



## The associations of air pollution, traffic noise and green space with overweight throughout childhood: The PIAMA birth cohort study



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### ABSTRACT

**Background:** Air pollution, traffic noise and absence of green space may contribute to the development of overweight in children.

**Objectives:** To investigate the combined associations of air pollution, traffic noise and green space with overweight throughout childhood.

**Methods:** We used data for 3680 participants of the Dutch PIAMA birth cohort. We estimated exposure to air pollution, traffic noise and green space (i.e. the average Normalized Difference Vegetation Index (NDVI) and percentages of green space in circular buffers of 300 m and 3000 m) at the children's home addresses at the time of parental reported weight and height measurements. Associations of these exposures with overweight from age 3 to 17 years were analyzed by generalized linear mixed models, adjusting for potential confounders. Odds ratios (OR's) are presented for an interquartile range increase in exposure.

**Results:** odds of being overweight increased with increasing exposure to NO<sub>2</sub> (adjusted OR 1.40 [95% confidence interval (CI) 1.12–1.74] per 8.90 µg/m<sup>3</sup>) and tended to decrease with increasing exposure to green space in a 3000 m buffer (adjusted OR 0.86 [95% CI 0.71–1.04] per 0.13 increase in the NDVI; adjusted OR 0.86 [95% CI 0.71–1.03] per 29.5% increase in the total percentage of green space). After adjustment for NO<sub>2</sub>, the associations with green space in a 3000 m buffer weakened. No associations of traffic noise with overweight throughout childhood were found. In children living in an urban area, living further away from a park was associated with a lower odds of being overweight (adjusted OR 0.67 [95% CI 0.52–0.85] per 359.6 m).

**Conclusions:** Exposure to traffic-related air pollution, but not traffic noise or green space, may contribute to childhood overweight. Future studies examining the associations of green space with childhood overweight should account for air pollution exposure.

### 1. Introduction

Childhood overweight and obesity have emerged as major global public health problems. Air pollution, traffic noise and absence of green space may contribute to the development of overweight in children. Traffic-related air pollution may affect children's BMI through changes in basal metabolism due to effects on mitochondria and brown adipose tissue, or through pro-inflammatory central nervous system effects on appetite control (McConnell et al., 2016). Air pollution may also result

in metabolic dysfunction via increased oxidative stress and adipose tissue inflammation and decreased glucose utilization in skeletal muscle (An et al., 2018). Studies examining the associations of air pollution with children's weight have shown mixed results (An et al., 2018).

Traffic noise has been hypothesized to affect body composition through stress and sleep disturbances (Babisch, 2003; Pirrera et al., 2010). Studies in adults have found associations of exposure to road traffic and railway noise with markers of obesity (Christensen et al., 2015, 2016b; Pyko et al., 2015). On the contrary, a longitudinal study

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in children reported that residential exposure to road and railway traffic noise during pregnancy and early childhood were not significantly associated with a higher risk of overweight at seven years of age (Christensen et al., 2016a).

Green space has been hypothesized to have a beneficial effect on children's BMI by increasing physical activity levels or through stress reduction (Hartig et al., 2014; James et al., 2015). However, there is no consistent evidence for an association between residential exposure to green space and children's weight status (James et al., 2015; Lachowycz and Jones, 2011; Sanders et al., 2015).

Higher levels of green space are associated with lower concentrations of air pollution and lower levels of traffic noise (Hystad et al., 2014). Air pollution and noise share road traffic as a common source (Davies et al., 2009; Fecht et al., 2016). Since air pollution, traffic noise and green space levels are spatially correlated, it is important to examine the combined associations of these exposures with health outcomes. However, no studies have examined the combined associations of these three environmental exposures with overweight in children. The aim of the present study is therefore to investigate the individual and combined associations of air pollution, traffic noise and green space with overweight throughout childhood.

The percentage of the global population living in urban areas is projected to increase from 54% in 2015 to 60% in 2030 (World Health Organization, 2016). Because of the high urbanization, more people live in environments that are generally more polluted and less green. Since green spaces are less available in urban areas, green spaces may play a more important role for urban residents than for those living in suburban or rural areas. For these reasons, we also assessed the associations of air pollution, traffic noise and green space with overweight in children living in an urban area.

## 2. Methods

### 2.1. Study design and study population

We used data from the Dutch Prevention and Incidence of Asthma and Mite Allergy (PIAMA) birth cohort study. Detailed descriptions of the design of the PIAMA study have been published previously (Brunekreef et al., 2002; Wijga et al., 2014). In brief, pregnant women were recruited from the general population in three different regions of the Netherlands: north, central and west. Region north is largely rural, has a lower population density and substantially lower air pollution levels as compared to regions central and west. Region west includes the city of Rotterdam. The baseline study population consisted of 3963 children born in 1996/1997. Participating parents completed questionnaires during pregnancy, at the child's ages of three months and one year, and yearly thereafter until the child was eight. When the children were 11, 14 and 17 years old, the parents and children received separate questionnaires. The questionnaires comprised questions on growth and development, socio-demographic and lifestyle characteristics. The study protocol was approved by the medical ethical committees of the participating institutes and all parents gave written informed consent.

### 2.2. Assessment of overweight

Data on weight, height and the dates of the measurements were derived from the parental questionnaires. Parents were asked to report their child's weight and height measured by a medical professional, if this measurement took place within the last three months. Otherwise, parents were requested to measure their child's weight and height without shoes and heavy clothes themselves and to report it.

To facilitate longitudinal data analysis, weight and height measurements were grouped based on the exact age at the time of the weight and height measurements. This resulted in the following age categories: 0.5–1.5 years, 1.5–2.5 years, 2.5–3.5 years, 3.5–4.5 years, 4.5–5.5 years, 5.5–6.5 years, 6.5–7.5 years, 7.5–9.5 years, 10.5–13.5

years, 13.5–16.0 years, and 16.0–19.0 years. We restricted the dataset to one observation per child per age category. In case of multiple observations for one age category, we selected the most complete set (of weight and height) with age as close as possible to midpoint of the age category. Only data from age 2.5 to 3.5 years onwards were included in this analysis as no definition of overweight is available before the age of two years (Cole and Lobstein, 2012).

BMI (weight (kg)/height (m)<sup>2</sup>) was calculated from the weight and height measurements and overweight (including obesity) was defined according to age and sex-specific International Obesity Task Force cut-offs (Cole and Lobstein, 2012).

In this study, we included 3680 children for whom at least one BMI measurement was available from the age of three years until the age of 17 years.

### 2.3. Exposure assessment

We focused on recent exposure to air pollution, traffic noise and green space in this analysis. We estimated air pollution concentrations and traffic noise levels and assessed exposure to green space at the children's current home addresses at the time of the weight and height measurements. An overview of the residential exposures included in this study is provided in Table S1.

#### 2.3.1. Air pollution

We estimated annual average air pollution concentrations with land-use regression (LUR) models that were developed within the ESCAPE project. Details of the LUR model development have been described elsewhere (Beelen et al., 2013; Eeftens et al., 2012). In brief, air pollution monitoring campaigns were performed between February 2009 and February 2010 in the Netherlands/Belgium. Nitrogen dioxide (NO<sub>2</sub>) measurements were performed in three periods of 14 days, in the cold, warm and intermediate seasons, at 80 sites. Simultaneous measurements of particulate matter with a diameter of less than 2.5 μm (PM<sub>2.5</sub>), less than 10 μm (PM<sub>10</sub>), 2.5–10 μm (PM<sub>coarse</sub>) and PM<sub>2.5</sub> absorbance (a marker of black carbon) were performed at half of the sites. The three measurements were averaged after temporal adjustment using data from a continuous reference site to obtain the annual average concentrations for each site (Eeftens et al., 2012). Predictor variables on population density, traffic intensity and land-use derived from Geographic Information Systems (GIS) were used to model the spatial variation of the annual average air pollution concentrations in the Netherlands/Belgium. The performance of the LUR models was evaluated using leave-one out cross validation (R<sup>2</sup><sub>LOOCV</sub>) and ranged from 0.60 for PM<sub>10</sub> to 0.89 for PM<sub>2.5</sub> absorbance (Table S4). We used the regression models to estimate exposure to air pollution at all ages without back-extrapolation. In the present study, we included NO<sub>2</sub>, PM<sub>2.5</sub>, PM<sub>10</sub> and PM<sub>2.5</sub> absorbance.

#### 2.3.2. Traffic noise

We estimated annual average traffic noise exposure by the Standard Model Instrumentation for Noise Assessments (STAMINA), which has been developed by the Dutch National Institute for Public Health and the Environment (Schreurs et al., 2010). The STAMINA model implements the standard Dutch Calculation method for traffic and industrial noise and uses detailed information on the types of noise source and ground data (information regarding the ground impedance (water, grass, asphalt) and the presence of buildings). The model has a resolution of 10 × 10 m around the noise sources. At increasing distances from the noise source, the resolution gradually decreases to at most 80 × 80 m (Schreurs et al., 2010).

Daily average (Lden) and nighttime average (Lnight) road traffic and railway noise exposure were estimated for 2011. Lden is the annual average A-weighted noise level weighted with 5 dB(A) extra in the evening (19.00–23.00) and 10 dB(A) extra at night (23.00–07.00). Because of the high correlations between Lden and Lnight (r = 0.96 for

railway noise;  $r = 0.99$  for road traffic noise), we only used Lden in the analyses.

### 2.3.3. Green space

We used the Normalized Difference Vegetation Index (NDVI) to assess greenness levels surrounding the children's homes. The NDVI was derived from Landsat 5 Thematic Mapper (TM) data at  $30\text{ m} \times 30\text{ m}$  resolution. NDVI values range from  $-1$  to  $1$ , with higher values indicating more greenness (Weier and Herring, 2000). Negative values correspond to water and were set to zero. We created two maps of the Netherlands by combining cloud free images of 1) the summers of 2000 and 2002 and 2) the summer of 2010. From these maps, we calculated the average NDVI in circular buffers of 300 m and 3000 m around the children's homes for each of the two years separately.

We hypothesized that different types of green space may have different effects on children's weight. To distinguish the effects of different types of green space, we defined all green spaces within a population cluster (i.e. a locality with at least 25 predominantly residential buildings (Vliegen et al., 2006)) as 'urban green space'. We classified the remaining green spaces as 'agricultural green space' (fruit or tree nurseries, arable land, grassland or orchards) or 'natural green space' (heather or forests). We used two land-use maps of the Netherlands: Top10NL and Bestand Bodemgebruik. Top10NL is a detailed land-use map of the Netherlands that, in contrast to the NDVI, does not include street greenery and private green property (such as gardens) (Kadaster, 2017). Top10NL is only available from 2012 onwards. Therefore, we used Bestand Bodemgebruik to assess the percentages of green space at the time of the weight and height measurements preceding 2012. Bestand Bodemgebruik is less detailed than Top10NL (it contains fewer land-use categories), but in contrast to Top10NL, it contains a separate category for parks defined as public green spaces that can be used for relaxation (Centraal Bureau voor de Statistiek, 2008). We assessed the total percentage of green space and percentages of urban, agricultural and natural green space in buffers of 300 m and 3000 m around the children's homes for 1996, 2006 (based on Bestand Bodemgebruik) and 2016 (based on Top10NL). With Bestand Bodemgebruik and a detailed map covering all roads and paths of the Netherlands, we estimated the distance along roads (i.e. network distance) in meters from the children's homes to the nearest park entrance.

The NDVI map (2000/2002 or 2010) and land-use map (1996, 2006 or 2016) that was closest to the date of the weight and height measurement was used to assess exposure to green space at the time of the weight and height measurements. Surrounding greenness, the percentages of green space and distance to the nearest park were determined in ArcGIS 10.2.2 (Esri, Redlands, CA, USA).

### 2.4. Confounders

Maternal and paternal level of education (low, intermediate, high) were obtained from the 1 year questionnaire and information on maternal smoking during pregnancy (yes/no) from the pregnancy questionnaire. Parental smoking in the child's home (yes/no) was assessed through the repeated parental questionnaires from pregnancy until age 17. We used the status scores of 4-digit postal code areas from The Netherlands Institute for Social Research (SCP) of 1998 until 2014 to assess neighborhood socio-economic status (SES). Status scores include the average income, the percentage of residents with a low income, the percentage of low educated residents and the percentage unemployed subjects in a postal code area. A higher status score indicates a higher neighborhood SES (Knol, 2012).

The prevalence of overweight is different in the three regions of the Netherlands where our study participants live (north, central and west). Moreover, region north has substantially lower air pollution levels as compared to regions central and west. We have therefore adjusted our analyses for region.

### 2.5. Statistical analysis

First, we used natural splines to determine the linearity of the exposure-response relationships. To test whether the goodness-of-fit of the models with splines was significantly better than the goodness-of-fit of linear models (with one degree of freedom), we used the likelihood ratio test. Since there was no evidence of non-linearity, we used exposures as continuous variables in all analyses. We then analyzed the associations of air pollution, traffic noise and green space with overweight from age 3 to 17 years with generalized linear mixed models. A random subject-specific intercept was included to account for within-subject correlation across the repeated overweight measurements. We have decided not to examine the associations of the exposures with BMI growth trajectories, since we hypothesized that recent (rather than early life) exposure to green space may be associated with children's weight by increasing physical activity levels. Moreover, age-specific estimates, obtained from mixed models with exposure-age interaction terms, provide information on whether the associations of air pollution, traffic noise and green space with overweight differ across different ages.

We specified three models with increasing level of adjustment for potential confounders. Model I was adjusted for age and sex. Model II was adjusted for age, sex, maternal and paternal level of education, maternal smoking during pregnancy, parental smoking in the child's home and neighborhood SES. Model III was additionally adjusted for region (north, central or west). Associations with the percentages of urban, agricultural and natural green space were additionally adjusted for the other types of green space in the same buffer size. We considered model III as the main model and calculated age-specific estimates for model III only. Odds ratios (OR's) are presented for an interquartile range (IQR) increase in exposure. The majority of the children (between 58% and 86% in the different age categories) had no natural green space in a 300 m buffer around their homes. Therefore, we created a binary variable: natural green space in a buffer of 300 m yes/no.

We have additionally assessed the associations of air pollution, traffic noise and green space with overweight in children living in an urban area ( $\geq 1500$  addresses/km<sup>2</sup>). Children who have moved from an urban area to a non-urban area (or vice versa) during the study period were excluded from these analyses ( $n = 736$ ). The OR's are presented for the same increase in exposure as for the main analyses to facilitate the comparison of the results. We assessed the association between the distance to the nearest park and overweight only in children who lived in an urban area.

The statistical analyses were performed with SAS version 9.4, except the spline analyses, which we performed with R version 3.4.3 (R Core Team <http://www.R-project.org/>).

## 3. Results

### 3.1. Characteristics of the study population

The number of participants decreased over the course of the follow-up period, especially from age category 10.5–13.5 years onwards. To show the changes in our study population throughout the study period, characteristics of the study population for the youngest and oldest age category studied are presented in Table 1. There was a selective loss to follow-up of children with lower paternal and maternal education. Moreover, 25.9% of the children with data for the youngest age category had at least one parent who smoked, whereas this percentage was 9.0 for the children with data for the oldest age category. The prevalence of overweight children ranged from 7.9% in age category 2.5–3.5 to 11.5% in age categories 6.5–7.5 and 7.5–9.5 (Fig. 1).

### 3.2. Air pollution, traffic noise and green space

The distributions of the air pollution, traffic noise and green space

**Table 1**

Characteristics of the study population and the distribution of air pollution, traffic noise and green space levels for participants with data for the youngest (2.5–3.5 years) and oldest (16.0–19.0 years) age categories studied.

Characteristic	Participants with data at 2.5–3.5 years <sup>a</sup>	Participants with data at 16.0–19.0 years <sup>a</sup>
N	2735	1767
Sex (boys), n (%)	1418 (51.9)	873 (49.4)
Maternal level of education, n (%)		
Low	611 (22.6)	295 (16.8)
Intermediate	1129 (41.7)	716 (40.7)
High	967 (35.7)	750 (42.6)
Paternal level of education, n (%)		
Low	683 (25.4)	363 (20.7)
Intermediate	918 (34.2)	570 (32.5)
High	1087 (40.4)	819 (46.8)
Maternal smoking during pregnancy (yes), n (%)	446 (16.4)	231 (13.2)
Parental smoking in child's home (yes), n (%)	706 (25.9)	159 (9.0)
Neighborhood SES <sup>b</sup>	0.16 (−0.32 to 0.61)	0.25 (−0.50 to 0.96)
Children living in an urban area, n (%) <sup>c</sup>	1099 (40.2)	757 (43.1)
Region, n (%) <sup>d</sup>		
North	862 (31.6)	544 (31.0)
Central	1122 (41.1)	757 (43.1)
West	748 (27.4)	455 (25.9)
NO <sub>2</sub> (µg/m <sup>3</sup> ) <sup>e</sup>	23.6 (18.8–27.8)	22.8 (17.8–27.0)
PM <sub>2.5</sub> absorbance (10 <sup>−5</sup> /m) <sup>e</sup>	1.2 (1.1–1.4)	1.2 (1.0–1.3)
PM <sub>2.5</sub> (µg/m <sup>3</sup> ) <sup>e</sup>	16.5 (15.6–16.8)	16.5 (15.6–16.7)
PM <sub>10</sub> (µg/m <sup>3</sup> ) <sup>e</sup>	24.6 (24.1–25.2)	24.5 (24.0–25.0)
Road traffic noise (L <sub>den</sub> dB(A))	53.1 (49.9–56.8)	52.4 (49.3–56.5)
Railway noise (L <sub>den</sub> dB(A))	30.6 (29.0–37.9)	30.7 (29.0–38.2)
Average NDVI in 300 m buffer	0.56 (0.49–0.63)	0.55 (0.48–0.61)
Total percentage of green space in 300 m buffer	12.9 (4.0–29.6)	19.9 (11.6–33.4)
Percentage urban green in 300 m buffer	3.7 (0.0–10.5)	9.8 (4.3–15.6)
Percentage agricultural green in 300 m buffer	0.0 (0.0–16.5)	1.1 (0.0–17.0)
Percentage natural green in 300 m buffer	0.0 (0.0–0.0)	0.0 (0.0–1.3)
Average NDVI in 3000 m buffer	0.64 (0.57–0.71)	0.62 (0.56–0.68)
Total percentage of green space in 3000 m buffer	57.6 (42.2–71.2)	55.9 (42.4–67.0)
Percentage urban green in 3000 m buffer	5.5 (1.9–7.9)	6.1 (2.8–9.7)
Percentage agricultural green in 3000 m buffer	44.2 (25.0–62.0)	40.0 (23.3–55.9)
Percentage natural green in 3000 m buffer	3.2 (1.1–9.0)	4.2 (2.1–10.4)

Abbreviations: SES = socioeconomic status; NDVI = Normalized Difference Vegetation Index.

<sup>a</sup> Values are presented as median (25–75th percentiles) unless otherwise indicated.

<sup>b</sup> A higher score indicates a higher SES.

<sup>c</sup> Urban area: ≥ 1500 addresses/km<sup>2</sup>.

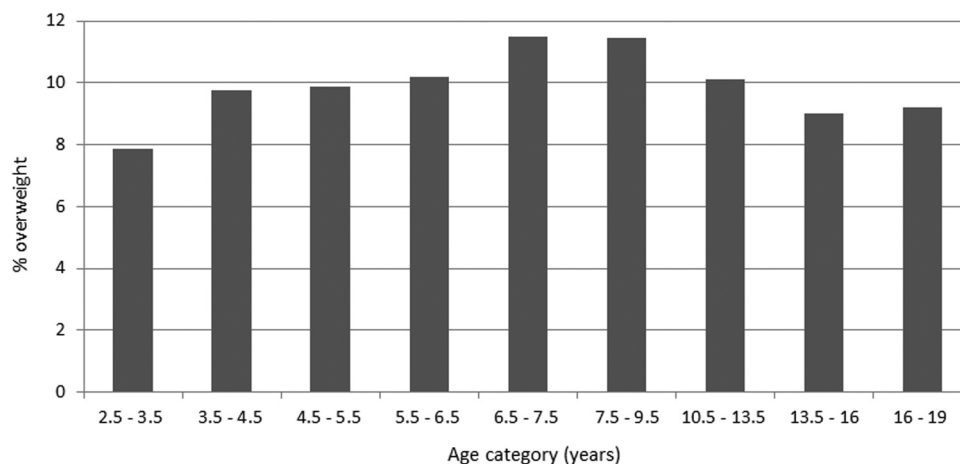
<sup>d</sup> North: provinces Groningen, Friesland, Drenthe; Central: provinces Utrecht, Gelderland, Flevoland; West: Rotterdam and surrounding municipalities.

<sup>e</sup> Air pollution is modeled based upon 2009 measurements for both years.

exposures for the youngest and oldest age categories studied are shown in Table 1. Children living in an urban area had a higher exposure to NO<sub>2</sub> and traffic noise and a lower exposure to green space compared to the whole study population (Table S2). Most of the children in this subgroup (96.2%) had a park within 1000 m of their homes.

Table S3 shows the Spearman correlations between the air

pollutants, traffic noise and green space indicators. The correlations of the estimated concentrations of NO<sub>2</sub> and PM<sub>2.5</sub> absorbance with road traffic noise were moderate (0.41 and 0.46, respectively). Correlations between the green space indicators and traffic noise ranged from −0.35 to 0.18. The percentage of urban green space in a buffer of 3000 m was moderately positively correlated with the various air pollutants,



**Fig. 1.** Percentage of overweight children per age category.

**Table 2**  
Associations of air pollution, traffic noise and green space with overweight from age 3 to 17 years.

Exposure (increment)	Model I <sup>a</sup> OR (95% CI)	Model II <sup>b</sup> OR (95% CI)	Model III <sup>c</sup> OR (95% CI)
NO <sub>2</sub> (8.90 µg/m <sup>3</sup> )	<b>1.21 (1.04–1.40)</b>	<b>1.21 (1.04–1.40)</b>	<b>1.40 (1.12–1.74)</b>
PM <sub>2.5</sub> absorbance (0.30 × 10 <sup>-5</sup> /m)	1.12 (0.97–1.28)	1.12 (0.98–1.29)	1.19 (0.98–1.44)
PM <sub>10</sub> (1.06 µg/m <sup>3</sup> )	0.98 (0.88–1.09)	0.99 (0.89–1.11)	1.00 (0.88–1.12)
PM <sub>2.5</sub> (1.17 µg/m <sup>3</sup> )	0.97 (0.80–1.18)	0.86 (0.71–1.05)	0.80 (0.59–1.09)
Road traffic noise (6.90 dB(A))	1.06 (0.93–1.20)	1.02 (0.90–1.16)	1.02 (0.90–1.16)
Railway noise (8.90 dB(A))	0.92 (0.80–1.05)	0.92 (0.80–1.05)	0.91 (0.79–1.04)
Average NDVI in 300 m buffer (0.13)	0.93 (0.82–1.06)	0.95 (0.83–1.08)	0.96 (0.83–1.10)
Total percentage of green space in 300 m buffer (25.38)	0.99 (0.89–1.10)	0.99 (0.88–1.10)	0.99 (0.88–1.11)
Percentage urban green in 300 m buffer (10.37)	1.09 (0.99–1.20)	1.09 (0.98–1.20)	1.08 (0.98–1.20)
Percentage agricultural green in 300 m buffer (17.55)	0.96 (0.88–1.04)	0.96 (0.88–1.05)	0.96 (0.88–1.05)
Natural green in 300 m buffer (yes vs. no)	1.03 (0.82–1.29)	1.03 (0.82–1.29)	1.03 (0.82–1.30)
Average NDVI in 3000 m buffer (0.13)	<b>0.84 (0.73–0.97)</b>	0.88 (0.76–1.03)	0.86 (0.71–1.04)
Total percentage of green space in 3000 m buffer (29.47)	<b>0.85 (0.73–1.00)</b>	0.87 (0.74–1.02)	0.86 (0.71–1.03)
Percentage urban green in 3000 m buffer (5.25)	1.04 (0.87–1.25)	1.06 (0.88–1.27)	1.05 (0.87–1.27)
Percentage agricultural green in 3000 m buffer (35.73)	0.86 (0.68–1.08)	0.88 (0.69–1.11)	0.85 (0.66–1.11)
Percentage natural green in 3000 m buffer (8.63)	0.99 (0.90–1.09)	1.01 (0.92–1.11)	1.01 (0.92–1.12)

Abbreviations: OR = odds ratio; CI = confidence interval; NDVI = Normalized Difference Vegetation Index.

ORs are shown for an interquartile range increase in exposure, except for natural green in a buffer of 300 m.

Associations with the percentages of urban, agricultural and natural green space are adjusted for the other types of green space in the same buffer size (plus additional confounders as detailed in footnote a–c).

Statistically significant results are highlighted in bold (p < 0.05).

<sup>a</sup> Adjusted for age and sex.

<sup>b</sup> Adjusted for age, sex, maternal level of education, paternal level of education, maternal smoking during pregnancy, parental smoking in child's home and neighborhood socioeconomic status.

<sup>c</sup> Includes model II and region.

whereas the correlations between the percentage of agricultural green space and the air pollutants were negative.

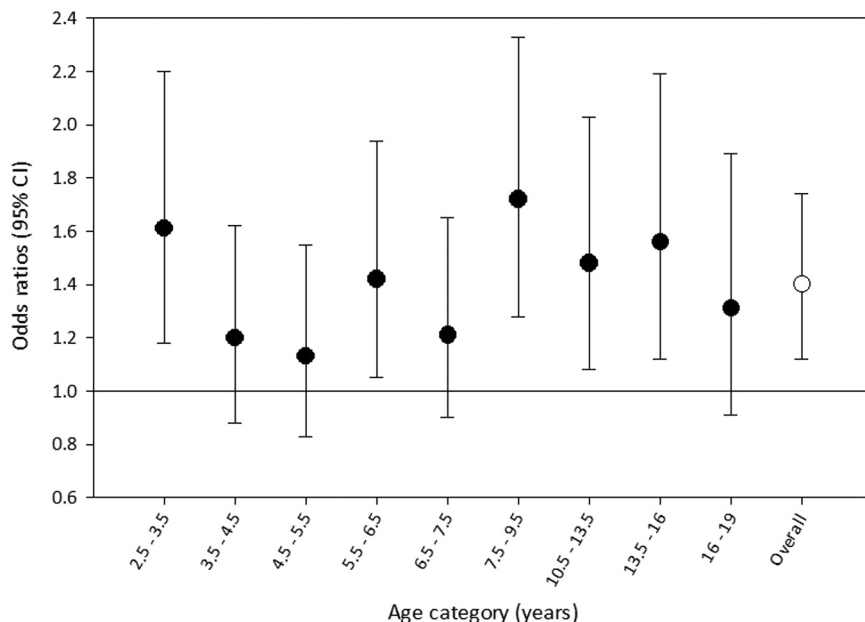
### 3.3. Associations of air pollution, traffic noise and green space with overweight

The associations of air pollution, traffic noise and green space with overweight from age 3 to 17 years are shown in Table 2. The odds of being overweight increased with increasing exposure to NO<sub>2</sub> (adjusted OR 1.40 [95% confidence interval (CI) 1.12–1.74] per 8.90 µg/m<sup>3</sup>) and PM<sub>2.5</sub> absorbance (adjusted OR 1.19 [95% CI 0.98–1.44] per 0.30 × 10<sup>-5</sup>/m). The odds of being overweight decreased with increasing average NDVI and total percentage of green space in a buffer of 3000 m. These associations were not statistically significant in models II

and III, though with little change in effect estimates (fully adjusted OR 0.86 [95% CI 0.71–1.04] per 0.13 increase in the average NDVI; fully adjusted OR 0.86 [95% CI 0.71–1.03] per 29.5% increase in the total percentage of green space). We found no associations of PM<sub>2.5</sub>, PM<sub>10</sub>, traffic noise and green space in a 300 m buffer with overweight from age 3 to 17 years.

Fig. 2 and S1 show the age-specific associations of air pollution, traffic noise and green space with overweight from age 3 to 17 years. We found a positive association of NO<sub>2</sub> with overweight across the age categories, whereas we found no consistent pattern of associations for the other exposures with overweight across the age categories (Fig. S1).

Since we observed a statistically significant association of NO<sub>2</sub> with overweight throughout childhood, we explored two- and three-exposure models with NO<sub>2</sub>, road traffic noise and the average NDVI or the



**Fig. 2.** Age-specific associations of NO<sub>2</sub> with overweight from age 3 to 17 years. ORs are shown for an interquartile range increase in exposure (8.90 µg/m<sup>3</sup>). Adjusted for age, sex, maternal level of education, paternal level of education, maternal smoking during pregnancy, parental smoking in child's home, neighborhood socioeconomic status and region.

**Table 3**

Associations of NO<sub>2</sub>, road traffic noise, the average NDVI and total percentage of green space in a 3000 m buffer with overweight from age 3 to 17 years from two- and three-exposure models.

Model <sup>a</sup>	Exposure	OR (95% CI)
NO <sub>2</sub> + road traffic noise	NO <sub>2</sub>	<b>1.47 (1.16–1.88)</b>
	Road traffic noise	0.93 (0.80–1.07)
NO <sub>2</sub> + NDVI 3000 m	NO <sub>2</sub>	<b>1.36 (1.08–1.72)</b>
	Average NDVI in 3000 m	0.94 (0.77–1.15)
NO <sub>2</sub> + total green 3000 m	NO <sub>2</sub>	<b>1.44 (1.09–1.90)</b>
	Total percentage of green space in 3000 m	1.03 (0.82–1.29)
NO <sub>2</sub> + road traffic noise + NDVI 3000 m	NO <sub>2</sub>	<b>1.44 (1.12–1.86)</b>
	Road traffic noise	0.93 (0.80–1.07)
	Average NDVI in 3000 m	0.94 (0.77–1.15)
NO <sub>2</sub> + road traffic noise + total green 3000 m	NO <sub>2</sub>	<b>1.54 (1.14–2.07)</b>
	Road traffic noise	0.92 (0.80–1.07)
	Total percentage of green space in 3000 m	1.04 (0.82–1.31)

Abbreviations: OR = odds ratio; CI = confidence interval; NDVI = Normalized Difference Vegetation Index.

ORs are shown for an interquartile range increase in exposure.

Statistically significant results are highlighted in bold ( $p < 0.05$ ).

<sup>a</sup> Adjusted for age, sex, maternal level of education, paternal level of education, maternal smoking during pregnancy, parental smoking in child's home, neighborhood socioeconomic status and region.

total percentage of green space in a 3000 m buffer (Table 3). The association of NO<sub>2</sub> with overweight remained after adjustment for road traffic noise (adjusted OR 1.47 [95% CI 1.16–1.88]) or green space in a 3000 m buffer (adjusted OR 1.36 [95% CI 1.08–1.72] after adjustment for the average NDVI; adjusted OR 1.44 [95% CI 1.09–1.90] after adjustment for the total percentage of green space). Results from three-exposure models were similar. Associations of the average NDVI and especially total percentage of green space in a 3000 m buffer with overweight weakened substantially after adjustment for NO<sub>2</sub>.

In children living in an urban area, we also observed a positive association of NO<sub>2</sub> with overweight from age 3 to 17 years (Table 4). This association was not statistically significant in models II and III, but the effect estimates were similar to the effect estimates in the whole study population (fully adjusted OR 1.44 [95% CI 0.95–2.19] per 8.90 µg/m<sup>3</sup>). A longer distance from the children's homes to the nearest park was associated with a lower odds of being overweight in this subgroup of children (adjusted OR 0.67 [95% CI 0.52–0.85] for an increase of 359.6 m). This was consistent across the age categories (Fig. S2). Consistently, albeit non-significant, we found that an increase in

the percentage of urban green space in buffers of 300 m and 3000 m was associated with a higher odds of being overweight in children living in an urban area (adjusted OR 1.15 [95% CI 0.94–1.40] for an increase of 10.4% in a 300 m buffer; adjusted OR 1.17 [95% CI 0.85–1.62] for an increase of 5.3% in a 3000 m buffer).

## 4. Discussion

### 4.1. Main findings

We found that the odds of being overweight from age 3 to 17 years increased with increasing exposure to NO<sub>2</sub> and decreased with an increasing average NDVI and total percentage of green space in a buffer of 3000 m. The association of NO<sub>2</sub> with overweight remained after adjustment for road traffic noise, the average NDVI or total percentage of green space in a buffer of 3000 m. After adjustment for NO<sub>2</sub>, the associations of green space in a buffer of 3000 m with overweight weakened substantially. We found no significant associations of particulate matter air pollution, traffic noise and green space in a buffer of 300 m with

**Table 4**

Associations of air pollution, traffic noise and green space with overweight from age 3 to 17 years in children living in an urban area ( $\geq 1500$  addresses/km<sup>2</sup>).

Exposure (increment)	Model I <sup>a</sup> OR (95% CI)	Model II <sup>b</sup> OR (95% CI)	Model III <sup>c</sup> OR (95% CI)
NO <sub>2</sub> (8.90 µg/m <sup>3</sup> )	<b>1.46 (1.04–2.03)</b>	1.32 (0.95–1.84)	1.44 (0.95–2.19)
PM <sub>2.5</sub> absorbance (0.30 × 10 <sup>-5</sup> /m)	1.01 (0.76–1.34)	1.01 (0.76–1.34)	0.97 (0.70–1.34)
PM <sub>10</sub> (1.06 µg/m <sup>3</sup> )	0.94 (0.78–1.12)	0.95 (0.79–1.14)	0.93 (0.76–1.12)
PM <sub>2.5</sub> (1.17 µg/m <sup>3</sup> )	0.82 (0.53–1.27)	0.88 (0.57–1.35)	0.72 (0.42–1.23)
Road traffic noise (6.90 dB(A))	0.96 (0.74–1.25)	0.93 (0.72–1.20)	0.92 (0.71–1.20)
Railway noise (8.90 dB(A))	0.84 (0.65–1.08)	0.87 (0.67–1.13)	0.87 (0.68–1.13)
Average NDVI in 300 m buffer (0.13)	0.86 (0.65–1.14)	0.94 (0.71–1.26)	0.96 (0.71–1.29)
Total percentage of green space in 300 m buffer (25.38)	1.11 (0.78–1.59)	1.10 (0.77–1.56)	1.09 (0.76–1.56)
Percentage urban green in 300 m buffer (10.37)	1.16 (0.95–1.40)	1.15 (0.95–1.40)	1.15 (0.94–1.40)
Average NDVI in 3000 m buffer (0.13)	<b>0.73 (0.56–0.97)</b>	0.82 (0.61–1.10)	0.76 (0.52–1.13)
Total percentage of green space in 3000 m buffer (29.47)	0.80 (0.53–1.21)	0.79 (0.51–1.21)	0.79 (0.50–1.25)
Percentage urban green in 3000 m buffer (5.25)	1.17 (0.86–1.61)	1.15 (0.84–1.58)	1.17 (0.85–1.62)
Distance from home to the nearest park (359.57 m)	<b>0.64 (0.50–0.81)</b>	<b>0.67 (0.53–0.85)</b>	<b>0.67 (0.52–0.85)</b>

Abbreviations: OR = odds ratio; CI = confidence interval; NDVI = Normalized Difference Vegetation Index.

Associations with the percentage of urban green space are adjusted for the percentage of agricultural and natural green space in the same buffer size (plus additional confounders as detailed in footnote a-c).

Statistically significant results are highlighted in bold ( $p < 0.05$ ).

<sup>a</sup> Adjusted for age and sex.

<sup>b</sup> Adjusted for age, sex, maternal level of education, paternal level of education, maternal smoking during pregnancy, parental smoking in child's home and neighborhood socioeconomic status.

<sup>c</sup> Includes model II and region.

overweight. In children living in an urban area, living further away from a park was associated with a lower odds of being overweight.

#### 4.2. Comparison with other studies and interpretation of the findings

We found a positive association of NO<sub>2</sub> with overweight across the age categories. The 95% confidence intervals of the age-specific estimates overlapped, however, and there were no indications for a consistent trend in associations across the age categories.

Our finding of an increased odds of being overweight with increasing exposure to NO<sub>2</sub> is in line with the findings from the Southern California Children's Health Study (CHS). McConnell et al. showed in 2944 participants of the 1993/1996 cohort that a higher exposure to NO<sub>x</sub> at the homes was associated with a larger increase in BMI from age 10 to 18 and a higher attained BMI at age 18 (McConnell et al., 2015). Jerrett et al. found in 4550 participants of the 2002/2003 cohort a 13.6% increase in annual BMI growth from age 5 to 11 when comparing the lowest to the highest tenth percentile of exposure to NO<sub>x</sub>, which resulted in an increase of nearly 0.4 BMI units on attained BMI at age 10 (Jerrett et al., 2014).

We found an increased odds of being overweight with increasing exposure to NO<sub>2</sub> and PM<sub>2.5</sub> absorbance, but not with exposure to PM<sub>2.5</sub> and PM<sub>10</sub>, which are less determined by traffic than NO<sub>2</sub> and PM<sub>2.5</sub> absorbance (European Environment Agency, 2017). Model performance was higher for NO<sub>2</sub> and PM<sub>2.5</sub> absorbance than for PM<sub>2.5</sub> and PM<sub>10</sub> (Table S4), which may at least partly explain why we did not find associations with particulate matter air pollution. Our findings may also indicate that specifically traffic-related air pollution is associated with children's weight. Traffic-related air pollution may affect children's weight through pro-inflammatory central nervous system effects on appetite control (McConnell et al., 2016). Air pollution may also result in metabolic dysfunction via increased oxidative stress and adipose tissue inflammation and decreased glucose utilization in skeletal muscle (An et al., 2018).

Alternatively, NO<sub>2</sub> concentrations may not be causally related to childhood overweight, but may represent traffic intensity near the children's homes. Traffic around the home may be associated with perceived lack of safety among children and parents, which may inhibit children's outdoor play or mobility on bicycle or foot. A previous analysis within the PIAMA study, however, has shown that the correlation between NO<sub>2</sub> and traffic intensity on the nearest street is low (0.2 for the birth and 8-year addresses) (Gehring et al., 2013). The low correlation between NO<sub>2</sub> and traffic intensity on the nearest street can be explained by the fact that traffic intensity on the nearest street is a determinant of NO<sub>2</sub> concentrations, but by far not the only one. The LUR model, used to estimate NO<sub>2</sub> concentrations, also includes regional NO<sub>2</sub> levels, the number of inhabitants in a 5000 m buffer and several traffic variables, such as the length of major roads in a 1000 m buffer. Moreover, no associations of overweight with road traffic noise, which is also determined by traffic density, were found in the present study. We therefore consider it unlikely that the association of NO<sub>2</sub> with childhood overweight in our study is explained by decreased physical activity levels associated with increased traffic density near the children's homes.

Future studies are needed to replicate our findings and to explore the pathways through which air pollution concentrations may be associated with children's weight.

Only two previous studies have assessed associations of traffic noise with children's weight (Christensen et al., 2016a; Weyde et al., 2018). Weyde et al. found that exposure to road traffic noise during early childhood was not associated with BMI trajectories from age 18 months to 8 years in 6403 children in Norway (Weyde et al., 2018). A study from Denmark did not find associations of road traffic and railway noise with the risk for overweight at seven years of age in 40,974 children (OR 1.06 [95% CI 0.99–1.12] per 10 dB increase in road traffic noise)

(Christensen et al., 2016a). In the present study, we also observed a non-significant positive association of road traffic noise with overweight in single-exposure models (OR 1.02 [95% CI 0.90–1.16] per 6.90 dB(A)). Since the association of traffic noise with childhood overweight has been sparsely investigated, more epidemiological studies are needed to explore this association.

In single-exposure models, we found that the odds of being overweight decreased with increasing average NDVI and total percentage of green space in a buffer of 3000 m. These associations were not robust against adjustment of multiple potential confounders. Findings from previous studies examining the associations of residential exposure to green space with children's weight have been inconsistent (James et al., 2015; Lachowycz and Jones, 2011; Sanders et al., 2015). Those studies differed in the assessment of exposure to green space (i.e. different buffer sizes or green space metrics were used), which may have contributed to the mixed findings. Our results are in line with a study by Davvand et al. that has shown that a higher average NDVI in several buffers around the children's homes was associated with a lower prevalence of overweight/obesity in children aged 9–12 years in Spain (Dadvand et al., 2014). Our findings are also consistent with a study from the United States that found that a higher average NDVI in a buffer of 1000 m around the children's homes was associated with lower BMI z-scores and a lower odds of increasing BMI z-scores over two years in children aged 3–16 years (Bell et al., 2008).

Results from two-exposure models indicate that the associations of green space in a buffer of 3000 m with overweight were confounded by NO<sub>2</sub> levels. The associations of green space in a buffer of 3000 m with overweight weakened after adjustment for NO<sub>2</sub>. Higher levels of green space in a buffer of 3000 m are associated with lower concentrations of NO<sub>2</sub> (Table S3). This means that the associations of green space in a buffer of 3000 m with overweight can be partly explained by lower NO<sub>2</sub> concentrations (as a result of less traffic in places with more green space). This indicates that not green space itself (by increasing physical activity levels or through stress reduction), but lower levels of traffic-related air pollution may decrease the odds of being overweight throughout childhood. To our knowledge, this is the first study that has examined the associations of both air pollution and green space on childhood overweight.

We observed that a longer distance from the children's homes to the nearest park was associated with a significantly lower odds of being overweight in children who live in an urban area. This is an unexpected finding, since it is hypothesized that green space has a beneficial effect on children's weight by providing opportunities for physical activity. The evidence for a beneficial effect of the availability of parks on children's weight is limited. The CHS found that more park acres within a 500 m distance from children's homes was associated with a lower BMI at age 18 (Wolch et al., 2011). The study by Davvand et al. has shown that living within 300 m of a park was not associated with overweight/obesity in children aged 9–12 years in Spain (Dadvand et al., 2014). Likewise, two studies from Canada found no associations of distance to the nearest park with overweight in children (Potestio et al., 2009; Potwarka et al., 2008).

We do not have an explanation for our finding that living further away from a park was associated with a lower odds of being overweight throughout childhood. In an earlier analysis within the PIAMA study, we found no association between distance to parks and the frequency of green space visits in adolescents aged 17 years (Bloemsma et al., 2018). This may indicate that children who live closest to a park do not necessarily visit parks more often than children who live further away from a park. In Dutch cities, parks tend to be located at some distance from the city centers. We may be dealing with some aspects of deprivation, associated with increasing distance from city centers, which is not adequately captured by including parental level of education and neighborhood SES in our analyses.

### 4.3. Strengths and limitations

Strengths of this study include the repeated measurements of children's weight and height from age 3 to 17 years and data on multiple environmental exposures that may be associated with childhood overweight. This enabled us to study the combined associations of air pollution, traffic noise and green space with overweight throughout childhood. We had detailed address histories for all children, which allowed the collection of virtually complete residential exposure data. Furthermore, we used several indicators to assess exposure to green space. Most previous studies only used the average NDVI or percentage of green space in several buffers around participant's homes to assess exposure to green space (James et al., 2015). We additionally examined the associations of different types of green space (urban, agricultural and natural) and distance to the nearest park with overweight in children.

Some potential limitations need to be addressed. Parents measured their child's weight and height themselves if the child's weight and height had not been measured by a medical professional within the last three months before completion of the questionnaire. The agreement between parental reported and measured weight and height has been investigated at ages four and eight within the PIAMA study and the mean difference between measured and parental reported BMI was small. Parents of children with a high BMI tended to underreport their child's weight (Bekkers et al., 2011; Scholtens et al., 2007). This indicates that some overweight children may have been misclassified as non-overweight in the present study, resulting in an underestimation of overweight prevalence. However, we consider it unlikely that this underestimation is associated with modeled levels of air pollution and traffic noise or objectively measured green space. Thus, misclassification of the outcome is most likely unrelated to the environmental determinants, indicating that spurious associations are unlikely.

We have adjusted our analyses for several important lifestyle indicators: maternal smoking during pregnancy, parental smoking in the child's home, parental level of education and neighborhood SES. The adjustment for these potential confounders has hardly changed the associations of the exposures with childhood overweight. We nevertheless have considered including indicators of physical activity and nutrition in our study, but we have decided not to adjust our analyses for physical activity or nutrition for several reasons. Firstly, physical activity is a potential mediator, rather than a confounder, of the association between green space and overweight. We did not perform a formal mediation analysis, because in two- and three-exposure models no associations of green space with childhood overweight were found. Secondly, there is no hypothesis on how physical activity or diet could be related to air pollution, traffic noise and green space levels. SES may be an underlying variable that is related to both health behavior (including physical activity and diet) and residential exposure to air pollution, traffic noise and green space (persons with a higher SES may live in neighborhoods with higher levels of green space and lower air pollution and noise levels). We have adjusted our analyses for both maternal and paternal level of education and neighborhood SES. Finally, previous analyses within the PIAMA study have shown that questionnaire reported snacking and fast food intake were not associated with childhood overweight, which was another reason not to consider these indicators as potential confounders in the current study (Berentzen et al., 2014; Wijga et al., 2010).

Given the number of associations that we have examined in this study, we cannot rule out the fact that our finding of an association between NO<sub>2</sub> and childhood overweight could have occurred by chance alone. However, the association of NO<sub>2</sub> with overweight was consistent across different models (models I, II and III and multi-exposure models) and across the age categories. We therefore consider it unlikely that this association is a chance finding.

A limitation of the current study is that we used purely spatial air pollution models that were based on measurement campaigns performed in 2009 and that we only had estimates for traffic noise for the

year 2011. However, we have good reasons to assume stable spatial contrasts in levels of air pollution and traffic noise since the start of the follow-up in our study (1999/2000). Several studies from Europe have shown that the spatial variation in air pollution and noise levels remained stable over periods of seven years and more (Cesaroni et al., 2012; Eeftens et al., 2011; Fecht et al., 2016). Moreover, a study by Gulliver et al. showed that spatial patterns of air pollution concentrations in Great Britain, estimated by LUR models, were broadly similar over a period of nearly 30 years (1962–1991) (Gulliver et al., 2011). In addition, measurement data from the Dutch National Air Quality Monitoring Network demonstrated that the annual average concentrations of PM<sub>10</sub> and NO<sub>2</sub> have not substantially changed between 2000 and 2007 (Beijk et al., 2008).

We examined associations of residential exposure to air pollution, traffic noise and green space with childhood overweight and disregarded exposures at the school addresses, where children also spend a substantial amount of time. However, a previous analysis within the PIAMA study has shown that the correlations between air pollution concentrations at home and school addresses were moderate to high (Milanzi et al., 2018). This indicates that measurement error, resulting from including residential exposure to air pollution only, is likely small. Another limitation is that we only had information on traffic noise levels outside the home and lacked information on potential individual level noise modifiers such as data on window type, indoor insulation and orientation of the bedroom. This may have led to misclassification of individual exposure to traffic noise.

We only had information on the quantity of green space and did not know if and how often our study population used the green areas located within the specified buffers around the homes. Information on green space visits was available when the children were 17 years old, but we did not know the frequency of green space visits throughout the study period (Bloemsma et al., 2018). Finally, information on the quality of green spaces was unavailable in the present study. Quality characteristics of green spaces such as aesthetics, safety and sport/play facilities may affect the use of green spaces for physical activity (McCormack et al., 2010).

## 5. Conclusion

Exposure to traffic-related air pollution, but not traffic noise or green space, may contribute to childhood overweight. Our results indicate that future studies examining the associations of green space with childhood overweight should account for air pollution concentrations.

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## Competing financial interests

The authors declare that they have no actual or potential competing financial interests.

## Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at [doi:10.1016/j.envres.2018.11.026](https://doi.org/10.1016/j.envres.2018.11.026).



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