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The role of aircraft noise annoyance and noise sensitivity in the association between aircraft noise levels and hypertension risk: Results of a pooled analysis from seven European countries

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ABSTRACT

Introduction: Many studies, including the HYENA and the DEBATS studies, showed a significant association between aircraft noise exposure and the risk of hypertension. Few studies have considered aircraft noise annoyance and noise sensitivity as factors of interest, especially in relation to hypertension risk, or as mediating or modifying factors. The present study aims 1) to investigate the risk of hypertension in relation to aircraft noise annoyance or noise sensitivity; and 2) to examine the role of modifier or mediator of these two factors in the association between aircraft noise levels and the risk of hypertension.
Methods: This study included 6,105 residents of ten European airports from the HYENA and DEBATS studies. Information on aircraft noise annoyance, noise sensitivity, and demographic, socioeconomic and lifestyle factors was collected during an interview performed at home. Participants were classified as hypertensive if they had either blood pressure levels above the WHO cut-off points or physician-diagnosed hypertension in conjunction with the use of antihypertensive medication. Outdoor aircraft noise exposure was estimated for each participant's home address. Poisson regression models with adjustment for potential confounders were used. Interactions between noise exposure and country were tested to consider possible differences between countries.
Results: An increase in aircraft noise levels at night was weekly but significantly associated with an increased risk of hypertension (RR = 1.03, 95% CI 1.01–1.06 for a 10-dB(A) increase in L_{night}). A significant association was found between aircraft noise annoyance and hypertension risk (RR = 1.06, 95%CI 1.00–1.13 for highly annoyed people compared to those who were not highly annoyed). The risk of hypertension was slightly higher for people highly sensitive to noise compared to people with low sensitivity in the UK (RR = 1.29, 95%CI 1.05-1.59) and in France (RR = 1.11, 95%CI 0.68-1.82), but not in the other countries. The association between aircraft noise levels and the risk of hypertension was higher among highly sensitive participants (RR = 1.00, 95%CI 0.96–1.04; RR = 1.03, 95%CI 0.90–1.11; RR = 1.12, 95%CI 1.01–1.24, with a 10-dB(A) increase in L_{night} for low, medium,

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and high sensitive people respectively) or, to a lesser extent, among highly annoyed participants (RR = 1.06, 95% CI 0.95-1.18 for a 10-dB(A) increase in L_{night} among highly annoyed participants, and RR = 1.02, 95%CI 0.99–1.06 among those not highly annoyed).
Conclusions: The present study confirms findings in the small number of available studies to date suggesting adverse health effects associated with aircraft noise annoyance and noise sensitivity. The findings also indicate possible modifier effects of aircraft noise annoyance and noise sensitivity in the relationship between aircraft noise levels and the risk of hypertension. However, further investigations are needed to better understand this role using specific methodology and tools related to mediation analysis and causal inference.

Authors contribution

For the HYENA consortium: Wolfgang Babisch (WB), Ennio Cadum (EC), Konstantina Dimakopoulou (KD), Danny Houthuijs (DH), Göran Pershagen (GP), Venetia Velonaki (VV) designed and conducted the original HYENA study. For the DEBATS study: Anne-Sophie Evrard (ASE) and Bernard Laumon (BL) with Jacques Lambert (JL) and Patricia Champelovier (PC) conceived and designed the DEBATS study. ASE and Marie Lefèvre (ML) conducted the study. JL interpreted the aircraft noise data and PC interpreted the annoyance data. ML was involved in data extraction and preparation. For the present study: Clémence Baudin (CB), ASE and Anna Hansell (AH) designed the study, CB performed the statistical analyses, supervised by AH, ASE and BL. The analyses were interpreted by CB, AH, ASE and BL, with the help of Stephen Stansfeld (SS). CB, AH and ASE drafted the initial report. All coauthors revised the report and approved the final version. ASE and AH are responsible for the overall content as the guarantors of this paper.

1. Introduction

The health of people living near airports in relation to aircraft noise exposure has been the focus of many research studies over the years. Adverse effects were reported in most of these, including annoyance (Babisch et al., 2009), sleep disturbance (Perron et al., 2012; Nassur et al., 2017), cardiovascular disease including hypertension (Hansell et al., 2013; Evrard et al., 2015, 2017; Jarup et al., 2008), altered cognitive performance among children (Haines et al., 2001; Stansfeld et al., 2005), and hormonal rhythm disruption (Selander et al., 2009; Lefèvre et al., 2017; Baudin et al., 2019). Psychological disorders have also been viewed as possible adverse effects of aircraft noise exposure, but a direct association has not been established (Baudin et al., 2018).

Several potential mechanisms could be responsible for noise-induced adverse effects. The noise reaction model proposed by Babisch (Babisch, 2002, 2003; Münzel et al., 2018) suggests both a direct pathway with direct nervous system impact and an indirect pathway related to cognitive processing of sound including annoyance and noise sensitivity. Both direct and indirect pathways can activate the autonomic nervous system and endocrine system. Additionally, both pathways may lead to disturbed sleep, which is associated with increased risk of cardiovascular disease (Huang et al., 2020; Münzel et al., 2020), decreased cognitive performance and potentially impacts on mental health (Zaharna and Guilleminault, 2010).

The association between noise exposure and noise annoyance has been extensively investigated, and aircraft noise has been found to be the most annoying noise source among all transportation noise sources when standardized for noise exposure level (Miedema and Oudshoorn, 2001; Brink et al., 2019). It has been suggested that annoyance due to aircraft noise has increased over the years (Guski et al., 2017). Significant associations between aircraft noise annoyance and mental health have been observed (Baudin et al., 2018; Tarnopolsky et al., 1980; van Kamp et al., 2007; Schreckenberg et al., 2010; Beutel et al., 2016).

The risk of hypertension has been very little studied in relation to aircraft noise annoyance. Babisch et al. did not show a direct association between aircraft noise annoyance and the risk of hypertension in the HYENA study (Babisch et al., 2013), whereas Bluhm et al. reported significant risk ratios for prevalence of self-reported doctor-diagnosed hypertension and the use of antihypertensive medication in relation to noise annoyance in the Stockholm Arlanda Airport study (Bluhm et al., 2004). Moreover, in two studies, aircraft noise annoyance has been found to be a modifying factor in the relationship between aircraft noise levels and hypertension risk, with a stronger association in participants annoyed by aircraft noise compared to not annoyed participants (Babisch et al., 2013; Eriksson et al., 2010). Some authors have interpreted the co-existence of an association between aircraft noise levels and noise annoyance, and of an association between noise annoyance and specific diseases such as hypertension, as a mediation by annoyance due to noise on these specific diseases (Tarnopolsky et al., 1980; Baron and Kenny, 1986). Therefore, the role of aircraft noise annoyance in the relationship between aircraft noise exposure and the risk of hypertension is still not clear.

Noise sensitivity might be a general indicator of environmental sensitivity and have effects independent of noise levels (Stansfeld and Shipley, 2015). The direct association between noise sensitivity and noise-induced adverse effects has also been little studied, but conclusions are consistent: noise sensitivity was found to be associated with increased blood pressure (Otten et al., 1990), health complaints (including cardiac complaints) (Stansfeld and Shipley, 2015; Nivison and Endresen, 1993; Baliatsas et al., 2016), hypertension and the use of psychotropic drugs (sleeping pills, tranquilizers and pain relievers) (Heinonen-Guzejev et al., 2004; Okokon et al., 2018). Moreover, some studies have highlighted stronger associations between noise exposure and adverse health effects in highly sensitive people. Thus, a modifying effect of noise sensitivity in the association between aircraft noise levels and anxiety and nervous complaints (Nivison and Endresen, 1993), psychological disorders (Miyakawa et al., 2008; Kishikawa et al., 2009), heart rate (di Nisi et al., 1987), and self-reported physical health problems (Schreckenberg et al., 2010; Nivison and Endresen, 1993; Stansfeld, 1992) has been suggested. Nevertheless, it has never been reported with the risk of hypertension, which deserves further investigation.

In this study, we pooled data from two major European studies on aircraft noise and health that used similar methodology, HYENA (HYpertension and Exposure to Noise near Airports) and DEBATS (Discussion on the health effects of aircrafts noise) to investigate the impact of aircraft noise annoyance and noise sensitivity on hypertension risk. We also investigated their modifying and mediating role on the relationship between aircraft noise levels and hypertension, as the larger numbers obtained by pooling the data helped provide additional power to explore interactions. The combined dataset includes some of Europe's busiest airports: London Heathrow (United Kingdom), Berlin Tegel (Germany), Amsterdam Schiphol (the Netherlands), City Airport Bromma and Stockholm Arlanda (Sweden), Milan Malpensa (Italy), and Athens Elephterios Venizelos (Greece) Airports in the HYENA study and Paris-Charles de Gaulle, Lyon-Saint-Exupéry, and Toulouse-Blagnac (France) in the DEBATS study (Airport Council International, 2013).

2. Methods

2.1. Study population

The HYENA cross-sectional study was conducted in 2004–6 and included 4,861 participants (2,953 men and 3,152 women) aged 45–70 years old at interview (Jarup et al., 2005). Participants were selected at random from available registers (e.g. registration office, electoral roll, health service). The DEBATS cross-sectional study was conducted in 2013 and included 1,244 participants (549 men and 695 women) over 18 years old at interview (Evrard et al., 2017). Participants in the study area were randomly selected from a phone directory, contacted by phone and included in the study when they agreed to participate.

Written informed consent was provided by all participants. For HYENA, each centre's ethical committee gave study approval; for DEBATS ethical approval came from the French Advisory Committee for Data Processing in Health Research and the French National Commission for Data Protection and the Liberties.

Both studies conducted a face-to-face interview with measurements of blood pressure (BP), weight and height. The questionnaire included items on socio-demographic information; smoking, alcohol consumption, physical activity and other lifestyle factors; medical history and medication use, sleep disturbance, annoyance by aircraft noise, and noise sensitivity.

2.2. Aircraft noise exposure assessment

The “Integrated Noise Model” (INM) (He et al., 2007) was used to estimate outdoor aircraft noise at the place of residence in 1-dBA intervals in all countries except the UK, which used a similar model to INM, the national Aircraft Noise Contour Model (ANCON v2) (Ollerhead et al., 1999). Home addresses of participants were linked to noise contour outputs from the noise models using geographical information systems (GIS) software.

While the WHO Environmental Noise Guidelines for the European Region referred to the day-evening-night level (L_{den}) as the exposure metrics of choice when considering health outcomes (WHO, 2018), aircraft noise levels at night (L_{night}) was preferred in the present analyses. The L_{den} is defined as a descriptor of noise levels based on energy equivalent noise levels over a whole day with a penalty of 10 dB(A) for night time noise (22.00–6.00 or 23.00–7.00) and 5 dB(A) for evening noise (i.e. 19.00–22.00 or 19.00–23.00) (European Environment Agency, 2020). These penalties take into account the level of annoyance due to aircraft noise in the evening and at night. As one of the main objectives of this study was to investigate the role of aircraft noise annoyance in the relationship between aircraft noise levels and the risk of hypertension, the use of the L_{den} would have biased the results downwards. In addition, as previous studies have shown associations between aircraft noise exposure – night-time exposure in particular – and the risk of hypertension (Evrard et al., 2017; Jarup et al., 2008), the L_{night} indicator was used for the main statistical analyses. It is defined as the average noise levels during night-time (22:00 to 6:00 or 23:00 to 7:00) (European Commission, 2002). The L_{den} was used in sensitivity analyses.

2.3. Annoyance due to aircraft noise

The standard ISO/ICBEN (International Commission on the Biological Effects of Noise) question "Thinking about the last 12 months, when you are here at home, how much does aircraft noise bother, disturb or annoy you?" (ISO, 2003), was used to assess annoyance from aircraft noise in HYENA and DEBATS. However, different scoring was used for answers in each study. Harmonization between the two annoyance scales and dichotomisation were made according to ICBEN working group's recommendations aiming to make the scales comparable, as published in Fields et al. paper (Fields et al., 2001). A large majority of studies dealing with noise annoyance has adopted this standardized definition for "highly annoyed people", using either the numeric or the verbal scale. In HYENA, the scoring was numeric with range 0–10 and assessed separately for night-time and daytime exposure. Night-time and day-time scores were averaged and ‘highly annoyed’ was defined as an average score ≥8. In sensitivity analyses, the highest score of day and night was used. In DEBATS, the scoring did not distinguish between day and night and was verbal, with answers being extremely, very, moderately, slightly or not at all annoyed. ‘Highly annoyed’ was here defined as reporting ‘extremely’ or ‘very’ annoyed.

2.4. Noise sensitivity

Noise sensitivity in HYENA was assessed using the short-form (10 statement version) of the Weinstein scale (Weinstein, 1978), where each item is scored numerically 1 to 6 on agreement with different statements about noise. One of the ten items is about sensitivity to noise: "Am I sensitive to noise?", scored numerically from 1 to 6. This single item is similar to the question on noise sensitivity used in the DEBATS study: "Regarding noise in general, compared to people around you, do you think that you are: much less sensitive than, or less sensitive than, or as sensitive as, or more sensitive or much more sensitive than people around you?". After consideration of the response distributions in each study, the following mapping was used: scores 1 and 2 for the noise sensitivity item in HYENA were considered as “low noise sensitive” and mapped to "much less sensitive" and "less sensitive" in DEBATS; scores 3 and 4 in HYENA considered as “medium noise sensitive” and mapped to "as sensitive" in DEBATS; and scores 5 and 6 considered as “highly noise sensitive” and mapped to "a little more sensitive" and " much more sensitive".

In addition, a sum score was calculated using the 10 items of the Weinstein's scale in the HYENA study and used in sensitivity analyses after being harmonizing with the DEBATS responses as follows: the tertiles of the country-standardized mean of the sum score in HYENA, and the five response categories in DEBATS, combined as 1st tertile with "much less sensitive" and "less sensitive", 2nd tertile with "as sensitive", and 3rd tertile with "a little more sensitive" and " much more sensitive".

2.5. Hypertension

Systolic BP (SBP) and diastolic BP (DBP) were both recorded using validated and automated BP instruments, both in HYENA and in DEBATS. The same protocol was applied in both studies. Specially trained staff assessed BP three times at home visits, for all the participants in a sitting position using the following schedule: (1) after a 5 min rest at the beginning of the interview, (2) after a further 1 min rest, (3) approximately 1 h later at the end of the interview. The mean of the first two readings was used to define SBP and DBP for the subsequent analyses. The third reading was used as a validity control: in sensitivity analyses, the mean of the last two readings was used instead of the mean of the first two readings: the results remained unchanged.

The WHO definition (Whitworth, 2003) was used to define hypertension, which is a SBP≥140 mm Hg or a DBP≥90 mm Hg. Additionally, participants were defined as hypertensive if they had reported a diagnosis of hypertension by a physician in conjunction with use of antihypertensive medication, irrespective of BP measurement.

2.6. Statistical analysis

Generalized linear models based on the binomial distribution with the log-link function were used to estimate relative risks (RR) with the hypertension status as outcome variable, and aircraft noise levels (M0 model), aircraft noise annoyance (M1 model), or noise sensitivity (M2 model) as the exposure variables, together with potential confounders as covariates.

The major potential confounders, being risk factors for hypertension as well as possibly associated with noise exposure, were defined *a priori* and included in statistical models: gender, age (continuous), education level (coded as quartiles of number of years in education previously standardized by country means), BMI (continuous), physical activity (2 categories: no or a little; regular), alcohol consumption (4 categories:

teetotaller; 1–7 units a week; 8–14 units/week; >14 units/week), smoking habits (five categories: non-smoker; ex-smoker; 1–10 units/day; 11–20 units/day; >20 units/day), and country (UK; Germany; The Netherlands; Sweden; Greece; Italy; France). To assess whether smoking would confound the effects of aircraft noise exposure, of aircraft noise annoyance and of noise sensitivity on hypertension, smoking was initially included in the regression models. However, smoking did not contribute significantly to the models and did not have any impact on the effect estimate of the three exposure variables, so smoking was not included in the final models (Evrard et al., 2017; Jarup et al., 2008). An interaction term between aircraft noise levels and country, between aircraft noise annoyance and country, and between noise sensitivity and country was also tested in M0, M1 and M2 models respectively, to account for potential differences in aircraft noise exposure or cultural differences in noise annoyance or noise sensitivity between countries (Namba et al., 1986).

The mediating and modifying effects of aircraft noise annoyance and noise sensitivity were investigated following Baron and Kenny's recommendations (Baron and Kenny, 1986). Results of the models including aircraft noise levels (M0 model), aircraft noise annoyance (M1 model), or noise sensitivity (M2 model) and both aircraft noise levels and aircraft noise annoyance (M3 model) or both aircraft noise levels and noise sensitivity (M4 model), together with potential confounders as covariates, were compared to assess a possible mediating effect of aircraft noise annoyance or of noise sensitivity.

The possible modifying effects of aircraft noise annoyance and of noise sensitivity were tested by including an interaction between aircraft noise annoyance and L_{night} (M5 model), and between noise sensitivity and L_{night} (M6 model) in the M0 model.

Sensitivity analyses were carried out for people between 45 and 70 years of age. For noise sensitivity, sensitivity analyses were carried out using the tertiles of the 10 item-Weinstein's scale in the HYENA study in combination with the DEBATS responses. Finally, separate analyses of HYENA and DEBATS datasets were carried out to help assess impact of the differences in setting and assessments in each study.

All statistical analyses were performed in SAS V. 9.4 (SAS Institute, Cary NC). Adjusted RRs along with their 95% confidence intervals (CIs) are reported.

3. Results

Statistical analyses included 5,886 participants with completed information for all the confounders included in the models (Fig. 1). Participation rates differed among the countries, from approximately 30% in France, Germany, Italy, and the UK to 46% in the Netherlands, 56% in Greece, and 78% in Sweden.

The study populations varied between aircraft noise levels regarding age, education level, physical activity, and alcohol consumption ($p < 0.01$). Differences were also observed between highly annoyed and not highly annoyed participants for age, education level, BMI, and alcohol consumption ($p < 0.05$). Finally, differences were shown between categories of noise sensitivity for gender, age, education level, BMI, and alcohol consumption ($p < 0.01$) (Table 1).

Overall, 51% of the participants were classified as hypertensive: it varied between 35% in France and 60% in Greece. Participants from the UK were the most exposed to aircraft noise at night (49.3 ± 10.5 dB(A)), compared to participants from Italy who were the least exposed (35.4 ± 6.4 dB(A)). Almost 20% of the participants reported being highly annoyed by aircraft noise: Greek participants were the most annoyed by aircraft noise (43%), whereas participants from Sweden were the least annoyed (10%). About 35% of the participants reported low sensitivity to noise, 32% medium sensitivity and 33% high sensitivity. Italian participants were the most sensitive to noise, whereas participants from Sweden were the least sensitive to noise (Table 2).

A 10 dB(A)-increase in night-time aircraft noise exposure (L_{night}) was significantly, albeit weakly, associated with an increased risk of

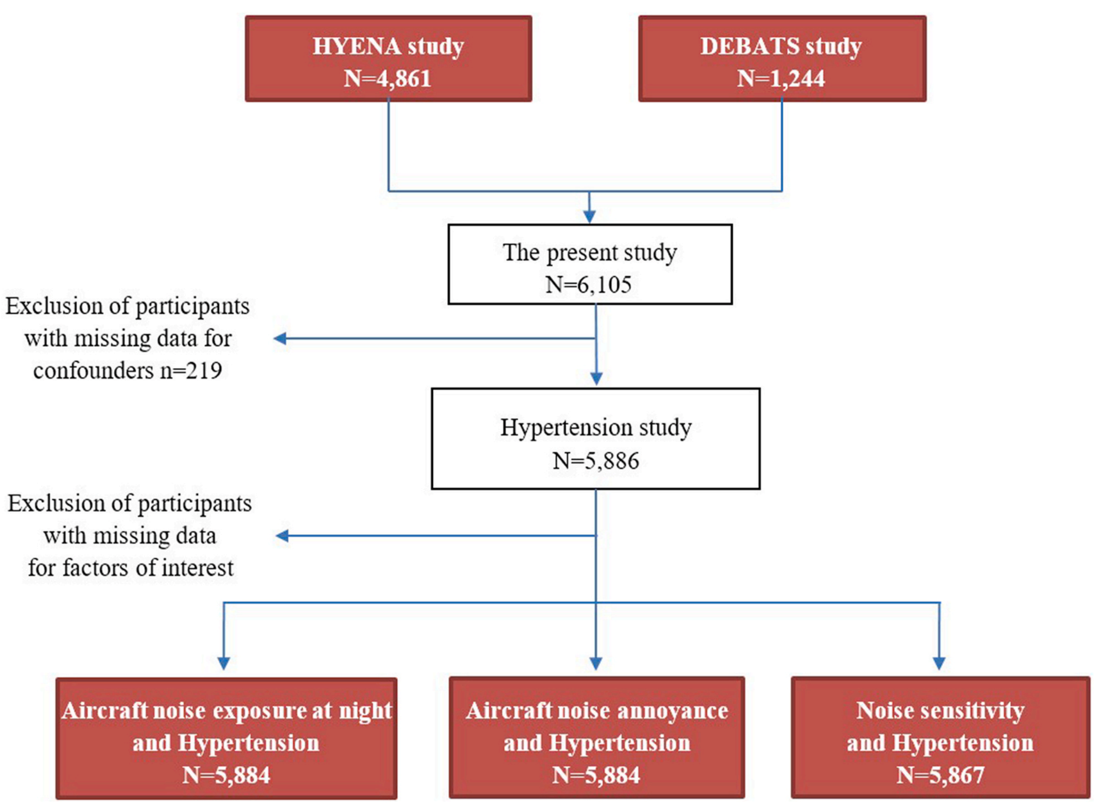

Fig. 1. Study population for the analyses about the risk of hypertension in relation to aircraft noise exposure, aircraft noise annoyance and noise sensitivity The model was adjusted for age, gender, education level, physical activity, BMI, alcohol consumption, and country.

Table 1
Study population characteristics stratified by categories of aircraft noise levels, aircraft noise annoyance and noise sensitivity.

	Aircraft noise level (L_{night})					Aircraft noise annoyance			Noise sensitivity			
	<40 dB(A)	40–44 dB(A)	45–49 dB(A)	≥50 dB(A)	p	Not highly annoyed	Highly annoyed	p	Low sensitivity	Medium sensitivity	High sensitivity	P
Hypertension					0.73			**<0.01**				**<0.01**
No	1260 *(43.9)*	442 *(15.4)*	500 *(17.4)*	668 *(23.3)*		2341 *(81.6)*	529 *(18.4)*		935 *(32.7)*	959 *(33.5)*	965 *(33.7)*	
Yes	1311 *(43.7)*	444 *(14.8)*	554 *(18.5)*	689 *(23.0)*		2362 *(78.8)*	634 *(21.2)*		1141 *(38.2)*	901 *(30.1)*	948 *(31.7)*	
Gender [a]					0.23			0.95				**<0.01**
Men	1284 *(44.9)*	416 *(14.6)*	518 *(18.1)*	640 *(22.4)*		2289 *(80.1)*	568 *(19.9)*		1140 *(40.1)*	909 *(32.0)*	796 *(28.0)*	
Women	1290 *(42.6)*	473 *(15.6)*	542 *(17.9)*	723 *(23.9)*		2427 *(80.2)*	600 *(19.8)*		939 *(31.1)*	960 *(31.8)*	1123 *(37.2)*	
Age [b]	56.8 *(8.6)*	55.6 *(11.1)*	56.2 *(10.4)*	55.7 *(11.0)*	**<0.01**	56.1 *(10.1)*	57.1 *(9.1)*	**<0.01**	56.7 *(9.5)*	55.8 *(10.8)*	56.3 *(9.5)*	**0.01**
Education [a]					**<0.01**			**<0.01**				**<0.01**
1st qrt	554 *(35.1)*	332 *(21)*	308 *(19.5)*	386 *(24.4)*		1221 *(77.4)*	357 *(22.6)*		579 *(36.8)*	517 *(32.9)*	476 *(30.3)*	
2nd qrt	587 *(41.8)*	143 *(10.2)*	260 *(18.5)*	415 *(29.5)*		1174 *(83.6)*	231 *(16.4)*		543 *(38.8)*	449 *(32.1)*	408 *(29.1)*	
3rd qrt	672 *(48.6)*	165 *(11.9)*	229 *(16.6)*	317 *(22.9)*		1123 *(81.2)*	260 *(18.8)*		482 *(34.9)*	417 *(30.2)*	482 *(34.9)*	
4th qrt	761 *(50.1)*	249 *(16.4)*	263 *(17.3)*	245 *(16.1)*		1198 *(78.9)*	320 *(21.1)*		475 *(31.4)*	486 *(32.1)*	553 *(36.5)*	
BMI [b]	26.8 *(4.7)*	26.8 *(5.0)*	26.9 *(4.6)*	27.2 *(4.8)*	0.07	26.9 *(4.8)*	27.2 *(4.6)*	**0.05**	27.3 *(4.9)*	26.7 *(4.6)*	26.8 *(4.7)*	**<0.01**
Physical activity [a]					**<0.01**			0.19				0.46
No or little	1254 *(41)*	463 *(15.1)*	568 *(18.6)*	773 *(25.3)*		2430 *(79.5)*	627 *(20.5)*		1066 *(34.9)*	994 *(32.6)*	992 *(32.5)*	
Regular	1320 *(46.7)*	426 *(15.1)*	492 *(17.4)*	590 *(20.9)*		2286 *(80.9)*	541 *(19.1)*		1013 *(36)*	875 *(31.1)*	927 *(32.9)*	
Alcohol (units/week) [a]					**<0.01**			**<0.01**				**<0.01**
teetotaller	646 *(38.7)*	263 *(15.7)*	324 *(19.4)*	438 *(26.2)*		1290 *(77.2)*	380 *(22.8)*		549 *(33)*	510 *(30.6)*	606 *(36.4)*	
1-7	1251 *(44.8)*	413 *(14.8)*	512 *(18.4)*	614 *(22.0)*		2250 *(80.6)*	540 *(19.4)*		997 *(35.8)*	896 *(32.2)*	892 *(32)*	
8-14	400 *(47.8)*	119 *(14.2)*	140 *(16.7)*	178 *(21.3)*		709 *(84.7)*	128 *(15.3)*		324 *(38.9)*	285 *(34.2)*	224 *(26.9)*	
>14	277 *(47.1)*	94 *(16)*	84 *(14.3)*	133 *(22.6)*		467 *(79.6)*	120 *(20.4)*		209 *(35.8)*	178 *(30.5)*	197 *(33.7)*	
Aircraft noise annoyance					**<0.01**							**<0.01**
Not highly annoyed	2341 *(49.6)*	644 *(13.7)*	780 *(16.5)*	951 *(20.2)*					1857 *(39.5)*	1486 *(31.6)*	1357 *(28.9)*	
Highly annoyed	232 *(19.9)*	244 *(20.9)*	280 *(24)*	412 *(35.3)*					220 *(18.9)*	383 *(32.9)*	562 *(48.2)*	
Noise sensitivity					**<0.01**			**<0.01**				
Low	987 *(47.5)*	250 *(12)*	392 *(18.9)*	450 *(21.6)*		1857 *(89.4)*	220 *(10.6)*					
Medium	735 *(39.3)*	339 *(18.1)*	320 *(17.1)*	475 *(25.4)*		1486 *(79.5)*	383 *(20.5)*					
High	845 *(44.0)*	295 *(15.4)*	347 *(18.1)*	432 *(22.5)*		1357 *(70.7)*	562 *(29.3)*					
TOTAL	**2574** *(43.7)*	**889** *(15.1)*	**1060** *(18.0)*	**1363** *(23.2)*		**4716** *(80.2)*	**1168** *(19.9)*		**2079** *(35.4)*	**1869** *(31.9)*	**1919** *(32.7)*	

[a] N *(%)*.
[b] Mean (±SD).

Table 2
Characteristics of hypertension, aircraft noise exposure, aircraft noise annoyance and noise sensitivity by country (UK: United Kingdom; GE: Germany; NL: The Netherlands; SW: Sweden; GR: Greece; IT: Italy; FR: France).

	UK	GE	NL	SW	GR	IT	FR	Overall	P
Hypertension [a]	308 *(52.6)*	550 *(56.8)*	490 *(55.9)*	534 *(53.9)*	368 *(59.7)*	329 *(52.8)*	419 *(34.7)*	2998 *(51.1)*	**<0.01**
Aircraft noise levels (L_{night}) [b]	49.3 *(10.5)*	40.2 *(10.0)*	42.2 *(8.9)*	39.5 *(7.9)*	41.7 *(4.6)*	35.4 *(6.4)*	45.1 *(6.4)*	42.0 *(8.9)*	**<0.01**
Aircraft noise annoyance [a]									
Not highly annoyed	395 *(67.4)*	816 *(84.2)*	779 *(88.9)*	893 *(90.1)*	349 *(56.6)*	485 *(77.8)*	999 *(81.8)*	4716 *(80.1)*	**<0.01**
Highly annoyed	191 *(32.6)*	153 *(15.8)*	97 *(11.1)*	98 *(9.9)*	268 *(43.4)*	138 *(22.2)*	223 *(18.2)*	1168 *(19.9)*	
Noise sensitivity [a]									
Low	132 *(22.8)*	389 *(40.2)*	361 *(41.3)*	516 *(52.1)*	209 *(33.9)*	202 *(32.5)*	270 *(22.2)*	2079 *(35.4)*	**<0.01**
Medium	193 *(33.3)*	282 *(29.1)*	293 *(33.5)*	222 *(22.4)*	162 *(26.3)*	134 *(21.5)*	583 *(48.0)*	1869 *(31.9)*	
High	255 *(44.0)*	297 *(30.7)*	221 *(25.3)*	253 *(25.5)*	246 *(39.9)*	286 *(46.0)*	361 *(29.7)*	1919 *(32.7)*	

[a] N (%).
[b] Mean (±SD).

Table 3
Relative risks for the risk of hypertension in relation to a 10 dB(A)-increase in night-time aircraft noise exposure (L_{night}) and/or aircraft noise annoyance or noise sensitivity.

	M0 model		M1 model		M2 model		M3 model		M4 model	
	RR	95% CI	RR	95% CI	RR	95% CI	RR	95% CI	RR	95% CI
L_{night}	**1.03**	**(1.01–1.06)**					**1.03**	**(1.00–1.06)**	**1.03**	**(1.00–1.06)**
Aircraft noise annoyance										
Not highly annoyed			**1.00**	***ref***			1.00	*ref*		
Highly annoyed			**1.06**	**(1.00–1.13)**			1.05	(0.99–1.11)		
Noise sensitivity										
Low					1.00	*ref*			1.00	*ref*
Medium					0.98	(0. 92–1.03)			0.97	(0.92–1.03)
High					0.98	(0.92–1.04)			0.98	(0.92–1.04)

M0 model = L_{night} + confounders; M1 model = aircraft noise annoyance + confounders; M2 model = noise sensitivity + confounders; M3 model = L_{night} + aircraft noise annoyance + confounders; **M4 model** = L_{night} + noise sensitivity + confounders. For each model, confounders were gender, age, education level, physical activity, BMI, alcohol consumption, and country.

hypertension (RR = 1.03, 95%CI 1.01–1.06) (Table 3, M0 model), without any difference between countries.

Aircraft noise annoyance was also significantly associated with the risk of hypertension (RR = 1.06, 95%CI 1.00–1.13 for highly annoyed people compared to those who were not highly annoyed) (Table 3, M1 model), without any difference between countries.

The interaction between noise sensitivity and country was significant, showing differences in RRs among countries. All RRs were very close to 1 in all countries except in the UK and France (in the UK, RR = 1.08, 95%CI 0.87-1.34 for medium sensitivity compared to low sensitivity, RR = 1.29, 95%CI 1.05-1.59 for high sensitivity compared to low sensitivity; in France, RR = 1.00, 95%CI 0.61-1.65 for medium sensitivity compared to low sensitivity; RR = 1.11, 95%CI 0.68-1.82 for high sensitivity compared to low sensitivity) (Fig. 2, M2 model).

When aircraft noise annoyance was included in the M0 model together with L_{night} and confounders, RRs for aircraft noise levels and noise annoyance remained very similar (Table 3, M3 model). When noise sensitivity was included in the M0 model together with L_{night} and confounders, the results were unchanged (Table 3, M4 model).

The interaction between aircraft noise annoyance and aircraft noise levels at night (L_{night}) was not significant ($p = 0.36$), nevertheless the association between aircraft noise levels at night (L_{night}) and the risk of hypertension was a little higher for highly annoyed participants (RR = 1.06, 95%CI 0.95-1.18 for a 10-dB(A) increase in L_{night}) compared to not highly annoyed participants (RR = 1.02, 95%CI 0.99–1.06) (Table 4, M5 model).

The interaction between noise sensitivity and aircraft noise levels at night (L_{night}) was statistically significant ($p < 0.01$): the association between aircraft noise levels at night (L_{night}) and the risk of hypertension increased with the level of noise sensitivity and was significant only among highly sensitive participants (RR = 1.00, 95%CI 0.96–1.04; RR = 1.03, 95%CI 0.90–1.11; RR = 1.12, 95%CI 1.01–1.24, with a 10-dB(A) increase in L_{night} for low, medium, and high sensitive people respectively) (Table 4, M6 model).

Sensitivity analyses using the Lden gave similar results but with lower and non-significant odds ratios (Tables S1 and S2). The results of sensitivity analyses limited to the participants between 45 and 70 years of age were similar (results not shown). In addition, sensitivity analyses using the noise sensitivity variable taking into account the tertiles of the Weinstein scale for the HYENA study in combination with the question of the DEBATS study led to similar results (results not shown). Finally, sensitivity analyses using HYENA and DEBATS datasets separately showed similar results. In both studies, aircraft noise levels at night (L_{night}) were associated with the risk of hypertension. Aircraft noise annoyance was not significantly associated with hypertension risk but showed increased RRs for highly annoyed participants compared to participants who were not highly annoyed. When aircraft noise levels at night (L_{night}) and aircraft noise annoyance were included together in the models with the confounders, RRs became slightly lower (Table S3, M0, M1 and M3 models). Moreover, in both studies, relative risks for aircraft noise levels at night (L_{night}) related to hypertension risk were higher among highly sensitive participants and to a lesser extent, among highly annoyed participants (Table S4, M5 and M6 models).

4. Discussion

This study reports the results of a pooled analysis of the HYENA and the DEBATS datasets, providing a higher statistical power especially when investigating the modifier/mediator role of aircraft noise annoyance and noise sensitivity in the relationship between aircraft noise levels and hypertension risk.

The results of the present study are consistent with the relationship between night-time aircraft noise exposure (L_{night})and the risk of hypertension found by Jarup et al. in the HYENA study (odds-ratio (OR) = 1.14, 95%CI 1.01–1.23 for both sexes) (Jarup et al., 2008) and Evrard et al. in the DEBATS study (OR = 1.10, 95%CI 0.90–1.37 for both sexes

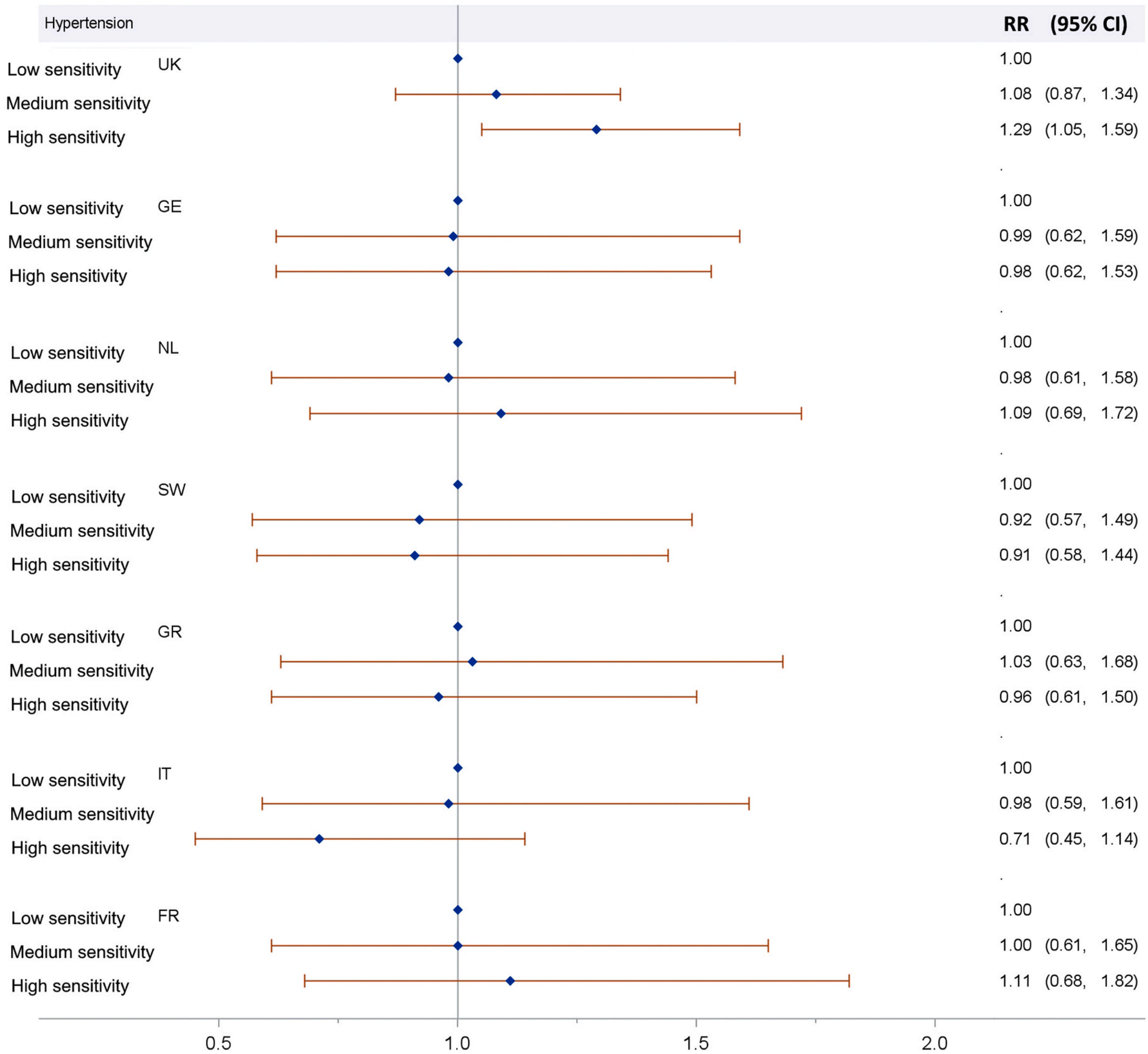

Fig. 2. Relative risks (RRs) for the risk of hypertension in relation to noise sensitivity (M2 model including the interaction between noise sensitivity and country).

Table 4
Relative risks for the risk of hypertension in relation to a 10 dB(A)-increase in night-time aircraft noise exposure (L_{night}) according to the level of annoyance and sensitivity to noise.

	Annoyance due to aircraft noise (M5 Model)					Noise sensitivity (M6 Model)						
	Not highly annoyed		Highly annoyed		$p_{interaction}$	Low sensitivity		Medium sensitivity		High sensitivity		$p_{interaction}$
Noise levels	RR	95% CI	RR	95% CI		RR	95% CI	RR	95% CI	RR	95% CI	
L_{night}	1.02	(0.99–1.06)	1.06	(0.95–1.18)	0.36	1.00	(0.96–1.04)	1.03	(0.90–1.11)	**1.12**	**(1.01–1.24)**	<0.01

M5 model: M0 model including the interaction between L_{night} and noise annoyance.
M6 model: M0 model including the interaction between L_{night} and noise sensitivity.
Both models were adjusted for age, gender, education level, physical activity, BMI, alcohol consumption, and country.

and 1.34, 95%CI 1.00–1.97 in men only) (Evrard et al., 2017). However, these studies used a logistic regression which estimates ORs; but ORs tends to overestimate the risk ratio and this overestimation becomes larger with increasing incidence of the outcome. The present study used a Poisson regression, which is better suited to high prevalence of hypertension in the study population (51%), thus leading to an association that was certainly significant, but of lower intensity (RR = 1.03, 95%CI 1.01–1.06 for both sexes). When reanalyzing the HYENA dataset with a Poisson regression instead of a logistic regression as presented in the paper below (Jarup et al., 2008), we yielded a RR = 1.06, 95%CI 1.01–1.11 for both sexes. Similarly, results on the DEBATS dataset only yielded a RR = 1.05, 95%CI 0.94–1.18 for both sexes and a RR = 1.17, 95%CI 1.01–1.37 in men only (Evrard et al., 2017). These relative risks were very close to those found in the present study. Also using a Poisson regression, Eriksson et al. did not show any association between aircraft noise exposure (L_{den}) and cumulative risk of hypertension (RR = 1.00; 95% CI 0.91–1.11) (Eriksson et al., 2010). However, this result is poorly comparable due to differences in methodology.

When finding a significant association between aircraft noise annoyance and the risk of hypertension, the results are consistent with those of the study around Stockholm Arlanda Airport, where self-reported doctor-diagnosed hypertension was also shown to be associated with aircraft noise annoyance (Bluhm et al., 2004). In contrast, Babisch et al. did not show an association between aircraft noise annoyance and the risk of hypertension in the HYENA study. However, in this latter study, noise annoyance was rated during the day and during the night separately, and then both were combined in a way that the highest rating (day or night) was considered (Babisch et al., 2013).

The present results did not show any significant association between noise sensitivity and hypertension risk when all countries were considered all together. But the interaction term between noise sensitivity and country was significant, showing differences in RRs among countries. All RRs were very close to 1 in all countries except in the UK and France where the RRs were higher than 1, but not significantly, for people highly sensitive to noise compared to people with low sensitivity to noise. This result is therefore partially consistent with the one of the Heinonen-Guzejev's study showing an increased risk for reported hypertension with noise sensitivity (Heinonen-Guzejev et al., 2004). However, this study had a different setting and included participants exposed to different noise sources (not only aircraft noise). This clearly may affect the association between noise sensitivity and hypertension.

When night-time aircraft noise exposure (L_{night}) was included in the models together with aircraft noise annoyance and confounders (M3 model) or together with noise sensitivity and confounders (M4 model), the significant association for night-time exposure found in the M0 model was unchanged. This does not suggest the possibility of a mediating effect of aircraft noise annoyance or noise sensitivity in the relationship between aircraft noise levels and the risk of hypertension, as it has been previously shown in the relationship between aircraft noise levels and mental health well-being (Tarnopolsky et al., 1980; van Kamp and Davies, 2008; Schreckenberg et al., 2017).

The interaction between aircraft noise annoyance and aircraft noise at night (L_{night}) was non-significant, but the RR for hypertension risk with a 10-dB(A) increase in aircraft noise at night (L_{night}) was slightly higher among highly annoyed participants compared to those not highly annoyed. The fact that an interaction term in a statistical model turns out to be non-significant may simply be due to lack of statistical power, because approximately four times as many individuals would be needed to be able to detect effect modification in the model as compared to main effect analyses. Thus, a modifying effect of aircraft noise annoyance in the relationship between aircraft noise levels and hypertension risk cannot be excluded in the present study.

The significant interaction between noise sensitivity and aircraft noise at night (L_{night}) indicates a possible modifying effect of noise sensitivity in the relationship between aircraft noise levels and hypertension risk. This modifier role of noise sensitivity has been shown previously between aircraft noise levels and anxiety and nervous complaints (Nivison and Endresen, 1993), psychological disorders (Miyakawa et al., 2008; Kishikawa et al., 2009), heart rate (di Nisi et al., 1987), and self-reported physical health problems (Schreckenberg et al., 2010; Nivison and Endresen, 1993; Stansfeld, 1992), but no previous studies have considered it for hypertension.

As with any epidemiological study, it is not possible to exclude residual confounding, even though we were able to adjust for known major confounding factors. One concern is that areas near airports might be more socio-economically deprived because aircraft noise makes them less desirable places to live and property prices are depressed (Nelson, 2004; Dekkers and van der Straaten, 2009; Sedoarisoa, 2015). Higher deprivation levels might be expected to lead to poorer general health (Franks et al., 1982). However, we did adjust for education level, which was the common measure of socio-economic status across the different countries.

Another limitation is potential for selection bias. Firstly, there was a low response rate in most of the participating countries. However, only minor differences were found between the characteristics of the participants and those of the non-responders according to aircraft noise exposure categories (Evrard et al., 2017; Jarup et al., 2008). Secondly, there were different age criteria for selection of participants in the study - people were 45–70 years of age in the HYENA study, whereas participants of the DEBATS study were 18–90 years of age. It has been shown that the prevalence of hypertension considerably increases from 40 years of age, which would explain the higher prevalence in the HYENA study (Ashman et al., 2016). However, when analyses were limited to participants between 45 and 70 years of age, the results were unchanged. Further sources of bias relate to country-specific factors, including differences in prevalence between countries. To account for this, we used models including country as a confounder and then including an interaction term between country and factors of interest (aircraft noise levels, aircraft noise annoyance and noise sensitivity). This interaction was significant when investigating noise sensitivity in relation to hypertension risk. Finally, it may be that people who considered themselves highly sensitive to noise may be reluctant to live in noisy conditions and therefore move away from noisy areas leading to a lower proportion of sensitive people among those living near airports, especially in the noisiest areas. There is little information available to judge whether this has happened. However, if it did occur, it would have led to an underestimation of the associations observed in the present study.

Another limitation of this study is that noise sensitivity and noise annoyance were not assessed in exactly the same way in the HYENA and the DEBATS studies. This may explain the fact that the interaction term between noise sensitivity and country was significant, while previous studies have not shown effects of cultural differences on noise sensitivity (Kliuchko et al., 2015). Even if the same question about aircraft noise annoyance was used for all the participants, differences in the prevalence of aircraft noise annoyance were found across countries in the present study (Table 2), thus suggesting a different level of appreciation in the question depending on cultural or climate conditions, consistent with previous studies (Namba et al., 1986). Nevertheless, the interaction term between aircraft noise annoyance and country was not significant, suggesting no difference in associations with health outcomes across countries. We consider that bias related to the different ways of assessing annoyance and noise sensitivity in both studies is limited. Indeed, sensitivity analyses carried out separately for the HYENA and the DEBATS participants showed similar results compared to pooled-analyses results (Table S3), including higher RRs for hypertension in relation to aircraft noise levels among people with high noise sensitivity or to a lesser extent among those highly annoyed (Table S4).

Finally, the cross-section design of this study makes it difficult to assess temporality and causality. While hypertension risk might be increased as a result of noise annoyance or in people sensitive to noise, it is also possible that people with poorer health might be more at risk of being annoyed by noise or to report higher sensitivity to noise and then be more willing to attribute their symptoms or condition to noise (Babisch et al., 2003).

5. Conclusion

This pooled analysis based on seven European countries was consistent with previous results suggesting that aircraft noise levels are associated, albeit weakly, with the risk of hypertension, and aircraft noise annoyance is associated with hypertension risk. They also suggest a possible modifying effect of aircraft noise annoyance in the relationship between aircraft noise exposure and the risk of hypertension. This is to our knowledge the first study to examine the role of noise sensitivity in the relationship between aircraft noise levels and hypertension risk, finding that this association was higher among highly sensitive participants. It is important that future studies of health effects related to noise exposure take noise annoyance and noise sensitivity into account, in particular by using appropriate statistical models related to mediation analysis and causal inference.

Declarations

Ethics approval

The research undertaken by each of the HYENA partners was covered by local agreements concerning the ethical use of data and the protection of confidentiality of individuals. Ethics approvals have been obtained in all partner countries.

The DEBATS study was approved by two national authorities in France: the French Advisory Committee for Data Processing in Health Research and the French National Commission for Data Protection and Liberties.

The present study was approved by the University Ethics Sub-Committee of Medicine and Biological Sciences from the University of Leicester.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envres.2020.110179.

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