ENVIRONMENTAL NOISE, HEALTH AND COGNITION

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1 INTRODUCTION

I have decided for this lecture to focus on two areas of my noise research: my initial work on noise sensitivity and its relation to psychiatric disorder and, secondly, research on aircraft and road traffic noise and children's learning. During my career in noise research there have been many advances in noise and health research and I will also include some of these advances to illustrate some of the mechanisms of the effects on noise on health and to show how noise and health research has developed over the last 40 years.

2 NOISE SENSITIVITY AND PSYCHIATRIC DISORDER

2.1 Earlier research on aircraft noise and psychiatric disorder

I began my research in environmental noise and health in 1980 when I was part of Michael Shepherd and Alex Tarnopolsky's team investigating noise and psychiatric disorder at the Institute of Psychiatry. The primary aim of this research had been to see whether noise exposure caused psychiatric disorder. The Institute of Psychiatry research programme followed a study by Abey-Wickrama published in the Lancet which showed high levels of mental hospital admissions related to aircraft noise exposure.[1] The results of the initial community pilot study were equivocal showing that aircraft noise measured by the Noise and Number Index (NNI) was associated with psychiatric disorder in only three subgroups persons aged '15-44 of high education', 'women aged 15-44' and those in 'professional and managerial occupations'.[2] In the subsequent West London Survey of Psychiatric Morbidity of 5885 adults no association was found between aircraft noise and psychiatric morbidity in general except in two subgroups 'finished full-time education at age 19 years' and 'professionals'.[3] They concluded that noise … does not seem to be a frequent, severe, pathogenic factor in causing mental illness but that it is associated with symptomatic response in selected subgroups of the population.' Hence a focus on noise sensitivity as a potential indicator for identifying subgroups vulnerable to developing psychiatric disorder when exposed to noise.

2.2 Investigation of noise sensitivity and psychiatric disorder

My role was to investigate the role of noise sensitivity in psychiatric disorder, where noise sensitivity, a measure of attitudes to noise in general, indicated a self-reported tendency to respond to environmental noise more strongly than usual. I interviewed 77 women of high and low noise sensitivity living in areas of high and low aircraft noise around Heathrow airport. I found that noise sensitivity was a predictor of annoyance to noise, already known, and was associated with phobias and depression measured using a standardised psychiatric interview as well as with neuroticism and greater reactivity to other sensory stimuli.[4] In a follow up I also found that noise sensitive subjects scored more highly on a cognitive failures questionnaire which is also associated with neuroticism.[5] Physiological field measurements of blood pressure, heart rate and skin conductance were carried out in an attempt to find physiological correlates of the self-reported sensitivity. Noise sensitivity was associated with slower heart rates but was not related to auditory threshold on audiometry or blood pressure[6] – although it is sufficient to say these field measurements were fairly crude.

My doctoral thesis took this work further. In a six year follow up of the original sample noise sensitivity was stable over time and related to psychiatric disorder. It was hypothesised that noise sensitivity might be a vulnerability factor for mental illness. In a series of depressed inpatients and outpatients recovery was associated with a decline in noise sensitivity suggesting that their noise sensitivity was partly related to their depression. Nevertheless, they remained highly sensitive compared to a non-depressed control sample. In a laboratory experiment of reactions to noise, noise sensitive people tended to have higher levels of tonic physiological arousal, more phobic/defence startle responses to noise and lower habituation to noise.[7] I argued that noise sensitive people 'attend more readily to noise, perceive more threat from noise and may react more to noise than less sensitive people.' I concluded ' Noise sensitivity appears to be a self-perceived indicator of vulnerability to stressors in general not only noise, linked to perception of environmental threat and lack of environmental control combined with a tendency to negative affectivity'.[7]

2.3 Noise sensitivity in the Caerphilly Study

I was able to continue this noise research through collaboration with the Caerphilly Collaborative Heart Disease Study led by Peter Elwood from the MRC Epidemiology Unit in South Wales. This was a large epidemiological study of men examining risk factors for Ischaemic Heart Disease including noise exposure which was mapped by Wolfgang Babisch.[8] I managed to persuade them to include a measure of mental health, the General Health Questionnaire, and measures of noise sensitivity and annoyance. We found no direct association of road traffic noise exposure with psychiatric disorder but again noise sensitivity was associated with psychiatric disorder.[9] Noise sensitivity was also strongly associated with a measure of trait anxiety suggesting a link with negative affectivity and anxiety as a feature of personality.

An important aim of the research in Caerphilly was to investigate whether noise exposure was associated with psychiatric disorder measured by the General Health Questionnaire (GHQ), a commonly used screening questionnaire for depression and anxiety. In the cross sectional baseline analyses road traffic noise was not associated with psychiatric disorder on the GHQ even after adjusting for social class, employment and marital status. As these results were cross sectional there was a need for prospective studies. In 1996 we published prospective analyses from the Caerphilly Study that demonstrated a weak association between road traffic noise exposure and anxiety symptoms.[10] More recently there have several large studies that have found effects of road traffic noise on depression. For instance, in the Frankfurt NORAH Study[11] Seidler et al found increased odds of depression measured by insurance claims and prescription data in relation to road traffic noise, aircraft and rail noise with notably a larger odds associated with combined sources of noise, a generally rather un-researched topic. Similarly the recent involvement of large cohort studies in noise research where noise exposure assessed by noise mapping is linked to existing cohort studies has increased the power of studies to find significant associations with mental health outcomes. In the Heinz-Nixdorf recall study followed over 5 years modelled road traffic noise was associated with an increased relative risk for depressive symptoms maintained after adjustment for individual and area level socioeconomic status.[12]

2.4 The Bypass Study

One method of assessing of whether noise causes psychiatric disorder is to carry out an intervention study aiming to reduce noise and then examine whether there is a consequent reduction in psychiatric disorder. With Bernard Berry we carried a repeated measures intervention study in three towns in North Wales. Participants were residents aged 16 to 90 years old living in areas of high (75-78dBA) or low exposure to road traffic noise (55-58dBA). At baseline there was no difference in annoyance levels, psychiatric disorder or quality of life between noisy or quiet areas. The intervention was the introduction of a bypass around the main high street that resulted in a

reduction of noise exposure of 2-4dBA. After the opening of the bypass there was no measurable change in annoyance, psychiatric disorder or quality of life. We concluded that either a reduction in traffic noise level of less than 3dBA was insufficient to influence annoyance and mental health or that noise reduction was confounded by other sources of error complicating the local environment.[13]

2.5 Further studies on noise sensitivity

Another opportunity to assess the predictive power of noise sensitivity for ill-health came through the Whitehall II Study, a large cohort study of 10,000 civil servants which I had been involved with since its inception.[14] A single question on noise sensitivity measuring 'annoyance responses to noise in general' predicted depressive symptoms and psychiatric disorder at three follow up phases of the study , including at phase 3 three years after baseline (OR=1.56, 95%CI 1.29-1.88) adjusting for age, sex, employment grade, self-rated health and psychiatric disorder at baseline. There was no substantive association between noise sensitivity and cardiovascular morbidity and mortality.[15]

In further analyses in the Caerphilly Study we demonstrated that high noise sensitivity was associated with lower mortality risk.[16] There was also weak evidence that noise sensitivity moderated the association of road traffic noise exposure with psychiatric disorder. Noise sensitivity seems to be a specific predictor of psychiatric disorder and may be an indicator of current psychiatric disorder as part of a wider construct of environmental susceptibility. This may be linked to its association with trait anxiety. Noise sensitivity has been linked to a wider range of environmental sensitivities[17] but this has not been found in all studies.[18] Noise sensitivity may also increase the risk of psychiatric disorder when exposed to road traffic noise.

3 MECHANISMS FOR NOISE EFFECTS ON HEALTH

An important aspect of noise research over the last 40 years has been the exploration of potential mechanisms for the effects of noise on health. In this respect noise research has been at a disadvantage in comparison to air pollution. Air pollution is sometimes visible, in terms of smoke, and has very direct effects on the lungs which are easily understood by the public at large. By contrast, the effects of noise are intangible and mechanisms for health effects are not intuitively understood. I believe this is partly why noise research has not been as well funded as research on air pollution and why policy development in noise control is not well developed as that for air pollution. However, considerable progress has been made in understanding mechanisms of noise effects largely based on the stress hypothesis in which chronic exposure to environmental noise is associated with increased physiological arousal and chronically elevated levels of stress hormones such as cortisol.[19] [20] [21] While acute responses to noise such as orienting and defence/startle responses with elevation of heart rate, blood pressure and blood sugar tend to habituate over time, chronic exposure may give rise to long term health effects. Notably physiological responses to noise during the night while sleeping tend not to habituate even if the sleeper is not consciously aware of them.[22] Evidence on road traffic noise and high blood pressure has been increasing with the large European HYENA Study[23] and convincing meta-analyses from van Kempen and Babisch [24] suggesting small but consistent effects. It is notable that effects of noise on cardiovascular outcomes tend to be small. In comparison to many more proximal risk factors for cardiovascular risk such as smoking it is not surprising that effects are small. Nevertheless, as epidemiological studies have shown these risks tend to affect large numbers of people because noise exposure is so universal.

Generally there are thought to be two routes to health effects. First, the direct route where noise has direct effects on bodily physiological processes without conscious appraisal of the noise. Secondly,

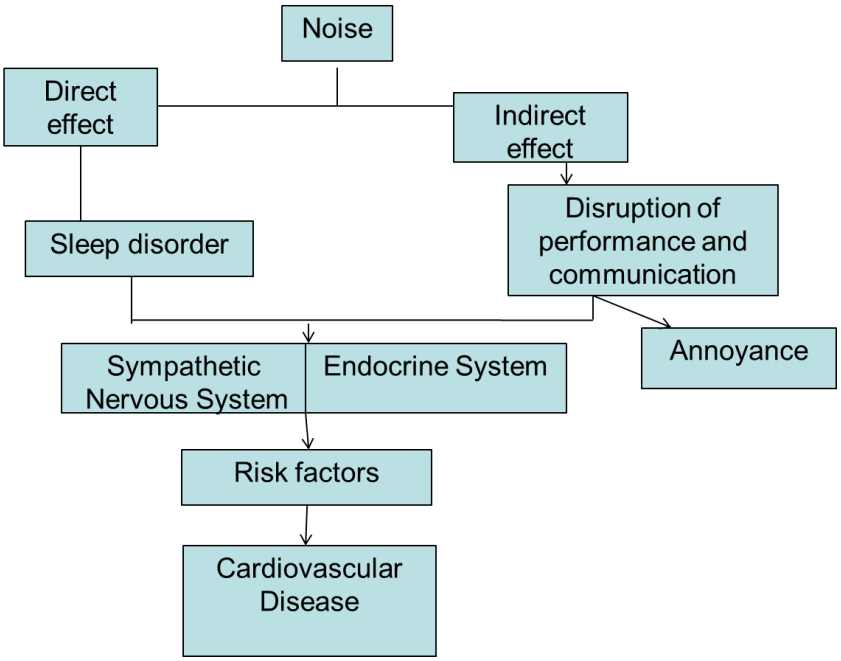

Figure 1 Noise effect model

where noise leads to annoyance with disruption of activities followed by an increase in stress responses. Chronic bodily exposure to stress causes the metabolic syndrome with elevated blood pressure, central obesity and elevated blood sugar. Thus it is not surprising that recent epidemiological studies have found very consistent associations between road traffic noise exposure and Type II diabetes mellitus and also road traffic noise and central obesity. Although the associations with central obesity have largely been cross-sectional studies[25 26] there have been longitudinal studies.[27] Many of the studies of diabetes have been longitudinal and have demonstrated exposure-effect relationships.[28 29] Two other mechanisms have become evident. First, is that there is evidence from a number of studies of road traffic noise that noise exposure during sleep may be important as a risk factor for coronary heart disease where insomnia has also been recognised as a risk factor for depression. Secondly, in some ways similar to air pollution, noise exposure may also disrupt the immune system. Evidence of this comes from the recent studies from Sorensen's group which show increased risk for breast, colo-rectal cancers and non-Hodgkin's Lymphoma associated with noise exposure.[30 31]

4 NOISE AND CHILDREN'S LEARNING

4.1 Heathrow studies in Aircraft noise and children's learning

Another part of my noise research has involved examining the effects of environmental noise on children's learning. When I started there was already work suggesting that road traffic noise and aircraft noise had an impact on children's cognitive abilities exemplified by Gary Evan's reviews[32] and Staffan Hygge's work on the Munich study where cognitive deficits in children living around Munich airport disappeared when the airport site moved and developed in a new group of children around the new airport.[33] Why might children be susceptible to noise and other environmental stressors? It may be that noise is affecting them during critical learning periods, they may not have sufficiently developed coping repertoires to deal with noise, the learning tasks they carry out may be vulnerable to the effects of noise or the settings of school and home may make them more prone to noise effects.

Our first study was the School's Health and Environment Study sponsored by Local Authorities opposed to the development of Terminal 5 at Heathrow Airport. In this study of 340 children aged 8-11 years attending four schools in high aircraft noise areas (16 outdoor Leq >66dBA) and four matched control schools exposed to lower levels of aircraft noise (16hr outdoor Leq < 57dBA) we found chronic aircraft noise exposure was associated with poorer reading comprehension and higher levels of noise annoyance.[34] There were no effects on mental health or cortisol levels. This study was small and the effects needed further examination in a larger sample. The West London Schools Study examined children 8-11 years old from10 schools exposed to high aircraft noise levels (16 hour outdoor Leq > 63dB) and 10 schools exposed to lower levels of aircraft noise (16 hour outdoor Leq < 57dB) around Heathrow airport. We found that aircraft noise was not associated with mean reading score on the standardised Suffolk Reading Scale, memory, attention or stress responses. However, higher aircraft noise exposure was associated with impaired reading on the more difficult test items of the reading scale.[35]

4.2 SATs Study

At this point we took a different approach and took advantage of the standardised assessment tests (SATS) that were obligatory for all primary school children. Using multi-level modelling, SATS for Key Stage 2 were examined in 11,000 children aged 11 years from 128 schools for 8 levels of aircraft noise (54-75 dBA, 16Leq). Analyses were carried out at both school and individual level with adjustments made for socioeconomic and school quality factors. Aircraft noise exposure was significantly associated with poorer reading performance but was not associated with the 'control' English outcomes of spelling and handwriting.[36] Aircraft noise exposure was also associated with poorer performance on a national standardised test of mathematics. However, after adjustment for socioeconomic position the association between aircraft noise and poorer reading performance was no longer statistically significant. This raised an important issue that bedevils studies of environmental stressors and health – is the association of noise and reading confounded by socioeconomic position or are stressors such as noise exposure part of an array of factors that are one of the constituents of the effects of socioeconomic position on health and reading? If the latter is the case then adjusting for socioeconomic position may be seen as over-adjustment. Through my involvement in the Whitehall II Study attempting to explain the occupational grade differences in health in London based civil servants I was very aware of the effects of social position on health where there were strong associations between higher levels of social disadvantage and ill-health.[14] Matching schools by levels of social disadvantage or adjusting for different indices of social disadvantage in analyses attempts to overcome this problem but is not entirely satisfactory.

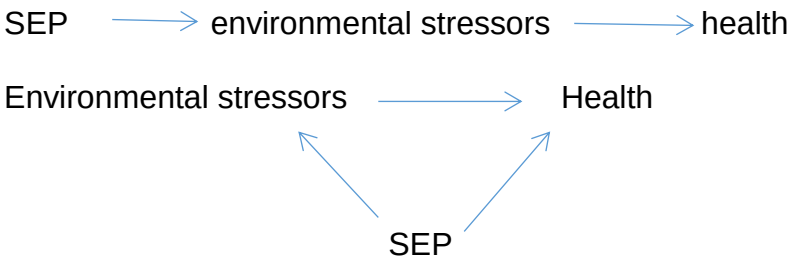

Figure 2 Socioeconomic position and environmental stressors

4.3 RANCH Study

The existing studies at this point had a number of disadvantages: small sample size, insufficient adjustment for confounding and no assessment of exposure-effect relationships. This led us to develop the Road Traffic and Aircraft Noise Exposure and Children's Cognition and Health

(RANCH) Study. This was a collaboration between Sweden, the Netherlands, Spain and the UK funded by the EU 5th Framework Programme. In this study we assessed 2844 children aged 9-10 years old attending 89 schools in the Netherlands, Spain and the UK around three major airports. Children were selected across a range of aircraft noise exposure at school and schools were matched by socioeconomic position within each country. We measured cognitive and health outcomes with standardised questionnaires and tests administered in the classroom. We found linear exposure-effect associations between exposure to aircraft noise and impairment of reading comprehension (p=0.0097), recognition memory (p=0.0141) and a non-linear association with annoyance (p<0.0001). These associations were adjusted for mother's education, socioeconomic position, longstanding illness and extent of classroom insulation.[37] Findings were consistent across the three countries, despite demographic differences, adding weight to the robustness of the association. Unexpectedly road traffic noise exposure was linearly associated with increases in episodic memory (conceptual recall p=0.0066; information recall p=0.0489) but was also associated with annoyance ((p=0.0047). There were no effects on sustained attention, self-rated health or overall mental health. We concluded that aircraft noise could impair cognitive development in children and that schools exposed to high levels of aircraft noise were not healthy environments for children. Further analysis indicated that reading age was delayed by up to 2 months in the UK and 1 month in the Netherlands for a 5dB change in noise exposure.[38] It is interesting that the same linear exposure-effect relationship between aircraft noise and reading impairment was found in the NORAH Study around Frankfurt Airport although at slightly lower noise levels.[39] In the NORAH Study a 10dB increase in aircraft noise was associated with a decrement on the reading test of one tenth of a standard deviation corresponding to one month reading delay.

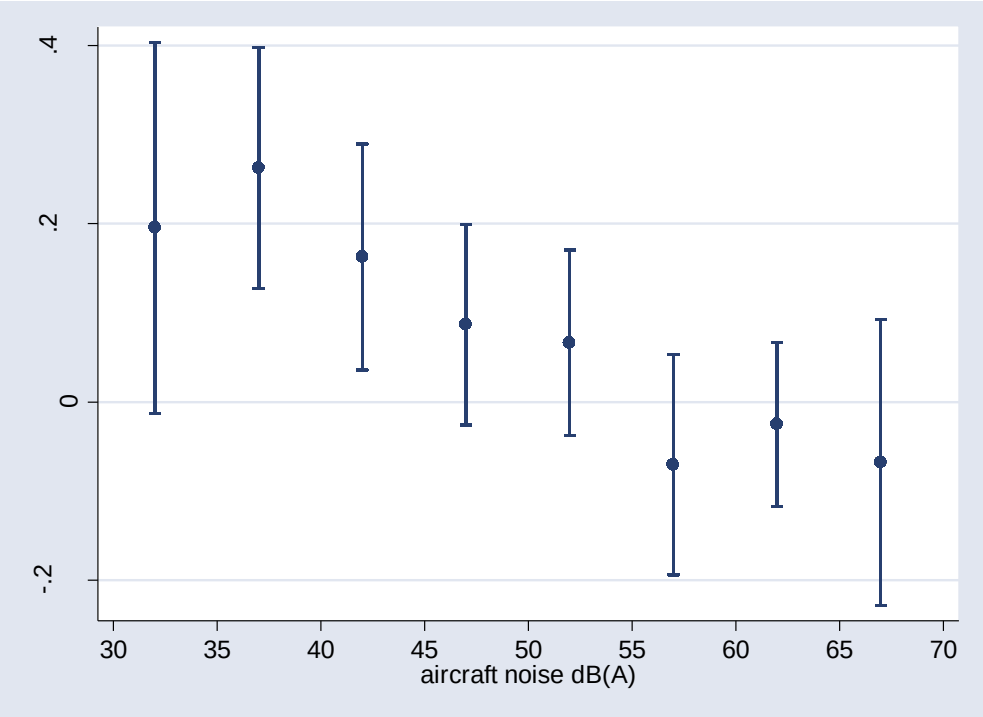

Figure 3 Exposure-effect relationship between aircraft noise at school and reading comprehension

In 1283 children from the RANCH Study we also examined the association between aircraft noise and children's blood pressure finding that blood pressure at home but not at school was related to aircraft noise – there were different results in the Netherlands and the UK so no unequivocal conclusions could be drawn.[40] Although no overall effects of aircraft noise were found on mental health an intriguing association was found between aircraft noise and hyperactivity symptoms which had also been found in the previous West London Schools Study. We concluded that children who were already distractible from hyperactivity might be further distracted by exposure to aircraft

noise.[41] We also examined whether early biological risk might interact with noise exposure to increase the risk of mental health problems in childhood. Low birth weight and premature birth were associated with more conduct problems and emotional symptoms in childhood but there was no interaction with aircraft or road traffic noise exposure.[42]

4.4 Longitudinal follow up of the RANCH Study

The RANCH Study was, of course, cross-sectional and stronger evidence for causality is provided by longitudinal studies where the noise exposure precedes the outcome. The UK sample of the RANCH Study was followed up by Charlotte Clark in 461 children 6 years after the original study at ages of 15-16 years.[43] Aircraft noise exposure at primary school was associated with a non-significant decrease in reading comprehension at follow up. There was also a weak non-significant association between aircraft noise at secondary school and reading comprehension after adjustment for sociodemographic factors. This was a small scale study where the small sample size may have precluded finding significant effects. Overall, few studies have examined sleep disturbance as a mediator of noise effects on cognitive performance. There have been many hypotheses about the mechanism of the effects of noise on reading impairment. One hypothesis is that aircraft noise at night disturbs sleep which results in cognitive impairment. However, an analysis of the cross-sectional Munich and RANCH datasets together found that self-reported sleep disturbance did not mediate the association of aircraft noise exposure and cognitive impairment in children.[44]

4.5 Air pollution, noise and children's cognitive impairments

An important issue to resolve has been whether exposure to air pollution could explain the association between noise and reading impairment. Air pollution is fairly closely associated with road traffic noise but is less so with aircraft noise. Secondary analysis in 719 children from the RANCH Study showed that air pollution exposure was not associated with cognitive and health outcomes. Aircraft noise exposure was associated with poorer reading comprehension, poorer recognition memory, conceptual recall memory and information recall memory after adjustment for nitrogen dioxide levels.[45] Road traffic noise was not associated with cognition or health before or after adjustment for air pollution. Overall, it did not appear that the associations of aircraft noise with cognitive impairment could be explained by air pollution. As a way of summarising these results on children's cognition Charlotte Clark has recently carried out a meta-analysis of the results on reading comprehension including the Schools Environment and Health Study, the West London Schools Study, and the UK RANCH study. The results demonstrated that a 1dB estimate in aircraft noise exposure at school was associated with a -0.007 (-0.012 to -0.001) decrease in reading score and a 4% increase in odds of scoring well below or below average on the reading test. The analyses also found that a 1dB increase in aircraft noise exposure at school was associated with a 0.017 (0.007 to 0.028) increase in hyperactivity score.[46]

4.6 Mechanisms of the noise effects on children's reading

The exact mechanism of the effects of aircraft noise on children's reading comprehension is still uncertain. Several explanations have been proposed. First, that noise interferes with communication between teacher and pupil. In the noisiest schools teachers may have to stop teaching while aircraft fly over and if this is frequent it may interrupt communication and lead to teacher and child fatigue with consequent reduction in motivation and morale in teachers. Other mechanisms include that children develop learned helplessness in the face of noise exposure which is out of the child's control. One mechanism that goes back to Donald Broadbent is that noise

impairs attention. In this mechanism noise exposure may lead to narrowing of the attention span so that children may exclude useful communication as well as noise. Noise also causes annoyance in children and teachers, especially if they feel their activities are being disturbed or it causes difficulties with communication. In some children annoyance may lead to stress responses but there is little evidence currently to suggest that annoyance is a mediating variable between aircraft noise and cognitive impairment.

5 REVIEWS OF NON-AUDITORY EFFECTS OF ENVIRONMENTAL NOISE ON HEALTH

5.1 Reviews on non-auditory effects

Part of my involvement in the field of noise and health research has been as a reviewer of non-auditory effects of noise on health. In 1997 at the request of Bob Maynard at the Department of Health together with Mary Haines I carried out a review of the non-auditory effects of noise on health published to accompany a seminar at the Institute of Environment and Health.[47] In the final part of my talk I thought it might be instructive to see how the research field has changed since then. In terms of cardiovascular disease at the time the evidence was slight; there were convincing studies of occupational noise and high blood pressure and animal studies on prolonged noise exposure and high blood pressure. There was one Dutch community survey which found that high aircraft noise exposure was associated with increased medical treatment for heart trouble and hypertension, more cardiovascular drug use and higher blood pressure.[48] In general, I concluded 'there is little evidence from community studies that environmental noise is related to hypertension, but there is some evidence that environmental noise may be a risk factor for coronary heart disease'.

In 2008 the results of the large European Study HYENA were published examining aircraft and road traffic noise around 6 major European airports and finding significant associations with raised blood pressure for aircraft noise at night and road traffic noise above 65dBA.[23] In 2011 a very large cohort study of the total adult Swiss population found significant associations between aircraft noise exposure and mortality from myocardial infarction with larger hazard ratios for those with longer duration of exposure.[49] In 2013 an ecological study of aircraft noise around Heathrow Airport was published which showed that aircraft noise exposure was associated with increased hospital admissions for stroke, coronary heart disease and cardiovascular disease with similar trends shown for mortality.[50] There have also been prospective studies of road traffic noise showing associations with stroke[51] and in a larger nationwide study.[52] In 2018 the systematic review carried out for the updated Environmental Noise Guidelines for the European Region were published.[53] Despite the low quality of some of the evidence these showed significant associations between aircraft noise exposure and incident ischaemic heart disease and road traffic noise and prevalent and incident ischaemic heart disease. Since then in a nationwide Danish study of 2.5 million households of those aged over 50 years road traffic noise exposure was associated with higher risks of myocardial infarction, angina pectoris, ischaemic heart disease and heart failure adjusting for air pollution measured by $PM_{2.5.}$ [54] Similarly, in a UK study of Biobank data road traffic noise was significantly associated with increased risk of stroke, cardiovascular disease and all-cause mortality.[55] In a 15 year follow up of the Swiss prospective cohort study road, rail and aircraft noise were associated with increased risk of myocardial infarction and road and rail noise was associated with increased risk of CHD mortality.[56] Interestingly the associations were linear and began below 40dBL_{den} for road and rail noise with stronger risks in men than women. Largely studies have shown that cardiovascular effects of noise are independent of air pollution exposure. [56]

5.2 WHO Environmental Noise Guidelines for the European Region

The publication of the World Health Organization Environmental Noise Guidelines for the European Region in 2018 was an advance in terms of the systematic reviews of noise effects on health.[57] For the first time, nine systematic reviews of the recent literature on noise and health were carried out to derive evidence-based exposure-response relationships for five sources of noise (aircraft, road, train, leisure and wind turbine) and five critical health outcomes (Cardiovascular disease, Annoyance, Sleep disturbance, Cognitive impairment, Hearing impairment and Tinnitus) and three important health outcomes (Diabetes and metabolic disorders, Adverse birth outcomes, Quality of Life, mental health and well-being). This was the basis for deriving new evidence-based recommendations to protect human health.

6 CONCLUSIONS

Overall, the evidence of the effects of environmental noise on health has increased enormously in the last few years with the advent of large epidemiological studies with noise mapping and modelling and since 1997 the evidence base is much stronger. The evidence is strong for road traffic noise and hypertension, myocardial infarction, stroke and mortality. This is also the case for aircraft noise exposure and myocardial infarction, stroke and mortality. In children there is strong evidence for aircraft noise and reading comprehension. In the future there should be a greater focus on understanding the mechanisms of these noise effects.

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