Knowledge gaps concerning health impacts of environmental noise

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Summary
In its DALY report (2011) the World Health Organization listed several health outcomes of noise and estimated an annual loss of 1 million healthy years due to environmental noise. Currently, WHO updates its noise guidelines based on reviews on the impact of environmental noise on annoyance, sleep, cardio-vascular and metabolic systems, cognition, mental health, hearing, and adverse birth outcomes and on the health effects of noise interventions. Resent large-scaled studies such as the Swiss SiRENE study and the German NORAH study have strengthened the evidence of the impact of environmental noise on mental and physical health. Researchers often refer to stress models when explaining the environmental noise's health-related impact. However, there are still some knowledge gaps with regard to the health impact of noise. These gaps refer to the exposure and the health impact side of exposure-response relationships. Among others, concern has been raised, whether continuous sound level or rating levels (e.g. L_{den}) are adequate descriptors of exposure in exposure-response relationships for all outcomes or whether other indicators, e.g. the maximum sound level, are more appropriate. The exact pathways from noise exposure to long-term health effects and the interrelationship between different health outcomes are still unclear. This refers to gaps in theory. The general stress model is not specific enough to allow for verifiable or even exactly testable predictions. Effect differences of noise from different sources at comparable continuous sound levels are to be explained. For some noise sources, e.g. railway noise and industrial noise, we need more studies. Moreover, the health impacts of noise from multiple noise sources are still unclear. For annoyance some models for explaining the impact of combined noise sources exist, such models are lacking for sleep disturbances and other health effects. For noise annoyance, ICBEN has recommended an internationally standardised method for the assessment. Such standardisation is needed also for the assessment of other health outcomes. In this contribution these and other gaps regarding noise health impacts are described.

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1. Introduction

It is well known that environmental noise has an impact of human-beings' health. In its DALY report [1] the World Health Organization (WHO) has listed annoyance, sleep disturbances, cognitive impairment of children, tinnitus and ischaemic heart diseases as health outcomes of environmental noise. WHO estimates a loss of about 1 MM healthy years for the European Region per year due to environmental noise. As a basis for the upcoming WHO Guidelines for the European Region new systematic evidence reviews have been carried. These reviews of studies published between 2000 and 2014/2015 refer to effects of environmental noise on annoyance, sleep, the cardio-vascular and metabolic systems (hypertension, ischaemic heart disease, stroke blood pressure in children, diabetes, and obesity), cognitive performance, mental health, adverse birth outcomes, and hearing. In addition, the impact of interventions on noise reductions and the potential benefits for health were reviewed [2].

Recent studies published since 2014 have shown further evidence of an association between transportation noise and health. For example, results of a laboratory sub-study within the frame of the Swiss SiRENE study on short-term and long-term effects of transportation noise exposure suggest short-term effects of nocturnal, in particular intermittent transportation noise on glucose and insulin levels [3]. This finding supports a causal relation-

ship between noise exposure and long-term metabolic diseases. The results of the German NORAH study on transportation noise-related annoyance, cognition and health of residents around airports (2011-13, published 2015 and later) are largely in line with previous findings on noise annoyance, sleep cardio-vascular effects, health-related quality of life and cognitive impairment of children [4]. Furthermore, the study found evidence for an association between noise exposure and the incidence of depression for all transportation noise sources [5]. This is confirmed by other studies recently published, e.g. the Heinz Nixdorf Recall study, which showed an association between road traffic noise and the incidence of high depressive symptoms [6].

In summary, there is a growing number of studies reporting evidence of health impacts of environmental noise. However, there are still some knowledge gaps with regard to the health impact of noise.

2. The need for a comprehensive noise impact model on health

With regard to the impact of noise auditory and non-auditory effects can be distinguished [6]. The auditory effects refer to hearing loss or hearing impairments whereas non-auditory effects refer to stress-related effects outside the hearing system. Most effects of environmental noise, in particular the effects of transportation noise are non-auditory.

Noise effect researchers explain the non-auditory health-related impacts of environmental noise in terms of stress responses to noise. That is, noise is regarded as an environmental stressor beside others such as air pollution. One of the prominent noise-related stress models is the noise reactions scheme proposed by Babisch [8]-[9] in which he adopts the general stress concept [10]to the field of noise and describes the link between noise and cardio-vascular diseases and the relevant risk factors (mediators) in between. In this scheme disturbances (e.g. sleep disturbances), stress indicators (e.g. stress hormone releases), risk factors (e.g. blood pressure) and manifest diseases (e.g. hypertension, ischaemic heart diseases) are distinguished. Babisch does not aim to exactly explain and predict the psychophysiological processes underlying the causal link between noise and health diseases by means of this scheme, but rather regards the model as helpful "for hypothesis testing in noise epidemiology" (Babisch, 2002, p. 5). The advantage of this model is that it provides a biological plausible overview about relevant factors in the causal chain from environmental noise to cardio-vascular diseases.

With reference to Babisch's noise reaction scheme Münzel et al. [11], for example, present a more specific description of the pathophysiological mechanisms of the link between environmental noise and cardio-metabolic diseases. However, these models based on the general stress concept describe the link between noise exposure, mediator variables and long-term manifest health outcomes as uni-directional. The general stress model is not specific enough to allow for verifiable predictions and to describe the bio-psycho-social complexity of the impact of noise on human beings. Still, the psycho-physiological pathways from noise exposure to long-term health effects and the interrelationship between mediating responses, context factors and different health outcomes including loops in the causal chain are not fully understood. For example, to what extent annoyance judgements include sleep disturbances or, vice versa, residents more noise annoyed show less sleep quality, is not clear.

The stress theory would predict that on the long run responses to noise such as annoyance would lead to reduction in mental health and this is supported by studies on health-related quality of life [9]. However, the reversed causality in the sense that those suffering from poor mental health are also more sensitive to noise and belong to a vulnerable group that have less resources to cope with noise and, thus, in consequence, are more annoyed [13] is also discussed and can be predicted from stress theory. It is argued that this reversed causality of the annoyance – health association might also be true for (reported) physical health [14]. Actually, there is some evidence that annoyance and mental health are reciprocally related to each other and that the strength of the paths from annoyance to health and vice versa is different in steady-state conditions and conditions of (expected) changes in noise exposure [15]. It might be that any change in experience or awareness concerning environmental noise, regardless whether a change in exposure occur or not (e.g. reports, media information on health risks of noise) changes

the strength of the paths between annoyance and other health outcomes.

The relationships between noise exposure, personal, situational and social context factors and subjective noise responses have been studied extensively [16]. But there is also some evidence that context factors, including situational and attitudinal ones, modify the noise–response relationship for physiological outcomes. For example, 'quiet area' and type of home moderate the noise impact on children's blood pressure [17], and attitudinal factors (attitudes towards aviation) were found to be associated with physiological sleep parameters [18].

Some authors argue that noise exposure on a long-term level in particular leads to impairments of physical health when there is less (perceived) opportunity to recover from the stress due to environmental noise [19]. On the other hand, studies have shown that outdoor recovery and physical activities, which are important for the capacity to cope with stressful situations, occur less in high noise exposed areas [20]-[21], which at the end might increase the risk of stress-induced, chronical physical and mental health risks. This indicates a complex relationship between noise exposure, coping and recovery, and health. That is, environmental noise might have a twofold impact on health: It harms, in particular in case of less opportunity to recover from the environmental stress and it disturbs outdoor recovery from stress in terms of staying in the garden, visiting green areas, doing physical activities, etc.

In the report of the network of European researchers on noise and health (the ENNAH project)[22], funded by the European Commission 7th Framework Program, more complex causal diagrams for the association between (road traffic) noise exposure including several modifying factors are presented that were drawn in an expert workshop. However, as the authors state, no firm conclusions can be drawn because of conflicting evidence.
The unclear interrelationships between noise exposure, different noise effects and potentially mediating factors are not just an academic problem but important for noise policy, too. For example, for noise abatement strategies it would be important to know more about the relationship between annoyance and other health outcomes and to know whether strategies aiming to reduce annoyance by means of the management of acoustical and non-acoustical context-related factors would also improve further mental and physical health outcomes. A promising way of research on this topic is the recently started Horizon 2020-project ANIMA [23].

Another example: If noise annoyance during waking hours had an impact on the threshold of noise-induced awakenings at night-time, for noise policies this would mean that, even when mainly the nocturnal noise is associated with physical health outcomes (e.g. [24]), protection from noise at night-time would not be sufficient for health improvement. In addition, the relationship between acute reactions such as awakenings and long-term health effects are unclear. That is, it is unknown against how many additional awakenings per night residents should have to be protected in order to avoid long-term health effects.

Finally, if we would have a better understanding of the non-acoustical, contextual impact factors on noise responses, what they have in common and at what stage of the noise stress processing they actually affect the response process, we would be better able to consider these factors – as long as they are modifiable (see [25]) - in noise control management.

3. Knowledge gaps and research needs in noise impact research

Within the ENNAH project (2009-11) the researchers identified knowledge gaps and future research needs on the basis of literature research and workshops [22]. Some of these gaps and research needs have been addressed in recent European studies such as the Swiss SiRENE study [3] the French DEBATS [26]) or the German NORAH study [4]. However, there are still knowledge gaps left, which e.g. are addressed by Stansfeld et al. [2]. The authors list further research needs and remaining knowledge gaps that turned out from WHO Evidence reviews that were done as part of the WHO Environmental Noise Guidelines for the European Region. These needs and gaps refer to (1) the study design, (2) noise exposure assessment, (3) populations and life course approaches, (4) confounding factors and effect modification, (5) health outcomes, and (6) interventions.

With regard to the **study design,** [2] mentions the need for longitudinal and retrospective studies. This is seen as in particular important for studies on mental health, cognition, and hearing loss. For example, it is known that aircraft noise leads to the impairment of reading performance of primary school children [27]-[28]. The long-term impact when children move to secondary school is not that clear. Clark et al. [29] reported low evidence of long-term term effects of aircraft noise on reading comprehension (a statistically non-significant decrease at follow-up). However, their study suffers from loss-to-follow up from overall half of the original sample in the primary school. So, further research is needed here, also with regard to other noise sources. With regard to mental health, for example, longitudinal studies would be helpful for unveiling the pathways from exposure to depression and the role of annoyance and sleep disturbances within the causal chain. Other arguments for the need of longitudinal studies as mentioned by [2] are the study of long-term effects of acute effects during sleep and the investigation of the mediating role of annoyance and sleep disturbances on health (see Chapter 2). In line with the recommendation of longitudinal studies in future research, Stansfeld et al. [2] discuss the value of a life course approach in noise effect research. This includes the study of the long-term health-related consequences of noise exposure during childhood or the long-term effects of prenatal exposure and the impact of cumulative exposure later in life.

With regard to noise exposure assessment there is need for the assessment of **individuals' noise 'dosis'.** That is, the assessment should include the exposure during individuals' different whereabouts during 24 hours (at home, workplace, stays for leisure time, errands, etc.) [2].

The **harmonisation** of the environmental noise assessment in Europe is regarded as useful for comparisons between noise effect studies. However, among others, concern has been raised, whether average sound rating levels (e.g. L_{den}) are adequate descriptors of exposure in exposure-response relationships for all outcomes or whether **alternative noise metrics**, e.g. the maximum sound level alone or in combination with the number of events are more appropriate. For example, in a recent German expert report a suggestion for the implementation of maximum sound level criteria in German noise regulation for the impact assessment of railway noise at night-time has been made on the basis of re-analyses of study data on nocturnal railway noise effects [30]-[32]. Further studies are needed to verify the results and conclusions of this expert report. For aircraft noise, Guski et al. [33] recently presented the concept of the research project 'L_{eq}+X' that includes the re-analysis of Swiss and German aircraft noise annoyance data in order to identify the advantages and disadvantages of supplemental noise metrics in addition to average sound level metrics (e.g. L_{Aeq}, L_{den}, L_{dn}) in exposure-response models. For this, the continuous sound level, number of flight movements, maximum sound level, fleet mix, and combinations of these acoustical variables for different times of day will be included in exposure-response analyses on annoyance and (reported) disturbances. Among others, this re-analysis was initiated in order to identify possible explanations for the shift in exposure-response curves for aircraft noise annoyance over time and for the differences between exposure-response functions estimated at different airports [34].

In line with this, the **differences in the effect of different noise sources** needs further consideration. While meta-analyses on transportation noise annoyance and reported sleep disturbances indicate differences in the sense of people – at least in occidental countries – being more annoyed and sleep disturbed by aircraft noise and less annoyed and sleep disturbed by railway noise than by road traffic noise [35]-[36], this is not necessarily true for physiological health outcomes, e.g. for physiologically measured sleep quality [37]. And also for noise annoyance, the latest WHO Evidence review on environmental noise annoyance [38] shows that e.g. the difference in annoyance in favour of railway noise as compared to road traffic noise (so-called 'railway bonus') has diminished and partly went into reverse. Here, the knowledge gap refers to the lack of clarity about the underlying mechanism of the impact of noise of different sources and the best acoustical parameter(s) as well as non-acoustical factors for describing the affecting elements of the exposure and the context that induce the outcomes.

For some **sources of environmental noise we have little or mixed evidence for health impacts**, in particular for risks of health diseases. These are particularly railway noise, industrial noise and wind turbine noise. According to the latest WHO

reviews for wind turbine noise no meta-analysis aggregating the results of original studies was carried out because of low study quality indicating that estimates of effects are judged as very uncertain. This means an encouragement of future research to continue to address these sources in high-quality epidemiological studies. Examples for such research are recently published studies (and therefore not included in the WHO reviews) on the health impact of wind turbine noise, carried out in Canada [39] and Denmark [40].

Another knowledge gap referring to the noise exposure as mentioned by [2] is the **combined impact of multiple sources**. This is not fully understood for most of the health outcome of noise. For annoyance some models for explaining the impact of multiple noise sources exist. In particular the dominant source model and the annoyance equivalents model are the most prominent and reliable ones [40]-[41]. The dominant source model indicates that the total annoyance is equivalent to the highest source-specific noise annoyance of all involved single noise sources [42]. Based on source-specific exposure-response functions for the percentage of people annoyed (either little annoyed, annoyed, or highly annoyed) and taking road traffic as a reference source the annoyance equivalents model translates the source-specific average sound pressure levels from single noise sources into equally annoying average sound pressure levels of road traffic noise. These transformed sound pressure levels are then summed up to a total sound pressure level. The corresponding percentage annoyed is defined using the respective exposure-response function for the reference source, road traffic [41]. This method is also described by the European Environment Agency (EEA) in its good practice guide on noise exposure and potential health effects [43]. According to [41] this model works for transportation noise sources and, in principle, for industrial noise without substantial impulsive or tonal components. However, in the EEA guide report the model is also extended to shunting yards and wind turbines.

To the knowledge of the author, for other health outcomes, e.g. sleep disturbances and cardio-vascular health diseases comparable reliable models on the impact of noise from multiple sources are lacking.

It is not only that the impact of combined noise from multiple sources on health is of interest for future research but also the combined impact of noise and other environmental stressors, e.g. air pollution. According to [2] knowledge gaps concerning confounding factors and effect modification refer among others to combined effects of air pollution and noise on health. The different causal pathways of noise and air pollution to health outcomes should be investigated in future studies.

In 2001, Team #6 of the International Commission on Biological Effects of Noise (ICBEN) published a **recommendation for an international standard** of the assessment of noise annoyance including the wording of the annoyance questions and the use of two annoyance scales, a verbal 5-point scale and a numerical 11-point response scale. The development of the recommended annoyance scales bases on international psychometric studies following the same research protocol. [44]. Beside the criticism of assessing annoyance with just two single items [45], the standardisation enables the comparison of study results and provide "a high-quality, reliable measure of a general reaction to a noise experienced in a residential environment" [44] (p. 643). The annoyance assessment as recommended by ICBEN has been widely accepted in the scientific community. For other health outcomes such standardisation does not exist. On the closing ceremony of the 12th ICBEN congress on Noise as a Public Health Problem in 2017 in Zurich it was stated that generating official ICBEN recommendations for the use of standardised outcomes and assessments for different noise effects is regarded as one of the major goals for ICBEN during the next years.

Again, this is not only an academic issue. For the European noise policy it is important that noise guidelines, regulations and noise abatement strategies refer to health impacts of noise that are defined and measured in a similar way following a scientific sound high-quality standard.

While there are many **studies on interventions examining noise management and changes in noise exposure** (e.g. improvement due to noise abatement, increase in exposure due to expansion of infrastructure), the impact of noise exposure changes on health outcomes are less studied. In the WHO review on noise interventions Brown and van Kamp [46] examined 43 transportation noise

intervention studies with regard to the impact of the change in noise exposure on health published between 1980 and 2014. They found a considerable diversity between studies with regard to study quality and a thinly spread across source types, outcomes and intervention types. Most of the studies showed a risk of bias. The most studied outcome is annoyance and results of most of the studies indicate an excess response in annoyance persistent over time. Following the implications described by the authors of [46] more interventions studies are needed in particular for other noise sources than road traffic noise, particularly for aircraft and railway noise, and for health outcomes other than or in addition to annoyance. The future studies should be of high quality, following a standardised protocol for a before-after study design that facilitates study comparability and considers both short- and long-term health effects.

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