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Title: The role of noise annoyance and noise sensitivity in the effect of aircraft noise on self-reported health: the results of the DEBATS longitudinal study in France

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Abstract

Background: Transportation noise seems to impair self-reported health status (SRHS). However, only a few studies have considered the role of noise annoyance and noise sensitivity in this deleterious effect. This study aims investigating mediator and moderator roles of noise annoyance and noise sensitivity.

Methods: The DEBATS longitudinal study included in 2013, 1,244 participants aged over 18 years and living around three French airports. These participants were followed up in 2015 and 2017. They self-reported their perceived health status, aircraft noise annoyance, and their noise sensitivity *via* a questionnaire during the three visits. Noise maps were used to estimate aircraft noise levels at the facade of participants' residence. Generalized linear mixed models with a random intercept at the participant level were used.

Results: Aircraft noise levels were associated with severe annoyance. Severe annoyance tent to be associated, with impaired SRHS. Aircraft noise levels were associated with impaired SHRS only in men (OR = 1.47, 95% CI = (1.02, 2.11), for a 10-dBA L_{den} increase in aircraft noise levels) with a weaker association adjusted for annoyance (OR = 1.36, 95% CI = (0.94, 1.98)). The association was stronger in men who reported high noise sensitivity (OR = 1.84, 95% CI = (0.92, 3.70), versus OR = 1.39, 95% CI = (0.90, 2.14), for men who were not highly sensitive to noise).

Conclusion: From our results, the deleterious effect of aircraft noise on SRHS could be mediated by noise annoyance and moderated by noise sensitivity. Further studies using causal inference methods are needed for identifying causal effect of exposure, mediator and moderator.

Key words: epidemiology, aircraft noise exposure, general health, self-reported health, mediation analysis.

Introduction

According to recent systematic WHO reviews, transportation noise (road traffic noise, aircraft noise and railway noise) exposure is associated with impaired subjective health (self-reported health status (SRHS), general health, wellbeing, mental health) and impaired quality of life [1–3]. However, only few studies have investigated the relationship between aircraft noise and impaired SRHS in adult populations. SRHS is often used in health research as a predictor of mortality and overall health status [4]. SRHS is defined as a subjective measure of health in which an individual considers all aspects of their health [4,5]. A study conducted in the USA in 2000 showed that residents exposed to aircraft noise had worse general health than unexposed residents [6]. This result is consistent with those of two other cross-sectional studies in which increased aircraft noise levels were found to be associated with impaired SRHS [7,8]. The study conducted by Schreckenberg et al. in Germany in 2010 also showed that higher aircraft noise levels were associated with poorer quality of life, such as poor vitality and poor physical health [9]. A longitudinal study in Switzerland in 2020 found no association between aircraft noise levels and quality of life [10]. These results regarding aircraft noise seem to confirm those obtained with road traffic noise [11–14] and those with all transportation noise combined [15,16].

It has been suggested that observed health effects of noise could be partly mediated by other factors related to noise exposure. A mediator in the relationship between noise levels and health is an intermediate variable through which noise affects health. Noise annoyance has been found to mediate the health effects of noise such as impaired SHRS or quality of life [9,12,14], depression[17], mental well-being[18], and potentially the incidence of hypertension[19,20]. Indeed, in the WHO systematic review on environmental noise annoyance, a direct association was found between noise levels and noise annoyance [1], which in turn negatively affects health.

Noise sensitivity is considered an aspect of personality that increases the degree of reactivity to noise, whatever the noise level [21]. Noise sensitivity seems to be the most important non-acoustic factor influencing noise annoyance [21,22]. Previous studies showed an association between noise sensitivity and impaired SRHS or health-related quality of life [10,16,23,24]. The more noise sensitive participants were, the more they reported impaired perceived health. It has also been suggested that noise sensitivity may moderate the health effect of noise [8,24–26]. In other words, the association between noise levels and health issues may be higher in people who are highly sensitive to noise compared to those who are not. In a study conducted in Japan in 2009, Kishikawa et al. found that road traffic noise exposure was associated with poorer self-reported health in the noise-sensitive group, while no association was observed in the non-sensitive group [27].

Only few studies have investigated the relationship between aircraft noise and impaired SRHS, and even fewer have studied the mediating and moderating roles of aircraft noise annoyance and noise sensitivity in this association. Furthermore, all of the aforementioned studies that investigate these roles were cross-sectional studies.

In this context of lack of longitudinal studies, we propose to explore the relationship between aircraft noise exposure and impaired SRHS by considering the mediating and moderating roles of aircraft noise annoyance and noise sensitivity using data collected in the DEBATS longitudinal study conducted between 2013 and 2017 near three French airports.

Methods

Study population

The DEBATS (Discussion on the health effects of aircraft noise) study investigated the health effect of aircraft noise exposure. Participants were residents living near one of three major French airports (Paris-Charles de Gaulle, Lyon Saint-Exupéry, and Toulouse-Blagnac). They were randomly selected from a phone directory after stratification on four aircraft noise levels in terms of L_{den}: <50, 50 to 54, 55 to 59 and ≥ 60 dBA. L_{den} is the day-evening-night noise level.

It is a descriptor of noise level based on energy equivalent noise level over a whole day [6.00 – 18.00] with a penalty of 10 dBA for night time noise [in France: 22.00 - 6.00] and an additional penalty of 5 dBA for evening noise [in France: 18.00 - 22.00][28]. This indicator is used by the European Union for environmental noise management [29]. It is therefore one of the most used in epidemiological studies of the health effects of noise.

Participants were older than 18 years at inclusion and had lived in their dwelling for at least 1 year and for at least six months during the year. They completed a questionnaire administered during a face-to-face interview with an investigator at their home at inclusion in 2013, then at the first follow-up in 2015, and finally at the second follow-up in 2017. Demographic (sex, age, marital status), and socio-economic characteristics of the participants as well as information on their lifestyle (alcohol consumption, smoking, physical activity) were collected. They were also asked to assess their health status, their annoyance due to aircraft noise, and their sensitivity to noise.

Aircraft noise levels

Noise maps were used to estimate aircraft noise levels outside the participants' residence by linking noise levels to participants' addresses through a geographic information system. These noise maps were produced by Paris Airports and the French Civil Aviation Authority with the Integrated Noise Model [30], which allows the calculation of aircraft noise levels near airports. In our study, participants' exposure to aircraft noise was characterized using two energetic indicators: L_{den} and L_{Aeq24h}. L_{Aeq24h} is an unweighted indicator which corresponds to the energy equivalent noise level over a 24-hour period.

Self-reported health status

Participants self-assessed their health status by answering the following question: "In general, would you say that your health is excellent, good, fair, or poor?" For statistical analyses, this variable was dichotomized: participants who reported fair or poor health were compared to those who reported good or excellent health (reference).

Aircraft noise annoyance

Participants' aircraft noise annoyance was assessed with the following question recommended by the International Commission on the Biological Effects of Noise (ICBEN) [31]: "Thinking about the last 12 months, when you are here at home, how much does aircraft noise bother, disturb, or annoy you: extremely, very, moderately, slightly or not at all?". Following ISO/TS recommendations[32], we considered participants reporting "extremely" or "very" to this question to be highly annoyed by aircraft noise (severe annoyance), and those reporting "moderately", "slightly" or "not at all" to be not highly annoyed.

Noise sensitivity

Participants rated their sensitivity to noise by answering the following single question: "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?" We considered participants who reported being more or much more sensitive than people around them to be highly sensitive to noise, and those who reported being much less sensitive than, or less sensitive than, or as sensitive as people around them to be not highly sensitive to noise. Because noise sensitivity can be considered a stable personality trait [33,34], only the level of noise sensitivity reported in 2013 at study inclusion was considered in the statistical analyses.

Confounding factors

Factors associated with impaired SRHS in univariate analyses with a $p<=0.2$ and that modified the association between aircraft noise and impaired SRHS were considered as potential confounders The following variables were included in the models as confounders of the association between aircraft noise levels and impaired SRHS: age (in six categories: 18 to 34, 35 to 44, 45 to 54, 55 to 64, 65 to 74 and ≥ 75 years old), the number of people in the household (in four categories: 1, 2, 3 , more than 4 people), occupational activity (yes/no), income per consumption unit (CU) (in three categories: < 1550, 1550 to 2750 and ≥ 2750 euros per month; according to the definition of CU by Insee [35], the first adult in the household counts for 1 CU, other persons of 14 years or older count 0.5 CU and children under 14 years count for 0.3 CU), country of birth (France versus other country), and smoking habits (in three categories : never smoke, current smoker, smoker). Others variables such as sleep duration, alcohol consumption and education were also found in previous studies as potential confounders. But, in our study, these variables were not included in the final model because they did not modify the association between aircraft noise and impaired SRHS in the multivariate analysis including other confounders listed above.

Statistical analysis

The Pearson khi2 test (for categorical variables) and the Friedman test (for continuous variables) were used to compare the distributions of variables over the three visits.

To address the fact that the data analyzed came from the same participants at all three time points of the DEBATS longitudinal study (inclusion, first and second follow-up), generalized linear mixed models with a random intercept at the participants level were used (Glimmix procedure in SAS software). All analyses were conducted separately for men and women. Indeed, previous studies have shown that women in France tend to judge their health more severely than men [36].

Sensitivity analyses were conducted to assess the robustness of the results: 1) the study population was limited to participants who participated in all three visits, 2) the study population was limited to participants who had resided in their dwelling for more than 5 years at inclusion and who had not moved during the two follow-ups if they had not been lost to follow-up, 3) the analyses were conducted considering noise levels in two categories in terms of L_{den}: ≥ 50 dBA versus < 50 dBA. The results of these sensitivity analyses are reported in the online supplemental tables.

The mediating role of aircraft noise annoyance in the association between aircraft noise levels and impaired SRHS was investigated according to Baron and Kenny's recommendations [37], by comparing the results from the following three regression models that include confounding factors. The M1 model evaluated the association between aircraft noise levels and aircraft noise annoyance. The M2 model evaluated the association between aircraft noise annoyance and impaired SRHS after controlling for aircraft noise levels. The M3 model evaluated the association between aircraft noise levels and impaired SRHS. According to Baron and Kenny's recommendations, the mediation role hypothesis was validated if, i) aircraft noise levels were associated with the potential mediator (ie aircraft noise annoyance) (M1), ii) the potential mediator (ie aircraft noise annoyance) was associated with impaired SRHS after controlling for aircraft noise levels (M2) , and iii) the association between aircraft noise levels and impaired SRHS was weaker after controlling for the mediator (ie aircraft noise annoyance)(i.e. weaker in M2 than in M3).

We also evaluated the association between noise sensitivity and impaired SRHS after controlling for aircraft noise levels and all confounding factors (M4 model).The moderating role of aircraft noise annoyance and noise sensitivity in the relationship between aircraft noise levels and impaired SRHS was investigated by introducing an interaction term between aircraft noise levels and the potential moderator (aircraft noise annoyance or noise sensitivity) in the M2 model and in the M4 model respectively (M5 Model).

The associations between aircraft noise levels and aircraft noise annoyance or between aircraft noise levels and impaired SRHS were evaluated for a 10 dBA increase in aircraft noise levels. The corresponding odds ratios (OR) will be noted OR_{10dBA}. Unless otherwise stated, only the

ORs for L_{den} are reported in the text. The linearity of the relationship between aircraft noise levels and impaired SRHS was tested using the cubic spline function [38]. All statistical analyses were conducted using SAS software version 9.4. We considered 5% as the threshold for statistical significance.

Results

Table 1 shows the study population characteristics for the three visits. Among the 4,202 individuals eligible for the study, 1,244 (695 women and 549 men) agreed to participate and were included in the study at baseline (T0). Of these, 992 (549 women and 443 men) participated in the first follow-up (T2) in 2015 (80%) and 811 (438 women and 373 men) participated in the second follow-up (T4) in 2017 (82%).

For all three visits, aircraft noise levels ranged from 44 to 67 dBA in terms of L_{den}, for both men and women. The distributions of aircraft noise levels were relatively similar across the three visits for both men and women. The proportion of men/women reporting impaired SRHS was similar for all three visits (around 15%).

The proportion of participants who reported being highly annoyed by aircraft noise was similar for men and women at T0 (18%). This proportion increased over the two follow-ups (T2 and T4) for both men and women, and was slightly higher for women. Women were more likely to report being highly sensitive to noise than men. This proportion remained stable over time: about 34% for women and 25% for men. The proportion of participants who reported an income per consumption unit below 1,550 euros per month decreased from about 43% at baseline to 32% at T4, for women, and from about 37% at baseline to 25 % at T4 for men. The distribution of age, number of people in the household, and smoking habits changed slightly over time for both men and women.

Table 1: Characteristics of the study population for the three visits (T0, T2 and T4)

	Baseline (T0)				First follow-up (T2)				Second follow-up (T4)				p-value[1]	p-value[1]
	Women		Men		Women		Men		Women		Men		Women	Men
N	695		549		549		443		438		373			
Noise levels in L_{den} (dBA)													**< 0.01**	**< 0.01**
Quantiles (5% ; 50% ; 95%)	(44 ; 55 ; 63)		(44 ; 53 ; 62)		(44 ; 54 ; 62)		(44 ; 52 ; 62)		(44 ; 54 ; 62)		(44 ; 52 ; 62)			
SRHS[2]													0.29	0.98
Fair/poor	109	(15.7)	81	(14.8)	88	(16.0)	61	(13.8)	63	(14.4)	49	(13.1)		
Good/excellent	586	(84.3)	466	(85.2)	461	(84.0)	382	(86.2)	375	(85.6)	324	(86.9)		
Aircraft noise annoyance[2]													**< 0.01**	**0.02**
Highly annoyed	126	(18.1)	99	(18.1)	145	(26.4)	103	(23.3)	120	(27.4)	81	(21.7)		
Not highly annoyed	569	(81.9)	448	(81.9)	404	(73.6)	340	(76.7)	318	(72.6)	292	(78.3)		
Noise sensitivity[2]													0.55	0.73
Highly noise sensitive	234	(33.8)	135	(25.0)	197	(35.9)	112	(25.3)	147	(33.6)	96	(25.7)		
Not highly noise sensitive	459	(66.2)	405	(75.0)	352	(64.1)	331	(74.7)	291	(66.4)	277	(74.3)		
Age (years)[2]													**< 0.01**	**< 0.01**
18-34	152	(21.9)	74	(13.5)	79	(14.4)	46	(10.4)	45	(10.3)	22	(5.9)		
35-44	130	(18.7)	106	(19.4)	100	(18.2)	78	(17.6)	62	(14.2)	60	(16.1)		
45-54	133	(19.1)	132	(24.1)	116	(21.1)	106	(23.9)	100	(22.8)	101	(27.1)		
55-64	145	(20.9)	115	(21.0)	128	(23.3)	95	(21.4)	105	(24.0)	72	(19.3)		
65-74	90	(12.9)	94	(17.2)	82	(14.9)	94	(21.2)	80	(18.3)	90	(24.1)		
≥ 75	45	(6.5)	26	(4.8)	44	(8.0)	24	(5.4)	46	(10.5)	28	(7.5)		
Country of birth[2]													0.31	0.94
Other country	100	(14.4)	89	(16.3)	73	(13.3)	71	(16.0)	53	(12.1)	58	(15.5)		
France	595	(85.6)	458	(83.7)	476	(86.7)	372	(84.0)	385	(87.9)	315	(84.5)		
Occupational activity[2]													0.81	0.45
Yes	410	(59.0)	335	(61.0)	321	(58.5)	256	(57.8)	250	(57.1)	214	(57.4)		
No	285	(41.0)	214	(39.0)	228	(41.5)	187	(42.2)	188	(42.9)	159	(42.3)		
Income per consumption unit													**0.02**	**0.02**
< 1550 euros per month	297	(42.7)	201	(36.6)	208	(37.9)	147	(33.2)	142	(32.4)	95	(25.5)		
1550 to 2750 euros per month	297	(42.7)	235	(42.8)	264	(48.1)	218	(49.2)	238	(54.3)	202	(54.2)		
> 2750 euros per month	101	(14.5)	113	(20.6)	77	(14.0)	78	(17.6)	58	(13.2)	76	(20.4)		
Smoking habits[2]													0.07	0.86
Ex-smoker	149	(21.4)	181	(33.1)	107	(19.5)	146	(33.0)	94	(21.5)	130	(34.9)		
Current smoker	167	(24.0)	120	(21.9)	125	(22.8)	93	(21.0)	89	(20.3)	68	(18.2)		
Never smoke	379	(54.5)	246	(45.0)	317	(57.7)	204	(46.0)	255	(58.2)	175	(46.9)		
Number of people in the household [2]													**< 0.01**	0.09
1 person	158	(22.7)	102	(18.7)	123	(22.4)	73	(16.5)	109	(24.9)	57	(15.3)		
2 persons	239	(34.4)	197	(36.0)	193	(35.2)	176	(39.7)	146	(33.3)	163	(43.7)		
3 persons	109	(15.7)	98	(17.9)	95	(17.3)	80	(18.1)	80	(18.3)	57	(15.3)		
≥ 4 persons	189	(27.2)	150	(27.4)	138	(25.1)	114	(25.7)	103	(23.5)	96	(25.7)		

[1] The *Pearson khi2 test for categorial variables and the Friedman test for continuous variables were used for comparing characteristics during the three visits for both men and women*

[2] *n (%)*

Table 2 presents the adjusted OR and their 95% confidence intervals (95% CI) for the three mediation analysis models described in the methods section. Aircraft noise levels were associated with severe annoyance due to aircraft noise, for both, men (OR_{10dBA} = 2.78, 95% CI = (1.97, 3.92), M1 model) and women (OR_{10dBA} = 2.69, 95% CI = (2.01, 3.61), M1 model).

Severe annoyance due to aircraft noise tent to be associated with impaired SRHS (OR = 1.57, 95% CI = (0.98, 2.44), M2 model for men and OR = 1.35, 95% CI = (0.92, 1.98), M2 model for women).

No association was observed between aircraft noise levels and impaired SHRS for women (OR_{10dBA} = 1.00, 95% CI = 0.73, 1.37, M3 model). Aircraft noise levels were associated with impaired SHRS only in men (OR_{10dBA} = 1.47, 95% CI = (1.02, 2.11), M3 model). When aircraft noise annoyance and aircraft noise levels were both included in the M2 model, the OR for the association between aircraft noise levels and impaired SRHS decreased compared to the OR in model M3 (OR_{10dBA} = 1.36, 95% CI = (0.94, 1.98), M2 model).

Table 2: Adjusted odds ratios for the association between aircraft noise levels and aircraft noise annoyance, between aircraft noise annoyance and impaired SRHS, and between aircraft noise levels and impaired SRHS

		Women			Men		
Outcome		OR	95% CI		OR	95% CI	
M1 model							
Aircraft noise annoyance[2]	L_{Aeq24h}[1]	**2.90**	**2.11**	**3.97**	**3.10**	**2.12**	**4.52**
	L_{den}[1]	**2.69**	**2.01**	**3.61**	**2.78**	**1.97**	**3.92**
M2 model							
SRHS[3]	L_{Aeq24h}[1]	0.93	0.65	1.34	1.45	0.96	2.21
	Aircraft noise annoyance	1.35	0.92	1.98	1.56	0.97	2.52
	L_{den}[1]	0.95	0.69	1.30	1.36	0.94	1.98
	Aircraft noise annoyance	1.35	0.92	1.98	1.57	0.98	2.44
M3 model							
SRHS[3]	L_{Aeq24h}[1]	0.99	0.70	1.40	**1.58**	**1.05**	**2.37**
	L_{den}[1]	1.00	0.73	1.37	**1.47**	**1.02**	**2.11**

[1] For a 10 dBA increase in aircraft noise levels
[2] Severe aircraft noise annoyance was modeled
[3] Impaired SRHS was modeled
M1 model was adjusted for age, number of people in the household, occupational activity, economic dependency on airport activities, use of the noise source, fear of a plane crash, homeownership, type of housing, residential satisfaction, source- and authority-related attitudes, and noise sensitivity

Noise sensitivity was associated with impaired SRHS both in men (OR = 1.68, 9)5% CI = (1.00, 2.80), M4 model) and in women (OR = 1.48, 95% CI = (1.00, 2.17), M4 model) (results not shown).

Table 3 shows the results of the M5 model including an interaction term between aircraft noise levels and aircraft annoyance (left), and an interaction term between aircraft noise levels and noise sensitivity (right), for men and women separately. No association was observed between aircraft noise levels and impaired SRHS for either highly annoyed or not highly annoyed men. But for both, the ORs were relatively greater than 1 and very similar (OR_{10dBA} = 1.37, 95% CI = (0.64, 2.91), for men who were highly annoyed and OR_{10dBA} = 1.36, 95% CI = (0.89, 2.07), for men who were not highly annoyed). For women, no association was observed between aircraft noise levels and impaired SRHS, for either highly annoyed or not highly annoyed women.

Aircraft noise levels seems to be associated with impaired SHRS. This association, even if it was not significant, was slightly higher for men who reported high noise sensitivity (OR_{10dBA} = 1.84, 95% CI = (0.92, 3.70), versus OR_{10dBA} = 1.39, 95% CI = (0.90, 2.14), for men who were not highly sensitive to noise) even in absence of interaction (p = 0.50). For women, aircraft noise levels were not associated with impaired SHRS and there was no interaction between aircraft noise levels and noise sensitivity (p = 0.74).

Similar results were observed in sensitivity analyses when the study population was limited to participants who participated in all three visits, or to participants who had resided in their dwelling for more than 5 years at inclusion and who had not moved during the two follow-ups (online supplemental Table 1 and Table 2). When the analyses were conducted considering noise levels in two categories in terms of L_{den} (≥ 50 dBA versus < 50 dBA), aircraft noise levels were associated with impaired SRHS in men (OR = 1.84, 95% CI = (1.11, 3.06), M3 model) (online supplemental Table 3). When aircraft noise annoyance and aircraft noise levels were both included in the M2 model, the OR for the association between aircraft noise levels and impaired SRHS decreased (OR = 1.59, 95% CI = (0.99, 2.54), M2 model) (online supplemental Table 3). The association between aircraft noise levels and impaired SRHS was higher for men who were highly annoyed (OR = 2.71, 95% CI = (1.43, 5.14)) than for those who were not (OR = 1.64, 95% CI = (0.94, 2.85), M5 model), compared to the same reference group (men who were exposed to aircraft noise levels below 50 dBA and not highly annoyed) (online supplemental Table 4). The association between aircraft noise levels and impaired SRHS was also higher for men and women who were highly noise sensitive than for those who were not, compared to the same reference group (men or women who were exposed to aircraft noise levels below 50 dBA and not highly noise sensitive) (OR =3.00, 95% CI = (1.46, 6.18) for men who were highly noise sensitive and OR = 1.58, 95% CI = (0.87, 2.87) for men who were not; OR = 1.47, 95% CI = (0.81, 2.66) for women who were highly noise sensitive and OR = 1.05, 95% CI = (0.60, 1.81) for women who were not, M5 model) (online supplemental Table 4).

Table 3: Adjusted odds ratios for impaired SRHS in relation to aircraft noise levels in highly annoyed/noise-sensitive men and women compared to those who are not (M5 model)

		Not highly annoyed			Highly annoyed				Not highly noise-sensitive			Highly noise-sensitive			
		OR_{10dBA}	95% CI		OR_{10dBA}	95% CI		p-value[2]	OR_{10dBA}	95% CI		OR_{10dBA}	95% CI		p-value[2]
Women	N§	569/404/318			126/145/120				459/352/291			234/197/147			
	L_{Aeq24h}[1]	0.87	0.58	1.31	1.13	0.59	2.18	0.49	1.06	0.68	1.65	0.92	0.52	1.63	0.70
	L_{den}[1]	0.91	0.64	1.51	1.06	0.57	1.31	0.67	1.05	0.70	1.56	0.94	0.56	1.57	0.74
Men	N§	448/340/292			99/103/81				405/331/277			135/112/96			
	L_{Aeq24h}[1]	1.45	0.90	2.34	1.45	0.65	3.23	0.99	1.39	0.86	2.26	**2.31**	**1.06**	**5.03**	0.28
	L_{den}[1]	1.36	0.89	2.07	1.37	0.64	2.91	0.99	1.39	0.90	2.14	1.84	0.92	3.70	0.50

[1]*For a 10-dBA increase in aircraft noise levels*
[2] *p-value of interaction*
§ *N for T0/T2/T4*
All models were adjusted for age, number of people in the household, occupational activity, income per consumer unit, country of birth, and smoking habits

Discussion

This study is one of only a few longitudinal studies to investigate the relationship between aircraft noise levels and impaired SHRS. In addition, it is among the few studies to assess the role of aircraft noise annoyance and noise sensitivity in this association.

Aircraft noise levels were associated with aircraft noise annoyance (OR_{10dBA} = 2.78, 95% CI = (1.97, 3.92), M1 model, in men and OR_{10dBA} = 2.69, 95% CI = (2.01, 3.61), M1 model in women). This result is in line with the exposure–response curve for the percentage of people highly annoyed by aircraft noise in cross-sectional analyses previously conducted by Lefèvre et al. using only participant information collected at inclusion in the DEBATS study in 2013 [39]. The percentage of people highly annoyed by aircraft noise was also found as an increasing function of aircraft noise levels in the European Union standard curve [29] and in the WHO systematic review on environmental noise and annoyance [1].

This study found that aircraft noise annoyance was associated with impaired SRHS (OR = 1.57, 95% CI = (0.98, 2.44), in men and OR = 1.35, 95% CI = (0.92, 1.98), in women, M2 model, Table 2). This result is consistent with the one of a study investigating the association between severe aircraft annoyance and impaired health-related quality of life near Frankfurt airport in 2010: people highly annoyed by aircraft noise had lower vitality (OR_{10dBA}= 1.25; 95% CI: (1.13, 1.37)) and physical health scores (OR_{10dBA} =1.13; 95% CI: (1.01, 1.26)) than those who were not highly annoyed [9]. In addition, it was also consistent with those found by two cross-sectional studies that examined the association between road traffic noise annoyance and impaired SRHS or quality of life [12,14].

In this study, aircraft noise levels were associated with impaired SRHS in men (OR_{10dBA} = 1.47, 95% CI = (1.02, 2.11), M3 model). This result is consistent with those of the few cross-sectional studies investigating the association between severe aircraft annoyance and impaired general health, impaired SRHS or health-related quality of life [6,7,9]. The only one that did not find an association was also the only longitudinal study on the subject (Swiss cohort study SALPADIA) [10]. The gender difference observed in the present study was also found in some previous studies investigating the association between road traffic noise levels and impaired self-rated health [2,13]. The authors suggested that this gender difference may be due to a higher threshold for reporting poor health in men than in women. Indeed, some studies have shown that self-rated health may be a better predictor of severe health outcomes, such as mortality, in men than in women [40]. In the present study, the proportion of participants reporting poor health was similar for men and women. In addition, the distributions of aircraft noise levels were also similar for men and women. Further research is needed to better understand the observed gender differences.

After controlling for aircraft noise annoyance, the association between aircraft noise levels and impaired SRHS in men decreased. This result suggests that this effect would be partly due to aircraft noise annoyance and thus confirms the mediating role of aircraft noise annoyance in the relationship between aircraft noise levels and impaired SRHS [9,12,14].

There was no interaction between aircraft noise levels and aircraft noise annoyance ($p > 0.05$). The association between aircraft noise levels and impaired SRHS was similar in men who were highly annoyed and in those who were not. When the analyses were conducted considering noise levels in two categories in terms of L_{den} ($\geq$ 50 dBA versus < 50 dBA), the effect of aircraft noise on impaired SRHS was higher in people who were highly annoyed than in those who were not. This result suggests a moderated mediation of aircraft noise annoyance in the relationship between aircraft noise levels and impaired SRHS[41,42].

Noise sensitivity was associated with impaired SRHS: the more noise sensitive people were, the more they reported impaired SRHS. This finding is in line with the results of studies that have investigated this association, although the methods for assessing noise sensitivity were different[10,16,23,24]. Accounting for an interaction between aircraft noise levels and noise sensitivity in the models showed a higher association between aircraft noise levels and impaired SRHS for men who were highly noise-sensitive compared to those who were not. This was also the case when the analyses were conducted considering noise levels in two categories in terms of L_{den} (≥ 50 dBA versus < 50 dBA). This result suggests and confirms a moderating role of noise sensitivity in the relationship between aircraft noise levels and impaired SRHS [8,24–27]. The lack of interaction in this case could be due to an insufficient number of participants in each category, the interaction test being very sensitive to the size of the study samples.

The main strength of our study is its longitudinal design. Indeed, it involved information collected for the same participants on three successive times (at inclusion and then at two follow-ups), considering the different variations of the variables over time. Furthermore, the results of these longitudinal analyses strengthened the results previously obtained from a cross-sectional analysis using only inclusion data [8]. All but one [10] of the epidemiological studies that have investigated the relationship between noise levels, noise annoyance, noise sensitivity and perceived health status were cross-sectional studies. Potential bias related to lost to follow-up that is a major problem in longitudinal studies is very unlikely in the present study. Indeed, the rate of loss to follow-up was relatively low, with 65% of the 1244 recruited participants attending the last follow-up. Moreover, the results of a sensitivity analysis limiting the study population to the 811 participants who participated in all three visits remained relatively similar (online supplemental Table 4). Finally, baseline characteristics of participants lost to follow-up were similar to those of participants who remained in the study (results not shown).

Selection bias cannot be ruled out in this study but seems limited. Indeed, in the DEBATS study, the demographic characteristics of 40% of non-participants who completed a short questionnaire and those of participants were relatively similar [43]. However, these non-participants were probably not representative of all non-participants. In addition, people who believe they have a poor general health or who consider themselves sensitive to noise or potentially annoyed if exposed to high noise levels would avoid living in areas with high noise levels, especially near airports. Under these conditions, the results may be biased because of the under-representation of these people in noise-exposed areas around airports leading to an underestimation of the real associations observed in the present study.

A main weakness of the study is that the assessment of noise annoyance and noise sensitivity was based on a single question, which may not be specific enough, and could lead to misclassification. It has been shown that a single question does not adequately capture noise sensitivity in its various aspects [27,44]. The use of items with multiple questions related to noise sensitive seems to be more accurate (e.g., the Weinstein noise sensitivity scale [45] or the NoiSeQ [46]). In addition, an international standard was used for the annoyance assessment using a single item, with annoyance rated on a 5-point verbal scale. The fact that this is a standard does not prevent the annoyance assessment from having the same psychometric weakness as discussed for noise sensitivity. However, multi-question questionnaires were not introduced into the DEBATS questionnaire because it was already nearly an hour long and consideration of noise sensitivity in particular was not part of the original primary objectives of the study.

Exposure misclassification also cannot be ruled out in this study. Indeed, participants' noise exposure was estimated at home, outdoors. No information was available on their exposure to aircraft noise inside their home or during the day when they were outside their home, including at their workplace. This lack of information could have led to an underestimation of the association between aircraft noise exposure and impaired SRHS. It was not possible to estimate aircraft noise exposure indoors for the 1,244 participants in the longitudinal study, but , information was collected regarding the type of housing and the presence of windows or roof insulation. However, since these variables were not associated with either a degradation of SRHS or severe annoyance, they were not included in the final model. Finally, acoustic measurements were also performed for one week outside and inside the bedroom of a subsample of 112 participants in the DEBATS longitudinal study. The average relative difference between outdoor noise level estimates based on the noise maps produced by the Direction Générale de l'Aviation Civile using the INM model [30] and those calculated from the measurements was only 5% and the 95th percentile of that difference was 11%[47].

Another limitation concerns the standard statistical methods (the GLMM and the Baron & Kenny's approach) used in this study to explore mediation and moderation. They may be insufficient to control for all confounding factors, thus leading to confounding bias. Both annoyance and sensitivity to noise were found to be associated with self-reported health impairment. As mentioned in previous studies [10,17,18]it is also conceivable that health status may influence future reactions to noise such as noise annoyance and noise sensitivity [10]. This temporality of noise exposure, mediator/moderator (noise annoyance and noise sensitivty), and impaired SRHS was not considered with the standard method used, which may lead to bias and prevent a causal interpretation of the observed association. Causal inferences methods such as marginal structural models [48,49] are thus needed for identifying causal effect of exposure, mediator and moderator.

Conclusion

With its longitudinal design, this study confirms the mediating role of aircraft noise annoyance and the moderating role of noise sensitivity in the relationship between aircraft noise levels and impaired SRHS. These findings strengthen those of the few cross-sectional studies that have explored the association between transportation noise exposure and subjective health outcomes. For future research, we suggest the use of causal inference methods to better control for confounding factors in order to perform a causal interpretation of the results.

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Competing interests

The authors declare that they have no competing interests.

Authors' Contributions

Anne-Sophie Evrard (ASE) and Bernard (BL) conceived and designed the study. ASE conducted the study. Minon'tsikpo kossi Kodji (MK) and Lise Giorgis Allemand (LGA) did data preparation. MK performed the statistical analyses, supervised by ASE, Émilie Lanoy (EL) and LGA. The analyses were interpreted by MK with EL, LGA and ASE. MK and ASE drafted the initial report. All co-authors revised the report and approved the final version. ASE is responsible for the overall content as the guarantor of this paper.

Ethics approval and consent to participate

Two national authorities in France, the French Advisory Committee for Data Processing in Health Research (CCTIRS 11-405) and the French National Commission for Data Protection and the Liberties approved the present study (DR 2012-361).

The participants signed and returned an informed consent by mail.

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Supplemental Table 1: Adjusted odds ratios for the association between aircraft noise levels and impaired SRHS in participants who participated in the three visits, and in those who had resided in their dwelling for more than 5 years at inclusion and had not moved during the two follow-ups

		Participants who participated in the three visits						Participants who had resided in their dwelling for more than 5 years at inclusion and had not moved during the two follow-ups					
		Women			Men			Women			Men		
		(N=438)			(N=373)			(T0 : N=551 ; T2 : N=428 ; T4 : N=353)			(T0 : N=440 ; T2 : N=345 ; T4 : N=298)		
Outcome		OR	95% CI		OR	95% CI		OR	95% CI		OR	95% CI	
M1 model													
Aircraft noise annoyance[2]	L_{Aeq24h}[1]	**2.88**	**1.97**	**4.20**	**3.45**	**2.23**	**5.34**	**2.46**	**1.74**	**3.48**	**2.86**	**1.88**	**4.34**
	L_{den}[1]	**2.69**	**1.89**	**3.82**	**3.11**	**2.09**	**4.64**	**2.30**	**1.67**	**3.17**	**2.58**	**1.76**	**3.80**
M2 model													
SRHS[3]	L_{Aeq24h}[1]	1.01	0.65	1.58	1.53	0.93	2.52	0.92	0.61	1.38	**1.67**	**1.04**	**2.70**
	Aircraft noise annoyance	**1.56**	**1.00**	**2.43**	1.41	0.80	2.48	1.37	0.90	2.07	1.44	0.86	2.43
	L_{den}[1]	0.98	0.66	1.46	1.41	0.90	2.19	0.92	0.63	1.33	**1.62**	**1.05**	**2.50**
	Aircraft noise annoyance	**1.57**	**1.01**	**2.44**	1.42	0.81	2.51	1.37	0.90	2.07	1.44	0.85	2.43
M3 model													
SRHS[3]	L_{Aeq24h}[1]	1.11	0.72	1.72	**1.66**	**1.02**	**2.66**	0.98	0.66	1.46	**1.79**	**1.12**	**2.85**
	L_{den}[1]	1.06	0.72	1.58	1.50	0.98	2.31	0.97	0.68	1.40	**1.72**	**1.13**	**2.63**

[1] For a 10 dBA increase in aircraft noise levels
[2] Severe aircraft noise annoyance was modeled
[3] Impaired SRHS was modeled
M1 model was adjusted for age, number of people in the household, occupational activity, economic dependency on airport activities, use of the noise source, fear of a plane crash, homeownership, type of housing, residential satisfaction, source- and authority-related attitudes, and noise sensitivity
M2 and M3 models were adjusted for age, number of people in the household, occupational activity, income per consumer unit, country of birth, and smoking habits

Supplemental Table 2: Adjusted odds ratios for impaired SRHS in relation to aircraft noise levels in highly annoyed/noise-sensitive men and women compared to those who are not (M5 model) in participants who participated in the three visits, and in those who had resided in their dwelling for more than 5 years at inclusion and had not moved during the two follow-ups

		Not highly annoyed			**Highly annoyed**				**Not highly noise-sensitive**			**Highly noise-sensitive**			
		OR_{10dBA}	95% CI		OR_{10dBA}	95% CI		p-value[2]	OR_{10dBA}	95% CI		OR_{10dBA}	95% CI		p-value[2]
Participants who participated in the three visits															
Women	N	360			78				287			149			
	L_{Aeq24h}[1]	0.94	0.57	1.58	1.21	0.57	2.55	0.57	1.14	0.66	1.96	1.12	0.55	2.33	0.99
	L_{den}[1]	0.94	0.60	1.48	1.10	0.54	2.24	0.71	1.07	0.66	1.75	1.09	0.56	2.11	0.97
Men	N	305			68				282			88			
	L_{Aeq24h}[1]	1.46	0.83	2.56	1.80	0.68	4.72	0.71	1.44	0.82	2.54	2.34	0.92	5.96	0.39
	L_{den}[1]	1.34	0.82	2.20	1.68	0.66	4.24	0.67	1.40	0.85	2.32	1.82	0.78	4.25	0.60
Participants who had resided in their dwelling for more than 5 years at inclusion and had not moved during the two follow-ups															
Women	N[§]	447/303/249			104/125/104				362/279/235			187/147/116			
	L_{Aeq24h}[1]	0.86	0.54	1.38	1.07	0.54	2.15	0.59	1.09	0.65	1.81	0.86	0.45	1.65	0.58
	L_{den}[1]	0.86	0.58	1.35	1.03	0.53	1.98	0.69	1.05	0.66	1.67	0.89	0.50	1.61	0.67
Men	N[§]	352/254/226			88/91/72				331/263/229			103/78/66			
	L_{Aeq24h}[1]	1.69	0.98	2.92	1.62	0.67	3.91	0.93	1.61	0.93	2.77	**2.57**	**1.01**	**6.51**	0.39
	L_{den}[1]	1.62	0.99	2.65	1.62	0.70	3.74	0.99	1.66	1.01	2.73	2.12	0.91	4.96	0.62

[1]For a 10-dBA increase in aircraft noise levels
[2] p-value of interaction
[§] N for T0/T2/T4
All models were adjusted for age, number of people in the household, occupational activity, income per consumer unit, country of birth, and smoking habits

Supplemental Table 3: Adjusted odds ratios for the association between aircraft noise levels and aircraft noise annoyance, between aircraft noise annoyance and impaired SRHS, and between aircraft noise levels and impaired SRHS considering aircraft noise levels in two categories (< 50 dBA versus ≥ 50 dBA)

		Women			Men		
		OR	95% CI		OR	95% CI	
M1 model							
Aircraft noise annoyance[2]	L_{den}[1]	**3.09**	**2.00**	**4.78**	**2.82**	**1.76**	**4.54**
M2 model							
SRHS[3]	L_{den}[1]	0.92	0.60	1.43	**1.71**	**1.02**	**2.86**
	Aircraft noise annoyance	1.34	0.92	1.96	1.59	0.99	2.54
M3 model							
SRHS[3]	L_{den}[1]	0.97	0.63	1.49	**1.84**	**1.11**	**3.06**

[1] Noise levels ≥ 50dBA vs < 50 dBA
[2] Severe aircraft noise annoyance was modeled
[3] Impaired SRHS was modeled
M1 model was adjusted for age, number of people in the household, occupational activity, economic dependency on airport activities, use of the noise source, fear of a plane crash, homeownership, type of housing, residential satisfaction, source- and authority-related attitudes, and noise sensitivity
M2 and M3 models were adjusted for age, number of people in the household, occupational activity, income per consumer unit, country of birth, and smoking habits

Supplemental Table 4: Adjusted odds ratios for impaired SRHS in relation to aircraft noise levels in highly annoyed/noise-sensitive men and women compared to those who are not (M5 model) considering aircraft noise levels in binary (< 50 dBA versus ≥ 50 dBA)

		Not highly annoyed			Highly annoyed			Not highly noise-sensitive			Highly noise-sensitive		
		OR	95% CI		OR	95% CI		OR	95% CI		OR	95% CI	
Women	N[§]	569/404/318			126/145/120			459/352/291			234/197/147		
	L_{den} < 50dBA	Ref	-	-	1.62	0.61	4.34	Ref	-	-	1.74	0.81	3.78
	L_{den} ≥ 50dBA	0.94	0.59	1.50	1.25	0.74	2.13	1.05	0.60	1.81	1.47	0.81	2.66
Men	N[§]	448/340/292			99/103/81			405/331/277			135/112/96		
	L_{den} < 50dBA	Ref	-	-	1.38	0.39	4.93	Ref	-	-	1.03	0.37	2.92
	L_{den} ≥ 50dBA	1.64	0.94	2.85	**2.71**	**1.43**	**5.14**	1.58	0.87	2.87	**3.00**	**1.46**	**6.18**

[§] *N for T0/T2/T4*

All models were adjusted for age, number of people in the household, occupational activity, income per consumer unit, country of birth and smoking habits