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Aircraft and road traffic noise and children's cognition and health: a cross-national study

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Summary

Background Exposure to environmental stressors can impair children's health and their cognitive development. The effects of air pollution, lead, and chemicals have been studied, but there has been less emphasis on the effects of noise. Our aim, therefore, was to assess the effect of exposure to aircraft and road traffic noise on cognitive performance and health in children.

Methods We did a cross-national, cross-sectional study in which we assessed 2844 of 3207 children aged 9–10 years who were attending 89 schools of 77 approached in the Netherlands, 27 in Spain, and 30 in the UK located in local authority areas around three major airports. We selected children by extent of exposure to external aircraft and road traffic noise at school as predicted from noise contour maps, modelling, and on-site measurements, and matched schools within countries for socioeconomic status. We measured cognitive and health outcomes with standardised tests and questionnaires administered in the classroom. We also used a questionnaire to obtain information from parents about socioeconomic status, their education, and ethnic origin.

Findings We identified linear exposure-effect associations between exposure to chronic aircraft noise and impairment of reading comprehension ($p=0\cdot0097$) and recognition memory ($p=0\cdot0141$), and a non-linear association with annoyance ($p<0\cdot0001$) maintained after adjustment for mother's education, socioeconomic status, longstanding illness, and extent of classroom insulation against noise. Exposure to road traffic noise was linearly associated with increases in episodic memory (conceptual recall: $p=0\cdot0066$; information recall: $p=0\cdot0489$), but also with annoyance ($p=0\cdot0047$). Neither aircraft noise nor traffic noise affected sustained attention, self-reported health, or overall mental health.

Interpretation Our findings indicate that a chronic environmental stressor—aircraft noise—could impair cognitive development in children, specifically reading comprehension. Schools exposed to high levels of aircraft noise are not healthy educational environments.

Introduction

An understanding of the way the environment affects children's health and development is central to sustainable living and to the prevention of illness.[1] The effects of air pollution and lead are well known, but less attention has been paid to environmental noise.[2,3] Noise, an ubiquitous environmental pollutant, is a public-health issue because it leads to annoyance, reduces environmental quality, and might affect health and cognition.[4] Children could be particularly vulnerable to the effects of noise because of its potential to interfere with learning at a critical developmental stage, and because they have less capacity than adults do to anticipate, understand, and cope with stressors.[5]

Attention, memory, and reading are all involved in cognitive development at primary school age (5–11 years). Children attend to information that is then encoded in memory through processes of rehearsal, organisation, and elaboration.[6] Strategies for retrieval of information from memory develop gradually. Reading depends on perception and memory and, at an early stage, awareness of speech sounds, which could be distorted by ambient noise.[7] Environmental stressors can have a great effect on the degree to which information is processed, retained, and recalled.[8]

We set up the RANCH project (road traffic and aircraft noise exposure and children's cognition and health: exposure-effect relationships and combined effects) to investigate the relation between exposure to aircraft and road traffic noise and cognitive and health outcomes. We postulated that exposure to these types of noise would be associated with impaired cognitive function and health, including annoyance in children.

Methods

Participants

Between April and October, 2002, we enrolled children aged 9–10 years from primary schools near Schiphol, Barajas, and Heathrow—airports in the Netherlands, Spain, and the UK—to a cross-sectional study. We selected schools on the basis of increasing levels of exposure to aircraft and road traffic noise with the same systematic method in every country so as to examine exposure-effect relations. We classified schools in a four-by-four grid of noise exposure in every country. We randomly selected two schools within every cell so as to

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examine the effects of increasing aircraft noise within low road traffic noise, increasing road traffic noise within low aircraft noise, and the effects of combinations of aircraft noise and road traffic noise. We matched chosen schools by the socioeconomic status of the pupils, which we measured by eligibility for free school meals, and by main language spoken at home. We selected those schools exposed to the highest amounts of aircraft noise first. In the Netherlands, we used a neighbourhood-level indicator of property value and the proportion of non-Europeans living in the area and attending the school to match schools.

We excluded from our study non-state schools in the UK and Spain, but included them in the Netherlands where degrees of achievement do not differ appreciably between school type. We also excluded schools at which noise surveys indicated either the presence of a dominant noise other than aircraft or road traffic noise, or at which insulation against noise was above a certain threshold (double or triple-glazed classroom windows) as identified with a predefined protocol with categories of likely internal-to-external noise level differences for every classroom, although some highly insulated schools were included in the Netherlands. In every noise exposure cell, in every country, we selected two schools according to a protocol. In the UK and Spain, we selected two classes of children of mixed sex from each school, and in the Netherlands one class (most Dutch schools only had one class in this age group). If there were more than two classes in the year, then we randomly selected two or one, dependent on the country. We did not exclude any children from the selected classes.

We obtained written consent from the children and their parents. In the UK, ethical approval for the study was provided by the East London and the City Local Research Ethics Committee, East Berkshire Local Research Ethics Committee, Hillingdon Local Research Ethics Committee, and Hounslow District Research Ethics Committee. In the Netherlands, ethical approval was given by the Medical Ethics Committee of The Netherlands Organisation for Applied Scientific Research, Leiden. In Spain, ethical approval was given by the Consejo Superior De Investigaciones Cientificas (CSIC) Bioethical Commission, Madrid.

Procedures

To assess exposure to noise, we used external noise measurements (dB[A]) as the independent variable (dB[A] is the unit of A-weighted sound pressure level, where A-weighted means that the sound pressure levels in various frequency bands across the audible range have been weighted in accordance with differences in hearing sensitivity at different frequencies). In the UK, we based aircraft noise assessments external to the schools on the 16-h outdoor LAeq contours provided by the Civil Aviation Authority. These contours give the average continuous equivalent sound level of aircraft noise within an area from 0700 h to 2300 h within a specified period. We initially defined road traffic noise by use of a simplified form of the UK standard calculation of road traffic noise (CRTN) prediction method, using a combination of information including proximity to motorways, major roads, minor roads, and traffic flow data.[9] We confirmed external traffic noise levels by visits and noise measurements. In the Netherlands, noise assessments were provided by modelled data on road and aircraft noise exposure linked to school locations with geographical information systems. In Spain, we visited all 96 preselected schools and made direct external measurements of road traffic noise. Aircraft noise assessment in Spain was based on predicted contours. In all three countries, we also took acute measurements of noise exposure in the classroom and outdoors at the time of testing of cognitive function, to identify any unexpected sources of noise apart from aircraft or road traffic noise that might interfere in the test situation and to assess exposure to acute aircraft and road traffic noise. The measures of acute noise exposure, using microphones, provided level differences. For aircraft noise events this measurement could be taken, in some schools, using the highest intensity points in the noise events, where interior aircraft noise levels were detectable against ambient interior noise levels.

With respect to cognitive outcomes, we measured reading comprehension with nationally standardised and normed tests—Suffolk reading scale,[10] CITO (Centraal Instituute Toets Ontwikkeling) readability index for elementary and special education,[11] and the ECL-2 (Evaluación de la Compresión Lectora, nivel 2).[12] We assessed episodic memory (recognition and recall) by a task adapted from the child memory scale.[13] This task assessed time delayed cued recall and delayed recognition of two stories presented on compact disc. Sustained attention was measured by adapting the Toulouse Pieron test for classroom use.[14] We used a modified version of the search and memory task[15,16] to measure working memory, and assessed prospective memory by asking children to write their initials in the margin when they reached two predefined points in two of the tests.

To assess health outcomes, we gave children a questionnaire that included questions on perceived health, and perceptions of noise and annoyance based on standard adult questions.[17] We also sent a questionnaire home for the parents to complete, which included questions on the perceived health of their child, and which we used to ascertain their children's mental health as measured by the parental version of the strengths and difficulties questionnaire[18]—a well validated measure of child psychological distress, sociodemographic context variables, environmental attitudes, and noise annoyance.

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We assessed sociodemographic factors as potential confounding factors and included socioeconomic position (employment status, housing tenure, crowding—an objective measure of the number of people per room at home [1·5 people per room in Spain and the UK, 1 person per room in the Netherlands]), maternal education, ethnic origin, and main language spoken at home, developing comparable measures across countries.

We did pilot studies to assess the feasibility of the cognitive tests in the Netherlands, Spain, and the UK, and, separately, the reliability, validity, and psychometric properties of the tests used against comparison tests. We translated tests and instructions from English into Dutch and Spanish, and back translated to ensure accurate conceptual translation. After piloting, we made minor alterations to the cognitive tests and environment questionnaires, mainly to improve the language and to make them more user friendly. The results of the cognitive tests were normally distributed with no floor or ceiling effects.

We did group testing in 2-h slots under close supervision to a standardised protocol (available from authors) that governed the administration of the tests across countries. In all countries, we did the tests in classrooms in the morning in the second quarter of the year. We ensured strict adherence to the protocol via cross-country quality control visits. We administered tests in a fixed order. We measured the internal and external noise levels at the schools under the supervision of local noise measurement specialists, working to a standardised noise protocol (available from authors).

Statistical analysis

We dealt with the potential confounding effects of sociodemographic factors through-the-study design (eg, by exclusion or matching) and by statistical adjustment of findings. We did analyses of the pooled data from the UK, the Netherlands, and Spain with multilevel modelling, including exposure to aircraft noise and road traffic noise as continuous variables. The advantage of multilevel modelling is its ability to

	Pooled sample	UK	Netherlands	Spain
Pupil level data				
Response rate				
Child	2844 (89%)	1174 (87%)	762 (92%)	908 (88%)
Parent	2276 (80%)	960 (82%)	658 (86%)	658 (72%)
Median age (range)	10 y 6 m (8 y 10 m–12 y 10 m)	10 y 3 m (8 y 10 m–11 y 11 m)	10 y 5 m (8 y 10 m–12 y 10 m)	10 y 11 m (9 y 5 m–12 y 4 m)
Sex				
Boys	1064/2261 (47%)	433/960 (45%)	321/643 (50%)	310/658 (47%)
Girls	1197/2261 (53%)	527/960 (55%)	322/643 (50%)	348/658 (53%)
Employed				
No	337/2256 (15%)	217/952 (23%)	48/651 (7%)	72/653 (11%)
Yes	1919/2256 (85%)	735/952 (77%)	603/651 (93%)	581/653 (89%)
Crowding				
No	1745/2218 (79%)	717/928 (77%)	444/645 (69%)	584/645 (91%)
Yes	473/2218 (21%)	211/928 (23%)	201/645 (31%)	61/645 (9%)
Home owner				
No	619/2232 (28%)	398/944 (42%)	123/652 (19%)	98/636 (15%)
Yes	1613/2232 (72%)	546/944 (58%)	529/652 (81%)	538/636 (85%)
Mean mother's education (SD)*	0·50 (0·28)	0·50 (0·28)	0·50 (0·28)	0·50 (0·28)
Long standing illness				
No	1724/2280 (76%)	703/953 (74%)	481/657 (73%)	540/670 (81%)
Yes	556/2280 (24%)	250/953 (26%)	176/657 (27%)	130/670 (19%)
Main language spoken at school				
No	269/2253 (12%)	211/960 (22%)	42/637 (7%)	16/656 (2%)
Yes	1984/2253 (88%)	749/960 (78%)	595/637 (93%)	640/656 (98%)
Mean parental support scale (SD)†	10·1 (2·0)	10·1 (1·9)	8·8 (1·9)	11·1 (1·5)
School level data				
Number of schools	89	29	33	27
Median noise exposure, dB(A) (range)				
Aircraft	52 (30–77)	52 (34–68)	54 (41–68)	43 (30–77)
Road traffic	51 (32–71)	48 (37–67)	53 (32–66)	53 (43–71)
Classroom insulation				
Single glazing	50 (56·2%)	17 (58·6%)	15 (45·5%)	18 (66·7%)
Double glazing	35 (39·3%)	12 (41·4%)	14 (42·2%)	9 (33·3%)
Triple glazing	4 (4·5%)	0	4 (12·1%)	0

Data are number (%) unless otherwise indicated. y=years. m=months. *Ranked index of standard qualification in every country. †Ordinal scale, range 3–12. Missing values: age 5%, sex <1%, employment 5%, crowding 7%, home ownership 6%, mother's education 7%, long standing illness 4%, main language 5%, parental support 6%, classroom insulation 0%.

Table 1: **Sociodemographic characteristics of participants**

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	Reading comprehension (n=2010)				Recognition (n=1998)			
	Model 1		Model 2		Model 1		Model 2	
	β (SE)	p	β (SE)	p	β (SE)	p	β (SE)	p
Fixed coefficients								
Intercept	0·248 (0·625)		–1·36 (0·625)		26·68 (1·51)		22·96 (1·55)	
Aircraft noise	–0·009 (0·003)	0·0089	–0·008 (0·003)	0·0097	–0·021 (0·008)	0·0082	–0·018 (0·007)	0·0141
Road noise			0·002 (0·004)	0·5413			0·005 (0·009)	0·6237
Spain	Ref		Ref		Ref		Ref	
UK	0·051 (0·089)	0·5657	0·272 (0·082)	0·0010	–0·066 (0·210)	0·7529	0·427 (0·206)	0·0383
Netherlands	0·067 (0·087)	0·4403	0·320 (0·085)	0·0002	0·213 (0·206)	0·3026	0·560 (0·211)	0·0080
Age	0·043 (0·154)	0·7800	0·162 (0·147)	0·2708	–0·085 (0·368)	0·8206	0·037 (0·361)	0·9191
Sex (female)	–0·015 (0·044)	0·7319	–0·056 (0·042)	0·1804	–0·076 (0·106)	0·4772	–0·134 (0·104)	0·1967
Employed			0·080 (0·065)	0·2159			0·350 (0·159)	0·0281
Crowded			–0·073 (0·055)	0·1797			–0·123 (0·134)	0·3584
Home owner			0·206 (0·053)	<0·0001			0·579 (0·132)	<0·0001
Mother's education			–0·713 (0·078)	<0·0001			–0·691 (0·191)	0·0003
Long standing illness			–0·148 (0·049)	0·0028			–0·045 (0·121)	0·7089
Speak main language at home			0·183 (0·076)	0·0163			0·962 (0·190)	<0·0001
Parental support			0·085 (0·012)	<0·0001			0·131 (0·029)	<0·0001
Classroom glazing			0·002 (0·028)	0·9522			0·064 (0·070)	0·3650
Random parameters (↓)								
Level 2: school	0·041 (0·013)		0·023 (0·010)		0·221 (0·071)		0·163 (0·060)	
Level 1: pupil	0·952 (0·031)		0·865 (0·028)		5·51 (0·178)		5·20 (0·168)	

Table 2: **Multilevel models for aircraft noise and reading comprehension and recognition**

take into account effects at the level of the school and the pupil simultaneously. We initially adjusted all pooled analyses for age, sex, country, and noise (model 1), and subsequently for socioeconomic status and mother's education. The final model also adjusted for children's longstanding illness, main language spoken at home, parental support for schoolwork, and the type of glazing in the windows of the child's classroom (model 2). Separately we tested whether the results of the final model changed after adjustment for acute noise exposure during testing. We also examined, interactions between noise level, sociodemographic factors, and the outcomes. We tested for significance by comparing the goodness of fit of different models with a χ^2 test of deviance.

We investigated the possibility of a curvilinear exposure-effect relation between noise (either aircraft or road traffic) and every cognitive and health outcome with fractional polynomial models.[19] We chose the best fitting model from a set of two degree fractional polynomials (of the form β_1*aircraft noise*^{p_1} + β_2 *aircraft noise*^{p_2} where p_1 and p_2 belong to the set –2, –1, –0·5, 0, 0·5, 1, 2, 3), then compared the goodness of fit (deviance) of this model with that of a straight line model to test for departure from a straight line relation.

Role of the funding source

The sponsors of the study had no role in study design, data collection, data analysis, data interpretation, or writing of the report. The corresponding author had full access to all the data in the study and had final responsibility for the decision to submit for publication.

Results

2844 children from 89 schools participated (table 1). In the UK, Spain, and the Netherlands, one of 30, none of 27, and 33 of 77 schools, respectively, declined to participate. From the pool of primary schools identified near airports in the UK and Spain, we excluded 26 and 19 non-state schools, respectively. Child response rates were universally high (table 1). Home ownership, parental employment status, and the proportion of children whose main language was not the native language differed across countries and have been adjusted for in analyses.

The range of exposure to noise around the schools varied across countries, reflecting the distribution of noise; nevertheless, there was considerable overlap (table 1). In analysis we have pooled the data from the three airport noise field studies and analysed the exposure-effect relationships across the total sample,

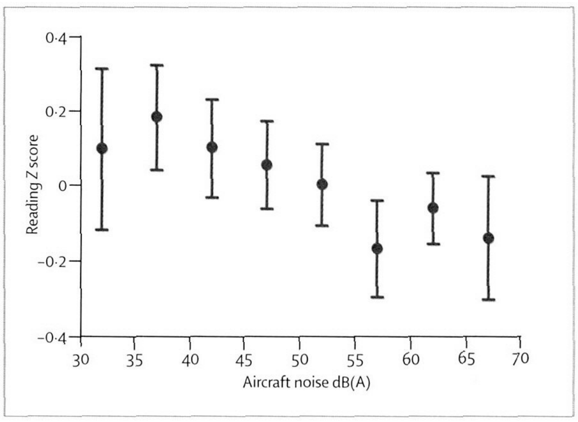

Figure 1: **Adjusted mean reading Z score (95% CI) for 5 dB bands of aircraft noise (adjusted for age, sex, and country)**

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	β (SE)	95% CI	p
Cued recall conceptual (n=1975)			
Model 1	−0·006 (0·005)	−0·015 to 0·003	
Model 2	−0·004 (0·004)	−0·012 to 0·003	0·2684
Cued recall information (n=1974)			
Model 1	−0·030 (0·018)	−0·065 to 0·006	
Model 2	−0·022 (0·016)	−0·053 to 0·008	0·1531
Prospective memory* (n=1958)			
Model 1	−0·015 (0·009)	−0·033 to 0·003	
Model 2	−0·015 (0·009)	−0·033 to 0·003	0·1250
Working memory (n=1938)			
Model 1	−0·024 (0·022)	−0·067 to 0·019	
Model 2	−0·021 (0·021)	−0·064 to 0·022	0·3412
Sustained attention (n=1938)			
Model 1	−0·051 (0·115)	−0·277 to 0·175	
Model 2	−0·037 (0·115)	−0·263 to 0·189	0·7471
Mental health (n=2014)			
Model 1	0·015 (0·014)	−0·012 to 0·042	
Model 2	0·013 (0·013)	−0·012 to 0·038	0·3098
Self-reported health (n=1970)			
Model 1	−0·001 (0·002)	−0·005 to 0·003	
Model 2	−0·002 (0·002)	−0·006 to 0·002	0·4345
Noise annoyance (n=1969)			
Model 1	0·037 (0·004)	0·029 to 0·045	
Model 2†	0·037 (0·004)	0·029 to 0·045	0·0001

*Binomial multilevel modelling done; β therefore indicates success or failure on task. †Adjusted for country, age, sex, socioeconomic status, mother's education, length of enrolment at school, classroom glazing, ethnic origin.

Table 3: **Cognitive and health outcomes and aircraft noise exposure**

using continuous data for aircraft noise and road traffic noise prediction.

With respect to cognitive effects, in analyses of the pooled data from the UK, the Netherlands, and Spain, exposure to chronic aircraft noise was associated with a significant impairment in reading comprehension that was maintained after full adjustment (table 2). The effect sizes at different exposure levels for aircraft noise for reading across countries were consistent (test for heterogeneity p=0·9 and in the same direction of association). A 5 dB difference in aircraft noise was equivalent to a 2-month reading delay in the UK and a 1-month reading delay in the Netherlands. There are no national data available for Spain. In the Netherlands and Spain, a 20 dB increase in aircraft noise was associated with a decrement of one-eighth of an SD on the reading test; in the UK the decrement was one-fifth of an SD. The size of the effect did not differ by socioeconomic status. Figure 1 shows reading comprehension by 5 dB bands of aircraft noise adjusted for age, sex, and country. There was no significant departure from linearity (p=0·99 for comparison of straight line fit with the best fitting fractional polynomial curve).

We measured episodic memory in terms of recognition and cued recall. Cued recall included assessment of information recall and conceptual recall. Exposure to aircraft noise was linearly associated with a significant impairment in recognition, but not information recall or conceptual recall (table 2 and table 3). For recognition memory, the heterogeneity test was not significant (p=0·104), indicating that the effects did not significantly differ in magnitude across countries. Aircraft noise was also not associated with impairment in working memory, prospective memory, or sustained attention. Road traffic noise was associated with a significant increase in scores for the episodic memory scales of information recall and conceptual recall that were maintained after full adjustment (table 4). The effect sizes for information recall and conceptual recall were not significantly different

	Conceptual recall (n=1975)				Information recall (n=1974)			
	Model 1		Model 2		Model 1		Model 2	
	β (SE)	p	β (SE)	p	β (SE)	p	β (SE)	p
Fixed coefficients								
Intercept	4·07 (0·850)		2·41 (0·834)		17·63 (3·28)		11·68 (3·24)	
Aircraft noise			−0·004 (0·004)	0·2653			−0·022 (0·016)	0·1513
Road noise	0·013 (0·006)	0·0201	0·013 (0·005)	0·0066	0·040 (0·022)	0·0713	0·038 (0·019)	0·0489
Spain	Ref		Ref		Ref		Ref	
UK	0·790 (0·117)	<0·0001	1·10 (0·108)	<0·0001	1·21 (0·462)	0·0082	2·43 (0·438)	<0·0001
Netherlands	0·521 (0·112)	<0·0001	0·806 (0·110)	<0·0001	−1·08 (0·447)	0·0160	−0·025 (0·445)	0·9545
Age	−0·052 (0·204)	0·7998	0·074 (0·197)	0·7079	−0·455 (0·780)	0·5611	0·033 (0·759)	0·9653
Sex (female)	−0·113 (0·059)	0·0554	−0·150 (0·057)	0·0088	−0·236 (0·224)	0·2910	−0·363 (0·218)	0·0956
Employed			0·009 (0·088)	0·9219			0·260 (0·335)	0·4365
Crowded			−0·115 (0·074)	0·1187			−0·420 (0·281)	0·1347
Home owner			0·294 (0·072)	<0·0001			1·24 (0·276)	<0·0001
Mother's education			−0·607 (0·106)	<0·0001			−2·28 (0·403)	<0·0001
Long standing illness			−0·015 (0·067)	0·8207			0·154 (0·253)	0·5426
Speak main language at home			0·535 (0·103)	<0·0001			1·74 (0·399)	<0·0001
Parental support			0·081 (0·016)	<0·0001			0·288 (0·061)	<0·0001
Classroom glazing			0·018 (0·036)	0·6226			0·092 (0·149)	0·5349
Random parameters (↓)								
Level 2: school	0·075 (0·025)		0·032 (0·018)		1·31 (0·406)		0·729 (0·291)	
Level 1: pupil	1·66 (0·054)		1·57 (0·051)		23·98 (0·783)		22·61 (0·738)	

Table 4: **Multilevel models for road traffic noise and cued recall**

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	β (SE)	95% CI	p
Reading comprehension (n=2010)			
Model 1	0·003 (0·004)	−0·005 to 0·012	
Model 2	0·002 (0·004)	−0·005 to 0·009	0·5417
Recognition (n=1998)			
Model 1	0·006 (0·010)	−0·014 to 0·026	
Model 2	0·005 (0·009)	−0·013 to 0·023	0·6240
Prospective memory* (n=1958)			
Model 1	0·007 (0·012)	−0·017 to 0·031	
Model 2	0·007 (0·012)	−0·017 to 0·031	0·1360
Working memory (n=1938)			
Model 1	0·033 (0·027)	−0·020 to 0·087	
Model 2	0·030 (0·027)	−0·023 to 0·083	0·2742
Sustained attention (n=1938)			
Model 1	−0·020 (0·143)	−0·300 to 0·261	
Model 2	−0·046 (0·144)	−0·328 to 0·237	0·7499
Mental health (n=2014)			
Model 1	−0·012 (0·017)	−0·045 to 0·021	
Model 2	−0·018 (0·016)	−0·049 to 0·013	0·2747
Self-reported health (n=1970)			
Model 1	0·005 (0·003)	−0·001 to 0·011	
Model 2	0·005 (0·003)	−0·0004 to 0·010	0·0725
Noise annoyance (n=1969)			
Model 1	0·017 (0·004)	0·009 to 0·025	
Model 2†	0·016 (0·004)	0·008 to 0·024	0·0047

*Binomial multilevel modelling done; β therefore indicates success or failure on task.
†Adjusted for country, age, sex, socioeconomic status, mother's education, length of enrolment at school, classroom glazing, ethnic origin.

Table 5: **Cognitive and health outcomes and exposure to road traffic noise**

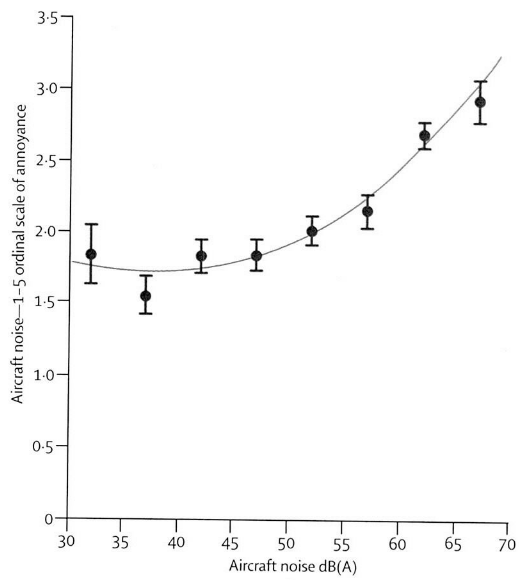

Figure 2: **Adjusted mean annoyance (95% CI) for 5 dB bands of aircraft noise (adjusted for age, sex, and country) and fitted curve***
*Fractional polynomial curve fitted to continuous aircraft noise of form $-0{\cdot}188X^{2}+0{\cdot}107X^{2}*\log(x)$ (where x=aircraft noise/10).

between countries (p=0·9 for information recall, p=0·7 for conceptual recall) and were consistent in the direction of the association with exposure to road traffic noise. There was no significant departure from linearity for information recall or conceptual recall (p=0·67 and p=0·99 for comparison of straight line fit with the best fitting fractional polynomial curve, respectively). These effects were stronger for children from crowded homes than for those whose homes were not crowded (interaction p=0·01 for both information and conceptual recall). We noted no effects of road traffic noise on reading comprehension, recognition, working memory, prospective memory, and sustained attention (table 5).

With respect to health effects, increasing exposure to both aircraft noise and road traffic noise was associated with increasing annoyance responses in children. This finding was maintained after full adjustment (table 2 and table 5). Figure 2 shows annoyance from aircraft noise by 5 dB bands adjusted for age, sex, and country. The best fitting fractional polynomial curve was non-linear and showed a steeper dose-response gradient at higher levels of aircraft noise (p=0·018, test for departure from straight line fit).

There was a linear association between road traffic noise and annoyance adjusted for age, sex, and country (p=0·11 for comparison of straight line fit with best fitting fractional polynomial curve). We noted no effects of either aircraft noise or road traffic noise on self-reported health or mental health.

Discussion

Our findings indicate a linear exposure-effect association between exposure to aircraft noise and impaired reading comprehension and recognition memory in children, and between exposure to road traffic noise and increased functioning of episodic memory, in terms of information and conceptual recall. Our results also show non-linear and linear exposure-response associations between aircraft and road traffic noise, respectively, and annoyance. Neither aircraft noise nor road traffic noise affected sustained attention, self-reported health, or mental health.

By comparison with previous studies,[20–23] our results are robust because we used data from three countries with different sociodemographic profiles, our questionnaire response rates were high, we made careful and detailed noise assessments and measured the effect of confounding factors, we adjusted for acute noise exposure, and we used standardised outcome measures. Results for aircraft noise and reading comprehension across the three countries were largely similar—ie, we noted cross-cultural replication of findings. The advantage of multilevel modelling is that it can also adjust for variance in cognitive function between schools and between countries. The limitations of our study are: that it was cross-sectional rather than longitudinal; we studied a small age range; we focused largely on exposure to noise in schools, though noise at home might also affect health outcomes; and we used different noise assessment techniques in the three countries. However, using the pooled sample, we were able to combine exposure sites with different associations between noise exposure and

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socioeconomic position and thus adjust, to some extent, and more so than in previous studies,[20,22,23] for socioeconomic status as a potential confounding factor. Contrary to previous work done in the UK,[20] socioeconomic status did not explain the association between noise and cognitive function in children.

An effect of aircraft noise on reading is consistent with previous findings.[21–25] Exposure to aircraft noise has been related to impairments of children's cognition in terms of reading comprehension, long-term memory, and motivation.[21–26] Tasks that involve central processing and language comprehension, such as reading, attention, problem solving, and memory seem most affected by exposure to noise. With a few exceptions,[20,27] most studies have compared groups exposed to high levels and low levels of noise, and have not examined exposure-effect relations. Moreover, most studies in children have focused on aircraft noise rather than road traffic noise. These exposure-effect associations, in combination with results from earlier studies,[21–25] suggest a causal effect of exposure to aircraft noise on children's reading comprehension. This effect is significant though small in magnitude, but does show a linear exposure-effect relation. In practical terms, aircraft noise might have only a small effect on the development of reading, but the effect of long-term exposure remains unknown.

Aircraft noise, because of its intensity, the location of the source, and its variability and unpredictability, is likely to have a greater effect on children's reading than road traffic noise, which might be of a more constant intensity.[28,29] In adults, sound that shows appreciable variation over time (changing state) impairs cognitive function whereas sound that does not vary (steady state) has little effect.[29,30] The noise of aircraft flyovers has an unpredictable rise time that might attract attention and distract children from learning tasks.

This notion does not explain why exposure to road traffic noise was related to improved episodic memory scores. Road traffic noise is unlikely to increase arousal sufficiently to improve performance on the memory tasks we used, which are difficult and might be impaired by increased arousal. Another explanation is confounding, but the only significant interaction between road traffic noise, sociodemographic status, and episodic memory was for crowding, in which the effects were stronger for those from crowded households. This unexplained finding needs further study. The absence of an association between road traffic noise and reading is inconsistent with previous studies, but the highest noise levels we recorded were 71 dB LAeq, which is lower than in previous work.[31]

Noise exposure is associated with annoyance and impairment of quality of life in children. This association is stronger for aircraft than for road traffic noise, as in adults. We noted no association between aircraft or road traffic noise and self-reported health or mental health, though other studies have shown effects of aircraft noise on blood pressure.[26,32]

Further research is needed to understand the psychological mechanisms of these cognitive effects. Children might adapt to noise interference during activities by filtering out the unwanted noise stimuli. This tuning out strategy might overgeneralise to situations where noise is not present, such that children tune out stimuli indiscriminately.[21,33] This tuning out response is supported by the findings that children exposed to noise have deficits in attention, auditory discrimination,[33] and speech perception.[25] However, our findings indicate that sustained attention is not impaired by aircraft noise, and others[15,24] have shown that noise impairs both attention and recall[15,24] without attention mediating the effect on cued recall. Teacher frustration and interruptions in communication between teachers and children could also be a mechanism for cognitive effects.[31] Similarly, learned helplessness has been proposed as a mechanism to account for deficits in motivation in children exposed to noise.[34]

The effects of exposure to noise at home, as well as at school, the interaction with classroom acoustics, the potential protective effect of classroom insulation against noise, and what children and teachers can do to overcome these effects deserve further inquiry. Our results are relevant to the design and placement of schools in relation to airports, to the formulation of policy on noise and child health, and to a wider consideration of the effect of environmental stressors on children's cognitive development. Greater specification of exposure-effect relations is an important step in confirming a causal role for exposure to environmental noise in impairments of children's cognition.

Contributors

S A Stansfeld, M M Haines, J Head, and B Berglund formulated the study design and interpreted the results. S A Stansfeld wrote the original draft of the manuscript. C Clark did the analyses, interpreted the results, and commented on the manuscript. J Head advised on analyses. B F Berry designed the noise measurements and interpreted noise effects. S Hygge helped on the choice of instruments and interpretation of the cognitive effects. I Lopez-Barrio, P Fischer, and I van Kamp led on data collection in Spain and the Netherlands, and commented on drafts and interpreted results. E Öhrström commented on the instruments, on drafts, and interpreted results.

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Conflict of interest statement

We declare that we have no conflict of interest.

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