise	1	(1,481)	55	57
Shunting yard	1	(212}	38	41
Wind turbines	3	(1,820)	44	46

Note. Estimates for transportation noise derived from [128]; estimates for idustrial and shunting yard noise derived from [125],and estimates for wind turbine noise derived from [129]. Wind turbine noise estimates were derived by averaging the exposure-response functions for indoor and outdoor noise annoyance.

In summary, these results suggest that industrial noise, excluding noise from shunting yards, causes a similar or slightly higher percentage of noise annoyed residents as do road traffic noise, but is less annoying than wind turbine noise. In contrast, shunting yard noise seem to be much more annoying than road traffic noise, and also more annoying than wind turbine noise.

The data behind the exposure-response function for industrial noise (Figure 7) relates to eight industrial areas. These areas hosted several different industries, including industries producing paper, metal, glass, chemical and food products. It is therefore likely that a large variety of noises were generated at these sites, such as continuous noise from ventilation systems, impulse sounds from hammering or unloading of heavy goods, and noise from machines and generators. Despite this, the relationship between annoyance and L_{den} was fairly similar across the sites (cf. Figure 1. of [125]). This suggests that the variation in annoyance responses across different industrial sites is not too large to justify a single exposure-response function for this type of source (excluding shunting yards).

The difference between exposure-response functions for industrial noise (not shunting) and road-traffic noise should be interpreted with caution. The 95% confidence interval for the road traffic function (see [128]) is about ± 2.5 dB wide, and thereby includes the function for industrial noise. Furthermore, the confidence interval round the industrial function is likely to be wider than for road-traffic noise, given that the former function is based on a smaller number of studies and observations ([125] did not provide confidence intervals). More data is needed to determine if there is a sizeable difference in annoyance potential between industrial noise and road traffic noise. For now, it may only be concluded that the available data do not suggest a large difference in annoyance between the two sources.

The exposure-response function for industrial noise is clearly located below the function for wind turbine noise (Figure 7). Methodological differences between the wind-turbine studies [129] and Miedema and Vos's study [125] complicates the interpretation of this. The differences concern both exposure assessment and annoyance measurement. Exposure assessment, L_{den}, of wind turbine noise was based on prediction models including assumptions of wind speed variation over the year, whereas L_{den} of industrial noise was based on predictions of $L_{Aeq,24h}$ and data on when the industries were operating. It is unclear how these two exposure assessment methods differ in precision. Moreover, the exposure levels in the wind turbine noise studies were lower than in the studies of industrial noise, which means that comparison between the two sources rely on extrapolations of their exposure-response functions. Annoyance measurements in the wind turbine studies separated between experiences indoors and outdoors (the curve in Figure 7 represents an average of these measurements), whereas industrial noise annoyance was measured without reference to indoor or outdoor conditions. It is unclear how these differences in annoyance measurements may have influenced the results. It should be noted however, that both the indoor and the outdoor exposure-response functions for wind turbine noise would be located above the exposure-response function for industrial noise [129], which supports the conclusion of a sizeable difference in annoyance potential between the two sources.

What could make wind turbine noise more annoying than noise from other industrial sources? The ambient noise level may be an important factor. Wind turbines are often located in rural areas with low ambient noise levels, leading to high signal-to-noise ratios despite modest source levels. In contrast, industries are typically located in urban or suburban areas, close to major, and noisy, roads and railways. The signal-to-noise ratio for industrial noise could therefore be lower than for wind turbine noise despite a higher source level. A related factor is visual intrusion. Wind turbines studies have found that residents in homes from which the wind turbines are visible reported much higher annoyance than residents in homes from which the turbines could not be seen [132]. Possibly, wind turbines, which often are erected in non-industrialized environments, tend to be viewed as a less natural part of their environments than many industries, which often are located in built up areas close to cities and large roads and railways.

One question remains: What makes shunting noise so annoying? Miedema and Vos [125] discuss three factors: vibrations, noise from through trains, and the impulse character of the noise. Of these, vibrations seem to have been the most important factor in their study. Additional statistical analyses suggested that the extra noise annoyance of shunting yards partly was caused by annoyance due to vibrations, which also was assessed in the telephone interviews. Noise from through trains, not included in the L_{den} from shunting yards, was also found to explain a small part of the difference between shunting yard and industrial noise, although this explained less of the difference that vibrations. Including answer to questions on annoyance to impulse noise in the analyses did not, however, reduce the difference between shunting yard and industrial noise. Other industries also generated annoying impulse noise, which means that this factor did not strongly distinguish between the studied industrial sources and shunting yards. Note that these results should be interpreted with caution, given that only two shunting yards with only about 200 persons were investigated. It is difficult to determine to which extent these two shunting yards are representative for other shunting yards or for ordinary rail yards. Nevertheless, the results suggest that great care should be taken before dwellings are located close to such places.

7 Research needs

Overall, the knowledge on effects of environmental noise on human health is increasing. However, whereas the evidence is sufficient in some areas, it is inconclusive or lacking in others. One important reason for the inconclusiveness relates to methodological aspects, including study design, exposure characterization and outcome specification. Future challenges in noise and health research therefore include both targeting of prioritized health outcomes and methodological developments. Below, we summarize the main imminent research needs.

7.1 Exposure

The methods for assessing traffic noise exposure vary between and even within countries. To improve the comparability of noise data across Europe and to enable correct monitoring of trends in the exposure distribution, it is vital to harmonize the data collection procedures, for instance with respect to traffic counts, traffic composition and diurnal distributions, as well as the use of noise calculation models and indicators. The END provides a basis for this harmonization and common exposure assessment methods will be implemented in Europe through the CNOSSOS-EU program. Furthermore, activities are currently on-going to improve the noise calculation models, allowing for estimations at lower noise levels, such as at quiet facades and inner yards, and taking effects of exposure modifying factors into account, including acoustic insulation. These improvements will be valuable for correct assessments of the fraction of exposed persons at different exposure levels.

It is desirable that the Swedish noise exposure calculation methods are harmonized with European standards. Hopefully, the CNOSSOS-EU will be a useful tool to achieve this. However, for local action planning, urban planning as well as for health risk assessments, the END mappings of noise may not be detailed enough. The models should therefore be applied with a higher detail, including mapping of noise levels also below 55 dB and a finer resolution than the standard 5 dB-bands. Furthermore, they also need to be adapted to local conditions, for example including correction terms for temperature and use of studded tyres.

In studies on health effects of noise, efforts should also be made to improve the assessments of the individuals' exposure to noise, taking into account historical exposure, noise from multiple sources and variations throughout the day, that is, noise at home, work and during leisure time. Furthermore, it is important to distinguish between day-time and night-time noise exposure. Preferably, future studies should select more appropriate indicators of exposure, specific to the outcome under study.

7.2 Health effects

In general, the main focus regarding health effects of traffic noise has been on road traffic, most likely because this is the dominating source. Aircraft noise has been studied to some extent, in particular with regard to cognitive effects among children and hypertension in adults, but studies on railway noise are lacking for many health outcomes. To investigate the effects of changing noise characteristics, it is, however, of importance to comparatively study the effects of the three main traffic noise sources, both separately and combined.

The exposure-response models for traffic noise and annoyance as well as sleep disturbances may need to be up-dated, in particular for aircraft noise where an upward trend in the annoyance has been seen during the last decades, but also for railway noise. In addition, curves should be developed for combined exposures. Furthermore, an expansion of the models to include also somatic stress reactions, both short-term and long-term, would provide a better basis for making informed health-based decisions about guideline values and preventive measures.

Further studies are needed on industrial noise and annoyance. The published exposure-response functions for industrial noise are uncertain, because they are based on a single study limited to a few industrial sites. Updated exposure-response functions are needed to predict annoyance in future residential areas close to industrial areas. In Sweden, several such areas are planned close to harbours, an industrial noise source for which annoyance data is lacking. A specific study of harbour noise may be warranted, given that the noise may be particularly annoying, including low-frequency noise from ships and impulse noise from loading operations. Specific studies on rail yard noise could also be motivated. The available data suggest that shunting yard noise is extremely annoying, but it is unclear to what extent this generalizes to other types of rail yards. Since data is lacking on sleep disturbance, new questionnaire studies on industrial noise should include both questions on sleep disturbance and exposure assessment of night-time levels (equivalent levels, maximum levels, and number of events).

The evidence of long-term effects of noise on performance and learning is limited among children and lacking among adults. Further longitudinal studies on large-scale samples therefore remain a research priority in order to establish exposure-response functions for cognitive effects of traffic noise among both children and adults. The associations should be derived for day-time as well as night-time noise exposure and may take advantage of GIS-methods to assess noise exposure in different environments, such as at home, day-care/school or office.

The evidence for long-term health consequences of traffic noise on the cardiovascular system is increasing but still, to some extent, inconclusive, limited or lacking. Since most studies on cardiovascular effects of traffic noise are cross-sectional, limiting the possibilities to infer causality, further longitudinal studies are needed to demonstrate the causal pathways between sleep disturbance, physiological stress reactions and cardiovascular outcomes. Furthermore, the modifying roles of several factors, primarily sex, age, socio-economic position, noise annoyance and noise sensitivity, need to be clarified. One possibility for future investigations is to make use of already existing cohorts and to pool data from several international or national research centres. In countries with high quality disease and mortality registers, such as those available in Sweden, these could also be used to perform population-based studies. A particular focus should be put on deriving source-specific exposure-response associations for outcomes such as hypertension, ischemic heart disease, including myocardial infarction, and stroke. Efforts are also needed to disentangle the cardiovascular effects of noise and air pollution. Methods to separate the effects of the two exposures, as well as to investigate their interactive effects, should be developed.

Despite relatively clear biological mechanisms, there is a lack of evidence on the long-term effects of traffic noise on metabolic outcomes, such as blood lipids, markers of obesity and Type 2 diabetes. Metabolic disorders may arise as a consequence of sleep disturbances and/or chronic stress, which in turn could be caused by exposure to traffic noise. However, these associations are still hypothetical and need to be confirmed in epidemiological settings, preferably using a longitudinal study design.

For all of the included health outcomes in this review, additional information is needed on risk groups. Identification and definition of particularly vulnerable individuals in future studies on noise and health may assist in targeting preventive measures and in reducing the harmful effects of noise in the general population.

Finally, the estimates of burden of disease from environmental noise presented by the WHO in 2011 are more or less uncertain, mainly because of the limited quality of underlying exposure and outcome data. To improve the estimates of disease burden, it is necessary to produce better data of the exposure distribution across Europe as well as to derive more accurate exposure-response associations. In particular, additional evidence is needed on exposure-response associations between traffic noise and cognitive functioning as well as on cardiovascular diseases. Assessment of burden of disease from environmental noise in Sweden should preferable await more detailed data on these exposure-response models. Hopefully, however, future recalculations of the burden of disease from environmental noise will be more accurate and thereby provide a valuable tool for policy makers to quantify the health impacts of exposure to noise.

8 Appendix

8.1 Tables A1 to A4

Table A1. Percent annoyed (%A) and highly annoyed (%HA) subjects at various noise exposure levels (L_{den}) for aircraft, road traffic, and rail traffic, according to the ECs "Position paper on dose response relationships between transportation noise and annoyance".

	Aircraft		Road traffic		Rail traffic	
L_{den}	%A	%HA	%A	%HA	%A	%HA
45	11	1	6	1	3	0
50	19	5	11	4	5	1
55	28	10	18	6	10	2
60	38	17	26	10	15	5
65	48	26	35	16	23	9
70	60	37	47	25	34	14
74	73	49	61	37	47	23

Source: EC 2002 [40].

Table A2. WHOs summary of effect and threshold levels for effects where sufficient evidence is available.

Effect		Indicator	Threshold, dB
Biological effects	Change in cardiovascular activity	*	*
	EEG awakening	$L_{Amax,inside}$	35
	Motility, onset of motility	$L_{Amax,inside}$	32
	Changes in duration of various stages of sleep, in sleep structure and fragmentation of sleep	$L_{Amax,inside}$	35
Sleep quality	Waking up in the night and/or too early in the morning	$L_{Amax,inside}$	42
	Prolongation of the sleep inception period, difficulty getting to sleep	*	*
	Sleep fragmentation, reduced sleeping time	*	*
	Increased average motility when sleeping	$L_{night,outside}$	42
Well-being	Self-reported sleep disturbance	$L_{night,outside}$	42
	Use of somnifacient drugs and sedatives	$L_{night,outside}$	40
Medical conditions	Environmental insomnia**	$L_{night,outside}$	42

Source: WHO 2009.

* Although the effect has been shown to occur or a plausible biological pathway could be constructed, indicators or threshold levels could not be determined.

** Note that "environmental insomnia" is the result of diagnosis by a medical professional whilst "self-reported sleep disturbance" is essentially the same, but reported in the context of a social survey. Number of questions and exact wording may differ.

Table A3. WHOs summary of effects and threshold levels for effects where limited evidence is available.

Effect		Indicator	Estimated threshold, dB
Biological effects	Changes in (stress) hormone levels	*	*
Well-being	Drowsiness/tiredness during the day and evening	*	*
	Increased daytime irritability	*	*
	Impaired social contacts	*	*
	Complaints	$L_{night,outside}$	35
	Impaired cognitive performance	*	*
Medical conditions	Insomnia	*	*
	Hypertension	$L_{night,outside}$	50
	Obesity	*	*
	Depression (in women)	*	*
	Myocardial infarction	$L_{night,outside}$	50
	Reduction in life expectancy (premature mortality)	*	*
	Psychic disorders	$L_{night,outside}$	60
	(Occupational) accidents	*	*

Source: WHO 2009.

* Although the effect has been shown to occur or a plausible biological pathway could be constructed, indicators or threshold levels could not be determined.

** Note that as the evidence for the effects in this table is limited, the threshold levels also have a limited weight. In general they are based on expert judgment of the evidence.

Table A4. WHOs summary of effects of different levels of night noise on the population's health.

Average night noise level over a year	Health effects observed in the population
Up to 30 dB	Although individual sensitivities and circumstances may differ, it appears that up to this level no substantial biological effects are observed. $L_{night,outside}$ of 30 dB is equivalent to the no observed effect level (NOEL) for night noise.
30 to 40 dB	A number of effects on sleep are observed from this range: body movements, awakening, self-reported sleep disturbance, arousals. The intensity of the effect depends on the nature of the source and the number of events. Vulnerable groups (for example children, the chronically ill and the elderly) are more susceptible. However, even in the worst cases the effects seem modest. $L_{night,outside}$ of 40 dB is equivalent to the lowest observed adverse effect level (LOAEL) for night noise.
40 to 55 dB	Adverse health effects are observed among the exposed population. Many people have to adapt their lives to cope with the noise at night. Vulnerable groups are more severely affected.
Above 55 dB	The situation is considered increasingly danger ous for public health. Adverse health effects occur frequently, a sizeable proportion of the population is highly annoyed and sleep-dis turbed. There is evidence that the risk of cardiovascular disease increases.

Source: WHO 2009.

8.2 Calculation of DALYs

Disability-adjusted life years, DALYs, are used as a measure to quantify the overall disease burden and describe the number of years lost due to ill-health, disability or premature death. It combines in one measure the time lived with disability (YLD) and the time lost due to premature mortality (YLL) [3]

DALY = YLD + YLL

The YLD is the number of incident cases (I) multiplied by a disability weight (DW) and an average duration of disability in years (L). Disability weights allow non-fatal health states and deaths to be measured under a common unit and are measured on a scale from 0 to 1 where 1 represents death and 0 represent ideal health.

YLD = I * DW * L

The YLL corresponds to the number of deaths (N) multiplied by the standard life expectancy at the age at which death occurs (L).

YLL = N * L

The process for assessing total disease burden was in the WHO Night Noise Guidelines summarized in three steps:

a) Estimating the exposure distribution in a population
b) Selecting one or more appropriate relative risk estimates from the literature, generally from a recent meta-analysis; and
c) Estimating the population-attributable fraction.

More detailed information on environmental burden of disease assessments can be found in [112-114].

8.3 Abbreviations

CI	Confidence interval
CNOSSOS-EU	Common noise assessment methods in Europe
CVD	Cardiovascular disease
DALY	Disability-adjusted life years
dB(A)	A-weighted decibel
EC	European Commission
END	European Environmental Noise Directive
ENNAH	European Network on Noise And Health
EU	European Union
$L_{Aeq,16h}$	The A-weighed equivalent continuous sound pressure level for 16 hours daytime, that is, 07.00 h to 23.00
$L_{Aeq,24h}$	The A-weighted equivalent continuous sound pressure level for 24 hours
L_{Amax}	The A-weighted maximum sound pressure level, typical measured with an integration time of 125 ms ('fast') or 1 s ('slow')
L_{den}	The A-weighted 24-hour equivalent continuous sound pressure level, with an addition of 5 dB for evening noise events (EU standard 19.00–23.00) and 10 dB for night-time noise events (EU standard 23.00–07.00).
L_{dn}	The A-weighted 24-hour equivalent continuous sound pressure level, with an addition of 10 dB for night-time noise events (EU standard 23.00–07.00).
L_{night}	The A-weighted equivalent continuous sound pressure level during the night (EU standard 23.00–07.00).
WHO	World Health Organization
%A	Percentage annoyed
%HA	Percentage highly annoyed

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Current knowledge and research needs

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Environmental noise is an inevitable nuisance in the urban community. Despite efforts to restrict the exposure, noise constitutes an increasing problem, primarily as a consequence of a continuous urbanization and transportation growth. The major contributor to the overall burden of environmental noise is traffic, primarily road, railway and aircraft traffic, but noise from neighbours, construction sites and industrial plants also contribute. Absence of quiet and restorative areas in the society affects health and well-being. Annoyance, sleep disturbances, impaired communication, cognitive effects and physiological stress reactions are possible health impacts associated with an excess exposure to noise.

Researchers at the Institute of Environmental Medicine at Karolinska Institutet and the Department of Psychology at Stockholm University was assigned by the Swedish Environmental Protection Agency to produce a comprehensive review of recent research on non-auditory health effect of exposure to environmental noise. The review focuses on traffic noise, that is, road, railway and aircraft noise, and industrial noise, defined as noise from stationary sources, including industrial plants, shunting yards, and harbours.

The project is funded by a research grant from the Swedish Environmental Protection Agency and aims at providing a scientific basis and guidance for future work on noise abatement in Sweden. Furthermore, it aims to identify areas of special interest for future research on noise and health. Current knowledge as well as important research gaps have been identified for exposure assessment methods as well as health effects. In addition, a summary is provided of research needs for traffic noise and industrial noise.

RESEARCH
ENVIRONMENTAL
OBJECTIVES

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