The Effects of Chronic Aircraft Noise Exposure on Children's Cognition and Health: 3 Field Studies

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This article provides a review of three of the most important field studies to have examined the non-auditory effects of chronic aircraft noise exposure on children's cognition and health. The design of each of the studies is outlined, relevant methodological issues are highlighted and the findings from the studies are reported. Effects are reported on annoyance and quality of life, motivation and helplessness, stress responses as indexed by neuroendocrine tests and blood pressure measurements. In terms of cognitive performance, effects are reported on reading, attention and long-term and working memory.

Keywords: Aircraft-noise, children, health, cognition.

Introduction

The effects of noise on hearing have long been the focus of scientific investigation. The non-auditory effects of noise have, by contrast, been relatively neglected. However, it is now clear that chronic exposure to noise can give rise to psychological effects in terms of increased stress levels and impaired performance. As far as research on children is concerned, there have been a number of laboratory and field studies which have examined the non-auditory effects of noise. Laboratory studies are very important and useful in that they allow a greater level of control over the environmental conditions than is possible in the field. They do, however, suffer from the shortcoming that subjects are typically exposed to only short bursts of noise during the experimental procedures and so the generality of these findings to chronically noise-exposed children is questionable. Field studies allow children who have been exposed to noise over a prolonged period of time to be tested and therefore have greater ecological validity. In this article three of the most important field studies to investigate the non-auditory effects of noise will be reviewed. These studies are all principally concerned with aircraft noise exposure but other studies have looked at both road traffic noise (e.g. Lercher, 1996) and train noise (e.g. Bronzaf & McCarthy, 1975). The three studies to be reviewed were respectively carried out in schools close to Los Angeles, Munich and London – Heathrow airports. The first of these studies had a repeated measures design, the second was a longitudinal study, while the third was a cross-sectional study.

The issue of confounding factors is critical for field studies of this type. It may be the case that one or more additional factors may co-vary with noise exposure to give rise to observed effects. This problem can be addressed in two ways. Firstly, by matching different noise groups as far as possible on other factors which might cause effects e.g. social deprivation and, secondly, by making statistical adjustments to compensate for any differences between noise groups on other factors. All three of the studies here discussed have addressed the issue of confounding. Each of the studies will now be briefly introduced.

The Los Angeles Airport Study

The Los Angeles airport study (Cohen et al., 1980, Cohen et al., 1981) was a repeated measures field study which focused on schools
in the flight path of Los Angeles international airport. This was the first study of its kind ever to have been conducted and it provided both a methodological template and seminal results which have informed subsequent work. Four schools exposed to high levels of noise were included (N = 142) as well as three low-noise schools (N = 120). The low noise schools were matched with the high noise schools for overall scholastic performance of the children, ethnic and racial distribution of the children, social deprivation, and occupation and education of the parents.

All children were tested individually in a noise-insulated trailer that was taken to each of the participating schools. Testing was carried out in two 45-minute sessions which took place on consecutive days. The study included children from all noise-impacted third and fourth grade classrooms in the noise schools together with children from an equal number of classes in the quiet schools.

The matching process was only partially successful. The noise and quiet schools were well matched for level of parental education but there were significant differences for ethnic distribution. Moreover, there were significant differences in how long the children in the noise and quiet groups had lived in their present homes, those in the quiet schools having lived in the same home for longer, and in terms of how long they had attended their present schools, the quiet-school children again having been at their present school for longer. A regression analysis was employed to address the differences of racial distribution and mobility.

The children were followed up a year later in order to examine whether the effects observed at the first wave of data collection had persisted, become worse, or whether the children had adapted to their environment. A strength of the Los Angeles study was that it emphasised the length of time which the children had been exposed to noise. It is perhaps to be regretted, however, that the study included such a narrow range of cognitive outcome measures.

The Munich Airport Study
The Munich Airport study (Evans et al., 1995; Evans et al., 1998; Hygge et al., 2002) was a prospective study which took advantage of a naturally occurring experiment which resulted from the relocation of this major airport. The old airport was situated in an urban area of the city while the new airport is situated in a rural area outside the city. There were three waves of data collection. Wave 1 was shortly prior to the closure of the old airport, while Waves 2 and 3 were carried out one and two years later respectively.

At Wave 1 the participating children were recruited from the third and fourth grades and had a mean age of 10.8 years. These children were then followed up at Waves 2 and 3. Children were recruited from four groups: old airport – quiet (N = 43), old airport - noise (N = 65), new airport - quiet (N = 107), new airport - noise (N = 111). The children in the noise and quiet schools were matched for sociodemographic characteristics. In order to take part in the study children had to have a minimum of two years residency and be fluent German speakers, thereby ruling out confounds with language proficiency. Children were also screened for normal hearing.

Testing was carried out on an individual basis in a sound-attenuated trailer which was taken to each of the participating schools. The tests were conducted in a fixed order on two consecutive days. The natural experiment which this study took advantage of represents a unique strength of this study and something which no other study has yet to replicate. Whether the size of the sample used in this study is large enough to adequately address the question of the role of confounding factors in the relationship between noise and outcome measures is debatable.

The West London Schools Study
The West London Schools Study (Haines et al., 2001b) was a cross-sectional study which was carried out in schools in the area surrounding Heathrow airport. A total of twenty schools took part in the study, 10 high noise schools (N = 236) and 10 control low noise schools (N = 215).
Attempts were made to match the samples on age, sex, existing noise protection, socio-economic status and main language spoken at home. Parent questionnaires (N = 361) and teacher questionnaires (N = 25) were also completed.

The matching process was only partly successful. The noise and quiet groups were well matched on age, sex and socio-economic status but the noise group was more likely to be non-white and to speak a language other than English at home. Unlike the other two studies the tests were group administered in the classroom. This occurred according to a fixed ordering. While, unlike the other two studies, children were not given a hearing test to screen for hearing difficulties, both teachers and parents were asked to indicate if they had knowledge of hearing problems in the children. The results from this showed no significant differences according to noise exposure group. An important strength of the West London Schools Study over the other two studies was the larger sample size, which allowed the role of confounding factors in the relationship between noise and outcome measures to be adequately accounted for. Another important strength of this study over earlier studies was the use of multi-level modelling statistical techniques. This made it possible to adjust analytically for the potentially confounding effects of school characteristics on associations between noise and outcome measures at the individual level. A weakness of the West London Schools Study was that it was not longitudinal and so could not track the effects of noise over time.

Taken together, these three studies have identified a broad range of effects from chronic noise exposure. In the following sections these effects will be reviewed. For clarity, these are divided into, firstly, stress responses and health outcome measures and, secondly, cognition and performance measures.

**Stress response and health outcome measures**

Table 1 summarises the findings from the stress response and health outcome measures across the three studies. A tick indicates that a significant effect was observed while “–“ indicates that no test was run.

**Annoyance**

Annoyance as a consequence of chronic exposure to aircraft noise was assessed in both the Munich study and the WLSS.

In the Munich study the children gave magnitude estimates of noise annoyance. Short bursts of noise were presented over headphones at different levels. Three kinds of noise were used: broadband noise, road traffic noise and aircraft noise. The children also indicated how annoying they found community noise levels. The results show that at Wave 1 children in the noise condition were significantly more annoyed by community noise than those in the quiet condition. No annoyance results appear to have been presented for Waves 2 or 3.

Quality of life was also assessed in the Munich study. For this purpose the KINDL was used, a valid and reliable indicator of the four main areas of quality of life, namely, psychological,
physical, social and functional daily life (Bullinger et al., 1994). While the data for each of these subscales at Wave 1 indicated a tendency towards a higher quality of life in the quiet group, there was only a significant effect for the psychological subscale. The prospective data indicates that quality of life became significantly worse in the noise-impacted communities 18 months after the opening of the new airport while in the quiet communities it remained relatively stable $F(2, 202) = 3.07, p < 0.05$.

In the West London Schools Study annoyance was measured by means of four standard questions (Fields et al., 1998) which were adapted for children. These questions used a 5-point Likert scale to assess the level of annoyance which the children felt when they heard aircraft and road traffic noise at home and at school, in the last 12 months. The higher the noise annoyance levels the higher the score. The results indicate that children in the noise schools had significantly higher annoyance levels than children in the quiet schools after adjustment for age, main language spoken and social deprivation and multi-level modelling taking account of school level differences ($p < 0.0001$).

Taken together, the results from these two studies indicate quite clearly that chronically noise-exposed children experience increased levels of annoyance and diminished quality of life. The question of what the long term implications of annoyance might be is one for future research.

**Motivation and helplessness**

There is some evidence (Cohen et al., 1980, 1986) that children chronically exposed to noise are more likely to have impaired motivation and experience learned helplessness. Both the Los Angeles and Munich studies tested for effects on motivation and learned helplessness.

In the Los Angeles study this issue was investigated by examining whether success or failure on a puzzle-solving task would affect performance on a second puzzle-solving task. Response to failure is a standard measure of vulnerability to helplessness. For the first task half of the children were given an insoluble puzzle to work on, while the remaining children were given one that could be solved. All children were then given another puzzle which was soluble. The children were given 2.5 minutes to solve the first puzzle and 4 minutes to solve the second. It was predicted that noise-exposed children would be more affected by the failure experience and would be more likely to give-up on the second puzzle than their quiet condition counterparts. The results indicate that children in the noise group were more likely to give up on the second puzzle and that this was irrespective of whether they had had a success or failure experience on the first puzzle, $F(1, 246) = 11.15, p < 0.001$. The prospective data is consistent with this finding. In the follow-up study children in the noise condition were more likely to fail to solve the second puzzle than either those in the noise abated classrooms or those in the quiet classrooms, $F(2, 235) = 4.12, p < 0.02$.

In the Munich study a similar paradigm to that used in the Los Angeles study was used to assess motivation. Children were first given an insoluble puzzle followed by a soluble puzzle. The index of motivation was the number of attempts made to solve the first puzzle. The results showed a significant effect for this test. Children in the noise condition made fewer attempts to solve the first puzzle than did those in the quiet condition $t(130) = 2.35, p < 0.02$.

Taken together, these results consistently suggest that living in a noisy environment does indeed impair motivation.

**Neuroendocrine indicators of stress**

In both the Munich study and West London Schools Study urine samples were taken in order to investigate whether neuroendocrine indicators of stress would differ significantly between noise and quiet groups.

In the Munich study adrenaline, noradrenaline and cortisol levels were examined. The results indicate that overnight resting levels of both adrenaline, $r(120) = 2.89, p < 0.025$, and noradrenaline, $r(120) = 3.43, p < 0.001$, were
significantly different between the noise and quiet groups. In the case of cortisol levels, however, no significant difference was observed. The prospective data indicate significant increases in levels of catecholamines in those children exposed to noise from the new airport after opening: $F(2, 200) = 36.86, p < 0.001$ for adrenaline; $F(2, 200) = 22.31, p < 0.001$ for noradrenaline. The same trend was not observed in the case of cortisol.

In the West London Schools Study overnight urinary catecholamines (adrenaline and noradrenaline) were tested in a subsample. Free unbound cortisol was also measured. Contrary to the findings of the Munich study there were no significant differences found in the case of either catecholamine or cortisol levels between noise and quiet groups.

The issue of whether chronically noise exposed children have raised stress levels as indicated by neuroendocrinal indicators of stress is still unresolved. The evidence from the Munich and West London Schools Studies provides partial evidence that this may be the case. It is important to emphasise that the observed increases in catecholamine levels were small and do not have clinical implications although they can be interpreted as physiological markers of stress. The long-term consequences of these modest increases in stress hormones are no however known and may be injurious to health.

Blood pressure
Blood pressure measurements were taken in the Los Angeles and Munich studies. In the Los Angeles study resting systolic and diastolic blood pressure was measured using an automated blood pressure recorder. Measurements were taken on the first and second days of testing and it is the mean of these which are reported as the measures for systolic and diastolic blood pressure. Blood pressure was also measured by means of an automated recorder in the Munich study. An average of six resting measurements taken over two consecutive days were calculated for the baseline readings. For both systolic and diastolic blood pressure the reliability estimates for the six readings exceeded alpha of 0.85.

The results from the blood pressure measurements in Wave 1 of the Los Angeles study show significant effects for noise exposure. Thus both systolic $F(1, 245) = 4.61, p < 0.03$, and diastolic, $F(1, 245) = 4.86, p < 0.03$, blood pressure were found to be significantly higher in the noise-exposed groups than in controls. At Wave 2 no such significant effects were observed. This might be attributed to the fact that a relatively high proportion of children in the noise condition who had high blood pressure at Wave 1 were lost to attrition at Wave 2.

The data from the blood pressure measurements in the Munich study show a small non-significant association between resting systolic blood pressure and noise exposure $F(1, 109) = 3.03, p < 0.08$. No such association was found with diastolic blood pressure. A significantly lower reactivity in systolic blood pressure was observed in chronically noise exposed children compared with control children, $F(1, 109) = 15.62, p < 0.001$.

The findings from both the Los Angeles and Munich studies provide evidence for chronic noise exposure being associated with increased physiological stress as indicated by raised blood pressure. As with the increases in catecholamines, the increases in blood pressure which have been observed are very small and should be interpreted as physiological markers of stress rather than as having clinical implications. However, heightened blood pressure over a long period may have serious consequences for health.

Other stress response and health outcome measures
The West London Schools Study used the Lewis Child Stress Scale (Lewis et al., 1994) to assess how stressful the children would find hypothetical life events and also how often the children have experienced stressful life events. The results showed that children in the noise and
quiet conditions did not differ in terms of how stressful they perceived events to be but that children in the quiet condition had experienced more stressful life events than children in the noise condition after adjustment for age, main language spoken at home and deprivation \((p < 0.05)\).

The West London Schools Study also included a measure of the children’s psychological morbidity – the Strengths and Difficulties Questionnaire or SDQ (Goodman, 1994). This questionnaire is made up of subscales for hyperactivity, emotional, conduct problems, peer problems and prosocial behaviour and was completed by a parent or carer. The results showed that noise-exposed children were more likely to suffer from hyperactivity \((p < 0.001)\). This result was unexpected and was inconsistent with the results from a previous study in the same area (Haines et al., 2001a).

In the Los Angeles study absenteeism was examined as a potential indicator of health effects of chronic noise exposure. Unexpectedly, noise-exposed children had a higher attendance rate than their non noise-exposed counterparts \(F(1, 237) = 21.80, p < 0.001\).

These findings do not give a clear message as far as the relationship between noise and stress is concerned. The relationship with hyperactivity is particularly interesting and merits further research.

### Cognition and performance measures

Table 2 summarises the findings from the cognition and performance measures across the three studies. A tick indicates that a significant effect was observed while “—” indicates that no test was run.

### Reading

All three studies investigated whether chronic noise exposure might have an effect on reading.

In the Los Angeles study reading was not actually tested but instead school records or reading performance were used. No effect was found for reading performance, a result which Cohen et al. attribute to the experimental design. They argue that this lack of findings may be attributable to their experimental design in which, and in contrast to earlier studies, noise group and quiet group children attend different schools. However, this was also true of the Munich and West London Studies, which have found significant effects for reading. A more important criticism of Cohen et al.’s methodology is that by using archival reading achievement scores they have confounded chronic and acute noise exposure.

In the Munich study two subscales of the Biglmaier (1969) Reading Test (a valid and reliable German standardised reading test) were administered under quiet conditions. These required children to read aloud paragraphs as well as word lists. The results were as follows. At the old airport for the most difficult

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paragraphs there was a difference between the noise and quiet groups at Wave 1, \( t(82) = 2.79, p < 0.007 \), but not at Waves 2 or 3. At the new airport there were no significant effects. In the case of the word list subscale, at the old airport at Wave 1 there was a significant difference between the noise and quiet groups \( t(99) = 2.68, p < 0.009 \), but not at Waves 2 or 3. In the case of the new airport, there was a difference between the noise and quiet groups at Wave 3 which approached significance, \( t(154) = 1.80, p < 0.074 \), with no significant differences at either Waves 1 or 2.

In the West London Schools Study reading was assessed by means of the Suffolk Reading Scale (Hagley, 1987) Level 2. This is a test of reading comprehension which contains 70 multiple-choice questions each having four potential answers. The test has been standardised and has good construct validity, test-retest reliability and internal consistency (Hagley, 1987). Taking the test as a whole, there was no significant difference in performance between children in the noise and quiet groups. However, when the 15 most difficult items of the test were analysed separately a significant difference was found between the two noise-exposure conditions, and this remained after adjustment for age, main language and deprivation, \( F(1, 417) = 4.75, p = 0.032 \).

Taken together, the results from the reading tests in the Munich and West London Schools Studies seem to point to the same conclusion: that chronic exposure to aircraft noise impairs children’s performance on difficult, and only difficult, reading test items. The results from the Los Angeles study are probably anomalous and attributable to experimental design, although it should be pointed out that the West London Schools Study can also be criticised for using reading test results which were collected under ambient sound conditions.

The results from the three waves of the Munich study provide strong causal evidence for the negative effect of chronic noise exposure on reading. The fact that the reduction in noise exposure after the closure of the old airport was associated with a reduction in impairment, together with the fact that there was evidence for the onset of impairment at the new airport, provides compelling evidence to support this conclusion. Moreover, the fact that the strength of the effect on the word list test at the new airport was non significant at Wave 2 (\( t < 1 \)) and, as noted above, significant at Wave 3, suggests that the effect of the noise is cumulative.

### Long-term episodic memory

Tests of long-term episodic memory were included in both the Munich and West London Schools Studies. In the Munich study the test of episodic memory took the following form. Each child read an interesting text for 12 minutes during which random, intermittent broadband noise was presented. The following day the child’s long-term recall of the text was assessed by the child writing down as much as they could remember of the text that they had read. This took place in silence. Acute noise was introduced at encoding in order to make the task more difficult. Hygge (1997) found that children’s performance on this test was sensitive to acute noise exposure. Consistent with the hypothesis the results showed that at the old airport at Wave 1 there was a marginally significant difference between the noise and quiet groups \( t(104) = 1.88, p < 0.062 \) but not at either Wave 2 or Wave 3. At the new airport, there was a difference between groups at Wave 3 \( t(208) = 2.72, p < 0.007 \) but not at Waves 1 or 2.

The episodic memory test in the West London Schools Study was based closely on that used in the Munich study. It was adapted for group administration from the Child Memory Scale or CMS (Cohen, 1997). This is a normed and psychometrically valid test of episodic memory which tests immediate and delayed recall and recognition of two stories. The stories were pre-recorded and presented to the children by means of an audio-cassette. The delayed recall part of the test took place after a thirty minute delay during which there was an interference task. The test was scored using a standardised scoring scheme which produced scores for immediate recall, delayed recall and recognition. The results for this test did not yield any significant
differences between the noise and quiet conditions.

Taken together these results do not carry a clear message as to whether noise exposure has an effect on episodic memory. The pattern of the Munich results in which the marginal effect at the old airport disappears after the closure of the airport coupled with the onset of a significant effect following the opening of the new airport provides strong causal evidence for effects on episodic memory. In view of this it is surprising that the West London Schools Study results were not consistent. This may in part be attributable to the difficulty in conceptualising and reliably measuring the construct of memory.

**Working memory**

Tests of working memory were included in both the Munich and West London Schools Studies. In the Munich study working memory was tested by presenting a series of consonants to the children at one second intervals over headphones. At random intervals the presentation stopped and the children were required to write down as many consonants as they could remember in sequence, beginning with the most recently presented. Credit was given for consonants recalled in the correct or adjacent positions. Analysis showed a tendency at the old airport at Wave 1 towards more correct responses in the quiet than in the noise condition $t(104) = 1.70, p < 0.092$. At Wave 2 the difference was in the opposite direction $t(104) = 1.63, p < 0.108$ and at Wave 3 no difference was observed. There were no differences across the waves at the new airport.

In the West London Schools Study a backward serial digit recall task was used as a test of working memory. This was adapted for group administration from a paradigm used in many children’s test batteries (e.g. WISC-III). The task consisted of ten trials each having two sets of either 2, 3, 4, 5 or 6 digits presented by means of an audio cassette. The children were given 20 seconds per trial to recall as many of the digits as they could. A digit span was calculated which was equal to the number of digits in the penultimate trial before the child was unable to correctly recall the digit sequence. No significant differences were found between the noise and quiet groups for this test.

Taken together, these results do not provide evidence for an effect of chronic noise exposure on working memory.

**Attention**

All three of the studies included tests of attention.

In the Los Angeles study it was hypothesised that children chronically exposed to noise would become inattentive to acoustic cues (Deutsch, 1964). This was tested by examining whether noise-exposed children are less distractible, this being assumed to be a consequence of being inattentive to acoustic cues. The children completed a task in which they were required to read through a text and cross out all the e’s. They were timed out after two minutes. There were two conditions of this task presented within a repeated measures design. In one condition the children completed the task in ambient noise conditions, while in the other a recording was played at a moderate volume of a male voice reading a story. The children completed each of the two conditions on consecutive days, the ordering being counterbalanced across subjects. The measure of distractibility was the children’s performance on the task under the distraction condition after adjustment for performance on the ambient condition. It was predicted that chronically noise-exposed children would be less affected by the distracting voice than non-noise exposed children. The results for Wave 1 show an interaction for performance in the distraction task and length of time enrolled at the school $F(1, 237) = 5.05, p < 0.03$. Children in the noise group performed better on the distraction task than their quiet group counterparts during their first two years in the noisy environment. However, after four years in the noisy environment they performed less well than those in the quiet group. At Wave 2 the noise-group children were again found to perform better than quiet-group children during their first two years.
but, contrary to the findings from Wave 1, after four years they were found to perform at a similar level to the quiet-group children.

In the Munich study two measures of attention were included. A visual search task required the children to search through twelve complex figures and find five simple figures which were embedded in them. The second test was a reaction time task the children were required to respond to random sequences of red and green lights by pressing keys to indicate the colour of the light. The children were required to carry out this task for five minutes in silence and then for a further five minutes in 85 dBA $L_{eq}$ aircraft noise. The results showed no significant effects for the embedded figures test. In the case of the reaction time test, at the old airport the noise group was significantly slower than the quiet group at Wave 2, $t(61) = 2.29, p = 0.026$. At the new airport the noise group was again found to be significantly slower than the quiet group at Wave 3, $t(121) = 2.09, p = 0.039$.

The West London Schools Study measured sustained attention by means of the Score task from the Test of Everyday Attention in Children or TEA-Ch (Manly et al., 1998; Version A). This task required children to imagine that they were keeping score of a computer game by counting the number of scoring sounds. In this way the task assessed the children’s ability to count tones with irregular stimulus intervals. There were a total of 10 trials and the test was scored according to the correct number of items counted. There were no significant results for this test.

Taken together, these results would appear to provide some evidence for an effect of chronic noise exposure on attention. The results from the Los Angeles study are particularly interesting in that they would appear to suggest that while noise does have an effect on attention that this effect diminishes over time. This finding might reflect adaptation to noise exposure and warrants further investigation.

**Conclusions**

Despite being carried out in different parts of the World, in different climatic and cultural conditions, and using methodologies which differed in certain respects these studies nonetheless produced a number of consistent findings. In terms of stress and health outcomes it would appear that children chronically exposed to high levels of aircraft noise consistently experience raised annoyance levels and raised blood pressure levels. There is some evidence from neuroendocrine indicators of raised stress response levels. There is also strong evidence from these studies that motivation may be impaired and that noise exposed children may experience a sense of helplessness.

In terms of cognitive and performance outcomes, there is strong evidence from the results of these studies that chronic noise exposure affects reading and attention. This is consistent with the findings from other studies e.g. Bronzaft and McCarthy, 1975, Broadbent, 1971. These three studies also provide some evidence for effects on long-term episodic and also working memory.

The findings from these studies point to a number of directions in which research in this area should now be taken. An important question, which has only begun to be addressed, is the effect of noise exposure over time. In particular, research must examine whether the effects which have been observed in the existing research persist over time, whether they become more severe, or whether children are able to adapt to noise and catch-up with their non noise-exposed counterparts. Another direction in which research should be taken is to address dose-response relationships. At what level of noise do effects begin to appear? This of course may be different for different noise sources. Relatedly, the effect of a combination of noise sources requires to be examined. Both the issues of dose-response relationships and combined effects are currently under investigation as part of a large European Commission-funded project (RANCH). The issue of the effects of chronic noise exposure on sleep were not examined in any of the three studies here discussed. This is however an important area which also requires further research.
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