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Aircraft noise and cardiovascular morbidity and mortality near Heathrow Airport: A case-crossover study

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ABSTRACT

Aircraft noise causes annoyance and sleep disturbance and there is some evidence of associations between long-term exposures and cardiovascular disease (CVD). We investigated short-term associations between previous day aircraft noise and cardiovascular events in a population of 6.3 million residing near Heathrow Airport using a case-crossover design and exposure data for different times of day and night. We included all recorded hospitalisations (n = 442,442) and deaths (n = 49,443) in 2014–2018 due to CVD. Conditional logistic regression was used to estimate the ORs and adjusted for NO_2 concentration, temperature, and holidays. We estimated an increase in risk for 10 dB increment in noise during the previous evening (L_{eve} OR = 1.007, 95% CI 0.999–1.015), particularly from 22:00–23:00 h (OR = 1.007, 95% CI 1.000–1.013), and the early morning hours 04:30–06:00 h (OR = 1.012, 95% CI 1.002–1.021) for all CVD admissions, but no significant associations with day-time noise. There was effect modification by age-sex, ethnicity, deprivation, and season, and some suggestion that high noise variability at night was associated with higher risks. Our findings are consistent with proposed mechanisms for short-term impacts of aircraft noise at night on CVD from experimental studies, including sleep disturbance, increases in blood pressure and stress hormone levels and impaired endothelial function.

1. Introduction

It is estimated that each year over 1 million disability-adjusted life-years are lost in western Europe due to environmental noise exposure (WHO 2011). The World Health Organisation 2018 Environmental noise guidelines for the European Region provide a strong recommendation to limit the average exposure to environmental noise to 45 dB during the daytime and 40 dB during the night-time, and 80% of respondents surveyed in 27 countries across the European Union felt that environmental noise affects their health (Environmental Noise Guidelines for the European Region. World Health Organization, Regional Office for Europe;, 2018).

A *meta*-analysis conducted as part of the 2018 World Health Organization guidelines on environmental noise found a relative risk of 1.09 (95%CI 1.04–1.15) for incidence of coronary heart disease per long-term exposure to L_{den} noise and 1.05 (95%CI 0.96–1.15) for incidence of stroke (van Kempen et al., 2018). Nevertheless, only two previous studies have investigated short-term effects on CVD. A study published in 2021 (Saucy et al., 2021) found acute increases in cardiovascular mortality associated with night-time aircraft noise from Zurich airport and the accompanying editorial (Münzel et al., 2021) called for further studies at airports with higher night-time exposures. However, a study following the April 2010 eruption of Iceland's Eyjafjallajökull volcano and the subsequent six day closure of London Heathrow did not find a significant difference in CVD hospital admission rates in the areas surrounding Heathrow airport during its closure (Pearson et al., 2016).

Environmental noise is associated with an increased risk of sleep disturbance and general annoyance, and there are good mechanistic pathways by which this may damage the vascular system including vascular oxidative stress and activation of the sympathetic nervous system, which may lead to the acute onset of a cardiovascular event. Experimental studies have shown that aircraft noise stimuli affect sleep,

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increase blood pressure and stress hormone levels and impair endothelial function in humans (Schmidt et al., 2013; Schmidt et al., 2015). Endothelial dysfunction is strongly associated with adverse cardiovascular events, and evidence shows that dysfunction can be induced a few hours after exposure to a stressor (Poitras and Pyke, 2013; Recio et al., 2016). Acute high levels of noise have also been shown to over-produce cortisol and alter lipid and lipoprotein levels in humans and lead to atherosclerosis (Qureshi et al., 2009), a common precursor to CVD. A cross-sectional study in Germany found a significant association between night-time road traffic noise exposure and atherosclerosis (Kalsch et al., 2014). Atherosclerotic lesions can induce cytokine cascades that then promote endothelial dysfunction (Recio et al., 2016). In a population-based study near four major European airports elevated blood pressure was consistently found immediately following a night-time aircraft event (Haralabidis et al., 2008). This suggests there may be evidence of a short-term association between aircraft noise exposure and cardiovascular morbidity, and therefore there is a need for further epidemiological studies to understand how aircraft noise may act as a trigger for cardiovascular events.

The present study aims to assess the short-term impact of aircraft noise at specific time periods throughout the day and night on short-term cardiovascular morbidity and mortality, after adjusting for air pollution and temperature in the population residing near Heathrow Airport. Heathrow Airport is one of the world's busiest airports, situated in a densely populated area in west London. Heathrow flight patterns change according to wind direction, with flight paths taking off to the west approximately 70% of the time due to westerly wind direction and a switch to the east approximately 30% of the time due to easterly wind direction (Porter, 2017). This provides short-term contrasts in noise levels that should aid detection of associations.

2. Methods

2.1. Study design

We used a time-stratified case-crossover study design with bidirectional control sampling, in which the days on which an event of interest occurred are compared to control days selected within the same month and on the same day of the week (Maclure, 1991; Mittleman et al., 1995). This individual-level design naturally adjusts for all time-invariant or slowly time-varying confounders, including, sex, smoking behaviour, and genetic factors. It utilizes all cases in the population without the need to recruit additional controls. The case-crossover design is useful in assessing the acute impact of a transient risk factor with minimal bias and has been used widely in environmental epidemiology, predominantly in temperature and air pollution studies as well as aircraft noise (Saucy et al., 2021; Konstantinoudis et al., 2022).

2.2. Study population

The study area was designed to capture the outer bounds of the Civil Aviation Authority (CAA) annual-average aircraft noise contours in 2011 and covered an approximate distance of 97 km east-to-west, and 47 km north-to-south centred on Heathrow Airport. This area encompasses roughly 6.3 million people and 155,000 postcodes with one postcode encompassing an average of 22 households (SD = 17) occupied by 53 residents (SD = 44) [Fig. 1].

2.3. Exposure data

Spatiotemporal aircraft noise sources originating from Heathrow were modelled in version 3b of the Aviation Environmental Design Tool (AEDT) (Aviation Environmental Design Tool (AEDT), N.D) by the environmental consultancy firm, Anderson Acoustics, with external guidance from the University of Leicester. AEDT noise surface estimates account for flight activity, terrain features and other meteorological parameters (see Supplementary Text 2). Radar tracks of individual flights were provided by Heathrow Airport, with a unique set of aircraft footprints constructed for each modelled time period. The created AEDT surfaces cover 1,826 days across the five years of 2014–2018. To reduce the computational demands of AEDT, each day was split into eight time bands, and a variable grid resolution was used. In total, 14,608 flight-activity-informed noise surfaces were constructed with a resolution of 100x100m near to Heathrow and a resolution of 200x200m at distant locales. The inner grid with a 100 m resolution covers the area from Datchet to Osterly Park, approximately 25 km east-to-west, and West Drayton to Ashford, approximately 15 km north-to-south.

The short-term set of average 'A' frequency weighted noise surfaces cover the following eight time bands of each day, defined by the diurnal variations in temperature and operational activity at Heathrow: 24:00–04:30 h, 04:30–06:00 h, 06:00–07:00 h, 07:00–15:00 h, 15:00–19:00 h, 19:00–22:00 h, 22:00–23:00 h, and 23:00–24:00 h. Daily metrics of L_{day}, L_{eve}, L_{night} L_{den} and L_{Aeq24} were then calculated from these surfaces [see Supplementary Text 1]. These time periods were chosen in discussion with the study advisory board and industry representatives to capture conventional time periods (i.e. 07:00–19:00 day, 19:00–23:00 evening, 23:00–07:00 night), together with timings that are aligned with Heathrow operations (i.e. 23:30–04:30 is a scheduled night flight ban, while 07:00–15:00 and 15:00–22:00 are main operational periods with scheduled respite periods). The 'A' Weighting is standard weighting of the audible frequencies designed to reflect the response of the human ear to noise. For further details on the AEDT modelling procedure refer to Supplementary Text 2 in the Supplementary Materials. Average continuous noise estimates from the day prior to the event were used in the analyses. Unlike the analysis of short-term impacts of aircraft noise from Zurich airport by Saucy et al. (Saucy et al., 2021; Saucy et al., 2020), data on the exact time of CVD event were unavailable in this population. Analyses in the present study were restricted to observations above 20 dB to account for reduced accuracy of the noise model at lower levels.

2.4. Health outcome data

All hospital admissions and deaths due to primary cardiovascular disease in the study area from 01/01/2014 to 31/12/2018 were included. We extracted post coded data on all hospital admissions and deaths from the Hospital Episode Statistics from NHS Digital and the mortality data from the Office for National Statistics held by the UK Small Area Health Statistics Unit at Imperial College London. Data were obtained for all events with primary cause of admission or death due to stroke (ICD-10 codes I61, I63-I64), coronary heart disease (ICD-10 I20-I25), and other cardiovascular disease (ICD-10 Chapter I) and linked to postcode-level noise estimates. If multiple CVD admissions were recorded in a day, one record was randomly selected for inclusion because the order of admissions in a calendar day or the time of admission were not available. Time of hospital episode and death were not available. The study was covered by national research ethics approval from the London-South East Research Ethics Committee - reference 17/LO/0846. Data access to confidential patient information without consent was covered by the Health Research Authority - Confidentiality Advisory Group under Regulation 5 of the Health Service (Control of Patient Information) Regulations 2002 ('section 251 support') - HRA CAG reference: 20/CAG/0028.

2.5. Covariate data

The environmental covariates included in the models were mean temperature and NO_2 concentration to adjust for potential confounding from transport emissions (Mills et al., 2015). Hourly dry air temperature measurements were captured at three National Oceanic and Atmospheric Administration Integrated Surface Database (NOAA-ISD) weather stations within 25 km of the study area. Hourly background

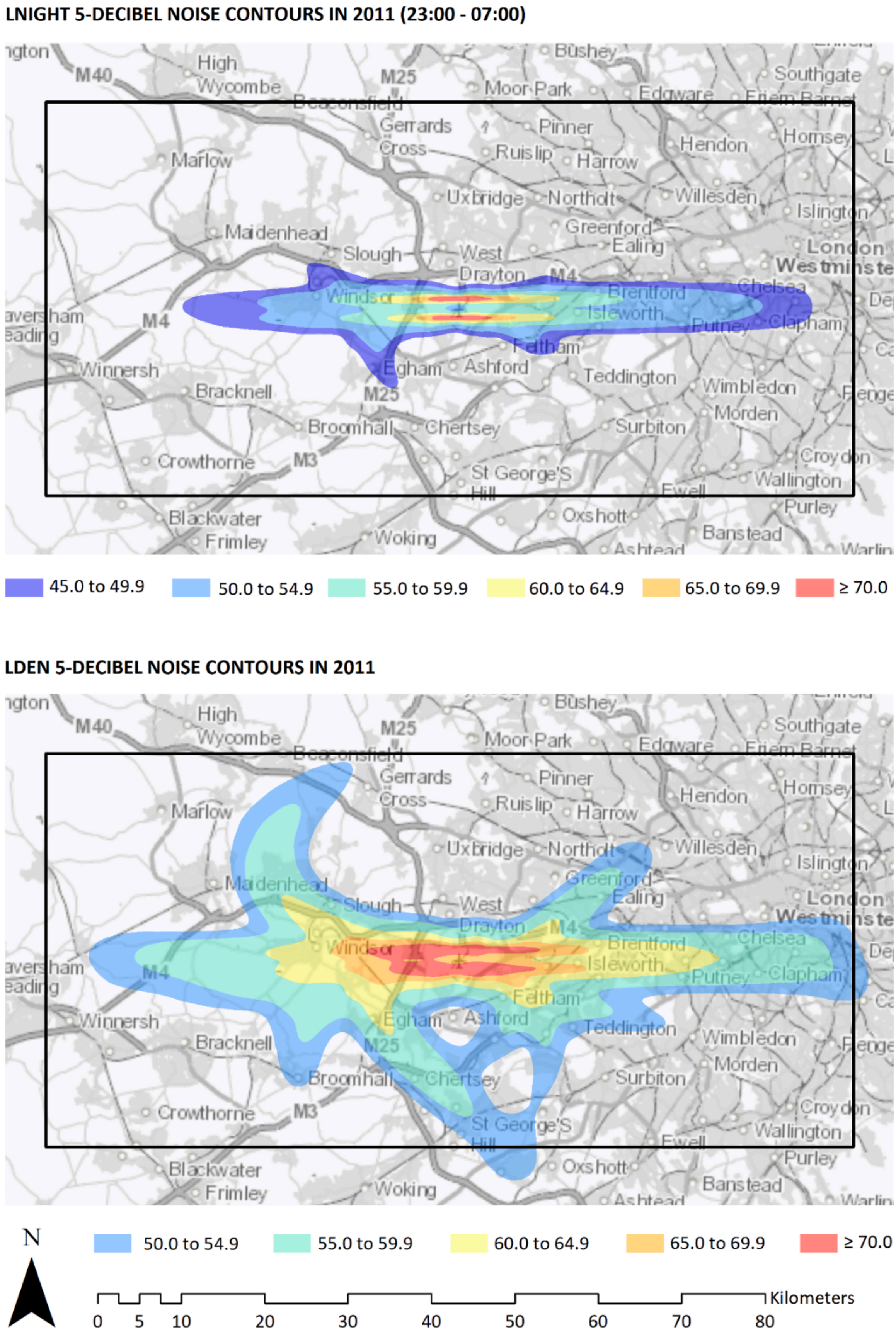

Fig. 1. The spatial extent of the AEDT modelling exercise (black bounding box) in relation to the Civil Aviation Authority (CAA) annual-average aircraft noise contours for 2011 for L_{night} (top) and L_{den} (bottom).

measurements of fine particulate matter were captured by six UK Automatic Urban and Rural Network (UK-AURN) sites within 25 km of the study area. Dry air temperature and background NO_2 concentrations were estimated at each residential postcode using a spatial interpolation technique known as inverse distance-squared weighting (IDW). For further details on dry air temperature and NO_2 estimates refer to Supplementary Text 3 in the Supplementary Materials.

Individual-level ethnicity data were available for all hospital admissions in the Hospital Episode Statistics data, and Census Output Area (COA)-level Carstairs Index quintile from the 2011 census was linked to admissions and deaths data. Carstairs Index is a commonly used indicator of material deprivation in health studies (Allik et al., 2016; Carstairs and Morris, 1990). For further details on Carstairs quintile calculation refer to Supplementary Text 4 in the Supplementary Materials. All estimates were also adjusted for the effect of holidays included in the models as a binary variable.

2.6. Statistical analyses

Patients with multiple cardiovascular records (indicating admission to the hospital) per day (n = 3018) had one record on the day randomly selected for inclusion, because the order of admissions within a calendar day or the time of admission were not available. Control periods were matched to case periods within the same year and month on the same day of the week, excluding control days on which an additional cardiovascular episode occurred (n = 15,856 control days). Control days on which a CVD event occurred were excluded because the patient would not have been at their home. 528 cases with no suitable control days were also excluded from analyses. A flowchart of the exclusion criteria and how they affected the number of cases/controls is presented in Supplementary Materials, Fig. 1.

Conditional logistic regression was used to estimate the odds ratio and 95% confidence intervals per 10 dB increase for the metrics L_{day}, L_{eve}, L_{night} L_{den} and L_{Aeq24} as well as for the eight pre-defined distinct time periods throughout the 24-hour period. We considered all CVD, CHD only and stroke only for both hospital episode and deaths. Estimates were adjusted for mean temperature, NO_2 concentration and the effect of holidays, as these are variables that change rapidly in time, while long-term confounders were accounted for by the case-crossover study design. Analyses were also stratified by age-sex, ethnicity, deprivation, and season to assess effect modification. We also assessed modification by variation in average noise levels using the mean coefficient of variation (CoV) over the 5-year period. We calculated CoV for each exposure time period by dividing the standard deviation by the mean noise level over the 5-year period. Areas above the mean CoV were categorised as high variation, in contrast to low variability in the areas with CoV below the mean value. [Supplementary Table 6]. All analyses were run in R Statistical Software (R: A language and environment for statistical computing. R Foundation for Statistical Computing, N.D.) using the *Epi* package (Carstensen et al., 2022).

3. Results

3.1. Descriptive

442,442 hospital admissions and 49,443 deaths due to

Table 1
Descriptive statistics for hospital admissions and deaths due to cardiovascular disease, and noise estimates for all CVD cases and controls.

	HOSPITAL EPISODES (n = 442442)						DEATHS (n = 49443)					
	All CVD		CHD		Stroke		All CVD		CHD		Stroke	
	n	%	n	%	n	%	n	%	n	%	n	%
Sex [a]												
Male	256,674	58.0%	81,278	69.9%	21,367	52.7%	26,011	52.6%	12,984	61.9%	4014	45.7%
Female	185,749	42.0%	34,941	30.1%	19,199	47.3%	23,432	47.4%	7984	38.1%	4771	54.3%
Age [a]												
<65	190,732	43.1%	49,936	43.0%	11,420	28.2%	7267	14.7%	3640	17.4%	834	9.5%
65+	250,705	56.7%	66,260	57.0%	29,106	71.7%	42,176	85.3%	17,328	82.6%	7951	90.5%
Deprivation												
1 (least)	57,060	12.9%	15,061	13.0%	5080	12.5%	7239	14.6%	2843	13.6%	1349	15.4%
2	55,076	12.4%	14,307	12.3%	5104	12.6%	6561	13.3%	2630	12.5%	1275	14.5%
3	72,775	16.4%	18,735	16.1%	6666	16.4%	8582	17.4%	3541	16.9%	1529	17.4%
4	106,033	24.0%	27,356	23.5%	9454	23.3%	11,606	23.5%	4984	23.8%	2012	22.9%
5	151,498	34.2%	40,763	35.1%	14,263	35.2%	15,455	31.3%	6970	33.2%	2620	29.8%
Season												
Summer	110,255	24.9%	29,215	25.1%	10,095	24.9%	11,260	22.8%	4728	22.5%	2060	23.4%
Summer Transition	73,835	16.7%	19,730	17.0%	6731	16.6%	7702	15.6%	3231	15.4%	1333	15.2%
Winter	184,625	41.7%	47,807	41.1%	16,838	41.5%	22,365	45.2%	9589	45.7%	3933	44.8%
Winter Transition	73,727	16.7%	19,470	16.8%	6903	17.0%	8116	16.4%	3420	16.3%	1459	16.6%
Ethnicity [b]												
South Asian	42,994	9.7%	18,049	15.5%	2711	6.7%						
Black	35,245	8.0%	5704	4.9%	4197	10.3%						
Other [c]	297,390	67.2%	73,658	63.4%	27,582	68.0%						
Missing	66,813	15.1%	18,811	16.2%	6077	15.0%						
	Case	Control	Case	Control								
Noise estimates (dB)	Mean	SD	Mean	SD	Mean	SD	Mean	SD				
2400–0430	2.01	6.0	2.0	6.0	2.0	6.1	2.1	6.1				
0430–0600	25.8	12.5	25.8	12.5	25.7	12.4	25.7	12.4				
0600–0700	40.8	8.8	40.8	8.8	40.6	8.6	40.6	8.6				
0700–1500	42.4	6.9	42.4	7.0	42.4	6.8	42.4	6.9				
1500–1900	41.9	6.9	41.9	6.9	41.9	6.8	41.92	6.8				
1900–2200	41.9	6.9	41.8	6.9	41.8	6.8	41.8	6.8				
2200–2300	39.5	7.4	39.5	7.4	39.5	7.4	39.5	7.4				
2300–2400	27.9	10.9	27.9	10.9	27.6	10.9	27.6	10.9				

[a] 19 hospital episodes missing sex, 1005 missing age.
[b] Ethnicity information not available for mortality data.
[c] Includes all other non-Black and non-South Asian ethnicities including white and mixed ethnicities.

cardiovascular disease were included in the analyses. Of the hospital admissions, 58.0% were male, 56.7% were over the age of 65, and of the 84.9% that reported ethnicity, 9.4% were Black and 11.4% were South Asian. Cases were evenly spread across the 5 years in the study period, with 41.7% occurring in winter and 24.9% occurring in summer. Among cardiovascular deaths, 52.6% were male, and 85.3% were over the age of 65. 45.2% of deaths occurred in the winter months, and 22.8% occurred in the summer months [Table 1A]. 1,489,619 and 168,122 control days were included for hospital admissions and for deaths, respectively.

Over the entire five-year period the mean L_{aeq24} for hospitalisation case days was 41.5 dB, and for control days 41.4 dB; for mortality case days 41.2 dB and control days 41.2 dB. Noise exposure varied greatly over the 24-hour period, with highest average noise between 15:00–19:00 h and lowest average noise between 24:00–04:30 h for both case and control periods. Among cases, the highest noise values were 76.2 dB and 78.8 dB for hospital admissions and deaths respectively; among controls they were 76.2 dB and 75.0 dB. During night-time and early morning hours 23:00–06:00 h values were often estimated to be 0.0 dB, indicating no flight activity [Table 1B].

3.2. Hospital admissions

There was evidence of a small increase in risk for 10 dB increment in noise during the previous evening (L_{eve} OR = 1.007, 95% CI 0.999–1.015), particularly from 22:00–23:00 h (OR = 1.007, 95% CI 1.000–1.013), and the early morning (04:30–06:00 h OR = 1.012, 95% CI 1.002–1.021) for all cardiovascular disease admissions [Table 2 and Fig. 2]. Similarly, we found evidence of an increase in risk associated with noise during the previous night for admissions due to stroke (24:00–04:40 h OR = 1.133, 95% CI 1.007–1.276). There was a similar but statistically non-significant pattern for admissions due to coronary heart disease [Fig. 2].

After stratifying by age and sex, the effect of aircraft noise on cardiovascular admissions was statistically significant in men over the age of 65 during the previous evening (L_{eve} OR = 1.021, 95% CI 1.006–1.036), specifically during 19:00–22:00 h (OR = 1.016, 95% CI 1.001–1.031) and 22:00–23:00 h (OR = 1.014, 95% CI 1.002–1.025). [Fig. 3A]. After stratifying by ethnicity, an association with early morning hours 04:30–06:00 h (OR = 1.054, 95% CI 1.014–1.095) was seen in cases who reported Black ethnicity and for other ethnicity (not South Asian or Black) with previous evening noise during the hour of 22:00–23:00 (OR = 1.008, 95% CI 1.001–1.017) for hospitalisations due to all cardiovascular disease [Fig. 3B]. There was also a significant increase in risk of CHD hospitalisation among cases who reported Black ethnicity associated with noise in early morning hours 04:30–06:00 h (OR = 1.111, 95% CI 1.011–1.220) and during the midday hours of 07:00–15:00 (OR = 1.085, 95% CI 1.022–1.153) [Supplementary Materials Fig. 2]. There was no evidence of effect modification by age and sex or ethnicity among stroke cases. There was the suggestion of a trend of increasing risk of hospitalisation with increasing deprivation across most time periods throughout the day, although there was also an increase in risk during early morning hours among individuals residing in areas in the least deprived (fifth quintile) of deprivation (04:30–06:00 h OR = 1.017, 95% CI 1.003–1.032). [Fig. 3C].

We also found evidence of effect modification by season. The effect of aircraft noise on CVD hospital admissions was strongest in the winter months, both in the early morning hours (04:30–06:00 h OR = 1.013, 95% CI 0.999–1.029) and evening hours (15:00–19:00 h OR = 1.011, 95% CI 1.000–1.022; 19:00–22:00 h OR = 1.022, 95% CI 1.008–1.035; 22:00–23:00 h OR = 1.016, 95% CI 1.007–1.026) [Fig. 3D]. A similar but smaller pattern was seen for CHD [Supplementary Materials Fig. 2].

Table 2
Odds ratio and 95% confidence intervals for hospitalizations and deaths due to all CVD per 10 dB increase L_{Aeq}. Estimates adjusted for NO_2 concentration, mean temperature and holiday effect.

	All CVD	CHD	Stroke
Hosp. Episodes			
L_{Aeq24}	1.003 (0.994, 1.012)	0.996 (0.979, 1.014)	1.004 (0.975, 1.034)
L_{day}	1.001 (0.993, 1.009)	0.999 (0.983, 1.015)	1.000 (0.974, 1.027)
L_{eve}	1.007 (0.999, 1.015)	1.000 (0.984, 1.016)	1.008 (0.981, 1.035)
L_{night}	0.995 (0.988, 1.001)	0.996 (0.982, 1.010)	0.997 (0.975, 1.020)
L_{den}	1.000 (0.992, 1.009)	0.991 (0.974, 1.008)	0.999 (0.971, 1.027)
Deaths			
L_{Aeq24}	1.001 (0.974, 1.028)	0.982 (0.942, 1.023)	0.980 (0.919, 1.045)
L_{day}	0.999 (0.975, 1.024)	0.984 (0.948, 1.021)	0.988 (0.932, 1.047)
L_{eve}	0.998 (0.974, 1.023)	0.982 (0.946, 1.020)	0.983 (0.928, 1.041)
L_{night}	0.987 (0.967, 1.008)	0.983 (0.951, 1.015)	0.994 (0.946, 1.044)
L_{den}	0.994 (0.969, 1.020)	0.983 (0.944, 1.023)	0.967 (0.909, 1.028)

3.3. Mortality

There was no evidence of an association between aircraft noise and deaths due to cardiovascular disease, with wide confidence intervals [Fig. 4].

3.4. Noise variability

There was some evidence that night-time aircraft noise on cardiovascular hospital admissions appeared to be modified by high noise variability, in particular by high variability. After stratifying by noise level (above/below mean) and coefficient of variation (above/below mean). Significant associations were seen in postcodes with high variation and low mean noise in both early morning (24:00–04:30 h OR = 1.008, 95% CI 1.000–1.015) and late night (22:00–23:00 h OR = 1.030, 95% CI 1.012–1.049) hours. There was also evidence of increased risk of CVD hospitalisation during the late night hours in postcodes with low variation and high mean noise (22:00–23:00 h OR = 1.019, 95% CI 1.000–1.038).

To a lesser extent, the effect on CVD mortality was also modified by variability in exposure to aircraft noise. Associations in postcodes with high variation and low mean noise was higher in the early morning hours (04:30–06:00 h OR = 0.998, 95% CI −0.977–1.020) and late night (23:00–24:00 h OR = 1.015, 95% CI 0.991–1.039) but not statistically significant. [Fig. 5].

3.5. Sensitivity analysis

These estimates assume that past hospitalisations had no impact on the risk of future hospitalisations. To test this assumption, we ran the analyses above again including only the first hospitalisation for the 60.8% of patients with more than one hospitalisation within the study period (n = 269915). The effect estimates did not change significantly, though the confidence intervals became slightly wider due to the reduced sample size [Supplementary Materials Fig. 3].

4. Discussion

There are very few previous studies of acute effects of aircraft noise on cardiovascular admissions and mortality. This study found small associations between aircraft noise and cardiovascular disease admissions mainly related to late evening and early night-time exposures, particularly in men over the age of 65, and for people identifying as

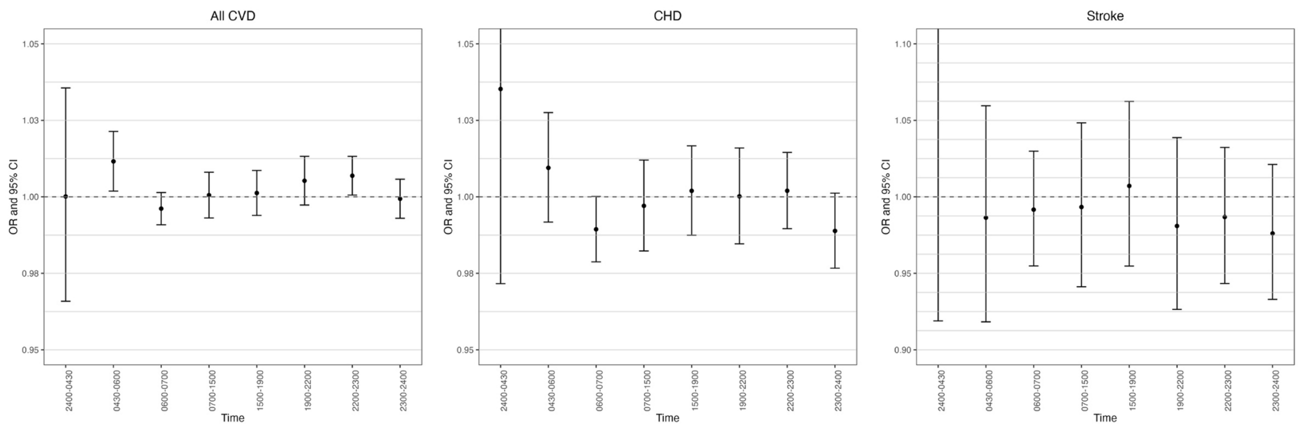

Fig. 2. Odds ratios and 95% confidence intervals for hospitalizations due to all CVD, CHD and Stroke per 10 dB increase L_{Aeq} at defined time points throughout the day, evening, and night. Estimates adjusted for NO_2 concentration, mean temperature and holiday effect.

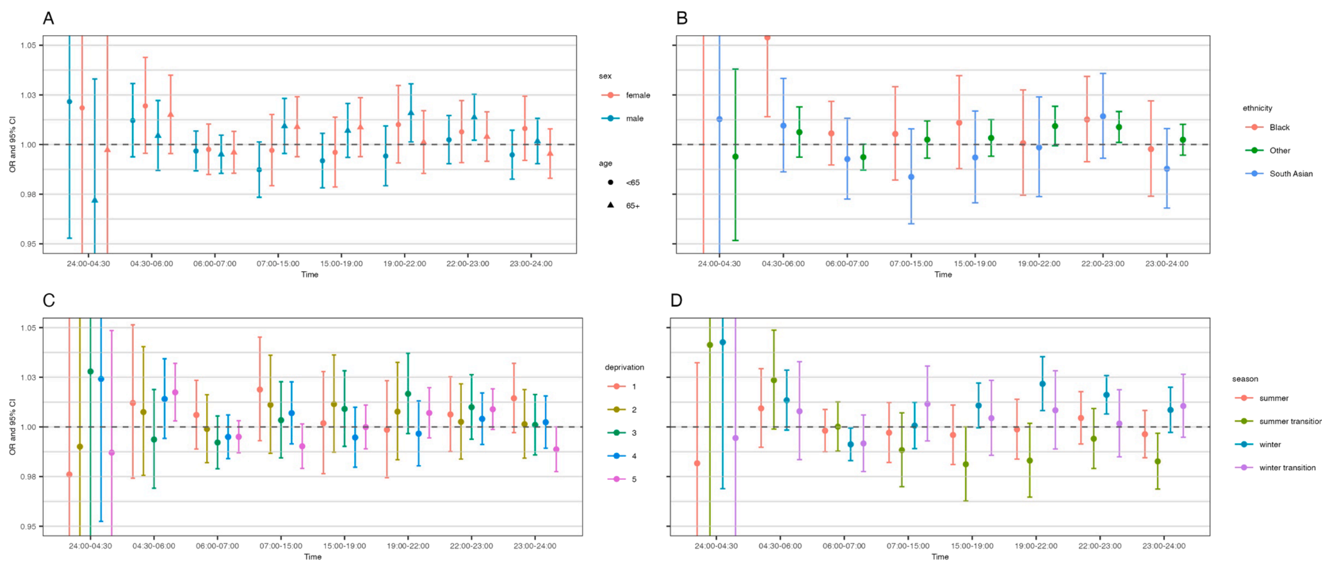

Fig. 3. Odds ratios and 95% confidence intervals for hospitalizations due to all CVD per 10 dB increase L_{Aeq}, stratified by (A) age-sex, (B) ethnicity, (C) deprivation and (D) season. Estimates adjusted for NO_2 concentration, mean temperature and holiday effect. *Note: summer = June-August; summer transition = May and September; winter = November-March; winter transition = April and October.*

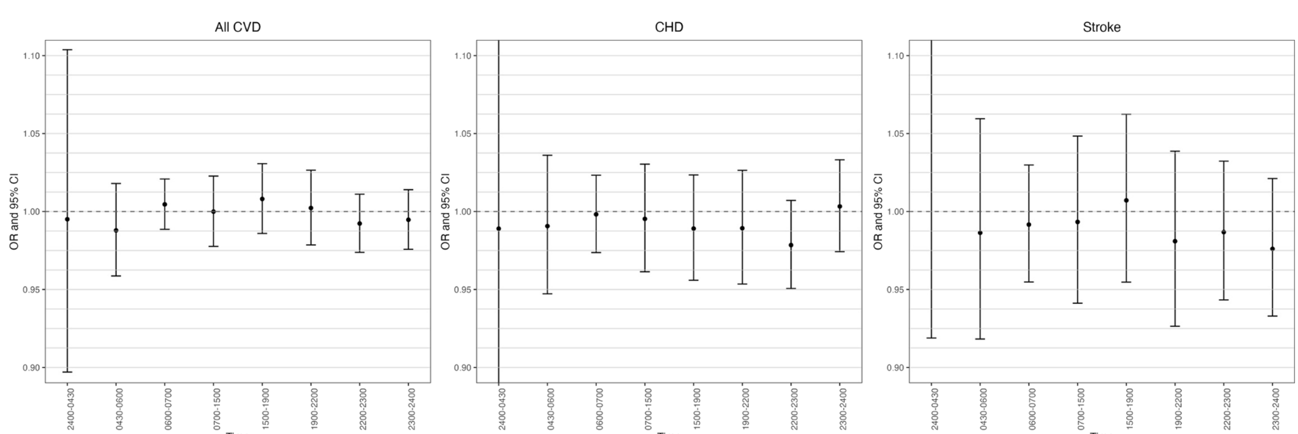

Fig. 4. Odds ratios and 95% confidence intervals for deaths due to all CVD, CHD and Stroke per 10 dB increase L_{Aeq} at defined time points throughout the day, evening, and night. Estimates adjusted for NO_2 concentration, mean temperature and holiday effect.

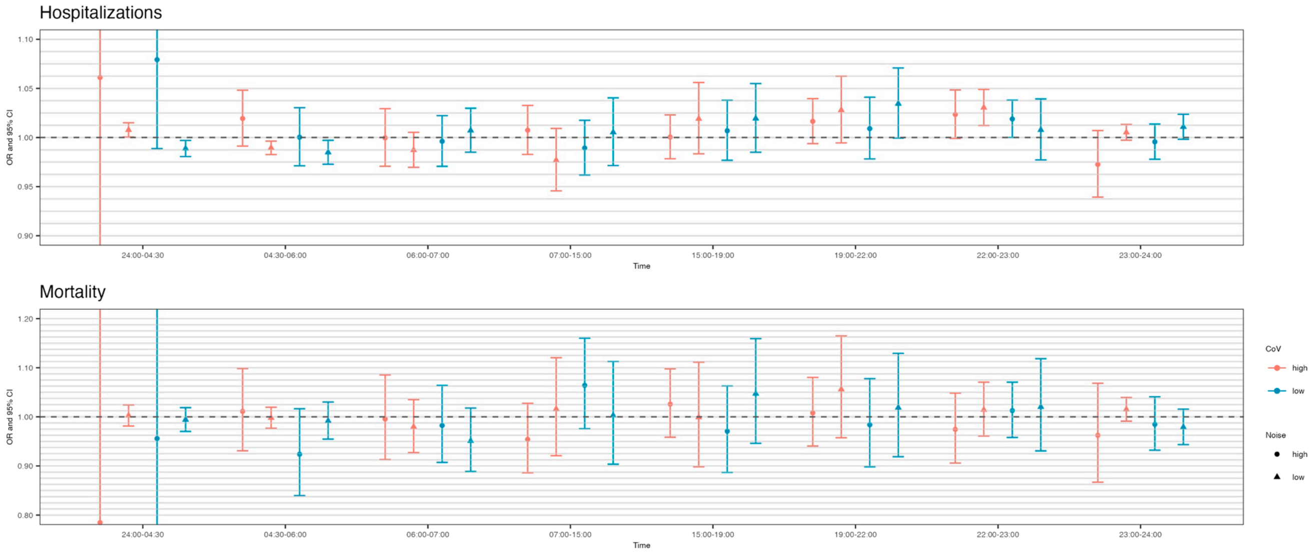

Fig. 5. Odds ratios and 95% confidence intervals for hospitalizations and mortality due to all CVD per 10 dB increase L_{Aeq}, stratified by coefficient of variation and mean noise level. Estimates adjusted for NO_2 concentration, mean temperature and holiday effect.

Black ethnicity. Hospital admission risk appeared to be highest in the winter months, which may suggest a behavioural effect modifier related to season, a decrease in exposure misclassification during the winter, or the unmeasured influence of another seasonal characteristic. This is consistent with multiple epidemiological studies indicating colder weather is associated with an increased risk of acute coronary heart syndromes (Rus and Mornoş, 2022). Lastly, we found that aircraft noise may have differential impact on cardiovascular hospitalisations dependent on noise variability and mean noise levels. Aircraft noise during early morning hours was more impactful in areas of high variability and high mean noise while night-time noise had a greater effect in areas of low variability, and high variability with low mean noise. These findings provide additional information on the association of variability in noise with increased risk of CVD events around major airports, thus warranting a more thorough investigation of the impact of variability in aircraft noise as an exposure. More so, increased risk associated with different levels of variability in aircraft noise may further suggest high predictability in health impact of noise exposure over time. Such evidence can provide useful insight for developing noise intervention measures in affected communities, particularly in developing respite period protocols, and at policy level.

A prior small area ecological study that examined long-term aircraft noise exposure in areas near Heathrow in relation to CVD, CHS and stroke found the relative risk of hospital admissions for CVD, CHD and stroke were 14%, 21% and 24% higher respectively in the noisiest areas compared to the quietest areas (Hansell et al., 2013). These findings for Heathrow and those from previous *meta*-analyses of aircraft noise and cardiovascular disease are an order of magnitude larger than those observed in this study of short-term exposures (van Kempen et al., 2018). This is consistent with findings of the short-term effect of air pollution on CVD compared with the long-term effect (Mills et al., 2015; Shah et al., March 24, 2015:; Atkinson et al., 2014).

The results of this study are generally consistent with the findings of the one previous case-crossover study of short-term aircraft noise exposure and cardiovascular morbidity and mortality. Saucy et al. in a study of Zurich airport found associations between deaths due to all CVD and night-time aircraft noise above 40 dB in the 2 h preceding the event, particularly in older people. While our study found an association between aircraft noise and hospital episodes in individuals over the age of 65, we did not see an association with deaths due to CVD (Saucy et al., 2021), though the shape of the relationship between aircraft noise and cardiovascular deaths is similar to that of the relationship with cardiovascular hospital admissions. This may be due to a much smaller number of mortality events compared to hospitalisation events in our data. We also did not find the effect modification by deprivation that was described by Saucy et al, though our findings suggest a trend of increasing risk with increasing deprivation. This may be due to chance or due to the lack of information on exact time of hospital admission and death in our data.

Our results in the present study are also consistent with studies of short-term exposures conducted on other sources of environmental noise, though the effect size is smaller. A study in Madrid found an increased risk in CVD deaths per 1 dB increase in road traffic L_{eqn} for both younger (OR = 1.033, 95% CI 1.017–1.049) and older (OR = 1.050, 95% CI 1.012–1.056) people (Recio et al., 2016). A subsequent paper from Madrid also found an association between both daytime and night-time urban noise and cardiovascular death, also with a stronger effect in people over 65 years (Tobías et al., 2015). This suggests a similar mechanism for the relationship between different sources of environmental noise, particularly at night, and cardiovascular risk.

4.1. Strengths

This study included virtually all hospitalisations and deaths due to cardiovascular disease in a population of 6.3 million people over five years, providing adequate statistical power to detect an effect. The use of modelled noise data at the postcode level and conducting individual-level analyses helped avoid ecological bias and allowed us to explore effect modification at the individual level. The case-crossover design controlled for important measured and unmeasured confounders including lifestyle factors, ethnicity, and age by design. Distinguishing between the effects of noise at specific periods of time throughout the day, evening and night provided supporting evidence for certain biological mechanisms observed in previous studies. Experimental studies have found that higher levels of night-time aircraft noise can increase blood pressure, decrease quality of sleep, and decrease endothelial function, all of which are associated with cardiovascular disease (Schmidt et al., 2013; Schmidt et al., 2015; Münzel et al., 2018). Lastly, using UK postcode-level exposure data ensures the risk of spatial misclassification is small.

4.2. Limitations

The limitations of this study include potential exposure misclassification caused by several data generalisations in the AEDT noise model:

Atmospheric pressure, relative humidity and wind speed are set as meteorological constants that reflect the 30-year average at the airport. These simplifications are a limit of current modelling practices, when estimating sub-annual average aircraft noise exposures.

The headwind speed is maintained at 8 knots, during the entire period of each operation. This may result in inaccurate aircraft performance parameters such as climb and speed, which are related to the location and intensity of noise.

Wind speed or direction are not used by the AEDT sound propagation calculations (i.e., a uniform dispersion in all directions is assumed at all times).

The terrain model only accounts for elevation of natural landscapes, and not man-made features. Therefore, containment and sheltering effects in urban locations are ignored.

The computational demands for creating sub-daily exposure surfaces:

Limited the spatial resolution of the model outputs, returning a coarser exposure gradient.

Dryer air temperatures were summarised into profiles that accounted for season and time of day across the 5-year study period. Therefore, the influence of unusual temperature events on sound propagation is not accounted for.

However, the AEDT model has demonstrated good agreement with actual aircraft noise measurements when modelling average estimates, with slight overestimation in departure flights and slight underestimation in arrivals, suggesting exposure misclassification due to the model should be minimal. Misclassification bias may also be introduced due to individuals moving outside of the postcode to which their exposure has been assigned at different periods throughout the day. We expect less exposure misclassification in the evening and night-time hours because individuals are more likely to be at their postcode of residence during these times. We also expect less misclassification among older individuals throughout the day and night, as they are less likely to travel away from home for work or school during the day. This may partially explain why effect estimates are highest during evening and night-time hours, and among individuals over the age of 65 years. Lastly, exposure misclassification may be introduced because data on exact time of admission and death were not available, and we were therefore unable to define the precise window of exposure before an event occurs. We therefore used exposure data from one day prior to the date of the event (rather than on day of event) to ensure the defined exposure window had truly preceded the CVD event.

5. Conclusion

These findings provide potential evidence that aircraft noise in the late evening and night-time may be associated with increased risk of cardiovascular hospitalisations and deaths in the population living within the Heathrow Airport noise contour. This is consistent with a mechanism of action via disturbed sleep and has implications for developing respite measures for the communities situated near busy airports. Further research into these potential respite mechanisms and behavioural interventions, including runway rotation and noise insulation initiatives, is needed to understand how best to translate the findings from this study into action.

CRediT authorship contribution statement

Nicole Itzkowitz: Formal analysis, Writing - original draft. **Xiangpu Gong:** Data curation. **Glory Atilola:** Formal analysis. **Garyfallos Konstantinousid:** Formal analysis. **Calvin Jephcote:** Data curation, Writing - review & editing. **John Gulliver:** Conceptualization, Data curation. **Anna L Hansell:** Conceptualization, Funding acquisition, Writing - review & editing. **Marta Blangiardo:** Conceptualization, Methodology, Supervision, Writing - review & editing.

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.

Data availability

The aircraft noise exposure data are available to other academic researchers on request.

Health outcomes and individual confounder data were obtained from the Small Area Health Statistics Unit (SAHSU), which does not have permission to supply data to third parties. The data can be requested through the Office for National Statistics (https://www.ons.gov.uk/) and NHS Digital https://digital.nhs.uk/data.

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 The Hospital Episode Statistics data were obtained from NHS Digital. The mortality, and population data used in this study were supplied by the Office for National Statistics (ONS), derived from the national mortality registrations and the Census.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envint.2023.108016.

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