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Noise annoyance - A modifier of the association between noise level and cardiovascular health?

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HIGHLIGHTS

- We assessed the associations between aircraft and road traffic noise and hypertension.
- We compared the predictive power of noise level and noise annoyance on hypertension.
- Road traffic noise was associated with a higher risk of hypertension.
- Noise annoyance had no substantial effect modifying impact on the associations.
- The noise level is more predictive for cardiovascular effects than noise annoyance.

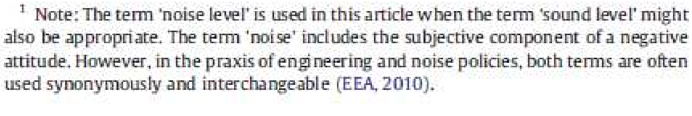
ABSTRACT

Objectives: The effect modifying impact of annoyance due to aircraft noise and road traffic noise on the relationships between the aircraft noise level and road traffic noise level on the prevalence of hypertension was investigated in 4861 subjects of the HYENA study (HYpertension and Exposure to Noise near Airports).
Methods: Different models were investigated either including the noise level and noise annoyance variables separately, or simultaneously, or together with an interaction term referring to the same noise source for the noise level and the noise annoyance.
Results: Significant effect modification was found with respect to the association between aircraft noise and hypertension. The association was stronger in more annoyed subjects. No clear interaction was found with respect to road traffic noise. The comparison of the magnitude of the main effects (per standard deviation or inter-quartile range) of noise level and noise annoyance variables revealed stronger associations with hypertension for the noise levels.
Conclusion: There is some indication that the noise level has a stronger predictive meaning for the relationship between noise exposure and hypertension than the reported noise annoyance (main effects). The results from the Hyena study support the hypothesis that noise annoyance acts as an effect modifier of the relationship between the noise level and hypertension.

1. Introduction

Environmental noise causes subjective discomfort which is assessed as reported noise annoyance (European Commission Working Group on Dose-Effect Relations, 2002; Miedema and Oudshoorn, 2001; ANSI S12.9 - Part 4, 2005). Environmental noise exposure (sound level) also causes physiological health effects, of which high blood pressure and ischemic heart diseases are the most investigated (van Kempen and Babisch, 2012; Babisch and van Kamp, 2009; Babisch, 2008). According to the noise reaction model (Fig. 1), two principal pathways are relevant for the development of adverse health effects due to noise (Job, 1996; Babisch, 2002). These refer to the ‘direct’ and the ‘indirect’ arousal and activation of the organism. The ‘direct’ pathway is determined by the instantaneous interaction of the acoustic nerve with different structures of the central nervous system. The ‘indirect’ pathway refers to the cognitive perception of the sound, its cortical activation and related emotional responses. Not only the noise level but also the noise annoyance has been shown to be associated with cardiovascular disorders (Ndrepepa and Twardella, 2011; Babisch, 2006). Both reaction chains can initiate physiological stress reactions, including hypothalamus, the limbic system, the autonomous nervous system, the pituitary and the adrenal gland. The general stress model is the biological mechanism for physiological dysfunction which may result in manifest physiological changes and health effects in the long run of chronic noise exposure. While the conscious experience with noise might be the primary source of stress reactions during daytime in awake subjects, the non-conscious biological response to noise may be the primary source of stress reactions during night-time in sleeping subjects—at even lower noise levels when the organism is at a much lower level of activation for physiological and mental recreation and restoration[1]. Since both factors refer – at least in parts – to different physiological mechanisms/pathways, the question arose whether the combination in a statistical model may have an additive or even synergistic effect on the physiological response (Rylander, 2004). In other words, since the noise level largely determines the noise annoyance, one would expect a stronger association between the noise level and physiological health effects in the presence of high noise annoyance (effect modification).

This article investigates the combined effects of noise level and noise annoyance on the prevalence of high blood pressure (hypertension). The particular focus was on noise annoyance as a potential effect modifier of the relationship between the noise level and the prevalence of hypertension. We refer to data of the large multi-centred European noise study HYENA (HYpertension and Exposure to Noise near Airports) where road traffic and aircraft noise data as well as annoyance data regarding both noise sources were assessed (Jarup et al., 2008). The study was approved by ethical committees within each collaborating research centre (country).



[1] Note: The term 'noise level' is used in this article when the term 'sound level' might also be appropriate. The term 'noise' includes the subjective component of a negative attitude. However, in the praxis of engineering and noise policies, both terms are often used synonymously and interchangeable (EEA, 2010).

2. Materials and methods

The study design and the methods for the assessment of the exposure, hypertension and annoyance are described in detail elsewhere (Babisch et al., 2009; Jarup et al., 2005, 2008). These descriptions are summarised in the following.

2.1. Study design

The HYENA study is a large-scale multi-centred study carried out simultaneously in 6 European countries to assess the relationship between aircraft noise and road traffic noise on the one hand,

and the prevalence of high blood pressure (hypertension) on the other. The study population included 4861 people (2404 men and 2467 women) aged between 45 and 70 years at the time of interview, and who had been living for at least 5 years, near one of six major European airports (London–Heathrow (GB), Berlin–Tegel (D), Amsterdam–Schiphol (NL), Stockholm–Arlanda (S), Milan–Malpensa (I) and Athens–Elephterios Venizelos (GR)). In Stockholm, also the citizens living near the City Airport (Bromma) were included to increase the number of exposed subjects. Subjects were selected at random from available registers (e.g. registration office, electoral roll, health service). To maximize exposure contrast, the population was stratified using existing noise contours. Areas with other sources of noise exposure (rail, industry, etc.) were largely excluded. Field work was carried out between 2003 and 2005.

2.2. Noise assessment

To facilitate comparability between the HYENA countries, the ‘Integrated Noise Model’ (INM) served as the standard model for the assessment of the aircraft noise exposure based on radar flight tracks (Gulding et al., 2002). For aircraft noise Lday,12hr, Levening,4hr and Lnight,8hr were calculated (day defined as the hours from 7:00 to 19:00 or 6:00 to 18:00, evening defined as the hours from 19:00 to 23:00 or 18:00 to 22:00 and night defined as the hours from 23:00 to 7:00 or 22:00 to 6:00, according to the ‘European Environmental Noise Directive’ (Directive, 2002/49/EC, 2002)). In the UK the model ‘Ancon’ was applied which fulfilled the requirements of the European Civil Aviation Conference (ECAC, 1997). Road traffic noise assessment was based on available noise data according to the national assessment methods (United Kingdom: “Calculation of Road Traffic Noise” (Department of Transport, 1988); Germany, Italy: “Richtlinien für den Lärmschutz an Straßen” (Bundesministerium für Verkehr, 1990); Greece, The Netherlands: "Standaard Rekenen Meetvoorschrift" (Ministry of Housing, Spatial Planning and the Environment, 2002); Sweden: "Nordic Prediction Method" (Bendtsen, 1999)) and the "Good Practice Guide for Strategic Noise Mapping" (Directive, 2002/49/EC, 2002; WG-AEN, 2006). The non-weighted average 24-hour noise indicator LAeq24h was universally available for all research areas. Exposure was assessed using models with 1 dB resolution for both exposures (5 dB for UK road traffic noise) and spatial resolution of 250 m×250 m for aircraft and 10 m×10 m for road traffic noise. The assessment was made for the year 2002 which was assumed to be representative for the five-year period preceding the health assessment. All noise levels were linked to each participant's home address using the geographical information system technique. Road noise levels referred to the most exposed facade. To minimize the impact of inaccuracies on the noise levels at the lower end, a cut-off value of 40 dB(A) for Lden was introduced for aircraft noise. The lower cut-off level for the road traffic noise level LAeq24h was set to 45 dB(A). It has been shown in previous studies that aircraft noise and road traffic noise were not correlated (Lden(air)−LAeq24h(road): rs=0.01, LAeq16h(air) −LAeq16h(road): rs=0.02, Lnight(air)−Lnight(road): rs=0.03). Noise levels during the day and the night were highly correlated, which justifies the use of only one indicator for each noise source for the assessment of associations (LAeq16h(air)−Lnight(air): rs=0.82, LAeq16h(road) −Lnight(road): rs=0.98) (Babisch et al., 2009).

2.3. Blood pressure assessment

High blood pressure (hypertension) was defined according to the criteria of the World Health Organization (WHO), i.e. a systolic blood pressure ≥140 mmHg and/or a diastolic blood pressure ≥90 mmHg (WHO, 1999; WHO and ISH, 2003). In the analysis, the blood pressure (BP) measurements that were carried out after at least 5 min rest during the home visits, following a standardized protocol. The blood pressure measurements were combined with information on diagnoses of hypertensive disease and medication, so that the main measure of hypertension was either according to the BP measurements using the WHO definition or a diagnosis of hypertension in conjunction with use of antihypertensive medication, which is commonly used in epidemiological studies of hypertension (Wolf-Maier et al., 2003).

2.4. Noise annoyance

During the home visits personal interviews were carried out (face-to-face interview). Noise annoyance was assessed using the non-verbal 11-point 'ICBEN scale' ranging from 0 to 10 (Fields et al., 2001). The battery of annoyance items amongst others referred to air and road traffic noise. The original questionnaire distinguished between the annoyance during the day and the night to account for differences between the location of the living room and the bedroom (noise levels referred to the most exposed facade). For the present analyses, the annoyance ratings due to noise during the day and the night were combined in a way that the highest rating (day or night) was considered. Comparative studies have shown that with respect to road traffic noise there is no difference between day and night annoyance when the average noise level (Leq) is the same (Hoeger et al., 2002). With respect to aircraft noise higher annoyance ratings during the night than during the day were only found for noise levels above 50 dB(A) (Hoeger et al., 2002). The studies carried out around the Zurich airport in Switzerland showed that the general annoyance due to aircraft noise was mostly determined by the outdoor noise exposure in front of the house and less by the indoor noise exposure (Brink et al., 2006).

For the assessment of interaction between the noise level and the annoyance and for stratified analyses, the continuous annoyance variables of the 11-point scale were collapsed into 3 categories (ratings 0–3, ratings 4–7, ratings 8–10). This categorization corresponded with the >28% criterion ('at least little annoyed') and the >72% criterion ('highly annoyed') used by Schulz and Miedema for converted scales which range from0 to 100 (European Commission Working Group on Dose-Effect Relations, 2002; Miedema and Oudshoorn, 2001; Schultz, 1978). Analyses were also carried out with dichotomized annoyance variables (ratings 0–7 vs. 8–10 and 0–3 vs. 4–10).

2.5. Statistical analyses

The present analyses refer to the same sample of 4861 subjects as the main analyses of the HYENA study (Jarup et al., 2008). Due to missing values the actual number of subjects varied slightly from analyses to analysis. Multiple logistic regression models were calculated where the dichotomous variable prevalence of hypertension was considered as the dependent variable (outcome) in logistic regression analysis. All results were adjusted for age, gender, body mass index, alcohol consumption, school education, physical activity at leisure, and study area (country/airport). Whole day 24 h noise indicators seemed to be most appropriate in conjunction with the combined day-night annoyance indicators. For aircraft noise the weighted day-evening-night noise indicator Lden was used as predictor variable which was available for all airports. For road traffic noise the 24 h average noise indicator LAeq24h was used instead, because Lden (road) was not available for all research areas.

To enable the comparison of the impact of different models on the effect estimates, different models were calculated: (1) the basic model including the noise level variables (Lden-air, LAeq24h-road) and all the confounders mentioned before; (2) a model where the noise variables were replaced by the continuous annoyance variables (annoyance-air, annoyance-road); (3) stratified models within the different factorial subgroups of annoyance, including both continuous noise level variables and all confounders; (4) a model including all noise level variables, all confounders, one of the categorical annoyance factors (air or road) and its interaction term with the respective noise level indicator. Both, the annoyance factor and the interaction term in the model, thus, referred to the same noise source; no crossover calculations were carried out (noise level referring to one source, annoyance to another). Only one interaction term at a time was included in each model for better interpretation of the interaction terms. The presence of effect modification (interaction) was decided upon the significance level of 0.05. All models were calculated as fixed effect models, including ‘country’ as a categorical factor (6 categories) for adjustment, using the statistical software package SPSS version 19 (command routines ‘Logistic Regression’). Adjusted odds rations (OR) and 95% confidence intervals (CI) were calculated as estimates of the relative risk.

3. Results

Table 1 shows the correlation (non-parametric Spearman correlation coefficient rs) between the noise variables and the continuous annoyance variables. Road traffic noise annoyance and aircraft noise annoyance were only little correlated (rs=0.23), probably linked through subjective noise sensitivity. Road traffic noise level and road traffic noise annoyance, as well as aircraft noise level and aircraft noise annoyance were moderately correlated (rs=0.49 and 0.41, respectively). No crossover correlations between noise levels and annoyance ratings were found (rs=−0.03 and −0.00, respectively). 32.6% subjects of the study sample were highly annoyed due to aircraft noise and 13.6% due to road traffic noise (annoyance ratings 8–10). The mean aircraft noise level (Lden) was 53.7 (standard deviation=8.8, interquartile range= 14.0) dB(A) and the mean aircraft noise annoyance in the study sample was 4.9 (standard deviation=3.7, interquartile range=7.0) scale units. The mean road traffic noise level (LAeq24h) was 52.8 (standard deviation=7.5, interquartile range=13.1) dB(A) and the mean road traffic noise annoyance in the study sample was 2.8 (standard deviation=3.2, interquartile range=5.0) scale units.

3.1. Aircraft noise

Table 2 shows the results of the different models regarding the associations between aircraft noise level and noise annoyance due to aircraft noise with the prevalence of hypertension — adjusted for confounders. In the model including only the aircraft noise and the road traffic noise level a non-significant odds ratio of OR=1.037 (CI=0.962–1.119) was found for aircraft noise per increase of the noise level by 10 dB(A). This estimate remained stable when the annoyance variables were also entered as main effects to the model (OR=1.036, CI=0.946–1.134). The annoyance due to aircraft noise was not significantly associated with hypertension in the models, neither in the model including only annoyance variables as explanatory factors, nor in the model including noise levels and annoyance variables simultaneously (OR=1.003 (CI=0.985–1.022) and OR=1.001 (CI=0.979–1.023), respectively, per unit of the continuous 11-point annoyance scale). The comparison of the effects of the noise level and the annoyance per standard deviation (noise level: OR=1.032, annoyance: OR=1.011) or inter-quartile range (noise level: OR=1.052, annoyance: 1.021) revealed a slightly stronger quantitative impact of the noise level on the risk of hypertension.

Stratified analyses regarding the annoyance due to aircraft noise (3 categories) showed a slight tendency towards a stronger association between aircraft noise level and hypertension in ‘moderately annoyed’ and ‘highly annoyed’ subjects compared with ‘low annoyed’ subjects (OR=1.112 and OR=1.084, respectively, vs. OR=0.944; confidence intervals are shown in Table 2). Neither any of the stratified associations, nor the respective interaction terms was significant (p=0.142). The result is also shown in Fig. 2. The widths of the error bars vary from cell to cell which is due to the different numbers of subjects in each cell. For example, the number of highly annoyed subjects was 63 in the lowest noise level category and 221 in the highest noise level category. When the upper two annoyance categories were combined (ratings 4–10=‘highly annoyed+moderately annoyed’ vs. ratings 0–3=‘low annoyed’) the interaction term was significant (p=0.048) indicating a stronger effect of the noise level in annoyed subjects. This was partly due to a lower risk of low annoyed subjects in the highest aircraft noise category (Fig. 2). On the other hand, when the lower two annoyance categories were combined (ratings 8–10=‘highly annoyed’ vs. ratings 0–7=‘low annoyed+moderately annoyed’), the interaction term was insignificant (p=0.466).

3.2. Road traffic noise

Table 3 shows the results of the different multiple models regarding the associations between road traffic noise level and noise annoyance due to road traffic noise with the prevalence of hypertension adjusted for confounders. In the model including only noise levels a significant odds ratio of OR=1.101 (CI=1.006–1.205) was found for road traffic noise per increase of the noise level by 10 dB(A). This estimate remained stable when the annoyance variables were also entered as main effects to the model (OR=1.106 (CI=1.003–1.219)). The annoyance due to road traffic noise was not significantly associated with hypertension, neither in the model including only annoyance variables as explanatory factors, nor in the model including noise levels and annoyance variables simultaneously (OR=1.005 (CI=0.984–1.026) and OR=0.997 (CI =0.975– 1.021), respectively, per unit of the continuous 11-point annoyance scale). The comparison of the effects of the noise level and the annoyance per standard deviation (noise level: OR=1.075, annoyance: OR=1.016) or inter-quartile range (noise level: OR=1.134, annoyance: 1.025 revealed a stronger quantitative impact of the noise level on the risk of hypertension.

Stratified analyses regarding the annoyance due to road traffic noise (3 categories) showed no uniform trend towards a stronger association between the road traffic noise level and hypertension with increasing annoyance due to road traffic noise. In ‘low annoyed’ and ‘highly annoyed’ subjects a tendency was found towards stronger associations between road traffic noise level and hypertension compared with ‘moderately annoyed’ subjects (OR=1.172 and OR=1.247, respectively, vs. OR=0.927; confidence intervals are shown in Table 3). Of the stratified associations only the effect in the ‘low annoyed’ subgroup was significant. The interaction term was not significant (p=0.182). The result is also shown in Fig. 3. The widths of the error bars vary from cell to cell which is due to the different numbers of subjects in each cell. For example, the number of highly annoyed subjects was 68 in the lowest noise level category and 174 in the highest noise level category. When the lower or upper two annoyance categories were combined the interaction terms were also insignificant (p=0.164 and 0.721, respectively).

Note: In the main HYENA analyses aircraft noise during the night was more strongly related with hypertension than aircraft noise during the day (Jarup et al., 2008). Effect modification was therefore also tested for models where the global aircraft noise indicator Lden was replaced by Lnight. This, however, did not make a difference regarding the interpretation of the present results on effect modification and combined exposures.
The interaction effect was significant with respect to daytime annoyance due to aircraft noise but not with night-time annoyance (although showing into the same direction).

4. Discussion

4.1. Methodological considerations

In noise effects' research the objective noise level and the subjective noise annoyance are usually used independently in separate statistical models as explanatory factors when assessing exposure-response relationships. The simultaneous consideration of the noise level and the noise annoyance in one multiple statistical model, in general, raises some conceptual considerations. Since noise annoyance is largely determined by the noise level, both factors, noise level and noise annoyance, are not independent of one another. The effect estimates cannot be interpreted independently from one another due to potential collinearity issues (Ndrepepa and Twardella, 2011). Only the total effect of both factors together then has a meaning. The same applies to models where additionally an interaction term is introduced. The interaction can be tested, but its magnitude cannot be interpreted on its own. This is why no quantitative effect estimates of interaction terms are shown in the present analyses. In a multiple model where one exposure indicator represents the noise level and the other in parts also the noise level, the partial noise level component of the noise annoyance might load on the adjusted noise level variable (or vice versa). What then is the meaning of the residual noise annoyance factor? It may rather represent the effect of all other components associated with the noise annoyance, including situational, attitudinal and personal characteristics (e.g. noise sensitivity) that determine the individual annoyance (Guski, 1999; Job, 1991; Quis, 2001). In such a model the variable cannot be interpreted as noise annoyance any longer. However, it may constitute a confounder with respect to those other personal and situational components and/or a potential effect modifier of the association between the noise level and health outcomes.

4.2. HYENA study

The data of a large multi-centred cross-sectional epidemiological study (HYENA) were used to assess possible effect modification (interaction) of noise annoyance on the relationship between road traffic or aircraft noise level and hypertension. 24 h noise level indicators (Lden and LAeq24h) were used in the analyses because they have been shown to be best predictors of the general annoyance due to road traffic noise (better than Lday or Lnight) [Paunovic, 2009 #2598]. The results in parts support the idea of noise annoyance as being a modifying factor of the relationship between aircraft noise and hypertension. No significant interaction terms, however, were found for road traffic noise and road traffic noise annoyance. When comparing the standardised main effects of the noise levels and related noise annoyances, the noise levels showed closer and significant (road traffic noise level) associations with hypertension than the noise annoyances. In the models where the noise level and the noise annoyance are considered simultaneously as main effect variables, the effect estimates of noise annoyance diminished slightly while the effect estimates of the noise level remained unchanged - compared with models where the objective or the subjective noise indicator were considered separate. The results suggest that the noise level may be a stronger predictor than the noise annoyance for the assessment of cardiovascular noise effects in populations. The noise annoyance, however, may be an effect modifier of the association identifying subjects that are at higher or lower risk due to the noise exposure level. The latter was, particularly, found for aircraft noise.

4.3. Limitations

The HYENA study is cross-sectional. Although it is unlikely that subjects with hypertension had moved into noise areas because of their health problem, it may have happened that subjects with hypertension over-reported their annoyance due to noise because they might have thought that the noise was the reason for their health problem. Reporting bias could be an explanation for the observed effect modification with respect to aircraft noise. Aircraft noise was the primary research objective of the HYENA study which was obvious to the study subjects. Therefore, the associations need to be confirmed in a prospective cohort study. The HYENA study was designed to significantly assess a mean difference of 3 mmHg systolic 2 mmHg diastolic blood pressure which needed about 700 subjects per country to achieve 80% power (Jarup et al., 2005). Although the study is amongst the largest of its kind, lack of statistical power could have been a problem. As a "rule of thumb" a 4-fold sample size is needed for the significant detection of interaction compared with the detection of main effects. Therefore no further breakdown of the results with respect to other variables (e. g. gender, age, country) was feasible, because it would require even more subjects for the analysis of 3-fold interactions.

4.4. Review of the literature

Only a few studies so far have considered the noise level and the noise annoyance simultaneously or alternatively as determinants of noise-related health effects such as hypertension and ischemic heart diseases. In the first analyses of the Stockholm Arlanda Airport study, crude prevalence ratios (PR) of self-reported doctor-diagnosed hypertension or the use of anti-hypertensive medication of PR=1.64, CI=1.21–1.22 or PR=1.61, CI=1.15–2.25, respectively, were reported in 417 male subjects for those 'exposed' and 'unexposed' to aircraft noise (Bluhm et al., 2004). When noise annoyance was considered instead of the noise level, risk ratios of PR=1.51, CI=1.00–2.29 and PR=1.73, CI=1.10–2.73, respectively, were found between 'major' and 'minor' disturbed subjects (results recalculated from the given data). These preliminary results suggested that the noise level and the noise annoyance were equally good predictors for the assessment of the impact of aircraft noise on health. However, open questions remained as to whether interaction was present.

In the main follow-up analyses of the study, an adjusted cumulative incidence rate ratio for hypertension (doctor-diagnosed or measured high blood pressure) of RR=1.02, CI=0.90–1.15 was found for the contrast of Lden ≥50 vs. b50 dB(A) of the aircraft noise level in 4721 men and women (when excluding subjects that had smoked preceding the blood pressure measurement it was RR=1.12, CI=0.94–1.33) (Eriksson et al., 2010). When the results were stratified according to the annoyance due to aircraft noise ('never or a few times per month' vs. 'a few times per week or every day'), significant interaction was found (pb0.01) in a way that annoyed subjects were at a higher risk due to the aircraft noise level (RR=1.42, CI=1.11– 1.82) then less annoyed subjects (RR=0.91, CI=0.77–1.07). The result supports the finding of the present study.

Similar results were found with respect to road traffic noise (Björk et al., 2006). The association between the noise level and self-reported treatment of hypertension was stronger in subjects that reported a higher annoyance due to road traffic noise (extreme group comparison: OR=1.90 vs. OR=1.05). In the Tyrol study slightly negative nonsignificant associations were found between road traffic noise level (LAeq24h ≥55 vs. b55 dB(A), OR=0.83, CI=0.64–1.10) as well as annoyance due to road traffic noise ('moderately or strongly' vs. 'less' annoyed, OR=0.92, CI=0.72–1.20) and self-reported hypertension in 1,989 study subjects (Lercher and Kofler, 1995, 1996). Regarding effect modification, a borderline significantly (interaction pb0.06) lower increase of the prevalence of hypertension due to highway noise with increasing noise level was found in subjects that were more annoyed compared with the subjects that were less annoyed by the noise (Lercher et al., 2011). It was speculated that a higher active behavioural coping in annoyed subjects could explain the protective effect of higher noise annoyance. These findings are supported by a laboratory experiment where more annoyed subjects showed less of an increase in the excretion of stress hormones (catecholamines) during noise exposure than less annoyed subjects when carrying out a performance test (Arvidsson and Lindvall, 1978). It was concluded that in this short-term experiment the increased stress hormone levels in the exposed subjects may merely reflect a functional adaption to the environment and may not necessarily be associated with feelings of annoyance. Subjects who perform well have a highly functional neurovegetative reaction capacity and may be resistant to the disturbing impact of noise stimulation as long as overstimulation does not occur — which, however, may no longer be the case in the long run when subjects are persistently exposed.

In the Berlin II Traffic Noise study no association was found between road traffic noise level and self-reported prevalence of hypertension (LAeq16h >70 vs. ≤60 dB(A), OR=1.00, CI=0.71–1.42), while a significant association was found with respect to annoyance due to road traffic noise and hypertension (categories 4+5 vs. 1+2 of a 5-point scale, OR=1.29, CI=1.05–1.60) in 2193 men of the population controls of a case–control study on the incidence of myocardial infarction (Babisch, 2006; Wiens, 1995). In the Spandau Health Survey the opposite was found. The association in 1351 subjects between the road traffic noise level and the prevalence of hypertension (LNight, bedroom >55 vs. b50 dB(A), OR=1.88, CI=1.10–3.22) was significant, while the association between noise annoyance due to road traffic noise and hypertension was not (categories 3+4+5 vs. 1+2 of a 5-point scale, OR=1.17, CI=0.71–1.92) (Maschke et al., 2003). Effect modification was not assessed in these studies.

A few studies have investigated the relationship of the noise level and alternatively the noise annoyance with ischemic heart diseases (e.g. myocardial infarction). In the Tyrol study a significant association between the road traffic noise level and the prevalence of self-reported angina pectoris (LAeq24h ≥55 vs. b55 dB(A), OR=2.01, CI=1.18–3.44) was reported in 1,989 subjects; the association between the annoyance due to road traffic noise and angina pectoris was not significant (‘moderately or strongly’ vs. ‘less’ annoyed, OR=1.32, CI=0.77–2.24) (Lercher, 1992). Regarding myocardial infarction no associations were found with respect to noise level and noise annoyance in this study (LAeq24h ≥55 vs. b55 dB(A), OR=0.96, CI=0.50–1.85; ‘moderately or strongly’ vs. ‘less’ annoyed, OR=0.82, CI=0.44–1.51). In the Caerphilly & Speedwell cohort studies no significant associations were found, neither between road traffic noise level and ischemic heart diseases (LAeq16h >65 vs. ≤55 dB(A), OR=1.07, CI=0.70–1.65), nor between annoyance due to road traffic noise and ischemic heart diseases (categories 4+5 vs. category 1 of a 5-point scale, OR=0.95, CI=0.52–1.75) (Babisch et al., 2003). In the Berlin III Road Traffic Noise study road noise level (LAeq16h >65 vs. b60 dB(A), OR=1.18, CI=0.93–1.49) and annoyance due to road traffic noise (annoyance during the night OR=1.10, CI=1.01–1.20 per unit on a 5-point scale) showed slightly positive associations with the incidence of acute myocardial infarction in 3054 men, while a slightly negative effect was found in 1061woman for both exposures (LAeq16h >65 vs. b60 dB(A), OR=0.84, CI=0.55–1.27; annoyance during the night OR=0.98 per unit of a 5-point scale, CI=0.84–1.14) (Babisch et al., 2005). Effect modification was not assessed in these studies.

In a study using a 24 h personal noise dosimetry a higher risk of high blood pressure in adults was only found with respect to night-time noise, not daytime noise (Weinmann et al., 2012). The dosimeters picked up sound from a variety of sound sources over the whole day, including pleasant, unpleasant and (wanted) self-made sounds. Consequently, it was found that subjectively ‘negative’ rated noise was associated with a tendency towards a higher risk of hypertension and ‘positive’ rated noise with a tendency towards a lower risk. Noise exposure during the night in the bedroom, however, is a definite source of sleep disturbance. The study shows that the perception and the type of sound is a modifier of noise effects. This is the reason why noise effects' research should always be source-specific (e. g. road, rail, air, industry, occupational, leisure etc.) resulting in different exposure-response curves for different noise sources. A 24 h average noise level including all these different noise sources would be inappropriate.

All in all there is some evidence from the literature that noise annoyance is an effect modifier of the relationship between the aircraft noise level and the risk of hypertension. However the data-base is scarce (1 study). With respect to road traffic noise the results are contradictory (2 studies). Regarding the comparison of the main effects of road traffic noise level and annoyance the results are also heterogeneous suggesting stronger effects for the noise level (1 study), stronger effects for noise annoyance (1 study), and more or less similar effects for both noise indicators (4 studies).

5. Conclusions

In principal, the noise level (objective exposure) as well as the noise annoyance (subjective exposure) may serve as explanatory variables for the assessment of cardiovascular diseases due to chronic noise exposure. There was some indication from the HYENA study that the noise level might have a stronger predictive meaning for the relationship between noise exposure and hypertension than the reported noise annoyance. However, no general conclusion can be drawn of whether one of the two exposures (noise level and noise annoyance) is a “better” predictor of cardiovascular risk than the other. Regarding effect modification, the results of the HYENA study support the findings from a Swedish cohort study showing that subjects that are more annoyed by aircraft noise are at a higher risk of hypertension with increasing exposure to aircraft noise (level).

Conflicts of interest statement

The authors declare no conflicts of interest.

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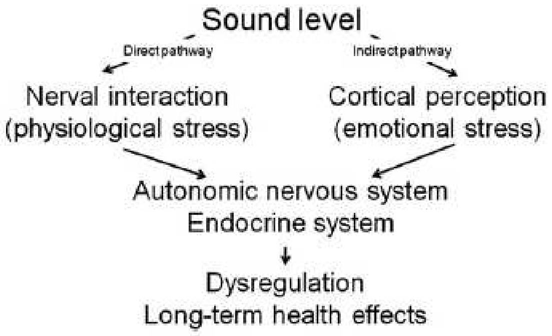

Fig. 1. Reaction model.

Table 1
Correlation matrix of noise level and noise annoyance variables.

	L_{den} aircraft noise	L_{Aeq24h} road traffic noise	Annoyance aircraft noise
L_{Aeq24h} road traffic noise	$r_s = 0.01$ $p = 0.517$	–	$r_s = -0.03$ $p = 0.031$
Annoyance aircraft noise	$r_s = 0.49$ $p = 0.000$	$r_s = -0.03$ $p = 0.031$	–
Annoyance road traffic noise	$r_s = -0.00$ $p = 0.783$	$r_s = 0.41$ $p = 0.000$	$r_s = 0.23$ $p = 0.000$

r_s = Spearman correlation coefficient, p = probability of significance test.

Table 2
Odds ratios (OR) and 95% confidence intervals (CI) of the relationship between aircraft noise level (effect per 10 dB(A)) and aircraft noise annoyance (effect per unit of the11-point scale) scale and the prevalence of hypertension. For stratified analyses and the assessment of interaction the continuous annoyance variables were categorised to 3-grade and 2-grade annoyance factors.

Variables in the model	N	$OR_{aircraft}$ (CI) Lden	$OR_{aircraft}$ (CI) annoyance	$P_{aircraft}$ Lden * annoyance
Noise levels (air, road),	4656	1.037 (0.962–1.119)		
Annoyances (air, road)	4660		1.003 (0.985–1.022)	
Noise levels (air, road) and	4656	1.036 (0.946–1.134)	1.001 (0.979–1.023)	
Annoyances (air, road)	4656	1.036 (0.946–1.134)	1.001 (0.979–1.023)	
Noise levels (air, road),				0.143
Annoyance air ratings 0–3	1851	0.944 (0.833–1.070)		
Annoyance air ratings 4–7	1289	1.112 (0.942–1.313)		
Annoyance air ratings 8–10	1516	1.084 (0.896–1.310)		
Noise levels (air, road)				0.048
Annoyance air ratings 0–3	1851	0.944 (0.833–1.070)		
Annoyance air ratings 4–10	2805	1.095 (0.970–1.235)		
Noise levels (air, road)				0.466
Annoyance air ratings 0–7	3140	1.021 (0.932–1.120)		
Annoyance air ratings 8–10	1516	1.084 (0.896–1.310)	–	

Adjusted for age, gender, body mass index, alcohol consumption, school education, physical activity at leisure, and study area (country/airport).
P = error probability of the interaction term.

Table 3
Odds ratios (OR) and 95% confidence intervals (CI) of the relationship between road traffic noise level (effect per 10 dB(A)) and road traffic noise annoyance (effect per unit of the11-point scale) scale and the prevalence of hypertension. For the analyses of interaction the continuous annoyance variables were categorised to 3-grade (categories 0–3 vs. 4–7, 8–10) and alternatively to 2-grade (categories 0–7 vs. 8–10) annoyance factors.

Variables in the model	N	OR_{road} (CI) LAeq24	OR_{road} (CI) annoyance	P_{road} LAeq24 * annoyance
Noise levels (air, road),	4656	1.101 (1.006–1.205)		
Annoyances (air, road)	4660		1.005 (0.984–1.026)	
Noise levels (air, road) and				
Annoyances (air, road)	4656	1.106 (1.003–1.219)	0.997 (0.975–1.021)	
Noise levels (air, road)				0.182
Annoyance road ratings 0–3	3131	1.172 (1.036–1.327)		
Annoyance road ratings 4–7	890	0.927 (0.749–1.147)		
Annoyance road ratings 8–10	635	1.247 (0.981–1.585)		
Noise levels (air, road):				0.164
Annoyance road ratings 0–3	3131	1.172 (1.036–1.327)		
Annoyance road ratings 4–10	1525	1.033 (0.885–1.205)		
Noise levels (air, road):				0.721
Annoyance road ratings 0–7	4021	1.108 (1.000–1.229)		
Annoyance road ratings 8–10	635	1.247 (0.981–1.585)		

Adjusted for age, gender, body mass index, alcohol consumption, school education, physical activity at leisure, and study area (country/airport).
P = error probability of the interaction term.

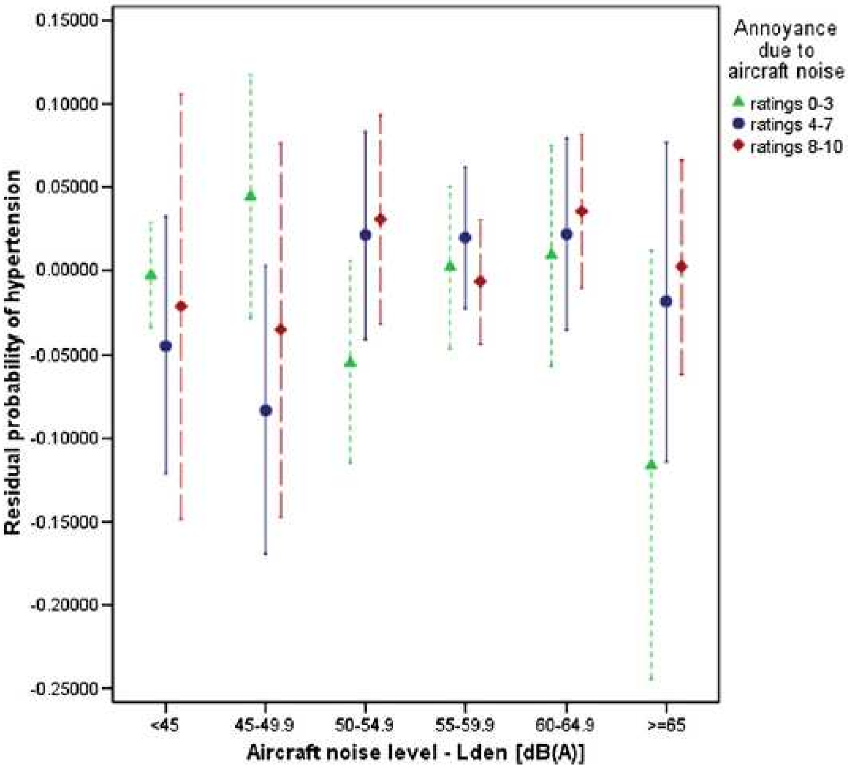

Fig. 2. Association between the aircraft noise level L_{den} and the prevalence of hypertension, stratified by the annoyance due to aircraft noise (3 categories).

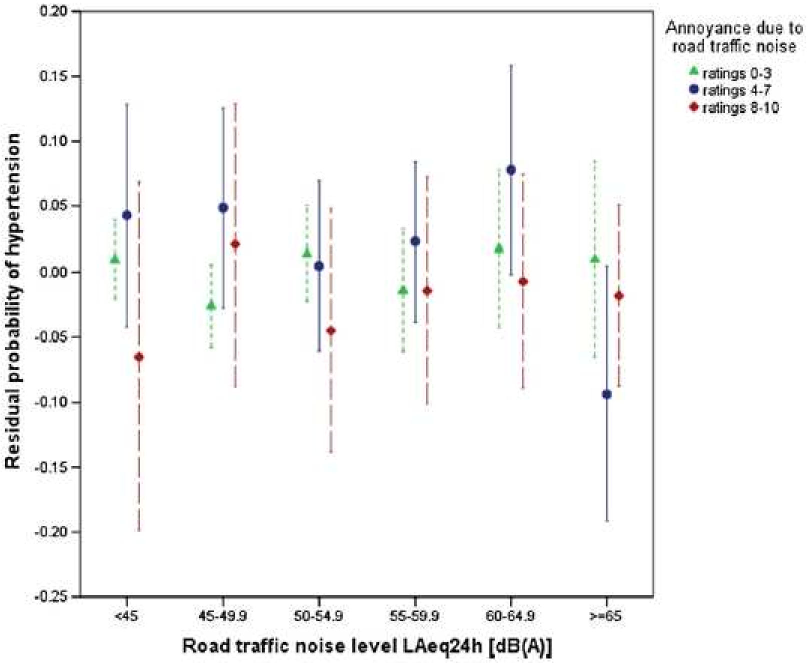

Fig. 3. Association between the road traffic noise level L_{Aeq24h} and the prevalence of hypertension, stratified by the annoyance due to road traffic noise (3 categories).