Neurobehavioral effects of exposure to traffic-related air pollution and transportation noise in primary schoolchildren

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Abstract

Background: Children living close to roads are exposed to both traffic noise and traffic-related air pollution. There are indications that both exposures affect cognitive functioning. So far, the effects of both exposures have only been investigated separately.

Objectives: To investigate the relationship between air pollution and transportation noise on the cognitive performance of primary schoolchildren in both the home and school setting.

Methods: Data acquired within RANCH from 553 children (aged 9–11 years) from 24 primary schools were analysed using multilevel modelling with adjustment for a range of socio-economic and life-style factors.

Results: Exposure to NO2 (which is in urban areas an indicator for traffic-related air pollution) at school was statistically significantly associated with a decrease in the memory span length measured during DMST (\(\chi^2=6.8, df=1, p=0.01\)). This remained after additional adjustment for transportation noise. Statistically significant associations were observed between road and air traffic noise exposure at school and the number of errors made during the ‘arrow’ (\(\chi^2=7.5, df=1, p=0.006\)) and ‘switch’ (\(\chi^2=4.8, df=1, p=0.028\)) conditions of the SAT. This remained after adjustment for NO2. No effects of air pollution exposure or transportation noise exposure at home were observed. Combined exposure of air pollution and road traffic noise had a significant effect on the reaction times measured during the SRTT and the ‘block’ and the ‘arrow’ conditions of the SAT.

Conclusions: Our results provide some support that prolonged exposure to traffic-related air pollution as well as to noise adversely affects cognitive functioning.

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1. Introduction

Studies investigating the effects of road traffic noise exposure in children indicate that long-term noise exposure can affect cognitive functioning (Cohen et al., 1973; Sanz et al., 1993; Hygge, 1997, 2003; Lercher et al., 2003). Children attending schools and/or living close to roads are not only exposed to traffic noise, but also to air pollution generated by traffic. Recent results indicate that exposure to air pollution may affect cognitive functioning as well (Suglia et al., 2008; Wang et al., 2009). Both exposures share the same source, so the effects could be attributed to both exposure types. However, as yet, the effects of road traffic noise and traffic-related air pollution exposure were only investigated separately.

There is increasing attention to the possible effects of air pollution on cognitive functioning. In a study investigating 202 primary schoolchildren (aged 8–11 years) living in Boston (U.S.) an association was found between the long-term concentration of black-carbon and decreased cognitive functioning (Suglia et al., 2008). This was in
line with the results of a Chinese study in which a relationship was found between chronic low-level traffic-related air pollution and neurobehavioral functions (Wang et al., 2009). Recently, Freire et al. (2010) reported a negative but statistically non-significant effect of NO₂ exposure on the motor and cognitive abilities of 210 children (aged 4 years) living in South Spain. It is hypothesised that air pollution causes oxidative stress and inflammatory reactions in the brain. This is supported by the results of animal and toxicological studies (Oberdörster et al., 2004; Elder et al., 2006). Oxidative stress is assumed to play a role in the development of Alzheimer’s and Parkinson’s diseases (Calderón-Garcidueñas et al., 2002, 2004; Campbell et al., 2005).

During the last 30 years, a number of studies investigating the effects of long-term exposure to air-, rail-, and road traffic noise among primary school children have been carried out. Cognitive effects were found on reading, attention, problem solving and memory (Cohen et al., 1980, 1981, 1986; Bronzwaer, 1981; Green et al., 1982; Sanz et al., 1993; Evans et al., 1995, 1998; Haines et al., 2001a, 2001b, c, 2002; Hygge et al., 2002; Lercher et al., 2003; Stansfeld et al., 2005; Shield and Dockrell, 2008). The evidence for an association between noise and cognitive functioning was the strongest for exposure to noise from air traffic. At the moment there is no theory that can adequately account for the circumstances in which noise will affect children’s cognitive performance. The mechanisms that have been reported in the literature (Cohen et al., 1986; Stansfeld et al., 2000) have in common that they are important for a child’s language acquisition.

The aim of the current analysis was to assess the possible relationship between exposure to traffic-related air pollution and transportation noise on children’s cognitive functioning. We acquired data from a Dutch subsample of schoolchildren living around Schiphol Amsterdam Airport that were gathered during the European 5th Framework project RANCH (Road traffic and Aircraft Noise exposure and children’s Cognition and Health). As part of RANCH, a cross-sectional study investigating the effects of aircraft and road traffic noise on the cognitive functioning, annoyance and health of children attending primary schools around three airports in the United Kingdom, Spain and The Netherlands was carried out (Stansfeld et al., 2005). In the Dutch subsample, from which the data were used here, cognitive functioning was measured by a selection of computerised neurobehavioral tests from the Neurobehavioral Evaluation System (NES) (Letz, 1991). Effects of noise exposure were only observed in the more difficult and demanding part of the Switching Attention Test (SAT) (Van Kempen et al., 2010). However, it was not possible to take into account the possible impact of air pollution. Recently, we obtained yearly averaged concentrations for PM₁₀ and NO₂ for both the home and school address of the participants.

2. Materials and methods

2.1. Selection and recruitment

Participants were 553 primary schoolchildren that were recruited from 620 children of 24 primary schools around Schiphol-Amsterdam Airport. The selection and recruitment of the children has been described in detail elsewhere (Van Kempen et al., 2010). Briefly, schools were selected from three Municipal Health Office areas around Schiphol Airport according to the distribution of the modelled aircraft and road traffic noise levels of the school, and were matched on socio-economic status. Road- and aircraft noise exposure was expressed as the yearly averaged continuous equivalent sound level for the period between 7:00 and 23:00 h ($L_{Aeq, 7–23 h}$). For socio-economic status a neighbourhood-level indicator of property value and the percentage of people with a non-western background were used. Schools for children with special needs were excluded. From the parents or caregivers written consent was obtained for their children to take part in our study. Ethical approval was given by the Medical Ethical Committee of The Netherlands Organisation for Applied Scientific Research, Leiden.

2.2. Cognitive performance

Cognitive performance was operationalized by means of a selection of neurobehavioral tests from the Neurobehavioral Evaluation System (NES) (Letz, 1991). The following tests were included:

- the Simple Reaction Time Test (SRTT) measures individual reaction times (ms);
- the Switching Attention Test (SAT) measures the child’s ability to switch rapidly between responses;
- the Hand–Eye Coordination Test (HECT) measures coordination;
- the Symbol Digit Substitution Test (SDST) measures perceptual coding and attention; and
- the Digit Memory Span Test (DMST) the subject’s ability to memorise as long as possible sequences.

The NES was administered in the period March–October 2002, during the afternoon in groups of eight children in a quiet room in school with the help of a personal computer and additional hardware (joystick/push button). The duration of the test was approximately 30 min. For further details of the NES, see also Letz (1991) and Van Kempen et al. (2010).

2.3. Air pollution exposure assessment

Air pollution exposure was assessed for each child by linking the school and home addresses to modelled concentrations ($\mu g/m^3$) for nitrogen dioxide (NO₂) and particulate matter (PM₁₀). The latter was estimated with a resolution of 100 × 100 m grids by means of a land use regression model (Hoek et al., 2008). The model was constructed on the basis of 2001 annual mean concentrations from the Dutch national air quality network, supplemented with data on traffic, population, topography and land use. A detailed description of the model can be found elsewhere (Vienneau et al., 2010).

2.4. Noise exposure assessment

Modelled aircraft noise levels (expressed in $L_{Aeq, 7–23 h}$) with a resolution of 250 × 250 m grids were obtained from the Dutch National Aerospace Laboratory (NLR) for the year 2001. These predicted the average noise exposure from 7 to 23 h for a period of one year. Road traffic noise levels (expressed in $L_{Aeq, 8–23 h}$) were estimated from modelled composite data from 2000 and 2001, with a resolution of 25 × 25 m grids using national standard methods (Blom, 2008).

2.5. Child and parent questionnaire

In the same period as the NES was administered, the children were given a self-administered questionnaire at school that included questions on perceived health, perceptions of noise, annoyance, and parental support. Furthermore, the children were given a questionnaire to take home for their caregiver (preferably the mother) to complete. The questionnaire requested information on the health and behaviour of the child, noise sources heard at home, annoyance, and potential confounding factors such as the type of window glazing of the child’s home, indicators for socio-economic status, country of birth and the main language spoken at home. These variables were only available for those children whose parents also completed the questionnaire (N = 485), so parent participation served as a selection criterion for inclusion in analysis.

2.6. Statistical analysis

Similar to the analyses investigating the impact aircraft and road traffic noise on cognitive performance (already reported in Van Kempen et al., 2010), the impact of air pollution was analysed with multi-level analyses carried out in SAS version 9 using the MIXED procedure. Multilevel modelling takes into account the hierarchical structure of the data (children grouped within schools) and enables effects at both the level of school and pupil to be included in the same model. Two-level (pupil and school) random intercept models were used. For the school situation the following three models were run: a model including exposure to NO₂ ($\mu g/m^3$) at school, age (yrs), and sex; the second model equals the first model with the addition of indicators for socio-economic status (crowding, home ownership, employment and mother’s education), longstanding illness (y/n), parental support, main language spoken at home is Dutch (y/n), and type of window glazing at school; the third model equals the second model with the addition of road- and air traffic noise exposure at school ($L_{Aeq, 7–23 h}$). Models 1–3 were additionally run by substituting exposure to NO₂ ($\mu g/m^3$) at school with exposure to NO₂ ($\mu g/m^3$) at home, by substituting noise exposure at school with noise exposure at home, and by substituting type of window glazing at school with double glazing at home (y/n). As a result of the analyses, coefficients (B) and standard errors were presented indicating
the change in score of the cognitive test per 10 μg/m³ increase in traffic-related air pollution. These were estimated under restricted maximum likelihood estimation (REML). The 95% confidence intervals (95% CI) were calculated by means of the estimated standard errors. Statistical significance was tested under full maximum likelihood estimation (ML), using a chi-square test ($\chi^2$) of deviation. To examine combined exposure effects, air pollution and road traffic noise, and air pollution and air traffic noise were entered as multiplicative interaction in model 3.

3. Results

3.1. Data description

485 children were eligible for data-analysis. Table 1 presents the general characteristics of these children and the schools they attend. Table 2 shows that there was sufficient variability in road traffic and aircraft noise levels and NO2 concentrations. Since this was not the case for PM10, the effect of PM10 on the neurobehavioral functioning of the children was not further investigated here.

Moderate correlations were found between NO2 and PM10 concentrations at home and school ($r$=0.5). Moderate correlations were also found between home and school road traffic noise levels ($L_{Aeq, 7–23}$ h) ($r$=0.6). High correlations were found between home and school aircraft noise levels ($L_{Aeq, 7–23}$ h). Correlations of aircraft noise exposure at school with air pollution levels at school were weak ($r$<0.1), as were the correlations between road traffic noise at school and air pollution ($r$~0.2). Correlations of aircraft noise exposure at home with air pollution levels at home were weak ($r$<0.1), as were correlations of road traffic noise exposure at home with air pollution levels at home ($r$~0.3).

3.2. Air pollution and neurobehavioral functioning

Tables 3 and 4 present the fully adjusted associations between NO2, road and air traffic noise exposure at school and at home and the different scores on the NES tests. For the school situation, a statistically significant association between NO2 and the span length measured during DMST ($\chi^2$=6.8, df=1, $p=0.009$). For the other outcome measures, no associations with NO2 levels at school were found. Additional adjustment for road traffic noise and aircraft noise exposure at school had little effect on the associations observed between NO2 at school and the different outcomes of the NES tests: NO2 exposure at school remained significantly associated with the span length measured during DMST ($\chi^2$=5.9, df=1, $p=0.015$). There were no significant associations between NO2 exposure at home and cognition either before or after the additional adjustment for road traffic and aircraft noise exposure at home (Table 4).

3.3. Noise exposure and neurobehavioral functioning

For the school situation, a statistically significant association between road traffic noise exposure and the number of errors made during the ‘arrow’ condition of the SAT ($\chi^2$=7.5, df=1, $p=0.006$). Aircraft noise exposure at school was associated with the number of errors made during the ‘switch’ condition of the SAT ($\chi^2$=4.8, df=1, $p=0.028$). Additional adjustment for NO2 exposure had little effect on the associations observed between road and aircraft noise exposure at school and neurobehavioral functioning: after additional adjustment for NO2 exposure at school, road traffic noise exposure at school remained associated with the number of errors made during the ‘arrow’ condition of the SAT ($\chi^2$=8.5, df=1, $p=0.004$). Air traffic noise at school remained also associated with the number of errors made during the ‘switch’ condition of the SAT ($\chi^2$=4.4, df=1, $p=0.04$). There were no significant associations observed between road or aircraft noise exposure at home and neurobehavioral functioning either before or after the additional adjustment for NO2 exposure at home (Table 4).

3.4. The interaction between air pollution and transportation noise

A significant interaction was found between exposure to air pollution and road traffic noise exposure at school for the reaction times measured during the ‘block’ condition of SAT ($\chi^2$=4.1, df=1, $p=0.043$): Fig. 1 shows that high NO2 concentrations at

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Home</th>
<th>School</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of participating schools</td>
<td>24</td>
<td>485</td>
</tr>
<tr>
<td>Girls, %</td>
<td>48.8</td>
<td>91.9</td>
</tr>
<tr>
<td>Mean age (SD) (yrs)</td>
<td>10.5 (0.6)</td>
<td>10.5 (0.6)</td>
</tr>
<tr>
<td>Socio-economic status</td>
<td>32.9</td>
<td>91.9</td>
</tr>
<tr>
<td>Crowding in the home, %</td>
<td>32.9</td>
<td>91.9</td>
</tr>
<tr>
<td>Parental homeownership, %</td>
<td>32.9</td>
<td>91.9</td>
</tr>
<tr>
<td>Employed parents, %</td>
<td>32.9</td>
<td>91.9</td>
</tr>
<tr>
<td>Mean mother’s education (index 0–1) (SD)</td>
<td>0.3 (0.3)</td>
<td>0.3 (0.3)</td>
</tr>
<tr>
<td>Long-standing illness, %</td>
<td>27.7</td>
<td>27.7</td>
</tr>
<tr>
<td>Main language spoken at home is Dutch, %</td>
<td>93.4</td>
<td>93.4</td>
</tr>
<tr>
<td>Parental support (scale 1–12) (SD)</td>
<td>8.6 (1.9)</td>
<td>8.6 (1.9)</td>
</tr>
</tbody>
</table>

| Glazing at school, % | 47.8 | 49.5 |
| Single | 47.8 | 49.5 |
| Double | 2.7 | 2.7 |
| Double glazing at home, % | 56.0 | 56.0 |

* This is an objective measure of the number of children per room at home. If the number of people is smaller or equal to the number of rooms, then the child's household is defined as crowded.

* Measure of the highest employment status in the child's household. At least one of the parents has to do paid work for at least 19 h per week.

* A relative index ranging from 0 to 1, with higher number indicating low educational attainment.

* Based on parental reports of the child having either attention deficit hyperactivity disorder (ADHD), asthma/bronchitis, eczema, epilepsy, depression, diabetes or dyslexia.

* Parental support for school work is assessed by a self-report scale in the children's questionnaire. Abbreviations: SD, Standard Deviation.
The association between air pollution (NO₂) exposure, road- and air traffic noise at school and cognitive functioning, after adjustment for confounders \(^a\) (n=485).

<table>
<thead>
<tr>
<th>Domain</th>
<th>Test (condition)</th>
<th>Exposure</th>
<th>B (95% CI)</th>
<th>B (95% CI)</th>
<th>B (95% CI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Memory</td>
<td>DMST, span length</td>
<td>NO₂</td>
<td>-0.16 (-0.28–0.04)*</td>
<td>-0.16 (-0.29–0.02)*</td>
<td>-0.03 (-0.12–0.06)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>RTN</td>
<td>0.00 (0.08–0.09)</td>
<td>0.03 (0.06–0.13)</td>
<td>0.05 (0.06–0.15)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ACN</td>
<td>0.03 (0.06–0.13)</td>
<td>0.05 (0.06–0.15)</td>
<td>0.07 (0.08–0.16)</td>
</tr>
<tr>
<td>Attention</td>
<td>SRTT, reaction time (ms)</td>
<td>NO₂</td>
<td>-0.09 (-9.95–7.96)</td>
<td>-1.18 (-11.73–9.36)</td>
<td>1.64 (-4.49–7.77)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>RTN</td>
<td>1.90 (4.65–8.44)</td>
<td>0.80 (8.34–6.75)</td>
<td>-0.72 (-8.22–6.78)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ACN</td>
<td>0.03 (0.06–0.13)</td>
<td>0.05 (0.06–0.15)</td>
<td>0.07 (0.08–0.16)</td>
</tr>
<tr>
<td>SAT, block, no. of errors</td>
<td>NO₂</td>
<td>-0.01 (-0.21–0.18)</td>
<td>-0.01 (-0.22–0.20)</td>
<td>0.00 (-0.13–0.12)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>RTN</td>
<td>0.00 (-0.13–0.11)</td>
<td>0.01 (-0.14–0.16)</td>
<td>0.01 (-0.14–0.16)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ACN</td>
<td>0.01 (-0.14–0.16)</td>
<td>0.01 (-0.14–0.16)</td>
<td>0.01 (-0.14–0.16)</td>
</tr>
<tr>
<td>SAT, block, reaction time (ms)</td>
<td>NO₂</td>
<td>8.16 (-6.70–23.03)</td>
<td>7.38 (-8.52–23.28)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>RTN</td>
<td>1.69 (-8.18–11.56)</td>
<td>2.64 (-8.74–14.01)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>ACN</td>
<td>2.01 (-9.18–13.46)</td>
<td>2.14 (-9.18–13.46)</td>
<td></td>
</tr>
<tr>
<td>SAT, arrow, no. of errors</td>
<td>NO₂</td>
<td>0.01 (-0.33–0.35)</td>
<td>-0.16 (-0.49–0.16)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>RTN</td>
<td>0.30 (0.10–0.50)</td>
<td>-0.12 (-0.35–0.11)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>ACN</td>
<td>0.26 (0.07–0.45)</td>
<td>-0.11 (-0.34–0.12)</td>
<td></td>
</tr>
<tr>
<td>SAT, arrow, reaction time (ms)</td>
<td>NO₂</td>
<td>8.22 (-12.29–28.72)</td>
<td>11.42 (-10.45–33.29)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>RTN</td>
<td>-4.43 (-18.00–9.15)</td>
<td>-1.96 (-14.69–10.76)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>ACN</td>
<td>13.48 (-2.16–29.23)</td>
<td>12.71 (-2.87–28.29)</td>
<td></td>
</tr>
<tr>
<td>SAT, switch, no. of errors</td>
<td>NO₂</td>
<td>-0.34 (-1.68–0.99)</td>
<td>-0.63 (-1.92–0.67)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>RTN</td>
<td>0.71 (-0.11–1.52)</td>
<td>0.92 (-0.02–1.85)*</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>ACN</td>
<td>0.57 (-0.19–1.33)</td>
<td>0.97 (0.04–1.90)*</td>
<td></td>
</tr>
<tr>
<td>SAT, switch, reaction time (ms)</td>
<td>NO₂</td>
<td>1.91 (-31.29–35.11)</td>
<td>11.40 (-23.94–46.74)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>RTN</td>
<td>-15.14 (-37.70–7.43)</td>
<td>-12.50 (-33.20–8.20)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>ACN</td>
<td>11.69 (-14.24–37.61)</td>
<td>10.64 (-14.66–35.93)</td>
<td></td>
</tr>
<tr>
<td>Locomotion</td>
<td>HECT, deviation (pixels)</td>
<td>NO₂</td>
<td>0.06 (-0.02–0.13)</td>
<td>0.04 (0.04–0.13)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>RTN</td>
<td>0.03 (-0.02–0.08)</td>
<td>0.04 (0.01–0.09)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>ACN</td>
<td>0.01 (-0.05–0.07)</td>
<td>0.01 (-0.05–0.07)</td>
<td></td>
</tr>
<tr>
<td>Perceptual coding</td>
<td>SDST, latency</td>
<td>NO₂</td>
<td>0.05 (-0.07–0.17)</td>
<td>0.02 (-0.11–0.16)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>RTN</td>
<td>0.04 (-0.04–0.13)</td>
<td>0.05 (-0.03–0.12)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>ACN</td>
<td>-0.06 (-0.16–0.04)</td>
<td>-0.06 (-0.16–0.03)</td>
<td></td>
</tr>
</tbody>
</table>

* All models are adjusted for age, gender, employment status, crowding, home ownership, mother's education, long-standing illness, main language spoken at home, parental support, and type of window glazing at school.

* Significant association at \( z < 0.05 \), tested by means of a \( \chi^2 \)-test; Abbreviations: B, estimated change per 10 μg/m³ increase in NO₂ or estimated change per 10 dB(A) increase in road- or aircraft noise traffic level; 95% CI, 95% confidence intervals calculated by means of the standard error; NO₂, exposure to nitrogen dioxide at school; RTN, exposure to road traffic noise at school; ACN, exposure to aircraft noise at school; DMST, Digit Memory Span Test; SRTT, Simple Reaction Time Test; SAT, Switching Attention Test; HECT, Hand–Eye Coordination Test; SDST, Symbol Digit Substitution Test; ms, milliseconds.

School had more of an effect upon the reaction time in high road traffic noise exposure categories than in low traffic noise exposure categories. For the other NES outcomes, no significant effects of combined exposure to air pollution and road traffic noise exposure at school were found. Also no significant effects of combined exposure of air pollution and air traffic noise at school were found.

The interaction between exposure of air pollution and road traffic noise exposure at home was only significant for the reaction times measured during SRTT \( (\chi^2=8.4, \text{df}=1, p=0.004) \) and the ‘arrow’ condition of SAT \( (\chi^2=5.3, \text{df}=1, p=0.02) \). Fig. 1 shows that high NO₂ concentrations at home had more an effect upon the reaction times in high road traffic noise exposure categories than in low traffic noise exposure categories.

### 4. Discussion

#### 4.1. Neurobehavioral effects of air pollution

We assessed the effect of air pollution and noise on children’s cognitive functioning. Air pollution at school was found to be associated with a decrease in the span length measured during DMST. No associations were found between NO₂ exposure at school and reaction speed, switching attention, locomotion and perceptual coding. No effects of air pollution at home were found. Until now only three other studies investigated the effects of air pollution on the cognitive functioning in children: Suglia et al. (2008) investigated the effects of exposure to black carbon at home on the cognitive functioning of 202 primary school children living in Boston (US). After adjustment for age, gender, primary language spoken at home and mother’s education, significant effects of exposure to black carbon were found on intelligence, active learning and memory. Wang et al. (2009) investigated the effects of traffic-related air pollution in 963 children (aged 8–10 years) attending two schools in China. After correction for age, sex, body mass index, educational attainment of the father, second hand smoking, open kitchen, and household fuel, they found that the cognitive test scores of children attending the primary school in an area with higher levels of air pollution were lower than the cognitive test scores of children attending the primary school in an area with lower levels of air pollution. Similar to our study, cognitive functioning was measured by means of, amongst others, NES tests (Wang et al., 2009). Since Wang et al. (2009) compared two groups of children instead of children exposed to a broad range of air pollution, the power of their study was limited: a continuous association is a stronger indication for the existence of a relationship than a contrast between two groups. Recently, Freire et al. (2010) reported on the results of a study on the association between NO₂ exposure and the cognitive functioning of 210 children aged 4 years, living in southern Spain: Children exposed to higher NO₂ levels.
(> 24.75 μg/m³) showed a statistically non-significant decrease in scores on the McCarthy Scales of Children's Abilities (MSCA), after adjustment for potential confounding factors such as body weight, body length, gestational age, smoking during pregnancy, place of residence, and indicators of socio-economic status. Similar to our study, annual mean NO₂ concentrations at the address of the participating children were assessed by means of land-use-regression modelling. By means of the MSCA some cognitive domains (e.g. memory) were measured that were comparable with the cognitive domains measured by means of tests from the NES.

In addition to children, some studies investigated the effects of air pollution on the cognitive functioning of adults: Power et al. (2011) investigated the association between long-term exposure to black-carbon and cognition among 680 white elderly men (aged 71 ± 7 years) from an ongoing longitudinal cohort established in 1963. Black Carbon was assessed by means of a validated spatiotemporal land-use regression model. Cognitive functioning was assessed by means of seven tests derived from established cognitive test batteries including the NES and the Mini-Mental State Examination (MMSE). After adjustment for confounders such as age, education, first language, and computer experience, black carbon exposure was found to be significantly associated with the risk of having a low score on the MMSE (Power et al., 2011). In another recent study investigating 1764 adults (aged 37.5 ± 10.9 years) living in the US, associations were found between PM₁₀, O₂ (both yearly averaged concentrations) and perceptual coding and aspects of attention and short-term memory. After adjustment for age, sex, education and family income, the association disappeared as was the case in most studies investigating the association between exposure to fine PM and mild cognitive impairment (MCI) among 399 German women (aged 68–79 years) who lived for more than 20 years at the same residential address. For women of age less than 75 years, the scores of tests measuring MCI were significantly reduced if the participant's residential address was within a distance of 50 m to the next busy road with a traffic density of more than 10,000 cars per day. No association between distance to the next busy road and MCI was found among women older than 75 years. Also no association was found between the long-term concentration of PM₁₀ and cognitive functioning (Ranft et al., 2009).

As was the case in most studies investigating the association between air pollution and cognitive functioning, the scores of the cognitive tests in our analyses were related to yearly average concentrations of air pollution. It cannot be excluded that our results may be caused by short-term variations in air pollution. Animal and toxicological studies have demonstrated that short-term exposures to air pollution cause inflammatory reactions and oxidative stress in the brain (Suglia et al., 2008). Recently, Crüts...
et al. (2008) found changes in the electroencephalograms (EEG) of ten human volunteers during and after a short-term (one hour) exposure to diesel exhaust. Local information on the exposure to air pollution shortly before the measurement of cognitive functioning, was not available for our study.

4.2. Location of exposure: school versus home.

Despite the much larger amount of time spent at home, no effects of exposure to air pollution at home were found. This was also the case with the effects of noise exposure: Only for the school situation statistically significant associations were observed between road and air traffic noise exposure at school and the number of faults made during the ‘arrow’ and the ‘switch’ conditions of the SAT, respectively; no effects of home noise exposure were found. It is possible that exposure to air pollution and noise at school or home is different and differently affected the cognitive functioning of the children: during school time more is asked of the children’s cognitive abilities compared to leisure time at home. The cognitive effects due to exposure to air pollution at school may also be explained by physical education and other exercise at school that increase ventilation rate and dose of pollutants to lungs and the brain and thereby increase the risk associated with exposure.

4.3. The interaction between air pollution and transportation noise.

Our data suggest independent effects of exposure to air pollution and exposure to transportation noise on children’s cognitive functioning: As Tables 3 and 4 show, additional adjustment for road traffic and aircraft noise exposure had little effect on the associations observed between NO₂ exposure and neurobehavioral functioning. Also, additional adjustment for NO₂ exposure had little effect on the associations observed between road and aircraft noise exposure and neurobehavioral functioning.

This is similar to what was found in studies investigating the effects of noise and air pollution on cardiovascular disease (Tobías et al., 2001; Linares et al., 2006; De Kluizenaar et al., 2007; Beelen et al., 2009; Selander et al., 2009). In these studies, the reported associations with air pollution hardly changed after additional adjustment for noise exposure, nor did the reported associations with noise after additional adjustment for air pollution.

Fig. 1. The relation between air pollution at school and the reaction time measured during the Block condition of the SAT, and the relation between air pollution at home reaction time measured during SRTT and the Arrow condition of the SAT, for different levels of road traffic noise exposure at home. The dotted vertical line corresponds to no effect of air pollution. The circles correspond to the estimated change in reaction time (ms) per 10 μg/m³ increase of air pollution and the horizontal lines correspond to the 95% confidence interval.
However, the interaction between exposure to NO$_2$ and road traffic noise at home was significantly but unexpectedly associated with the reaction times measured during SRTT and the ‘arrow’ condition of the SAT: high NO$_2$ concentrations at home had more of an effect upon the reaction times in high road traffic noise exposure categories than in low road traffic noise exposure categories. In other words: children living in areas with high levels of road traffic noise had a shorter reaction time as NO$_2$ concentrations increased. A comparable interaction effect was found in a Swedish case-control study investigating the relation between road traffic noise exposure, traffic-related air pollution (NO$_2$) and myocardial infarction (Selander et al., 2009).

4.4. Study strengths and limitations

A number of strengths and limitations of the RANCH-project were already mentioned elsewhere (Stansfeld et al., 2000; Van Kempen et al., 2010). Here, only issues that were specific for the current analysis will be addressed. This is the first study that links cognitive functioning in children with air pollution and exposure to transportation noise. As yet, the effects of noise and air pollution were investigated separately. Participants were distributed over both a broad range of noise exposure and air pollution, increasing the power of this study. Due to the low correlation between the noise and air pollution indicators it was possible to disentangle the effects of both exposure types. Since time activity studies (Freijer and De Loos, 1998; Xue et al., 2004) indicate that children spend more time at home, the current study investigated the effects of both school and home exposure on cognition. The hierarchical structure of the data (children within schools) has been taken into account, which was not always the case in analyses of previous studies.

The cross-sectional design of our study limits causal interpretations of the possible relation between air pollution and children's cognitive functioning. Furthermore, it is unknown to what extent the estimated outdoor air pollution levels and road traffic noise levels, used in the current analysis, reflect the average exposure of the children during their time at school or at home. However, exposure-misclassification because children move in and out different classrooms daily or move to a different classroom (front or rear) each year during their time at school cannot be excluded. The impact on our findings of exposure misclassification is unknown. The effect of possible infiltration of polluted air from outside into the classroom is also unknown: the results of a study investigating 241 children (aged 6–12 years) attending 6 primary schools in the Netherlands showed that differences in personal exposure between the children did not disappear after adjustment for outdoor sources of NO$_2$ (Rijnders et al., 2001). Another weak aspect of this study is that we did not take into account the effect of exposure to second-hand tobacco smoke. There is increasing evidence that exposure to second-hand smoking affects children's cognitive and behavioural functioning (Yolton et al., 2005). Although it cannot be excluded that our results were at least in part the consequence of exposure to tobacco smoke, the results of earlier studies investigating the association between air pollution and cognitive functioning hardly changed after additional adjustment for tobacco smoke exposure (Suglia et al., 2008; Chen and Schwartz, 2009; Ranft et al., 2009).

4.5. Interpretation of the results

In this study a statistically significant association was observed between air pollution at school and the memory span length measured during DMST; the result did not change after additional adjustment for noise. Secondly, statistically significant associations were observed between road- and air traffic noise at school and the number of errors made during the ‘arrow’ and the ‘switch’ conditions of the SAT, respectively. Finally, we observed that combined exposure of air pollution and road traffic noise had a significant effect on the reaction times measured during the SRTT and the ‘block’ and the ‘arrow’ conditions of the SAT. The meaning of these results is difficult to interpret. Both the decrease in memory span length in relation to air pollution and the elevation in the number of errors made during SAT found in relation to road traffic noise exposure were small and the clinical significance of such minor changes is difficult to determine. The internal consistency of the results is small; no clear relationship was found between air pollution and other cognitive outcomes. Therefore it cannot be excluded that our findings could be due to chance.

5. Conclusions

Our results provide some support that prolonged exposure to traffic-related air pollution as well as to noise adversely affects cognitive functioning. Although our data suggest independent effects of air pollution and noise on children’s cognitive functioning, some unexpected interactions between exposure to air pollution and road traffic noise were found. Given the novel research subject, more, and preferably longitudinal, studies are needed in order to draw general and definite conclusions with regard to the adverse effects of air pollution on cognitive functioning and the possible interaction between air pollution and transportation noise.

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