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BIOLOGICAL MECHANISMS RELATED TO CARDIOVASCULAR AND METABOLIC EFFECTS BY ENVIRONMENTAL NOISE

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ABSTRACT

The WHO Environmental Noise Guidelines for the European Region focus on several non-auditory health outcomes, including sleep disturbances, annoyance, cardiovascular and metabolic diseases, adverse birth outcomes, cognitive impairment, mental health and well-being. This paper primarily deals with biological mechanisms related to cardiovascular and metabolic effects by environmental noise. In particular, it focuses on etiological pathways related to stress mechanisms and the role of effect modification by perceptual and psychological factors.

Keywords

CARDIOVASCULAR DISEASES - ETIOLOGY

ENVIRONMENTAL EXPOSURE - ADVERSE EFFECTS

METABOLIC DISEASES - ETIOLOGY

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1 Summary

Environmental noise may induce acute cardiovascular and metabolic effects both directly, through subcortical connections, and indirectly by projections via the auditory cortex. The main effects include secretion of stress hormones and blood pressure elevations caused by vasoconstriction. These effects occur even during sleep. Studies on acute biological effects of noise in children are sparse but effects appear to be limited.

Although the mechanisms behind chronic effects of noise on the cardiovascular and metabolic systems are not fully understood, several plausible etiological pathways exist. Repeated stimulation of the sympathetic nervous system and hormonal abnormalities following long lasting over-activation of the HPA axis are probably of importance. Long-term consequences of noise-induced sleep loss may also play a significant role. There is a lack of studies investigating prolonged effects later in life of noise exposure during childhood.

Few studies have analysed potential modification by noise annoyance of the association between environmental noise exposure and cardiovascular outcomes, and the results appear inconsistent. This may suggest no or a weak effect of noise annoyance, but could also be the result of insufficient statistical power. In addition, noise annoyances may trigger protective coping strategies reducing the actual noise exposure and thereby counteracting aggravating effects of noise annoyance on cardiovascular health.

The notion that noise sensitive individuals are more susceptible to noise-induced cardiovascular disease has limited support. The experimental evidence for higher physiological reactivity in noise sensitive individuals following acute exposure is inconclusive and the few available analyses of epidemiological data on chronic effects by long term exposure provide no strong support for a modifying effect of noise sensitivity.

2 Pathways for non-auditory effects

The WHO Environmental Noise Guidelines for the European Region focus on several non-auditory health outcomes, including sleep disturbances, annoyance, cardiovascular diseases, adverse birth outcomes, cognitive impairment, mental health and well-being. This chapter primarily deals with biological mechanisms related to cardiovascular and metabolic effects by environmental noise. In particular, it focuses etiological pathways related to stress mechanisms and the role of effect modification by perceptual and psychological factors. Potential biological mechanisms behind non-auditory effects by environmental noise on other outcomes than cardiovascular and metabolic disease are discussed in the evidence reviews for the specific health effects.

2.1 General stress mechanisms

The main biological reaction model for non-auditory physiological responses to noise stimuli is based on the general stress theory. Initially, this theory involved a three-stage bodily response to external stressors: alarm, resistance and exhaustion [1]. Since then, the stress theory has evolved and new knowledge on biological effects of noise has emerged [2-4]. In addition to evoking physiological stress responses, adverse physiological effects of noise may also be mediated by sleep disturbances, such as awakenings and altered sleep patterns. Sleep is necessary for physiological, social and mental well-being, and disturbance of sleep may affect hormonal release, glucose regulation and cardiovascular function [5-7].

The auditory system is an important warning system which remains active also during sleep. Sounds are transmitted mechanically through the outer and middle ear to the sensory cells of the inner ear, which transduce the mechanical energy to electro-chemical activity and transmit it through auditory nerve fibres to various areas of the brain, including parts affecting the sympathetic nervous and endocrine systems [8]. Two distinct pathways can be discerned. A direct pathway goes through subcortical connections of the brain and involves structures such as the auditory thalamus, amygdala and hypothalamus. A second indirect pathway involves projections from the auditory thalamus to the auditory cortex, where information projects back to subcortical areas, including the amygdala. In sleeping individuals, the direct pathway is believed to be the predominant mechanism for physiological effects of noise [9].

Physiological effects of noise are generally induced by two different systems, the Sympathetic-Adrenal-Medullary (SAM) axis and the Hypothalamic-Pituitary-Adrenal (HPA) axis [10, 11]. The SAM axis describes a chain reaction caused by stressors acting on the central nervous system which leads to secretion of 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. Effects of adrenaline and noradrenaline include increased heart rate, stroke volume and blood pressure (by vasoconstriction of peripheral blood vessels), mobilization of glucose and free fatty acids as well as aggregation of thrombocytes [12].

The endocrine response of the HPA axis originates from hypothalamus where corticotrophin-releasing hormone is released, stimulating the pituitary gland to secrete adrenocorticotropic hormone [13]. This activates production of glucocorticoids, including cortisol, by the adrenal glands. Major functions of the HPA axis include maintenance of metabolic functions, modulation of immune function and preservation of cardiovascular tone. Specific effects of cortisol include elevation of blood glucose levels (by stimulation of glycogen synthesis and inhibition of peripheral utilization of glucose), lipolysis, immune suppression (e.g. decrease of circulating granulocytes and leucocytes) and elevations of blood pressure

(by vasoconstriction and renal retention of sodium) [12, 14]. Hyperactivity of the HPA axis, commonly seen in chronic stress situations, is characterized by a “defeat-type” of reaction and is associated with feelings of distress, anxiety and depression [15, 16].

2.2 Biological effects of noise

The evidence on biological effects of traffic noise is based on laboratory studies, field investigations and epidemiological research. Effects range from acute reactions to short-term loud noise, occurring within seconds or minutes from the initiation of a noise stimulus, to chronic effects of long-term exposure to more moderate noise levels, which may develop over years of exposure. The pathogenic mechanisms bridging the gap between acute and chronic effects of traffic noise are not fully understood [17]. However, several potential mechanisms have been put forward and are presented briefly below. Other issues that are also touched upon include whether the biological responses differ depending on the source (e.g. road, railway or aircraft traffic) and characteristics (intermittent or continuous) of the noise, time of day (day- or night-time), sex or age. It should be noted that the role of combined exposure to different sources of noise has received very little attention although this may have profound implications for the biological effects and etiological mechanisms.

2.2.1 Acute effects

As described above, acute biological effects of noise are mediated via activation of the SAM and HPA axes, resulting in the release of stress hormones such as adrenalin, noradrenalin and cortisol. Because they appear early on in the cause-effect chain of noise induced physiological disorders, stress hormones have been widely used for studying biological mechanisms and effects of noise in human adult populations [18-26]. Reviews have concluded that both intense high-impact sounds and environmental noise exposure may cause increased levels of stress hormones, although the results are sometimes diverging [12, 27].

The endocrine responses to noise appear to differ depending on a number of factors, such as the research setting, degree of habituation and informational content of the sound. For example, experimental settings may be stressful themselves, thereby possibly masking the effects of noise [12]. In observational settings, the varying secretory patterns of hormone excretion make interpretation of the findings difficult, in particular for cortisol which has a strong circadian rhythm. Excretion of adrenaline and noradrenalin following noise exposure has been suggested to depend on the degree of habituation to the noise [27]. Adrenaline appears elevated following non-habitual noise exposure, while noradrenaline is increased as a result of habitual exposure. The role of informational content has also been discussed with regard to immediate triggering of fight/flight or defeat reactions. For example, Ising and Kruppa claimed that the information conveyed by noise is often more relevant than the sound level [28]. Thus, activation of the neuroendocrine system may be modulated by the individual’s appraisal of a stressor as a threat.

Other commonly studied biological responses to noise, which are mediated through the nervous system or under the influence of stress hormones, include hemodynamic factors such as blood pressure, heart rate, stroke volume, cardiac output and vasoconstriction [18, 19, 29-33]. Also, some studies have used skin conductance to assess physiological arousal following noise exposure [34]. In a recent experimental investigation, thoracic electrical bioimpedance was used to assess hemodynamic factors, e.g. stroke volume, heart rate and blood pressure, and to evaluate sympathetic and parasympathetic activity of the autonomous nervous system [32]. The study showed that 10-min exposure to road traffic noise at 89 dB LA_{eq} increased blood pressure among both men and women in the range 2-4 mmHg. Once the noise

exposure ceased, blood pressure returned to pre-exposure levels and no associations were seen with heart rate. This indicates that the predominant mechanism for hemodynamic effects of noise was vasoconstriction, i.e. an increase of systemic vascular resistance. However, a recent field-study of night-time aircraft noise proposed that a parallel mechanism may be endothelial dysfunction, which is considered an early step in the development of atherosclerotic changes of the vasculature [26]. Furthermore, in an ambulatory 24-h study with repeated measurements it was found that individual day-time noise exposure (primarily < 65 dB LA_{eq}) was associated with immediate changes in heart rate variability[30]. These results suggest that noise exposure might increase arterial compliance and decrease arterial resistance to compensate for the elevation of blood pressure caused by an increased activity in the sympathetic nervous and endocrine systems.

Autonomic cardiovascular arousals may also arise during sleep [21, 25, 35-37]. Since the physiological responses to noise during sleep are largely unmodulated by conscious appraisal, the magnitude of the auditory stimuli may be more directly reflected than during the awake state. For instance, Di Nisi and colleagues investigated the cardiac and vasomotor modifications induced by noise in humans when awake and during sleep in relation to noise sensitivity [36]. It was found that the cardiovascular responses were greater during night-time than during the day, even if the sound intensity was lower. Effects of short-term changes of transportation noise on 24-h ambulatory blood pressure and heart rate during night-time was also reported in a subsample of the multicenter, cross-sectional study HYENA [37]. Increases in systolic (6.2 mmHg) and diastolic (7.4 mmHg) blood pressure were observed over 15 min intervals in which an aircraft noise event (>35 dBL_{Amax}) occurred. A non-significant increase in heart rate was also seen (5.4 bpm). Furthermore, the results were comparable for aircraft and road traffic noise events, suggesting no systematic difference in noise effects according to the source. Results from a laboratory study showed that the sleep stage as well as the presence of awakenings clearly influenced the extent of the response [25]. The greatest heart rate elevation occurred with awakenings from short wave (deep) sleep and the smallest from rapid eye movement (dream) sleep. With awakenings, noise evoked monophasic heart rate elevations for more than a minute but without awakenings, the heart rate elevations showed biphasic responses with considerably lower elevations. Furthermore, it appears that faster increases in noise levels cause steeper heart rate accelerations with earlier and higher maxima as well as greater increases in blood pressure than noise with longer rise times [25, 35].

Although highly relevant for understanding the pathogenic mechanisms behind noise induced illness, few studies have explored acute effects of noise on metabolic markers, such as blood glucose, serum insulin, blood lipids and markers of inflammation (e.g. CRP and IL-6). This is illustrated by an investigation of the potential impact of HPA axis activity on anthropometric, metabolic and hemodynamic risk factors for cardiovascular disease, type 2 diabetes and stroke [38]. By repeated diurnal salivary cortisol measurements, the status of the HPA axis was characterized in relation to BMI, waist/hip ratio, blood glucose, triglycerides, blood pressure and other risk factors. With a normally functioning HPA axis, the established risk factors tended to assemble in clusters (anthropometric, metabolic, cholesterol and hemodynamic). However, when there was a pathological HPA axis, the risk factors were highly correlated and assembled in one tight cluster. This suggests that a poorly regulated HPA axis has an overriding role for many established risk factors.

Biological effects of noise in children have mostly been studied in observational settings and primarily in relation to aircraft noise [39-45], although two recent epidemiological studies have focused on road traffic noise [46, 47]. As an example, in a prospective study investigating the effects of aircraft noise on blood pressure and stress hormones, 326 schoolchildren were observed before and after the opening of the Munich International Airport and closing of the old airport in 1992 [41]. Statistically significant increases of systolic blood pressure as well as adrenalin and noradrenalin concentrations were found

among children living in areas close to the new airport following its opening. The levels of cortisol also appeared elevated but the difference was not statistically significant. However, in the cross-sectional West London School Study, no difference in cortisol levels were found among children exposed to aircraft noise from London Heathrow airport in comparison to children from unexposed areas, even though the noise exposed children expressed more annoyance [43]. Results from the RANCH study, including two samples of children living near the airports London Heathrow and Amsterdam Schiphol, were not consistent but indicated higher systolic blood pressure in relation to aircraft noise in the home environment of the children [45]. Furthermore, two recent studies showed conflicting results regarding the association between road traffic noise exposure and blood pressure [46, 47]. Overall, the effects of noise that have been observed in children are generally small and appear to be of limited clinical relevance [48].

2.2.2 Chronic effects

Several studies indicate that acute biological effects of noise induced by autonomic cardiovascular arousals do not habituate over time to any major extent [17, 25, 35-37]. When experienced over an extended time period, these changes may increase the risk for chronic disease. However, some studies suggest that habituation may depend on the characteristics of the noise. For example, Sawada and colleagues showed that the hemodynamic responses to steady-state noises, but not intermittent noises, were diminished within minutes after initiation of a noise stimulus [33].

Repeated stimulation of the sympathetic nervous system and lasting elevated catecholamine levels may contribute to the development of atherosclerosis and make the blood more prone to coagulate, thus, increasing the risk of arterial obstruction and diseases such as stroke and myocardial infarction [10]. Furthermore, there is clear evidence that sympathetic activation contributes to the development and progression of hypertension [49]. One recent study investigated the association between fine particulate matter, road traffic noise and thoracic aortic calcification [50]. Such calcification is a measure of subclinical atherosclerosis and is independently related to the incidence of cardiovascular events. Adjusted for fine particulates, the results showed that road traffic noise during night-time was associated with increasing thoracic aortic calcification, however, no associations were seen with the daily average noise level (L_{den}).

Hormonal abnormalities following a long lasting over-activation of the HPA axis may also give rise to cardiovascular and metabolic complications [3, 10, 14, 51-54]. For instance, elevated cortisol levels may increase the risk of hypertension by an increased sensibility of the adrenergic receptors, thereby leading to increased vasoconstriction [14]. In addition, circulating levels of sex and growth hormones are diminished following HPA axis activation [51]. Cortisol is associated with an accumulation of body fat in central adipose tissues while sex and growth hormones result in the opposite, thus sustained activity of the HPA axis may lead to abdominal obesity. One explanation for the central accumulation of fat rather than in adipose tissue in other parts of the body is a higher density of corticosteroid receptors on the fat cells in the abdominal area [10]. Furthermore, hyperactivity of the HPA axis is followed by muscular insulin resistance, which is a strong predictor of type 2 diabetes and cardiovascular disease [51, 53-55]. Cortisol has an inhibitory effect on insulin and promotes the activity of lipoprotein lipase, responsible for conversion of triglycerides to free fatty acids. Elevated levels of free fatty acids inhibit glucose metabolism and induces hyperinsulinemia [53].

Chronic health effects of noise may also be mediated or induced by sleep disturbances. The activity of the sympathetic nervous system and the HPA axis is normally inhibited during sleep and the anabolic growth hormone is released [7]. These changes have restorative effects and lead to reduced heart rate

and blood pressure as well as decreased brain glucose metabolism. Effects of noise on sleep include cortical arousals and awakenings, sleep stage changes and autonomic cardiovascular arousals. There are also secondary or “next-day” effects, such as fatigue, drowsiness and reduced performance. Tertiary, or chronic, health effects of noise-disturbed sleep may arise as a consequence of the primary and secondary effects if these persist over an extended period of time [5, 6]. Non-habituating autonomic reactions are believed to be the primary causes of chronic health effects of noise, and the autonomic reactions during sleep may actually be exaggerated because of a reduced filter by cortical awareness [36]. Thus, long-term night-noise exposure may be of greater importance than daytime exposure.

Other consequences of sleep-deprivation which may be of importance for disease development include effects on the carbohydrate metabolism, influence on appetite regulation as well as impairment of immune system functioning. Studies have shown associations between sleep-restriction and impaired glucose tolerance, decreased insulin sensitivity as well as increased risk of Type 2 diabetes [56, 57]. The two hormones insulin and leptin are long-term regulators of food intake and exert sustained inhibitory effects on food intake while simultaneously increasing energy expenditure. In parallel, the hormone ghrelin act as a metabolic counterpart, stimulating appetite and maintaining body mass homeostasis. Disturbance of sleep may affect this balance by reducing leptin and increasing ghrelin, subsequently leading to increased adiposity and body mass index [58, 59]. Furthermore, a recent review showed that there are strong interrelationships between sleep quality and systemic inflammation [60]. For instance, sleep deprivation has been shown to increase the levels of circulating inflammation markers, such as IL-6, TNF-α and C-reactive protein. Systemic inflammation is associated with increased risks of morbidity and mortality from cardiovascular and other chronic diseases.

The mechanisms described above for chronic health effects of noise among adults are supported by an increasing number of epidemiological studies linking environmental noise exposure to cardiovascular diseases, such as hypertension, ischemic heart disease (including myocardial infarction) and stroke [61-64]. Chronic effects of long-term traffic noise on the metabolic system have only recently been addressed in epidemiological research. Currently, merely two studies are available and they have linked aircraft noise to increased waist circumference [65] and road traffic noise to incident type 2 diabetes [66].

2.3 Perceptual and psychological factors

Models of human reaction to stressors typically include an appraisal and coping component that moderates the relationship between physical exposure and physiological stress [67]. Since individuals differ greatly in how they perceive and react to noise, it is relevant to ask what role such individual differences play for the relationship between noise exposure and adverse health effects, primarily cardiovascular disease. This section reviews research on the influence of noise annoyance and noise sensitivity.

2.3.1 Noise annoyance

Noise annoyance is a feeling of displeasure or dissatisfaction evoked by noise exposure. It is typically measured with a single questionnaire item asking for an integrated assessment of the degree of annoyance evoked by a specific source, for example, road traffic noise as experienced during the last 12 months while at home [68].

There are several ways in which noise annoyance may influence the relationship between noise exposure and cardiovascular disease. Feelings of noise annoyance may aggravate the physiological

stress response through feed-back mechanisms from cortical to subcortical areas initiating physiological stress responses. Another type of mechanism involves coping, which indirectly may diminish as well as aggravate noise induced effects on ill health. For example, noise annoyed individuals may avoid opening windows at noise exposed facades (diminished risk) or noise annoyance may stimulate stress reducing but unhealthy dietary habits (aggravated risk).

It is also conceivable that noise annoyance plays no role for the relationship between noise exposure and cardiovascular disease. This would be the case if the relationship primarily is driven by direct links between noise exposure and subcortical areas initiating the physiological stress response, with little influence of feed-back from upstream areas involved in subjective noise appraisal. Noise induced physiological responses during sleep are well documented [69], and this indicates one pathway largely unmediated by auditory experience and appraisal.

Noise annoyance is strongly related to noise exposure, but also to non-acoustic factors, including age and noise sensitivity [70]. There is some support for an association between noise annoyance and cardiovascular disease, especially hypertension [71]. This association is consistent with a mediating or moderating role of noise annoyance on the relationship between noise exposure and cardiovascular disease, but could also be the result of confounding by noise exposure or by non-acoustic factors causing both annoyance and cardiovascular disease. To clarify this, noise annoyance has to be analysed jointly with noise exposure and cardiovascular outcomes [72]. A few studies, discussed below, have presented such analyses.

The HYENA study found significant relationships between night-time aircraft as well as daily road traffic noise exposure and risk of hypertension after adjusting for a number of risk factors [73]. Follow up analyses also adjusted for noise annoyance, but this did not affect the risk estimates which speaks against noise annoyance mediating the relationship between noise exposure and hypertension. However, some support was found for a stronger relationship between aircraft noise and hypertension among noise annoyed compared to non-annoyed residents, which agrees with the results of another study on aircraft-noise related incidence of hypertension [74]. The HYENA study also found a relation between aircraft noise exposure and morning saliva cortisol in women but this effect was independent of aircraft annoyance [24].

For road-traffic noise and hypertension, findings are inconclusive. Both a similar [72], stronger [75] and weaker [76] relationship has been reported for annoyed compared to non-annoyed residents. A weaker relationship may seem contradictory, but may result from active coping, for instance, if noise annoyed residents to a larger extent keep windows closed, thereby reducing their exposure. For road-traffic noise and myocardial infarction, a case-control study found risk estimates associated with road-traffic noise exposure to be particularly elevated in those annoyed by noise in the bedroom [77]. However, elevated risks were not observed for those reporting sleep disturbances or general road-traffic noise annoyance.

2.3.2 Noise sensitivity

Noise sensitivity is a personality trait characterized by a general susceptibility to noise [34]. It is measured in questionnaires, for example by asking the respondent to indicate how much or little he or she agrees with statements like “I am sensitivity to noise”, “There are often times when I want complete silence”, and “I find it hard to relax in a place that is noisy” [78].

Noise sensitivity is associated with the broader personality trait neuroticism [79-81], that is, a disposition to experience aversive emotional states, such as anxiety, sadness, worry and anger, and a tendency to be self-critical and feel personally inadequate, a component also referred to as negative

affectivity [82]. Prospective studies have shown that neuroticism is linked to future health problems and mortality, also from cardiovascular disease, and there is some evidence that neuroticism is associated with increased stressor-induced physiological responses, including electrodermal activity, cardiovascular reactivity and morning cortisol levels [83].

Although noise sensitivity seems to be uncorrelated with noise exposure, it is a strong predictor of noise annoyance and it modifies the noise exposure-annoyance relationship. For the same exposure, noise sensitive individuals tend to report more annoyance than non-sensitive individuals and this difference increases with exposure [84]. It is unclear whether this primarily relates to an increased tendency to report annoyance or if it also involves an increased physiological reactivity to acute noise exposure. There are some experimental results in support of the latter hypotheses [34, 85, 86]. In contrast, other studies have failed to demonstrate a higher reactivity in response to noise among noise sensitive individuals [87-89].

Few epidemiological studies on chronic cardiovascular effects of long-term noise exposure have reported analyses of noise sensitivity. However, Babisch [90] reanalysed data from three epidemiological studies on ischemic heart disease or hypertension in relation to road or aircraft noise, but found no support for increased risks of cardiovascular disease or hypertension among noise sensitive individuals. Noteworthy were the results from the HYENA study, where risk estimates in relation to aircraft noise appeared higher among noise sensitive individuals for self-reported hypertension, but not for hypertension determined with blood pressure measurements. This illustrates the problem of analysing self-reported outcomes in relation to noise sensitivity, since noise sensitive individuals probably tend to report more symptoms than non-sensitive individuals irrespective of health status, as has been found for individuals high in neuroticism and negative affectivity [91]. If symptom reporting is particularly amplified among those noise sensitive persons that are highly exposed to noise, this would lead to a spurious moderating effect of noise sensitivity on exposure-health relationships based on self-reported health outcomes. In line with this, a review of research on noise sensitivity and sleep disturbance found support for a link between noise sensitivity and noise induced sleep disturbance, but only for self-reported sleep problems, not for physiological indicators of disturbed sleep [92].

References

1. Selye H (1956). The stress of life. McGraw-Hill, New York.
2. Babisch W (2002). The noise/stress concept, risk assessment and research needs. Noise Health, 4(16): 1-11.
3. Björntorp P (1997). Stress and cardiovascular disease. Acta physiologica Scandinavica. Supplementum, 640: 144-8.
4. Henry J (1992). Biological basis of the stress response. Integrative Physiological and Behavioral Science, 27: 66-83.
5. Muzet A (2007). Environmental noise, sleep and health. Sleep Medicine Reviews, 11(2): 135-42.
6. Pirrera S, De Valck E, Cluydts R (2010). Nocturnal road traffic noise: A review on its assessment and consequences on sleep and health. Environment international, 36(5): 492-8.
7. Van Cauter E et al. (2008). Metabolic consequences of sleep and sleep loss. Sleep Medicine, 9 Suppl 1: S23-8.
8. Spreng M (2004). Noise induced nocturnal cortisol secretion and tolerable overhead flights. Noise Health, 6(22): 35-47.
9. Basner M et al. (2014). Auditory and non-auditory effects of noise on health. Lancet, 383(April 12): 1325-32.
10. Lundberg U (1999). Coping with stress: neuroendocrine reactions and implications for health. Noise Health, 1(4): 67-74.
11. Spreng M (2000). Central nervous system activation by noise. Noise Health, 2(7): 49-58.
12. Babisch W (2003). Stress hormones in the research on cardiovascular effects of noise. Noise Health, 5(18): 1-11.
13. Majzoub JA (2006). Corticotropin-releasing hormone physiology. European Journal of Endocrinology, 155: S71-S76.
14. Spreng M (2000). Possible health effects of noise induced cortisol increase. Noise Health, 2(7): 59-64.
15. Martinac M et al. (2014). Metabolic syndrome, activity of the hypothalamic-pituitary-adrenal axis and inflammatory mediators in depressive disorders. Acta Clinica Croatica, 53(1): 55.
16. Björntorp P (1996). Behavior and metabolic disease. International Journal of Behavioral Medicine, 3(4): 285-302.
17. Brink M (2012). A review of potential mechanisms in the genesis of long-term health effects due to noise-induced sleep disturbances. Proceedings of INTER-NOISE 2012, New York City, New York, USA.
18. Andrén L (1983). Cardiovascular effects of noise. Acta Physiologica Scandinavica. Supplementum, 657: 1-45.
19. Andrén L et al. (1982). Effects of noise on blood pressure and 'stress' hormones. Clinical Science, 62(2): 137-41.
20. Babisch W et al. (2001). Increased catecholamine levels in urine in subjects exposed to road traffic noise: the role of stress hormones in noise research. Environment International, 26(7-8): 475-81.
21. Griefahn B, Robens S (2010). Experimental studies on the effects of nocturnal noise on cortisol awakening response. Noise and Health, 12(47): 129-36.
22. Hébert S, Lupien SJ (2008). Salivary cortisol levels, subjective stress, and tinnitus intensityin tinnitus suffers during noise exposure in the laboratory. International Journal of Hygiene and Environmental Health, 212(1): 37-44.
23. Persson Waye K et al. (2003). Effects of nighttime low frequency noise on the cortisol response to awakening and subject sleep quality. Life Sciences, 72: 863-875.

24. Selander J et al. (2009). Saliva cortisol and exposure to aircraft noise in six European countries. Environmental Health Perspectives, 117(11): 1713-7.
25. Griefahn B et al. (2008). Autonomic arousals related to traffic noise during sleep. Sleep, 31(4): 569-77.
26. Schmidt FP et al. (2013). Effect of nighttime aircraft noise exposure on endothelial function and stress hormone release in healthy adults. European Heart Journal: eht269.
27. Ising H, Braun C (2000). Acute and chronic endocrine effects of noise: Review of the research conducted at the Institute for Water, Soil and Air Hygiene. Noise Health, 2(7): 7-24.
28. Ising H, Kruppa B (2004). Health effects caused by noise: evidence in the literature from the past 25 years. Noise Health, 6(22): 5-13.
29. Chang T-A et al. (2009). Effects of environmental noise exposure on ambulatory blood pressure in young adults. Environmental Research, 109: 900-05.
30. Chang T-A et al. (2012). Effects of environmental noise exposure on 24-h ambulatory vascular properties in adults. Environmental Research, 118: 112-17.
31. Kraus U et al. (2013). Individual daytime noise exposure during routine activities and heart rate variability in adults: A repeated measures study. Environmental Health Perspectives, 121(5): 607-612.
32. Paunović K et al. (2014). Thoracic bioelectrical impedance assessment of the hemodynamic reactions to recorded road-traffic noise in young adults. Environmental Research, 129: 52-58.
33. Sawada Y (1993). Hemodynamic effects of short-term noise exposure. Japanese Circulation Journal, 57: 862-72.
34. Stansfeld SA (1992). Noise, noise sensitivity and psychiatric disorder: epidemiological and psychophysiological studies. Psychological Medicine. Monograph supplement, 22: 1-44.
35. Carter N et al. (2002). Cardiovascular and autonomic response to environmental noise during sleep in night shift workers. Sleep, 25(4): 444-51.
36. Di Nisi J et al. (1990). Comparison of cardiovascular responses to noise during waking and sleeping in humans. Sleep, 13(2): 108-20.
37. Haralabidis AS et al. (2008). Acute effects of night-time noise exposure on blood pressure in populations living near airports. European Heart Journal, 29: 658-664.
38. Rosmond R, Björntorp P (2000). The hypothalamic-pituitary-adrenal axis activity as a predictor of cardiovascular disease, type 2 diabetes and stroke. Journal of Internal Medicine, 247(2): 188-97.
39. Cohen S et al. (1980). Physiological, motivational, and cognitive effects of aircraft noise on children: moving from the laboratory to the field. American Psychologist, 35(3): 231-43.
40. Cohen S et al. (1981). Aircraft noise and children: Longitudinal and cross-sectional evidence on adaptation to noise and the effectiveness of noise abatement. Journal of Personality and Social Psychology, 40(2): 331-45.
41. Evans GW, Bullinger M, Hygge S (1998). Chronic noise exposure and physiological response: a prospective study of children living under environmental stress. Psychological Science 9(1): 75-77.
42. Evans GW et al. (2001). Community noise exposure and stress in children. Journal of the Acoustical Society of America, 109(3): 1023-7.
43. Haines MM et al. (2001). The West London Schools Study: the effects of chronic aircraft noise exposure on child health. Psychological Medicine, 31(8): 1385-96.
44. Morrell SL (2003). Aircraft noise and child blood pressure. Doctoral thesis, University of Sydney.
45. van Kempen E et al. (2006). Noise exposure and children's blood pressure and heart rate: the RANCH project. Occupational and Environmental Medicine, 63: 632-39.

46. Bilenko N et al. (2013). Traffic-related air pollution and noise and children's blood pressure: results from the PIAMA birth cohort study. European Journal of Preventive Cardiology, September 18, doi: 10.1177/2047487313505821.
47. Liu C et al. (2014). The association between traffic-related air pollution and noise with blood pressure in children: results from the GINIplus and LISAplus studies. International Journal of Hygiene and Environmental Health, 217(4-5): 499-505.
48. Matheson MP, Stansfeld SA, Haines MM (2003). The effects of chronic aircraft noise exposure on children's cognition and health: 3 field studies. Noise Health, 5(19): 31-40.
49. Mancia G, Grassi G (2013). The central sympathetic nervous system in hypertension. Handbook of Clinical Neurology, 117: 329-35.
50. Kälsch H et al. (Heinz Nixdorf Recall Study Investigative Group 2014). Are air pollution and traffic noise independently associated with atherosclerosis: the Heinz Nixdorf Recall Study. European Heart Journal, 35(13): 853-60.
51. Björntorp P (1997). Body fat distribution, insulin resistance, and metabolic diseases. Nutrition, 13(9): 795-803.
52. Kyrou I, Tsigos C (2008). Chronic stress, visceral obesity and gonadal dysfunction. Hormones (Athens), 7(4): 287-93.
53. Rosmond R (2003). Stress induced disturbances of the HPA axis: a pathway to Type 2 diabetes? Medical Science Monitor, 9(2): 35-9.
54. Rosmond R (2005). Role of stress in the pathogenesis of the metabolic syndrome. Psychoneuroendocrinology, 30(1): 1-10.
55. Kyrou I, Chrousos GP, Tsigos C (2006). Stress, visceral obesity, and metabolic complications. Annals of the New York Academy of Sciences, 1083: 77-110.
56. Cappuccio FP et al. (2010). Quantity and quality of sleep and incidence of type 2 diabetes: a systematic review and meta-analysis. Diabetes Care, 33(2): 414-20.
57. Spiegel K, Leproult R, Van Cauter E (1999). Impact of sleep debt on metabolic and endocrine function. Lancet, 354(9188): 1435-9.
58. Chaput JP et al. (2007). Short sleep duration is associated with reduced leptin levels and increased adiposity: Results from the Quebec family study. Obesity (Silver Spring), 15(1): 253-61.
59. Taheri S et al. (2004). Short sleep duration is associated with reduced leptin, elevated ghrelin, and increased body mass index. PLOS Medicine, 1(3): e62.
60. Gamaldo CE, Shaikh AK, McArthur JC (2012). The sleep-immunity relationship. Neurologic Clinics, 30(4): 1313-43.
61. Babisch W et al. (2005). Traffic noise and risk of myocardial infarction. Epidemiology, 16(1): 33-40.
62. Huss A et al. (2010). Aircraft noise, air pollution, and mortality from myocardial infarction. Epidemiology, 21(6): 829-36.
63. Jarup L et al. (2008). Hypertension and exposure to noise near airports: the HYENA study. Environmental Health Perspectives, 116(3): 329-33.
64. Sørensen M et al. (2011). Road traffic noise and stroke: a prospective cohort study. European Heart Journal, 32(6): 737-44.
65. Eriksson C et al. (2014). Long-term aircraft noise exposure and Body Mass Index, waist circumference, and type 2 diabetes: A prospective study. Environmental Health Perspectives, May 2014.
66. Sørensen M et al. (2013). Long-Term Exposure to Road Traffic Noise and Incident Diabetes: A Cohort Study. Environmental Health Perspectives, 121: 217-222.
67. Lercher P (1996). Environmental noise and health: An integrated research perspective. Environmental International, 22(1): 117-129.

68. ISO, Acoustics-Assessment of noise annoyance by means of social and socio-acoustic surveys. ISO/TS 15666:2003(E). 2003, Geneva, Switzerland: ISO.
69. WHO, Guidelines for Community Noise, ed. B. Berglund, et al. 1999, Geneva: World Health Organization.
70. Miedema HME, Vos H (1999). Demographic and attitudinal factors that modify annoyance from transportation noise. Journal of the Acoustical Society of America, 105(6): 3336-3344.
71. Ndrepepa A, Twardella D (2011). Relationship between noise annoyance from road traffic noise and cardiovascular diseases: a meta-analysis. Noise and Health, 13(52): 251.
72. Babisch W et al. (2013). Noise annoyance – A modifier of the association between noise level and cardiovascular health? Science of the Total Environment, 452: 50-57.
73. Jarup L et al. (2008). Hypertension and exposure to noise near airports: the HYENA study. Environmental Health Perspectives, 116: 329-333.
74. Eriksson C et al. (2010). Aircraft noise and incidence of hypertension—gender specific effects. Environmental research, 110(8): 764-772.
75. Björk J et al. (2006). Road traffic noise in southern Sweden and its relation to annoyance, disturbance of daily activities and health. Scandinavian journal of work, environment & health: 392-401.
76. Lercher P et al. (2011). Cardiovascular effects of environmental noise: Research in Austria. Noise & Health, 13(52): 234-250.
77. Selander J et al. (2009a). Long-term exposure to road-traffic noise and myocardial infarction. Epidemiology, 20(2): 272-279.
78. Weinstein ND (1978). Individual differences in reactions to noise: A longitudinal study in a college dormitory. Journal of Applied Psychology, 63: 458-466.
79. Belojevic G, Jakovljevic B (2001). Factors influencing subjective noise sensitivity in an urban population. Noise and Health, 4(13): 17.
80. Heinonen-Guzejev M et al. (2004). Somatic and psychological characteristics of noise-sensitive adults in Finland. Archives of Environmental Health: An International Journal, 59(8): 410-417.
81. Smith A (2003). The concept of noise sensitivity: Implications for noise control. Noise & Health, 5(18): 57-59.
82. Watson D, Clark LA, Harkness AR (1994). Structures of personality and their relevance to psychopathology. Journal of abnormal psychology, 103(1): 18.
83. Lahey BB (2009). Public health significance of neuroticism. American Psychologist, 64(4): 241-256.
84. Miedema HME, Vos H (2003). Noise sensitivity and reactions to noise and other environmental conditions. Journal of the Acoustical Society of America, 113(3): 1492-1504.
85. Persson Waye K et al. (2002). Low frequency noise enhances cortisol among noise sensitive subjects during work performance. Life Sciences, 70: 745-758.
86. Griefahn B, Di Nisi J (1992). Mood and cardiovascular functions during noise, related to sensitivity, type of noise and sound pressure level. Journal of sound and vibration, 155(1): 111-123.
87. Ljungberg J, Neely G, Lundström R (2004). Cognitive performance and subjective experience during combined exposures to whole-body vibration and noise. International Archives of Occupational and Environmental Health, 77: 217-221.
88. Croy I, Smith MG, Waye KP (2013). Effects of train noise and vibration on human heart rate during sleep: an experimental study. Bmj Open, 3(5).
89. Notbohm G et al. (2013). Patterns of physiological and affective responses to vehicle pass-by noises. Noise & Health, 15(66): 355-366.
90. Babisch W, Noise sensitivity in cardiovascular noise studies, in Internoise 2001. 2010, Institute of Noise Control Engineering: Lisbon. p. 3763-3772.

91. Watson D, Pennebaker JW (1989). Health complaints, stress, and distress: exploring the central role of negative affectivity. Psychological review, 96(2): 234.
92. Laszlo H et al., Noise sensitivity and sleep disturbance, in Internoise 2012. 2012, ICBEN: New York.

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