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Longitudinal effects of aircraft noise exposure on children's health and cognition: A six-year follow-up of the UK RANCH cohort

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ABSTRACT

Cross-sectional evidence that environmental noise exposure at school shows negative associations with children's cognition and health has increased, yet longitudinal evidence is lacking. This study examined longitudinal associations of aircraft noise exposure at primary school on children's reading comprehension, noise annoyance, and psychological health at secondary school. This six-year follow-up of 461 children aged 15–16 years, who attended primary and secondary schools around London Heathrow airport, used annual average aircraft noise exposure at the schools from noise contour maps. Multilevel regression modelling showed that aircraft noise exposure at primary school was associated with a significant increase in noise annoyance and with a non-significant decrease in reading comprehension at follow-up. Aircraft noise at primary school was not associated with psychological health at follow-up. This is the first longitudinal study of its type, suggesting that aircraft noise exposure at school might impair reading comprehension, as well as increase noise annoyance in children.

1. Introduction

Exposure to transport noise in the environment is increasingly being seen as an important public health issue. Within Europe it has been estimated that 20% of the population (approximately 80 million people) are exposed to noise levels which scientists and health experts consider unacceptable (European Commission, 1996). The World Health Organisation recently estimated that traffic noise could conservatively account for over 1 million health years of life lost annually in the European Union and Western European countries (WHO, 2011). Evidence for traffic noise effects on human health outcomes such as cardiovascular disease (Jarup et al., 2008; van Kempen & Babisch, 2012), sleep (Basner, Griefahn, & Berg, 2010; Elmenhorst et al., 2012) and noise annoyance (Janssen, Vos, van Kempen, Breugelmans, & Miedema, 2011) has strengthened in recent years.

There is also growing evidence that environmental noise exposure such as aircraft or road traffic noise shows negative associations with children's cognition and health. To date, over 20 studies have shown a negative effect of environmental noise exposure on children's learning outcomes and cognitive performance (Evans & Hygge, 2007). Studies have demonstrated that children with chronic aircraft, road traffic or rail noise exposure at school have poorer reading ability, memory, and academic performance on nationally standardised tests than children who are not exposed to noise at school (Bronzaft, 1981; Bronzaft & McCarthy, 1975; Clark et al., 2006; Haines, Stansfeld, Brentnall, et al., 2001; Haines, Stansfeld, Head, & Job, 2002; Haines, Stansfeld, Job, Berglund, & Head, 2001a; Hygge, Evans, & Bullinger, 2002; Lercher, Evans, & Meis, 2003; Shield & Dockrell, 2008; Stansfeld et al., 2005). Studies have also demonstrated associations of environmental noise exposure on children's health and quality of life outcomes including noise annoyance and blood pressure (Evans, Hygge, & Bullinger, 1995; Haines et al., 2001; van Kempen et al., 2006; van Kempen et al., 2009; Stansfeld et al., 2005).

Many different mechanisms have been hypothesised to account for environmental noise effects on children's cognition and health including impaired attention (Cohen, Evans, Krantz, & Stokols, 1986; Evans & Lepore, 1993), increased arousal (Yerkes & Dodson, 1908), communication difficulties between teachers and pupils (Evans & Maxwell, 1997), frustration (Evans & Lepore, 1993), learned helplessness and motivation (Evans & Stecker, 2004; Peterson & Seligman, 1984), and sleep disturbance effects on performance the next day (HCN, 2004). Physiological and psychological stress responses have also been posited to account for the

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associations (Babisch, 2003; Evans & Lepore, 1993; Lazarus & Folkman, 1984; Selye, 1976; Stansfeld, Haines, Burr, Berry, & Lercher, 2000): psychologically children are believed to be poorer at appraising threat from environmental stressors and to have fewer well-developed coping strategies.

To date, few studies have examined exposure–effect relationships between noise exposure and children's cognition and health (Green, Pasternack, & Shore, 1982; Stansfeld et al., 2005). Such studies compare children from schools across a wide range of noise exposures, rather than comparing high exposure with low exposure, in order to be able to identify the exposure level at which noise effects on cognition begin. The European Union funded RANCH project (Road traffic noise and Aircraft Noise exposure and children's Cognition and Health), the largest study of noise and children's cognition and health to date, examined the cross-sectional associations of aircraft noise and road traffic noise exposure at primary school on the cognitive performance and health of 2844 9–10 year old children around Heathrow (London), Schiphol (Amsterdam), and Barajas (Madrid) airports. The study found exposure-effect associations between aircraft noise exposure at school and children's reading comprehension, recognition memory, noise annoyance, and hyperactivity scores after adjusting for a range of socioeconomic factors (Clark et al., 2006; van Kempen et al., 2009; Stansfeld et al., 2005; Stansfeld et al., 2009).

Further convincing evidence to suggest the existence of noise effects on children's cognition comes from intervention studies and natural experiments where changes in noise exposure associated with sound insulation or the closure of airports have been accompanied by changes in cognition. However, to date, there have been only three studies examining the effects of noise reduction on children's cognition (Bronzaft, 1981; Cohen, Evans, Krantz, & Stokols, 1981; Evans, Bullinger, & Hygge, 1998; Evans et al., 1995; Hygge et al., 2002), all of which suggest that noise reduction can eliminate effects on cognition.

However, many children will remain exposed to environmental noise throughout their childhood. Yet, very little is known about the potential long-term consequences of environmental noise exposure persisting throughout a child's schooling. Most of the evidence for environmental noise effects on children's cognition and health comes from cross-sectional studies. One follow-up study over a one-year period found that deficits in reading comprehension and noise annoyance responses persisted, suggesting that children did not adapt to noise exposure (Haines, Stansfeld, Job, Berglund, & Head, 2001b). If children do not adapt to their noise exposure, it is possible that associations between environmental noise and cognition and health could increase in terms of their impact over time. Longitudinal studies are much needed in this research field, to evaluate the long-term effects of environmental noise exposure on children's health and cognitive development; to further understand the causal pathways between noise exposure and cognition and health; to inform the design of preventive interventions; and to further inform policy (European Union, 2002).

2. Aims

This study followed-up the UK cohort from the RANCH project in secondary school, six years after the original primary school-based study. The study had the following aims:

i. To examine whether aircraft noise exposure at primary school showed longitudinal associations with reading comprehension, noise annoyance, and psychological health at follow-up six years later.
ii. To examine cross-sectional associations of aircraft noise exposure at secondary school on reading comprehension, noise annoyance, and psychological health, as few studies to date have examined noise associations on the health and cognition of children in this age group.
iii. To examine associations between cumulative aircraft noise exposure at primary and secondary school and reading comprehension, noise annoyance, and psychological health, to assess the combined effect of aircraft noise exposure across the child's schooling.

For each type of exposure (aircraft noise at primary school, aircraft noise at secondary school, and cumulative exposure) we hypothesised that children attending aircraft noise exposed schools would have poorer reading comprehension, higher noise annoyance, and higher hyperactivity scores than children attending low aircraft noise exposed schools. No associations were hypothesised between aircraft noise exposure at school and emotional symptom or conduct problem scores.

3. Method

3.1. Sampling and design

A quantitative prospective epidemiological follow-up of the UK RANCH cohort was carried out in 2008, six years after the initial RANCH baseline study which was conducted in 2001–2003. At baseline 9–10 year old children were selected to take part on the basis of aircraft and road traffic noise exposure at their schools around Heathrow airport in West London (Stansfeld et al., 2005). At follow-up participants attended secondary schools in West London with a range of aircraft noise exposure. At baseline, the schools were matched on sociodemographic factors. 29 primary schools participated at baseline and 27 secondary schools participated at follow-up (see Fig. 1).

Ethical approval for the baseline survey in the UK 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 the Hounslow District Research Ethics Committee in the United Kingdom. Ethical approval for the follow-up survey was obtained from the Queen Mary Research Ethics Committee [Reference QMREC2007/59].

3.2. Noise exposure assessment

Noise exposure at the child's school was estimated in dB(A): the A-weighting is used to approximate the typical sensitivity of the human ear. At baseline and follow-up aircraft noise estimates for each school were based on 16-h outdoor dB L_{Aeq} contours available nationally from the UK Civil Aviation Authority. These give the average noise exposure in dB (A) between 7 am and 11 pm for the postcode. Baseline data were from July to September 1999; follow up data were from July to September 2007. At baseline acute noise measurements during testing were taken inside and outside the classroom (see Fig. 2): however, acute noise had no influence on the association between aircraft noise and reading comprehension (Clark et al., 2006) so acute noise was not measured at follow-up. Aircraft noise exposure at baseline and follow-up are analysed as continuous variables in dB $L_{Aeq16\ h}$. The mean of the aircraft noise exposure at primary and secondary school variables was used to assess cumulative aircraft noise exposure at school. At baseline $L_{Aeq16\ h}$ estimates of road traffic noise exposure for the schools based upon a standardised method (H.M.S.O., 1998) and confirmed by noise measurements were also available (Stansfeld et al., 2005). At follow-up no road traffic noise

Fig. 1. Cognitive testing in the classroom at a UK primary school in the RANCH project.

exposure estimates were available due to lack of resources for the measurements.

3.3. Outcomes and confounding factors

3.3.1. Reading comprehension

Reading comprehension was measured using the *Suffolk Reading Scale 2* – Level 2 at baseline and Level 3 at follow-up (Hagley, 2002). These are established, nationally standardised tests. The Level 2 test is a 30 min test of 86 items suitable for 8–11 year olds and the Level 3 test is a 30 min test of 76 items suitable for 11–15 y 4 m.[1] The test contains multiple-choice sentence completion questions with 5 potential answers, which become progressively harder as the child works through the test. The test produces standardised scores using national norms and was converted to *Z*-scores for consistency with the baseline data (Clark et al., 2006).

3.3.2. Psychological health

The Strengths and Difficulties Questionnaire (SDQ) (Goodman, 1997) is a 25 item widely used, psychometrically valid instrument for detecting psychological morbidity in children aged 3–16 years (Goodman, 2001), which has scales assessing emotional symptoms, conduct problems, hyperactivity, peer problems, and pro-social behaviour. The scales added together (excluding pro-social behaviour) give a total psychological distress score. At baseline the parental version of the SDQ was used, whilst at follow-up, as the children were older, it was appropriate for them to self-complete the SDQ. The analyses use the continuous total difficulties, hyperactivity, conduct problem, and emotional symptom scores.

3.3.3. Noise annoyance

Aircraft noise annoyance at school was measured in a self-report child questionnaire at baseline and follow-up. An ISO standardised question, 'Thinking about the last year, when you were at school, how much does the noise from aircraft bother, disturb or annoy you ?' (ISO/TS, 2003) was used, with participants indicating their response using a 5 point scale (not at all, a little, quite a bit, very much, extremely). This was analysed as continuous data at baseline and follow-up.

3.3.4. Potential confounding factors

Areas with high environmental noise exposure are often socially deprived, and social deprivation is also associated with poorer performance on cognitive tasks (Haines et al., 2001), therefore our analyses need to take sociodemographic factors into account. Data was available from child and parent questionnaires at baseline assessing socioeconomic status, parent and child health, and demographic factors. The analyses use the same confounding factors identified at baseline, which were selected if the factor showed a significant association with any of the outcomes and/or to aircraft or road traffic noise exposure ($p < 0.05$) (Clark et al., 2006; Stansfeld et al., 2005). Parent report data on the following factors were selected: age; employment status (full- or part-time work/not working); crowding in the home (more than 1.5 persons per room); home ownership (rented or owned/mortgaged); long standing illness of the child (attention deficit hyperactivity disorder, asthma/bronchitis, eczema, epilepsy, depression, diabetes, or dyslexia); and mother's educational attainment (measured by a relative inequality index based on a ranked index of standard qualifications) (Mackenbach & Kunst, 1997). Child report of perceived parental support for school work at baseline and school data about the window glazing in the child's primary school classroom were also included (single or double glazed) (Clark et al., 2006; Stansfeld et al., 2005).

3.4. Procedure

Cohort members were traced using home address provided at baseline, through primary and secondary schools, and through Local Education Authorities (LEAs). The secondary school attended for 77.8% ($n = 1054$) of the sample was identified: no secondary school could be identified for 18.5% ($n = 251$) of the sample and a further 3.7% ($n = 50$) declined consent during the tracing phase (see Fig. 3). Whilst the baseline study was conducted in 29 schools in 3 boroughs, the sample was traced to 80 secondary schools in 13 boroughs. It was not feasible to follow-up the sample in boroughs where there were less than 12 cohort members or in boroughs outside West London (2.9%). Thus, 1015 cohort members from 58 secondary schools were eligible and invited to participate in the study (74.9% of the original sample). The participants were in year 11 (age 15–16 years).

[1] At the time of the study, no standardised reading test in the UK was suitable for children 16 years or older. Our sample included children aged 15 and 16 years of age. We discussed this with the publishers of the Suffolk Reading Scale 2, NFER-NELSON, who foresaw no additional problems of using the test with a sample up to 16 y 6 m (Personal Communication).

Fig. 2. Aircraft noise assessment at a UK primary school in the RANCH project.

Data was collected from March to May 2008, during a 45 min lesson. Written consent was obtained from the head teacher. Parents and participants received an information letter about the study one week prior to data collection; passive consent was obtained from parents who could opt their child out of the study. Written consent was obtained from the participant on the day of the study, after giving a further verbal explanation of the study and an opportunity to answer questions.

3.5. Statistical analysis

All analyses were carried out using STATA (Version 12) (STATA Corp LP, College Station, Texas). First, to assess the representativeness of the follow-up sample, the baseline characteristics and outcomes were compared for the participants and non-participants using *t*-tests and logistic regression. A comparison of the baseline multilevel regression model findings for the reading, annoyance, and psychological health outcomes (Clark et al., 2006; Stansfeld et al., 2005; Stansfeld et al., 2009) for the participants and non-participants was also made. Patterns of aircraft noise exposure at primary and secondary school were also examined descriptively.

Multiple imputation was used to address the issue of missing data in this longitudinal dataset (Sterne et al., 2009), using the *mi impute* programme. All exposure, outcome and confounding variables reported in this paper were included in the imputation equations (Collins, Schafer, & Kam, 2001). All participants in the follow-up study were included in the imputation models and 20 cycles of the imputation were run. Multilevel linear regression analyses were estimated using the *mi estimate* and *xtmixed* functions taking into account the hierarchical nature of the data, with longitudinal models clustering by primary school, and cross-sectional models clustering by secondary school. Separate models assessed the association of primary school, secondary school, and cumulative aircraft noise exposure on reading comprehension, noise annoyance, and psychological health at follow-up: models present the β coefficient associated with a 1 dBA increase in aircraft noise exposure. Unadjusted models included the noise exposure variable only: adjusted models included age, gender, employment, home ownership, crowding, mother's educational attainment, parental support for school work, long-standing illness of the child, main language spoken at home, and classroom glazing. Models for primary school aircraft noise exposure were also additionally adjusted for road traffic noise exposure, which was only available at baseline. Multilevel regression analyses conducted on complete case and the imputed datasets showed similar findings, therefore, the imputed regression results are presented.

4. Results

4.1. Description of the sample

Fig. 1 illustrates the participation rates for the study. Of the eligible sample ($N = 1015$), 461 participated (response rate 45.4%): 202 males (43.9%) and 259 females (56.1%), aged 15 y 5 m–17 y 7 m. 18.5% of the sample did not participate as head teachers refused consent in 11 out of 58 schools: few parents or participants refused consent (2.8%). 12% of participants had left the school, 16.5% were absent, and 4.6% attended special needs school or schools with <5 participants, which were excluded from the study for logistical reasons. Table 1 shows the descriptive statistics for the participants.

4.2. Comparison of baseline characteristics and associations for participants and non-participants

The participant and non-participant samples did not significantly differ in terms of baseline characteristics (see Table 1 footnote [d]) with the exception that participants were more likely to have had a double glazed classroom at baseline compared to the non-participants (41.3% versus 30.8%: OR 0.65, 95%CI 0.49,0.85, $p = 0.002$). In terms of the baseline outcomes (results not shown) participants had slightly higher mean score on the baseline reading test (0.06 versus −0.13: $t = -2.63$, df = 720, $p = 0.009$), and lower mean scores on the total difficulties (9.49 versus 10.61: $t = 2.67$, df = 772, $p = 0.008$), hyperactivity (3.57 versus 4.03: $t = 2.64$, df = 772, $p = 0.008$) and the conduct scale scores (1.57 versus 2.01: $t = 3.57$, df = 772, $p = 0.001$) compared to the non-participants. Overall, this suggests that the achieved sample may be slightly less representative of those in single glazed classrooms in primary school, and those with poorer psychological health and reading ability at baseline.

In both the participant and the non-participant samples we were able to replicate the baseline associations between aircraft noise and reading comprehension and noise annoyance (Clark et al., 2006; Stansfeld et al., 2005) (Table 2). The association for hyperactivity (Stansfeld et al., 2009) was not replicated in either of these smaller samples, although the coefficient for the participant

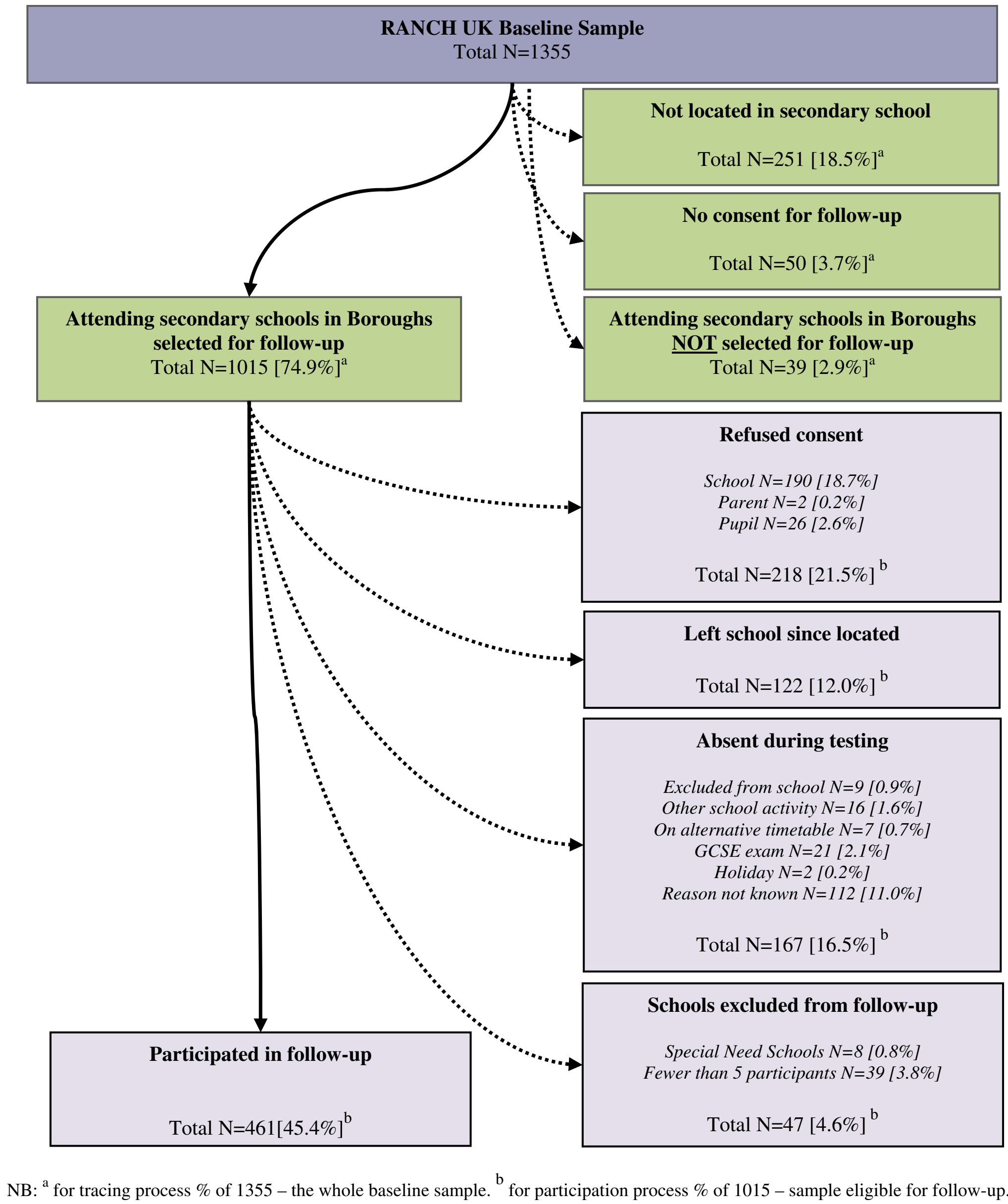

Fig. 3. Flow-chart illustrating the tracing of the baseline UK RANCH sample into secondary schools and participation rates in the follow-up study.

group ($\beta = 0.015$) was of a similar size to that shown in the larger three country sample ($\beta = 0.013$).

4.3. Patterns of aircraft noise exposure at school at baseline and follow-up

Baseline aircraft noise ranged from 34 dBA to 68 dBA with a mean exposure of 54 dBA. Follow-up, aircraft noise exposure ranged from <50 dBA[2] to 65.4 dBA with a mean exposure of 54 dBA. Table 3 illustrates the patterns of aircraft noise exposure at baseline and follow-up. Within exposure category percentages are presented to illustrate the movement of children from primary schools to secondary schools with similar, higher, or lower aircraft noise exposure. Overall, the majority of the children attended primary and secondary schools with similar noise exposure levels: 51.4% in the <51 dBA exposure category; 60.5% in the 51–56.9 dBA exposure category; and 64.4% in the 57–62.9 dBA category. Few children were exposed to >63 dBA at both primary and secondary school (5.3%), however, most children within the highest exposure in primary school were exposed to 57–62.9 dBA at secondary school (84.2%). Some children moved from quieter to noisier schools, with fewer moving from noisier to quieter schools.

4.4. Longitudinal associations between aircraft noise exposure at primary school and cognition and health at follow-up

Table 4 shows the unadjusted and adjusted imputed multilevel regression model analyses assessing the associations of aircraft noise exposure at primary school on children's cognition and health at follow-up.

[2] At follow-up the CAA would not provide noise data below 50.0 $L_{Aeq16\ h}$, so 50.0 dBA was assigned to all schools with noise levels at or below this level following sensitivity analyses.

Table 1
School- and pupil-level characteristics and outcome data for the RANCH UK follow-up sample (2008 $n = 461$).[e]

Characteristic/parameter	*n* (%)
School level data	
Aircraft noise exposure at primary school (L_{Aeq16} dB)	54 (34–68)[a]
Aircraft noise exposure at secondary school (L_{Aeq16} dB)	55 (49–68)[a]
Road traffic noise exposure at primary school (L_{Aeq16} dB)	51 (37–67)[a]
Cumulative aircraft noise exposure (L_{Aeq16} dB)	55 (42–67)[a]
Primary school classroom glazing	
Single glazing	269 (58.4)
Double glazing	142 (30.8)[d]
Mix of single & double	50 (10.8)
Pupil level data	
Age	16 y 1 m (15 y 5 m–17 y 7 m)[a]
Gender	
Male	202 (43.9)
Female	259 (56.1)
Parents' employment status at baseline	
Not employed	105 (22.8)
Employed	356 (77.2)
Crowding at home at baseline	
Not crowded	338 (73.4)
Crowded	123 (26.6)
Parents' home ownership at baseline	
Not owned	200 (43.3)
Owned	261 (56.7)
Long-standing illness at baseline	
No	340 (73.7)
Yes	121 (26.3)
Main language spoken at home	
No	129 (28.0)
Yes	332 (72.0)
Mother's education	0.51 ± 0.02[b]
Parental support scale at baseline	10.1 ± 0.09[b]
Outcome data	
Reading comprehension at secondary school[c]	−0.0006 ± 0.047[b]
Aircraft noise annoyance at secondary school	1.68 ± 0.04[b]
Psychological distress at secondary school	11.31 ± 0.27[b]
Emotional symptoms at secondary school	3.00 ± 0.12[b]
Conduct problems at secondary school	2.29 ± 0.09[b]
Hyperactivity at secondary school	4.40 ± 0.13[b]

[a] Mean and range.
[b] Mean ± standard error.
[c] *Z*-score.
[d] Significant difference observed between participants and non-participants for this parameter $p < 0.05$.
[e] All descriptive statistics in the table are from imputed data with the exception of [d].

Before adjustment for sociodemographic factors, a 1 dBA increase in aircraft noise exposure at primary school was associated with a decrease of −0.008 on the reading test, a −0.006 decrease in psychological distress, and a −0.009 decrease in emotional symptoms; and with an increase of 0.017 for annoyance, 0.002 for hyperactivity, and 0.010 for conduct problems. Only the association between aircraft noise exposure at primary school and noise annoyance remained statistically significant after adjustment for sociodemographic factors ($\beta = 0.019$, 95%CI 0.009,0.028, $p < 0.001$), with a weak association observed between aircraft noise exposure at primary school and reading comprehension ($\beta = -0.005$, 95% CI −0.017,0.007, $p = 0.435$).

4.5. Cross-sectional associations between aircraft noise exposure at secondary school and cognition and health at follow-up

Table 4 shows the unadjusted and adjusted imputed multilevel regression model analyses assessing the cross-sectional associations of aircraft noise exposure at secondary school on children's cognition and health.

Before adjustment for sociodemographic factors, a 1 dB increase in aircraft noise exposure at secondary school was associated with a decrease of −0.022 on the reading test, a −0.023 decrease in psychological distress, and a −0.034 decrease in emotional symptoms; and with an increase of 0.048 for annoyance, 0.001 for hyperactivity, and 0.011 for conduct problems. Only the association between aircraft noise at secondary school and noise annoyance was statistically significant after adjustment for sociodemographic factors (β for aircraft noise $= 0.043$, 95%CI 0.020,0.065, $p < 0.001$). This association also remained after further adjustment for aircraft noise annoyance at primary school (β for aircraft noise $= 0.043$, 95%CI 0.020,0.065, $p < 0.001$), which also showed a significant association with aircraft noise annoyance at secondary school ($\beta = 0.141$, 95%CI 0.057,0.234, $p < 0.001$). There was a weak non-significant cross-sectional association between aircraft noise at secondary school and reading comprehension after adjustment for sociodemographic factors ($\beta = -0.016$, 95%CI −0.050,0.018, $p = 0.357$).

4.6. Associations between cumulative aircraft noise exposure at primary and secondary school and cognition and health at follow-up

Table 4 also shows the unadjusted and adjusted imputed multilevel regression model analyses assessing the associations of cumulative aircraft noise exposure at primary and secondary school on children's cognition and health at follow-up.

For cumulative aircraft noise exposure at school, before adjustment for sociodemographic factors, a 1 dB increase in cumulative aircraft noise exposure was associated with a decrease of −0.014 for the reading test, a decrease of −0.002 for psychological distress, and a decrease of −0.021 for emotional symptoms; and with an increase of 0.030 for annoyance, 0.002 for hyperactivity, and 0.013 for conduct problems. The association between cumulative aircraft noise and noise annoyance remained statistically significant after adjustment for sociodemographic factors ($\beta = 0.031$, 95%CI 0.019,0.045, $p < 0.001$) and there was a weak non-significant association between cumulative exposure and reading comprehension ($\beta = -0.011$, 95%CI −0.028,0.006, $p = 0.222$).

5. Discussion

This is the first study to examine the long-term effects of aircraft noise exposure at primary school on children's later cognitive development and health. We found that in our sample some children remained exposed to high levels of aircraft noise at both primary and secondary school. Children exposed to aircraft noise at primary school reported significantly higher noise annoyance six years later at secondary school, even after taking noise annoyance at primary school into account. Non-significant negative associations were found between exposure to aircraft noise at primary school and poorer reading comprehension, but no association was observed between exposure to aircraft noise at primary school and poorer psychological health. Cumulative aircraft noise exposure at school and aircraft noise exposure at secondary school also showed significant associations with higher noise annoyance responses at secondary school, as well as non-significant negative associations with reading comprehension and no associations with psychological health.

5.1. Associations between aircraft noise and annoyance

This is the first study to examine longitudinal associations between children's noise annoyance responses, demonstrating independent associations of both aircraft noise exposure and noise

Table 2
Multilevel linear regression analysis showing odds ratios for a 1 dB increase in exposure to aircraft noise at primary school and baseline cognition and health outcomes for the UK follow-up sample ($N = 461$) compared with the non-participants ($N = 554$).[b]

	Participants at follow-up		Non-participants at follow-up	
	Adjusted for socio-demographic and other confounding factors[a]		Adjusted for socio-demographic and other confounding factors[a]	
	β (95%CI)	p-Value	β (95%CI)	p-Value
Reading comprehension at baseline				
Aircraft noise at primary school	−0.010 (−0.021,0.00002)	0.049	−0.018 (−0.032,0.003)	0.016
Aircraft noise annoyance at baseline				
Aircraft noise at primary school	0.034 (0.024,0.044)	<0.001	0.025 (0.013,0.038)	<0.001
Psychological distress at baseline				
Aircraft noise at primary school	−0.018 (−0.076,0.039)	0.534	−0.025 (−0.083,0.032)	0.390
Hyperactivity scores at baseline				
Aircraft noise at primary school	0.015 (−0.009,0.040)	0.226	−0.002 (−0.025,0.021)	0.837
Conduct problem scores at baseline				
Aircraft noise at primary school	−0.014 (−0.030,0.001)	0.083	−0.0007 (−0.018,0.016)	0.930
Emotional symptom scores at baseline				
Aircraft noise at primary school	−0.018 (−0.043,0.006)	0.144	−0.011 (−0.034,0.011)	0.335

[a] Adjusted for age, gender, parental employment, crowding in the home, home ownership, mother's education, long standing illness, main language spoken at home, parental support, classroom glazing, and road noise at primary school.
[b] Non-imputed results.

annoyance at primary school on noise annoyance measured six years later at secondary school. This finding supports our hypothesis that children attending aircraft noise exposed schools would have higher noise annoyance than children attending low aircraft noise exposed schools. Annoyance is an important health effect of noise (WHO, 2000): it is the primary outcome used to evaluate the effect of noise on communities and is indicative of a poorer quality of life, which may be associated with stress responses and subsequent illness (Clark & Stansfeld, 2007). Our findings could reflect continuities of noise exposure over the six years, so that those with high exposure in primary school and thus, high annoyance responses, also have high noise exposure and annoyance in secondary school.

5.2. Associations between aircraft noise and reading comprehension

The findings did not support our hypotheses that children attending aircraft noise exposed primary or secondary schools would have poorer reading comprehension at age 15–16. However, these conclusions need to be considered in the light of the limitations of small sample size which could potentially have influenced the findings. First, the coefficients for the effect of aircraft noise at primary and secondary school, as well as the cumulative noise measure, are negative, sizeable, and similar in magnitude to the earlier finding for reading comprehension at age 9–10 (Clark et al., 2006), but are not statistically significant. This suggests that whilst aircraft noise was associated with impaired performance on the reading comprehension test the achieved sample may not be large enough to detect a statistically significant difference. Some previous small-scale studies of noise effects on children's cognition failed to demonstrate associations with reading comprehension (Haines et al., 2001; Hygge et al., 2002), whilst larger studies have demonstrated associations (Clark et al., 2006; Stansfeld et al., 2005), which is suggestive of type II errors: large samples may be a prerequisite for conclusively demonstrating noise effects on children's cognition. Future studies need to ensure a large sample is followed over-time, to test whether associations of noise exposure in primary school on cognitive performance in secondary school can be demonstrated, as well as to further examine the effects of cumulative exposure.

Table 3
Noise exposure at primary and secondary schools in the UK RANCH follow-up study ($N = 461$).

Aircraft noise exposure at primary school ↓	Aircraft noise exposure at secondary school ↓			
	<51 dBA N (%)[a]	51–56.9 dBA N (%)[a]	57–62.9 dBA N (%)[a]	>63 dBA N (%)[a]
<51 dBA	75 (51.4)	38 (26.0)	33 (22.6)	0 (0.0)
51–56.9 dBA	20 (16.8)	72 (60.5)	27 (22.7)	0 (0.0)
57–62.9 dBA	8 (7.9)	27 (26.7)	65 (64.4)	1 (1.0)
>63 dBA	4 (4.2)	6 (6.3)	80 (84.2)	5 (5.3)

[a] Within category row %. NB: the schools were selected at baseline according to these categorizations of noise exposure.

The coefficient for the association of aircraft noise exposure at secondary school and cumulative exposure on reading comprehension at follow-up were three-times and two-times larger, respectively, than the coefficient observed for aircraft noise exposure at primary school. These findings are tentatively indicative of a larger, cumulative effect of noise exposure at school on the child's cognition, observable by the end of the child's school career. This conclusion is supported by a previous study over a one-year period, which found that deficits in reading comprehension persisted and that children did not adapt to their noise exposure (Haines et al., 2001b). However, to understand the causal pathways between noise exposure and cognition, and to design preventive interventions, there is a need for further longitudinal evidence of the effects of noise exposure throughout the child's education, perhaps utilising more sensitive measures of exposure. This study was not powered to examine patterns of change in noise exposure across primary and secondary school. We could not compare associations between aircraft noise exposure at primary school and reading comprehension at secondary school for those who moved to quieter schools with those who remained exposed to higher levels of aircraft noise. Future large-scale studies should examine whether associations between primary school aircraft noise and reading comprehension at secondary school might be explained by continuous exposure to noise across the child's schooling, or irrespective of aircraft noise exposure at secondary school. This question has policy implications, shedding light on whether there is a critical period for exposure or whether the effects of primary school noise exposure might be mitigated by a move to a quiet school.

5.3. Associations between aircraft noise and psychological health

This study found no associations between aircraft noise exposure at primary school or secondary school or cumulative exposure

Table 4
Multilevel linear regression analysis showing odds ratios for a 1 dB increase in exposure to a) aircraft noise at primary school, b) aircraft noise at secondary school, and c) cumulative aircraft noise exposure on cognition and health outcomes at follow-up ($N = 461$).[b]

	Unadjusted		Adjusted for socio-demographic and other confounding factors[a]	
	β (95%CI)	p-Value	β (95%CI)	p-Value
Reading comprehension at follow-up				
Aircraft noise at primary school	−0.008 (−0.021,0.004)	0.191	−0.005 (0.017,0.007)	0.435
Aircraft noise at secondary school	−0.022 (−0.061,0.018)	0.277	−0.016 (−0.050,0.018)	0.357
Cumulative aircraft noise at school	−0.014 (−0.033,0.003)	0.109	−0.011 (−0.028,0.006)	0.222
Aircraft noise annoyance at follow-up				
Aircraft noise at primary school	0.017 (0.008,0.027)	<0.001	0.019 (0.009,0.028)	<0.001
Aircraft noise at secondary school	0.048 (0.030,0.067)	<0.001	0.043 (0.020,0.065)	<0.001
Cumulative aircraft noise at school	0.030 (0.017,0.043)	<0.001	0.031 (0.019,0.045)	<0.001
Psychological distress at follow-up				
Aircraft noise at primary school	−0.006 (−0.077,0.065)	0.870	0.001 (−0.060,0.061)	0.998
Aircraft noise at secondary school	−0.023 (−0.168,0.122)	0.759	0.017 (−0.101,0.135)	0.781
Cumulative aircraft noise at school	−0.002 (−0.107,0.102)	0.962	0.015 (−0.069,0.100)	0.718
Hyperactivity scores at follow-up				
Aircraft noise at primary school	0.002 (−0.027,0.031)	0.900	0.006 (−0.022,0.033)	0.688
Aircraft noise at secondary school	0.001 (−0.053,0.055)	0.978	0.019 (−0.034,0.073)	0.476
Cumulative aircraft noise at school	0.002 (−0.040,0.044)	0.932	0.010 (−0.029,0.002)	0.613
Conduct problem scores at follow-up				
Aircraft noise at primary school	0.010 (−0.014,0.034)	0.421	0.006 (−0.017,0.029)	0.616
Aircraft noise at secondary school	0.011 (0.033,0.056)	0.617	0.015 (−0.031,0.060)	0.527
Cumulative aircraft noise at school	0.013 (−0.021,0.048)	0.438	0.008 (−0.024,0.041)	0.617
Emotional symptom scores at follow-up				
Aircraft noise at primary school	−0.009 (−0.039,0.021)	0.562	−0.008 (−0.035,0.019)	0.555
Aircraft noise at secondary school	−0.034 (−0.108,0.040)	0.372	−0.022 (−0.073,0.029)	0.394
Cumulative aircraft noise at school	−0.021 (−0.064,0.020)	0.315	−0.015 (−0.054,0.023)	0.436

[a] Adjusted for age, gender, parental employment, crowding in the home, home ownership, mother's education, long standing illness, main language spoken at home, parental support, classroom glazing, and road noise at primary school.
[b] Imputed results.

and psychological health. This supported our hypotheses that there would be no associations between aircraft noise exposure and emotional or conduct problem scores, but refuted our hypothesis that there would be an association between aircraft noise exposure and higher hyperactivity scores. The lack of a longitudinal association between aircraft noise and hyperactivity could be explained by the loss-to-follow-up of children who had high hyperactivity scores at baseline. However, as this is the first study to examine prospective associations further studies are required before definitive conclusions can be drawn, but, overall, this study suggests no long-term consequences for psychological health of aircraft noise exposure in primary school.

5.4. Limitations, strengths, and future research directions

One limitation of any prospective study is attrition. Our follow-up of the UK RANCH cohort was not planned at baseline: overall half the sample was lost because we either could not trace them from primary school, because schools refused to participate, or because of pupil absenteeism. Analyses comparing the baseline characteristics of participants and non-participants revealed little differential non-response by baseline sociodemographic or exposure variables, but some differences in cognition and psychological distress. We may have lost those pupils who were more likely to perform poorly on the reading comprehension test and with poorer psychological health. Therefore, given the level of attrition in the sample, we consider the results indicative rather than definitive. Further, the secondary schools may not be representative of the population or of aircraft noise exposures, as the sample was not selected on the basis of secondary school noise exposure. The results may also be country and cohort specific.

Further limitations include a lack of data about aircraft noise exposure at the child's home at follow-up; about internal classroom acoustics (Shield & Dockrell, 2008); and about secondary school road traffic noise exposure or air pollution (Clark et al., 2012; Franco Suglia, Gryparis, Schwartz, & Wright, 2008; Freire et al., 2010; Wang et al., 2009), although air pollution at primary school showed no associations with these cognitive and health outcomes at baseline in the UK RANCH cohort (Clark et al., 2012). We did not have access to information about whether the child remained in the same schools during the time between the two surveys: our conclusions are based on the assumption that children remained exposed to the same school-based noise levels across time, which could further limit our findings.

However, this is the first study to prospectively examine the effect of aircraft noise exposure in primary school and its effect on cognitive performance and health in secondary school and there are currently no other large scale studies of noise effects on children's cognition which could be followed-up in this way. Other strengths include data on a comprehensive range of individual-level confounding factors; the use of multilevel modelling; and the use of multiple imputation to deal with missing data, reducing bias in the analyses.

As well as the need for further longitudinal studies examining the long-term consequences of environmental noise exposure during schooling for children's later cognitive development and health, future research should also assess the potential protective effect of insulation for reducing environmental noise effects on cognition. Whilst cross-sectional evidence for environmental noise effects on children's cognition and health has increased in recent years, there is relatively little contemporary evidence about whether environmental remediation against noise exposure, such as insulation of school windows and roof-spaces, could reduce cognitive deficits and health effects.

5.5. Conclusion

The results of this project have relevance for national and local authorities involved in public health, transport planning, and land-use planning. This is the first study to attempt to quantify the long-term effects of environmental noise exposure during primary school for later cognitive development and health. Logistic difficulties tracing the sample from primary to secondary school may have led to underestimates of the effects of aircraft noise exposure in primary school for later cognition and health, and the findings need to be confirmed in further studies. In terms of policy implications, taken as a whole, the RANCH study findings indicate that a chronic environmental stressor – aircraft noise exposure at school – might impair cognitive development in children, specifically reading comprehension and is associated with noise annoyance responses. Taken as a whole, the evidence from the RANCH project supports the view that schools exposed to high levels of aircraft noise are not healthy educational environments. The WHO recently estimated that for children's cognitive performance, 45,036 disability-adjusted life years are lost each year in the Europe A region, for children aged 7–19 years due to environmental noise exposure (WHO, 2011).

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