Kabisch, N., Alonso, L., Dadvand, P., van den Bosch, M. (2019):
Urban natural environments and motor development in early life
Environ. Res. **179, Part A** , art. 108774

http://dx.doi.org/10.1016/j.envres.2019.108774

Kabisch, N., Alonso, L., Dadvand, P., Van den Bosch, M. (2019) Urban natural environments and motor development in early life. Environmental Research, 10.1016/j.envres.2019.108774

Urban natural environments and motor development in early life

Nadja Kabisch[1,2,*], Lucia Alonso[3,4,5], Payam Dadvand[3,4,5,#], Matilda van den Bosch[6,7#]

[1]*Department of Geography, Humboldt-Universität zu Berlin, Unter den Linden 6, 10099 Berlin, Germany*

[2]*Helmholtz-Centre for Environmental Research-UFZ Leipzig, Permoserstrasse 16, 04318 Leipzig, Germany*

[3] *Barcelona Institute for Global Health (ISGlobal), Doctor Aiguader 88, 08003 Barcelona, Spain*

[4] *Universitat Pompeu Fabra (UPF), Plaça de la Mercè, 10-12, 08002 Barcelona, Spain*

[5] *CIBER Epidemiología y Salud Pública (CIBERESP), Spain*

[6] *The School of Population and Public health, The University of British Columbia, 2206 East Mall, Vancouver BC, V6T 1Z3, Canada. E-mail: matilda.vandenbosch@ubc.ca*

[7] *The Department of Forest and Conservation Sciences, The University of British Columbia, 2424 Main Mall, Vancouver BC, V6T 1Z4, Canada. E-mail: matilda.vandenbosch@ubc.ca*

*Corresponding author

#Shared last authorship.

Abstract

An emerging body of evidence has associated natural environments with improved brain development in children; however, these studies have mainly focused on cognition and available evidence for motor development is still scarce. This study aimed to evaluate the protective association of neighbourhood greenspace with motor development deficits in children. We obtained data on motor development deficits (separately for fine and gross motor developments) at sub-district level from routine medical check-up of children prior to enrolment into primary schools in the city of Berlin (2015-2016). Neighbourhood natural environments across the sub-districts were measured with three different metrics: the average of satellite-based normalized difference vegetation index (NDVI), the share of public green spaces, and the share of both public blue and green spaces (composite nature) across the sub-district. We applied negative binominal models to estimate the association between neighbourhood natural environments and fine and gross motor development deficits (one at a time), controlled for relevant sociodemographic indicators. Higher neighbourhood public green space and composite nature were significantly associated with lower risk of motor development deficits; however, the association were not statistically significant when using NDVI. Our findings, if confirmed by future studies, could provide evidence for implementing targeted interventions to enhance motor development in urban children.

Keywords: motor development, pre-school children, urban nature, urban green space, NDVI, brain development

Funding

NK’s work was supported by the research project Environmental-Health Interactions in Cities (Green-EquityHEALTH) - Challenges for Human Well-Being under Global Changes (2017–2022), funded by the German Federal Ministry of Education and Research (BMBF; no. 01LN1705A). MvdB was supported by the Canadian Institutes of Health Research [Project Grant 156152]. PD is funded by a Ramón y Cajal fellowship (RYC-2012-10995) awarded by the Spanish Ministry of Economy and Competitiveness. The funding sources had no role in study design; collection, analysis and interpretation of data; writing of the report; or decision to submit the article for publication.

1. Introduction

1.1 Childhood development

Early childhood development is a strong predictor of health and wellbeing throughout the life course (Lloyd et al., 2010). The development of fine and gross motor skills is an essential part of this process. Gross motor skills involve the ability of the child to coordinate and execute movements in larger muscles such as arms, legs and back while fine motor skills encompasses the movements of small muscles, mainly in fingers and eyes (Cuffaro, 2011). Adequate motor development is important for a child's potential of play, physical activity, and interactions with the environment and others. Healthy motor development is contingent on numerous factors, including internal and external influences on the brain. The awareness of the impact of problems or deficits in motor development is increasing. Children with deficits may suffer from various issues, including difficulties with movement, speech, everyday activities and school participation (Seelaender et al., 2013). Impaired motor development can influence various health aspects also later in life, for instance predicting lower levels of physical activity in young adulthood (Aaltonen et al., 2015) and adult alcohol dependence (Manzardo et al., 2005).

The prevalence of deficits in motor development varies a lot between different studies – from 2% (Lingam et al., 2009) to 39% (Gaschler, 1990) in populations from UK and Germany respectively. General numbers suggest a prevalence of around 5-6% in school aged children (APA, 1994). Some studies indicate that the issue of impaired motor development has been increasing over time (Fleuren et al., 2007, Hadders-Algra, 2007) and, for example, in parts of Germany the occurrence tripled over a time period spanning from 1990 to 2007 (Seelaender et al., 2013). The reason for this increase is not entirely elucidated, but the change over time suggests environmental impacts. The increase has coincided with an on-going global urbanization leading to an increasing number of children living in urban environments and a hypothetical explanation for the increase is the urban-related lifestyle or environmental factors such as limited access to natural environments. Motor development deficits are considered to be multi-factorial conditions with both genetic background and environmental factors being involved in its pathogenesis (Pennington, 2006); however the relative contribution of each of these aetiologies is not clear. In this context, understanding the potential impact of modifiable factors on children's development is important for supporting interventions that can promote childhood health and prevent impaired development. From this perspective, environmental factors in children's homes and neighbourhoods are important to consider (van den Bosch et al., 2018). A few studies have analysed the association between home environment and motor development (Miquelote et al., 2012, Ammar et al., 2013, Cacola et al., 2015), but less is known about the influence of outdoor environments (Little and Sweller, 2015). While not directly analysing association to motor development, some studies have examined the importance of outdoor, natural environments (green and blue) for promoting children's active play and the influence on weight status and physical activity (Dyment and Bell, 2008, Abraham et al., 2010), which could have a subsequent impact on motor development and skills (Timmons et al., 2012). In times of increasing urbanisation and technology expansion there are growing concerns that opportunities for outdoor play and access to natural environments for children are decreasing (Singer et al., 2009, Veitch et al., 2006, Kiser, 2015). These findings require further attention.

1.2 Natural environments and childhood development

An accumulative body of evidence suggests that access to and exposure to urban natural environments have numerous health benefits (van den Bosch and Nieuwenhuijsen, 2017, WHO, 2016, Kabisch et al., 2017). To date, most studies have focused on adult populations, but existing research on the effects on childhood health indicate that natural environments improve mental wellbeing (McCormick, 2017), behavioural development (Amoly et al., 2014), cognitive skills (Dadvand et al., 2015), and birth outcomes (Dadvand et al., 2012). Studies also suggest that exposure to natural environments decrease overweight (Söderström et al., 2013), risk of schizophrenia (Engemann et al.), and Attention Deficit Hyperactivity Disorder (Taylor and Kuo, 2011, van den Berg and van den Berg, 2011). Potential effects of natural environments on childhood development could be through direct and indirect pathways. Natural environments provide children with unique opportunities such as encouraging discovery, engagement, risk taking, mastery and control, creativity and inspiring basic emotional states, increasing psychological restoration and strengthening sense of self, which are suggested to positively affect different aspects of brain development (de Keijzer et al., 2016, Chawla, 2015, Kahn Jr, 2002). Indirectly mediated pathways with potential impact on childhood development include increased physical activity (Söderström et al., 2013) and reduced stress (Van Aart et al., 2018), as well as regulating ecosystem services, such as mitigation of air pollution (Maher et al., 2013, Rao et al., 2014), noise (Dzhambov and Dimitrova, 2014), and extreme heat (Chen et al., 2014). These kind of harmful exposures can all have adverse effects on birth outcomes and brain development (Calderón-Garcidueñas et al., 2011, Arroyo et al., 2016, Gehring et al., 2014) and thus natural environments' potential for mitigating these exposures may have a positive impact.

While most studies seem to support the notion of an association between exposure to natural environments and childhood health, results are inconsistent and sometimes inconclusive (Kabisch et al., 2016, Amoly et al., 2014). This may partly be due to differences in exposure metrics, such as remote sensing indices, land cover or land use categories, or auditing tools (Rugel et al., 2017). To further clarify this issue, it is important to evaluate different types of metrics and assess relative predictive strength in relation to specific health outcomes.

1.3. Aims

This study aimed to evaluate the association between exposure to natural environments and deficits of fine and gross motor development in young children.

2. Materials and methods

This ecological study compared the prevalence of childhood motor development deficits in different sub-districts of Berlin, Germany, in association with the amount of natural environments at the sub-district level, adjusting for selected confounders and covariates.

2.1 Study area

Berlin, the German capital, is located in the lowlands of northern Germany. The administrative boundaries of the city extend over a region of more than 89,000 ha. Nearly 40% of the city is composed of natural areas, including 14.5% public green space, 18.3% urban forest area, and 6.7% water area, but these spaces are very heterogeneously distributed across the city (Kabisch & Haase, 2014) with high shares of urban forest in the south-western and south-eastern parts of the city. The suburban areas close to the city border connect to the high shares of urban forest, while other areas purely consist of agricultural land (Kabisch et al., 2017).

2.2 Study population and outcome variable

Berlin consists of 60 sub-districts with a mean area of 14.5 km^2 and a mean population number of 61,177 resulting in an average population density of almost 6,800 inhabitants per km^2 (2015). The geographical delineation of sub-districts is described further in a previous study (Kabisch et al., 2016), but, in principal, it is based on a spatial hierarchy of Berlin called "living environment areas" (LEAs) used for urban planning purposes. The sub-districts are comparable in terms of area and population numbers and also reflect homogeneity in living environments. We can thus expect that the neighbourhood and socioeconomic conditions are similar across the areas for our analysis, reducing the risk of baseline bias.

For this study, we obtained publicly available data from 2015, aggregated at the sub-district level, for a total sample of 31,867 children, aged 4 to 7 years. The data were provided by Berlin's Senate Department for Health and Social Issues (SenHS, 2015, 2016) and are based on the medical check-ups of every child, obligatory prior to school enrolment (Table 1). The SenHS database includes information on various childhood health outcomes and sociodemographic factors, such as immigration status and indicators of parental socioeconomic status (SES). The latter is defined by a composite measure, based on educational attainment, graduation, and current employment status. It creates a mean index of the sub-districts based on summarized index values of the parental household, ranging from 0 to 18 with lower numbers indicating more deprivation. Our main outcome of interest in this study was motor development. We used data on the number of children who were reported as having deficits in fine or gross motor development together with the total number of children examined in each sub-district to define the prevalence of deficits in that sub-district. For this study, deficits in motor development were defined in accordance with the standardised tests for assessing children's level of development in the medical check-up exam (SenHS). This standardised test (S-ENS, "Screening des Entwicklungsstandes bei Einschulungsuntersuchungen") is an established instrument that has been applied since 2005 (for details see Döpfner et al. (2005) and Petermann et al. (2009)). The S-ENS test includes sub-tests on motor, cognitive, and language development. All demands of each subtest are constructed in a way that children with normal age-based development should be able to meet all of them at the age of 5. Fine motor development is determined by a visomotoric subtest, including exercises to complete and copy figure drawings to test eye-hand coordination. Children are asked to complete simple line drawings and to copy/draw line drawings/figures as exact as possible. Children can score a maximum of 25 points and a result of less than 14 is classified as having a deficit in fine motor development. Gross motor development is assessed by a lateral jumps test. Children are asked to jump repeatedly from left to right and back over a central dividing line as many times as they can within ten seconds. The number of jumps is counted and values of 7 and lower is classified as a deficit in gross motor development (see also Zhou et al. 2018 for a similar test applied in the City of Hannover). The lateral jumps test has been found to correlate well with total scores of multi-item tests, such as the MOT 4-6 (Motor Function Test for 4- to 6- year-olds) (Zimmer R, 1987, Seelaender et al., 2013). We used data from 2015 for fine and gross development and to test the robustness of our results, we also analysed data from 2016 on fine motor development (no data were available for gross motor development for 2016).

2.3 *Exposure variables*

We used three different publicly available indicators of natural space exposure (see Table 1), including: (1) the Normalized Difference Vegetation index (NDVI) with annual mean value calculated from Landsat imagery (Landsat 8 OLI sensor and Landsat 7 ETM, spatial resolution 30m) from 2015. We aimed at integrating all available and usable images of a full vegetation period for 2015 following an automatized approach by Kabisch et al. (2019) to assess fully developed vegetation. We used images that cover months May-September for the city of Berlin. Landsat data were preselected for a cloud cover of less than 40%. NDVI was used to get information about fully developed vegetation. To account for occasional extreme values, we calculated the first principal component and transferred values into a yearly NDVI and a Classified Vegetation Cover (CVC), which is then referred to as "Yearly mean". For detailed description of used approach, see notes to Supplementary table 2 and protocols in Kabisch et al. (2019); (2) public urban green spaces based on land use data extracted from the Urban and

Environment Information System provided by Berlin's Senate Department for Urban Development and Housing (SenStadt, 2019). Public urban green space is calculated as percentage of public green space including urban parks, urban forests, allotment gardens, and cemeteries (all green spaces that are assumed to be of equal value for the public) in each sub-district; (3) an indicator of urban green and blue based on the same local data on percentage of green, but also including blue spaces, hereafter referred to as composite nature.

Data on air quality and noise were also obtained from the Berlin's Senate Department for Urban Development and Housing (SenUrban). Air quality data were provided as modelled annual mean values on a 500m x 500m raster for NO_x, NO_2, PM_{10} and $PM_{2.5}$. These models are developed from monitoring data (16 fixed measurement stations distributed across the city of Berlin) and predictive variables including urban built-up structures. The raster data were averaged over the spatial extent of the respective sub districts resulting in mean annual air pollution values for each sub district (for detailed information on air quality measurement network see SenStadt, 2018).

Noise data are based on a continuation of the strategic noise maps for Berlin created in 2012 (SenStadt, 2019) according to the Noise Mapping Decree (Federal Emission Protection Decree and Federal Emission Control Act) and the Noise Mapping Directive 2002/49/EC (Environmental Noise Directive). For the calculation of the noise maps for Berlin input data from the Digital Terrain Model DGM1, available for the Federal State of Berlin for the reference year 2015, were used. The following noise sources were included: road traffic (motor vehicles including busses for approximately 1,500km main street network), above-ground subway and tram traffic, industry and commercial sites (18 power plant sites) air traffic (airport Tegel and Schönefeld) and railway traffic. The noise model data provide a sound pressure level (in dB(A)) for each 10x10m grid cell in Berlin (Directive 2002/49/EC). We used the night time noise (Ln), which includes cumulative values of traffic noise sources between 10 pm and 6 am to account for the impact of noise on the health of children at their homes at night. Total values of noise consider the logarithmic decibel scale (e.g. volumes of two 50 dB(A) events add up to 53 dB(A), since the increase of 3 dB(A) is perceived by the ear as a doubling of impact. Two components of 50 dB(A) and 60 dB(A) add up to 60.4 dB(A)). For detailed information on noise mapping regulations and calculation model see SenStadt, 2017. Sub-district SES was also provided as mean values by the city department and reflects a composite measure of very low, low, medium, or high social status.

Table 1. Outcome and predictor variables included in the analyses, including sources: SenHS = Berlin's Senate Department for Health and Social Issues; USGS = U.S. Geological Survey; SenUrban= Berlin's Senate Department for Urban Development and Housing.

	Description	**Year**	**Data source**
Health-outcome variables			
Deficits in fine-motor development	Number of children with impaired fine motor ability Total number of children examined	2015, 2016	SenHS
Deficits in gross- motor development	Number of children with impaired gross motor ability Total number of children examined	2015	SenHS
Socioenvironmental variables			
Parental social status index	Mean index of social status in sub-districts (0-18) representing the social status of parents based on summarized values for educational attainment, graduation, current employment status in which each parent can gain values of 0-3 for each of the three parts. Higher values represent higher social status (see supplementary table 1 for further explanation).	2015, 2016	SenHS
Non-German (%)	Percentage of children with both parents being of non-German origin	2015, 2016	SenHS
Kindergarten attendance (%)	Percentage of children enrolled in kindergarten for at least 2 years	2015, 2016	SenHS
Smoker household	Percentage of children living in an household where at least one person smokes	2015, 2016	SenHS
Children with an own TV in their room	Percentage of children that own a television within their room.	2015, 2016	SenHS
Urban environment variables			
NDVI (mean)	The normalized difference vegetation index as mean value of "greenness" for an entire yearly vegetation period. See supplementary table 2 for list of images used.	2015	Landsat USGS
Public green space (%)	Percentage green spaces as defined by the Berlin Senate Department including urban parks, urban forests, allotment gardens and cemeteries (land use data)	2015	SenUrban
Composite nature (%)	Green and water spaces as defined by the Berlin Senate Department	2015	SenUrban
NO_x	Yearly mean city wide modelled air quality data provided as 500m x 500m raster in µg/m³. Update provided every 6 years.	2015	SenUrban
NO_2	Yearly mean city wide modelled air quality data provided as 500m x 500m raster in µg/m³. Update provided every 6 years.	2015	SenUrban
PM_{10}	Yearly mean city wide modelled air quality data provided as 500m x 500m raster in µg/m³. Update provided every 6 years.	2015	SenUrban
$PM_{2.5}$	Yearly mean city wide modelled air quality data provided as 500m x 500m raster in µg/m³. Update provided every 6 years.	2015	SenUrban
Noise (dB)	Annual mean night-time noise with main noise sources (road traffic, subway traffic, noise from industry and commerce and air traffic) during the night 22:00-06:00 based on a continuation of the strategic noise maps provided as 10m x 10m raster. Update provided every 6 years.	2015	SenUrban

Sub-district level SES	Index of social status of sub-district derived from the Berlin Senate Department. Values from 1-4; 1 = high social status, 2 = medium social status, 3 = low social status, 4 = very low social status. Based on: unemployment, long-term unemployment, children poverty, and receipt of aid money but not unemployed	2015	SenUrban

2.4 Statistical analysis

All data were linked at a sub-district aggregated level and percentage or mean values of each environmental exposure and confounder variable (Table 1) were calculated per each sub-district. For descriptive purposes, we conducted geospatial distribution analyses for the nature exposure variables, parental SES, non-German status, and the two outcome measures – fine and gross motor development. Spearman rank correlation analyses were used to preliminary examine relationships between the variables. Negative binominal (NB) models were fitted to estimate the association between the three different indicators of nature exposure (one at a time) and the number of children with fine or gross motor development deficits as the outcomes respectively. We included the number of children examined in each sub-district as an offset in the models. All models were adjusted for potential confounders - parental social status index and non-German origin. The estimated associations (incidence rate ratios, IRR) are reported for one interquartile (IQR) increase in each indicator of natural environment exposure. The significance level was selected at 0.05. The equation for the adjusted negative binominal regression model is:

$$\ln(\mu)=\beta_0+ \beta_1 x_{1+} \beta_2 x_{2+} \beta_3 x_3+\ln(t),$$

where μ is the mean of the outcome, β_0 the intercept, x_1 the exposure variable, β1 the regression coefficient of the exposure and ln(t) is the offset i.e. number of children examined in each sub-district. x_2 and x_3 are the confounders and β_2, β_3 their regression coefficients.

To evaluate the robustness of our findings, we conducted a number of sensitivity analyses by further adjustment of our analyses. The following variables were considered for the sensitivity analyses: PM_{10}, $PM_{2.5}$, NO_2, NO_X, noise, percentage of children with at least one smoker living with them in the household, percentage of children having an own TV, kindergarten attendance, and the social economic status of the neighbourhood. Some of these variables showed high correlation with covariates of the main analysis (Spearman Rank correlation coefficient greater than 0.8 in absolute value). To deal with multicollinearity problems, we performed sequential regression (Dormann et al., 2013). Using sequential regression, we regressed each new variable on the covariate of the principal model with which they are highly correlated and derived model residuals, which were afterwards included into the models. In particular, we regressed PM_{10}, $PM_{2.5}$, NO_2 and NO_X on NDVI (all separately), kindergarten attendance on Non-German households, and smoker household, children with an own TV (all separately) and sub-district SES of the neighbourhood on parental social status index of the child. In case of no or lower correlation, the variables were introduced as usual without using residuals. We used IBM SPSS Statistics 24 and R (version 3.5.2) for the statistical analyses. The same analyses were conducted for 2016 outcome data on fine motor development (no data on gross development available).

3 Results

3.1 Descriptive analyses

In the 60 sub-districts, the average prevalence of deficits in fine and gross motor development was 21.7% and 15.2% respectively. The values ranged from 6.9 % to 30.1 % for deficits in gross-motor development and between 7.9 % and 39.7 % for deficits in fine motor development (table 2).

Table 2. Descriptive statistics for data sample and variables used 2015 and 2016

	2015	**2016**
Demographic variables (*Medical check-up)*		
Total number of children checked	31,867	28,701
Mean age		
Median	5 years and 8 months	5 years and 9 months
Range	4-7 years	4-7 years
Sex		
Male	52.0 %	50.9 %
Female	48.0 %	49.1 %
Health-outcome variables (*Medical check-up)*		
Deficits in fine-motor development	21.7 %	21.7 %
Deficits in gross motor development	15.2 %	n.a.
Socioenvironmental variables (*Medical check-up)*		
Parental social status index lower level (0-8)	17.8 %	19.2 %
Parental social status index middle level (9-15)	47.4 %	43.9 %
Parental social status index higher level (16-18)	34.9 %	36.9 %
Non-German	29.3 %	31.5 %
Kindergarten attendance	87.0 %	88.3 %
Smoker household	34.2 %	34.8 %
Children with an own TV in their room	9.0 %	8.3 %
Urban environmental variables (City)		
NDVI (mean)	0.54	n.a.
Public green space	21.5 %	n.a.
Composite nature	22.3 %	n.a.
PM_{10} (mean)	19.6 µg/m^3	n.a.
$PM_{2.5}$ (mean)	13.7 µg/m^3	n.a.
NO_x (mean)	26.67 µg/m^3	n.a.
NO_2 (mean)	18.17 µg/m^3	n.a.
Noise (mean)	48.9 dB	n.a.
Sub-district level SES (median)	2	n.a.

3.2 Spatial distribution

Figure 1 shows the spatial distribution of the environmental, social, and motor development variables for the 60 sub-districts in Berlin in 2015. The amount of urban natural environments was highest in the sub-districts at the peripheral parts of the city, as measured by both NDVI and local city data, in particular along the south-eastern and south-western city borders. A few inner-city sub-districts had a very small proportion of natural environment, around 4-10 % as measured with city data. The spatial distribution of deficits in fine and gross motor development seemed somewhat correlated to each other. The mapping overview demonstrates potential intra-urban inequalities regarding distribution of deficits in motor development among children.

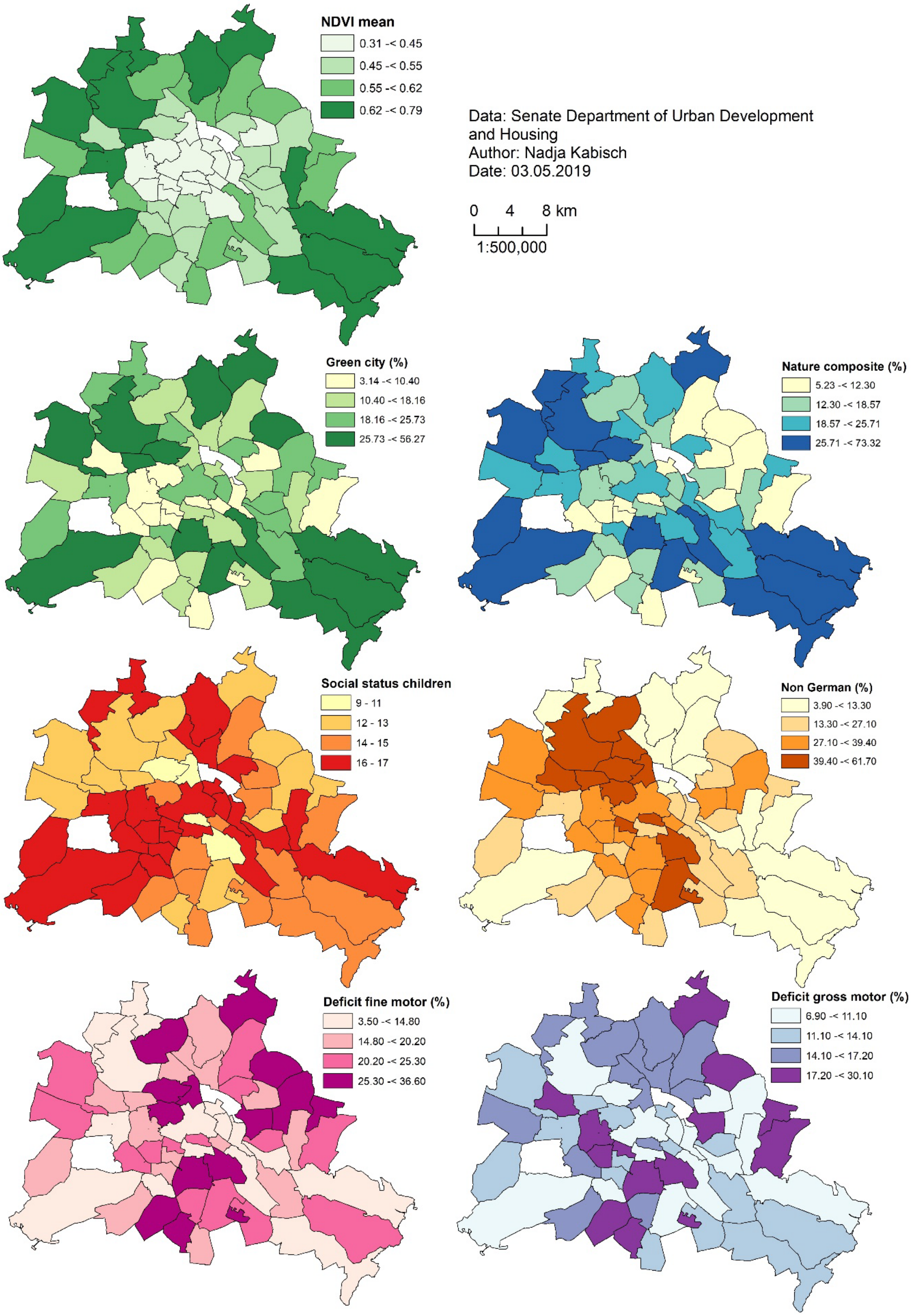

Figure 1. Intra-urban distribution of the various indicators of natural environments, socioeconomic status, non-German origin, and deficits in fine and gross motor development. Note: Classes in legends show quartiles.

3.3 Correlation analyses

Results from the correlation analyses are summarized in the correlation heat matrix in Figure 2. Spearman Rank Correlation coefficients show inverse relationships between parental SES and non-German origin (r_s = - 0.65) and smoking (r_s = - 0.89). Kindergarten attendance was positively correlated to parental SES (r_s = 0.75). We found no significant correlations between SES and the different natural environment indicators, but there was a significant inverse correlation between NDVI and non-German origin (r_s = - 0.37). SES and kindergarten attendance were significantly negatively correlated to deficits in both fine and gross motor development, while non-German origin showed a positive relation to deficits. Reporting a smoker in household was positively correlated to the outcome (r_s = 0.70 and 0.30 for deficits in fine and gross motor development respectively). Share urban composite nature was negatively correlated to gross motor development (r_s = - 0.25), but not to fine motor development. NDVI was strongly correlated to NO_x, NO_2, PM_{10} and PM $_{2.5}$ (r_s = - 0.80 - 0.83), but no significant correlations were found between air pollution and deficits in motor development.

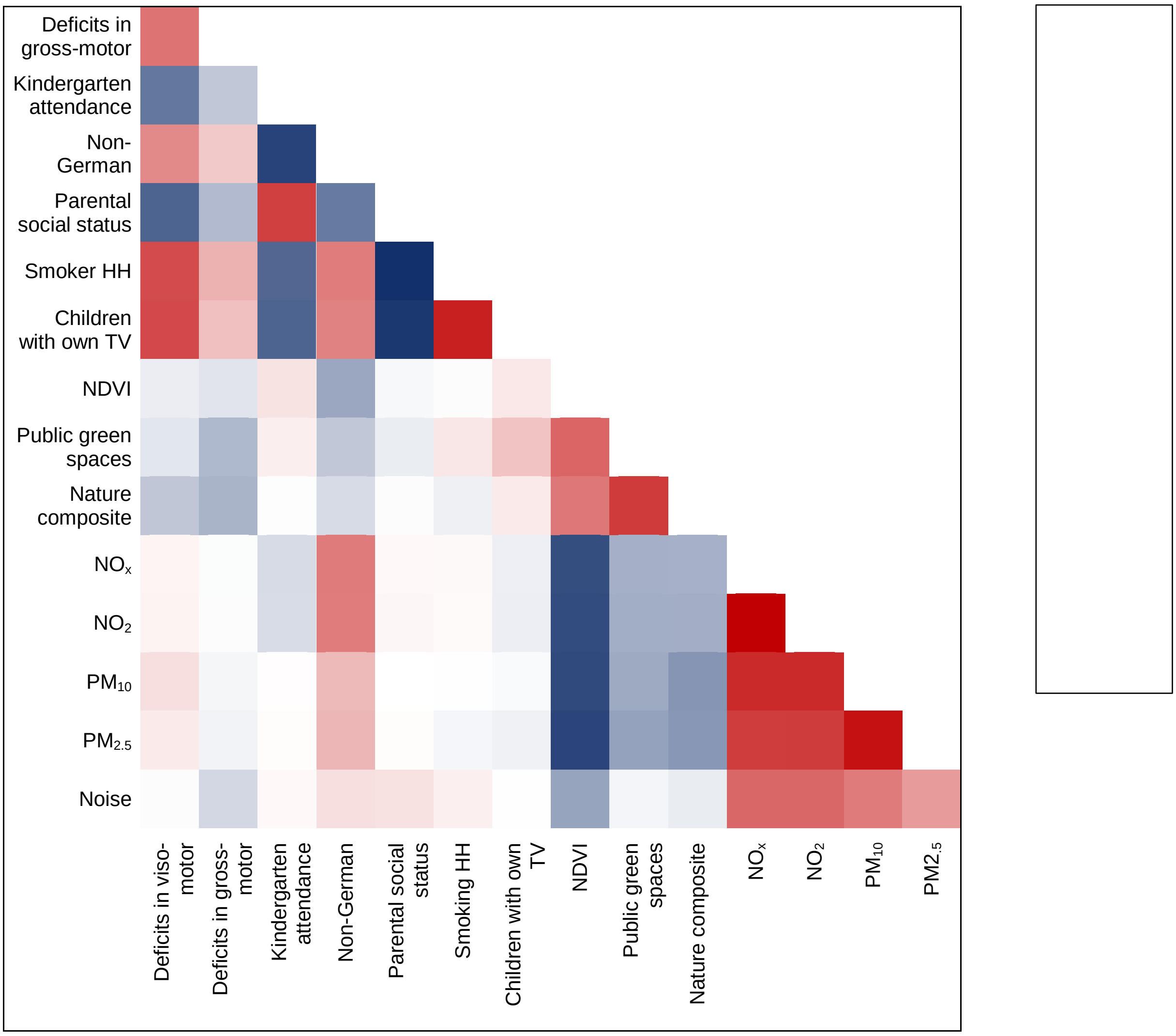

Figure 2. Spearman Rank Correlations between outcome and social and environmental exposure variables.

3.4 Association between natural environments and deficits in fine motor development (2015) – NB regression models

The non-adjusted NB models showed an inverse association between all natural environment exposure metrics and deficits in fine motor development (Table 3). The associations were statistically significant for composite nature (IRR = 0.92, 95% CI: 0.85-0.99).

In the adjusted models (including parental SES and non-German origin), the inverse association between deficits in fine motor development and composite nature remained significant (IRR = 0.91, 95% CI: 0.86-0.97), (Table 4). Also public green space was significantly associated with lower prevalence of fine motor development deficits in the adjusted models (IRR = 0.92, CI: 0.85-1.001). The association to average NDVI in the sub-district was also inverse, but not significant. Parental socioeconomic status explained most of the variance in all models and had a significant, inverse association with deficits in children fine motor development.

3.5 Association between natural environments and deficits in gross motor development (2015): NB models

In non-adjusted models (Table 3) we found an inverse association between indicators of natural environments and deficits in gross motor development with statistically significant associations for both composite nature and public green space (IRR = 0.90, 95% CI: 0.84-0.96; and IRR = 0.88, 95% CI: 0.81-0.96 respectively).

Similarly, in the adjusted models (Table 4), all three indicators of natural environment were inversely associated to gross motor development, reaching statistical significance for public green space (IRR = 0.86, CI:0.78-0.94) and composite nature (IRR = 0.90, CI:0.84-0.96). The association for the mean NDVI was not significant. In the adjusted models parental social status became significant at $p<0.05$ only in the model using percentage public green space as metric (IRR = 0.942, CI: 0.90 - 0.99).

Table 3. Non-adjusted associations of deficits in fine and gross motor development 2015 with an interquartile range increase in the indicators of natural environments. (Results from the negative binominal models).

	Model 1	Model 2	Model 3
Explanatory variables	**NDVI (mean value) IRR (95% CI)**	**Percentage public green space IRR (95% CI)**	**Percentage composite nature IRR (95% CI)**
Deficits in fine motor development			
Natural environment (NDVI, green, or composite)	0.963 (0.848,1.093)	0.960 (0.861,1.070)	0.916 (0.848,0.990)**
Deficits in gross motor development			
Natural environment (NDVI, green, or composite)	0.930 (0.836,1.035)	0.882 (0.807,0.964)**	0.899 (0.843,0.959)**

[1] Incidence rate ratio; * significant at $p<0.1$; ** significant at $p<0.05$

Table 4. Adjusted associations of deficits in fine and gross motor development 2015 with an interquartile range increase in the indicators of natural environments. (Results from the negative binominal models).

	Model 1	Model 2	Model 3
Explanatory variables	**NDVI (mean value) IRR[1] (95% CI)**	**Percentage public green space IRR[1] (95% CI)**	**Percentage composite nature IRR[1] (95% CI)**
Deficits in fine motor development			
Natural environment (NDVI, green, or composite)	0.952 (0.851,1.065)	0.923 (0.846,1.006)*	0.911 (0.859,0.966)**
Social status (parental) SES	0.882 (0.838,0.929)**	0.876 (0.835,0.920)**	0.879 (0.840,0.919)**
Non-German origin	1.000 (0.993,1.007)	0.999 (0.993,1.005)	0.999 (0.993,1.005)
Deficits in gross motor development			
Natural environment (NDVI, green, or composite)	0.917 (0.812,1.036)	0.859 (0.784,0.942)**	0.895 (0.839,0.955)**
Social status (parental) SES	0.953 (0.901,1.008)*	0.942 (0.896,0.992)**	0.953 (0.908,1.001)*
Non-German origin	0.999 (0.992,1.006)	0.997 (0.991,1.004)	0.999 (0.993,1.005)

[1] Incidence rate ratio; * significant at p<0.1; ** significant at p<0.05

3.6 *Association between natural environments and deficits in fine and gross motor development 2015: NB models, sensitivity analyses*

The inclusion of PM_{10}, $PM_{2.5}$, NO_2 and NO_x in the models with public green space and composite nature as exposures, and of noise for all nature exposure metrics, did not produce any important changes, neither in the estimates nor in the significance (see supplementary material table 3 a-e for examples of results from the sensitivity analysis). In the models using NDVI we observed that the pollutants decreased the association between NDVI and gross motor development. In the models using public green spaces and composite nature, the inclusion of kindergarten attendance and social economic status of the neighbourhood reduced the significance of socioeconomic status of the children to deficits in gross motor development.

3.7 *Analysis of data from 2016*

We also tested our findings by conducting the same analysis for the outcome fine motor development in 2016 (no data existed for gross development in 2016) and found similar associations as in the 2015 sample (see supplementary material table 4).

Finally, we conducted the sensitivity analysis adjusting by the same pollutants than in 2015. We could not find significant differences, with except that PM_{10} produces a decrease on the negative association between fine motor and NDVI in 2016 (IRR=0.9, CI 95%: 0.807-1.005).

4 Discussion

This study evaluated associations between neighbourhood level natural environment and prevalence of motor development deficits in a population-based sample of children in Berlin, Germany. In models adjusted for parental SES and non-German origin, we found a significant inverse association between percentage of composite nature (i.e. green and blue space) in the sub-district and deficits in fine and gross motor development. We also observed an inverse association between public green space and both fine and gross motor development deficits; however, the association for the fine motor development deficits was only marginally significant. For the average of NDVI (an indicator of general neighbourhood greenness), we also observed protective associations with fine and gross motor development deficits, but none of the associations were statistically significant.

4.1 Strengths and limitations

This study benefited from publicly available data from a large population-based sample of children with objective assessment of deficits in both fine and gross motor development. Our use of objective data on motor development obtained by professionals contributed to reducing the risk of outcome misclassification that is common in studies relying on parental reports of childhood motor development (Emond et al., 2005). We were also able to include a large number of social and environmental confounders to adjust our models. Social indicators, such as SES, kindergarten attendance, and smoking in household, were available from the same database. We used different metrics for assessing the exposure to natural environments which could cover different aspects of the exposure. All data on exposure and outcomes were temporally aligned for the year 2015. The use of freely available data, contributes to replicability and the methods used can easily be applied in other geographical contexts and settings.

Our study also faced some limitations. Due to the data protection regulations, we could not access individual level data. This lack of access forced us to apply an ecological design which may be prone to ecological bias and loss of information (Lakes and Burkart, 2016) due to use of aggregated data on sub-district level. The design also prevents the capability to establish a causal link, but the motor development outcome is novel and the study shall be considered as exploratory. Although we controlled our analyses for a wide range of important confounders/co-variates, we did not have data on other potentially influencing factors, such as maternal stress, history of preterm birth or low birth weight, childhood chronic conditions, parental health status, and parenting style (Huizink et al., 2003, Grace et al., 2016, Kopp, 2011, Sierau et al., 2016). In this context, we did not have data on the place of residence during the prenatal and early postnatal period, so we could evaluate these periods as potentially important windows of vulnerability. Moreover, our indicators of natural environment did not address the quality characteristics of these spaces such as safety or availability of playground which could have influenced our findings (Rugel et al., 2017). This study did not make use of tracking devices or other monitoring techniques; thus our data cannot inform on actual use of the natural environments. This is an aspect that should be considered in future studies on children's motor development.

4.2 Childhood motor development and socioenvironmental exposures

Motor development has been less studied in relation to environmental exposures, especially natural environments, compared to cognitive development and ability and our study is one of the first to report a possible association between childhood motor development and exposure to urban natural environments. Previous studies have found positive associations of urban green spaces on childhood cognitive and behavioural development (Dadvand et al., 2015, Markevych et al., 2014, Amoly et al., 2014), attention capacity (Mårtensson et al., 2009, Dadvand et al., 2017), and symptoms of attention deficit hyperactivity disorder (ADHD) (Taylor and Kuo, 2011, van den Berg and van den Berg, 2011, Markevych et al., 2018). Proposed mechanisms are improved birth outcomes (Dadvand et al., 2012) and increased opportunities for physical activity (Almanza et al., 2012), but also regulating ecosystem services (MA, 2005), such as reduced heat, noise, and air pollution with potential impact on childhood health and development. Similar mechanisms are plausible for motor development outcomes, but this has not been sufficiently analysed in previous research. Our study suggests that this effect should be further explored, including aspects of potential mediating pathways and mechanisms. This is particularly important since it has been suggested that early motor development can be a predictor of cognitive development and capacity (Burns et al., 2004).

The change in effect size following adjustment for air pollution and noise in our models suggests a potential mediation effect, something that should be further evaluated. Air pollution has been reported as a partly mediating factor in previous studies on the positive association between green spaces and childhood cognitive development (Dadvand et al., 2015) and neurodevelopment (Liao et al., 2019). The knowledge around the association between air pollution and motor development is limited, but a small number of studies suggest a negative impact, especially following exposure in early life (Wei et al., 2018, Yorifuji et al., 2016). The impact of noise is even less studied and our findings indicate that more research is needed. Several causal pathways between harmful exposures and impaired motor development are plausible, including chronic stress and neuro-inflammation with negative impact on neural growth.

In general, the socioenvironmental determinants of fine and gross motor development are insufficiently understood. A review from 2009 (Venetsanou and Kambas, 2010) suggested several potentially influencing factors, such as parental rearing style and general family environment. The review also pointed out parental SES as an important factor, discussing that part of this correlation could be explained by poorer access in deprived areas to healthy environments in which to be physically active and develop motor skills. In agreement with previous research (Syrengelas et al., 2014, Piek et al., 2008, Venetsanou and Kambas, 2010, Lejarraga et al., 2002), our study found that parental SES showed significant associations to both fine and gross motor development. In contrast to Reuben et al. (2019), however, the significant association to public green space remained also in the models that were adjusted for SES in our study. The geospatial distribution of natural environments in Berlin displays a somewhat complex pattern. Certain inner-city areas are relatively depleted of green space, but yet have high SES-levels, while some sub-districts in the north western parts are relatively green, but also house populations of poor SES. This unique spatial pattern may partly explain differences in findings between our research and previous studies.

Results from this study suggest an association between natural environments and motor development only in models using local land use data, but not when using NDVI as exposure indicator. This discrepancy reflects that different natural space metrics may measure different aspects of the environment (Rugel et al. 2017). NDVI is calculated from spectral reflectance of vegetation and basically determines whether an area is green (i.e. photosynthetically active) or not. The land use data we applied is more informative in the sense that it indicates natural spaces that are actually intended for public use, are publicly available and as such potentially providing health benefits. On the other hand, regulating ecosystem services, such as heat reduction or air pollution removal, would be appropriately measured by general exposure metrics, such as NDVI. What our study demonstrates is that it is important to consider different types of natural environment indicators in future studies on the health effects to eventually determine which type of metric is best used for predicting different health outcomes, depending on hypothesised pathway. For example, NDVI is an indicator of general greenness which may not necessarily be freely accessible and usable and thus it would not contribute to motor development. Land use data, on the other hand, more accurately indicate areas where children can be physically active and play, which would have a positive impact on their motor development. Previous studies have come to similar conclusions (Dadvand et al., 2014), indicating that the usefulness of NDVI is dependent on area and context and on which outcome is studied (Gascon et al., 2016).

5 Conclusion

The main contribution of this study is the novel outcome analysed – childhood fine and gross motor development, which has been surprisingly sparsely studied in relation to environmental exposures. Our study suggests that fine and gross motor development could be influenced by both socioeconomic and environmental factors, including natural environments, indicating a need for more research in the area. We recommend future studies to apply individual level data in a longitudinal design with repeated measures of both fine and gross motor development while using various metrics for characterizing the amount, quality , and use of natural environments surrounding children's residences and schools. With improved evidence, guidance for urban planning and public health interventions could be provided for improved childhood motor development through interactions with natural environments in their daily lives.

Acknowledgments

We would like to thank two anonymous reviewers for their helpful comments to an earlier version of the manuscript.

References

AALTONEN, S., LATVALA, A., ROSE, R. J., PULKKINEN, L., KUJALA, U. M., KAPRIO, J. & SILVENTOINEN, K. 2015. Motor Development and Physical Activity: A Longitudinal Discordant Twin-Pair Study. *Medicine and Science in Sports and Exercise,* 47**,** 2111-2118.

ABRAHAM, A., SOMMERHALDER, K. & ABEL, T. 2010. Landscape and well-being: A scoping study on the health-promoting impact of outdoor environments. *International Journal of Public Health,* 55**,** 59-69.

ALMANZA, E., JERRETT, M., DUNTON, G., SETO, E. & PENTZ, M. 2012. A study of community design, greenness, and physical activity in children using satellite, GPS and accelerometer data. *Health and Place,* 18**,** 46-54.

AMMAR, D., ACEVEDO, G. A. & CORDOVA, A. 2013. Affordances in the Home Environment for Motor Development: A Cross-Cultural Study between American and Lebanese Children. *Child Development Research,* 2013**,** 5.

AMOLY, E., DADVAND, P., FORNS, J., LÓPEZ-VICENTE, M., BASAGAÑA, X., JULVEZ, J., ALVAREZ-PEDREROL, M., NIEUWENHUIJSEN, M. J. & SUNYER, J. 2014. Green and Blue Spaces and Behavioral Development in Barcelona Schoolchildren: The BREATHE Project. *Environmental Health Perspectives,* 122**,** 1351-1358.

APA 1994. Diagnostic and Statistical Manual of Mental Disorders. 4th ed. American Psychiatric Association, Washington DC.

ARROYO, V., DÍAZ, J., ORTIZ, C., CARMONA, R., SÁEZ, M. & LINARES, C. 2016. Short term effect of air pollution, noise and heat waves on preterm births in Madrid (Spain). *Environmental Research,* 145**,** 162-168.

BURNS, Y., O'CALLAGHAN, M., MCDONELL, B. & ROGERS, Y. 2004. Movement and motor development in ELBW infants at 1 year is related to cognitive and motor abilities at 4 years. *Early Human Development,* 80**,** 19-29.

CACOLA, P. M., GABBARD, C., MONTEBELO, M. I. & SANTOS, D. C. 2015. Further Development and Validation of the Affordances in the Home Environment for Motor Development-Infant Scale (AHEMD-IS). *Phys Ther,* 95**,** 901-23.

CALDERÓN-GARCIDUEÑAS, L., ENGLE, R., MORA-TISCAREÑO, A., STYNER, M., GÓMEZ-GARZA, G., ZHU, H., JEWELLS, V., TORRES-JARDÓN, R., ROMERO, L. & MONROY-ACOSTA, M. E. 2011. Exposure to severe urban air pollution influences cognitive outcomes, brain volume and systemic inflammation in clinically healthy children. *Brain and cognition*.

CHAWLA, L. 2015. Benefits of Nature Contact for Children. *Journal of Planning Literature,* 30**,** 433-452.

CHEN, D., WANG, X., THATCHER, M., BARNETT, G., KACHENKO, A. & PRINCE, R. 2014. Urban vegetation for reducing heat related mortality. *Environmental Pollution,* 192**,** 275-284.

CUFFARO, M. A. 2011. Fine Motor Skills. *In:* GOLDSTEIN, S. & NAGLIERI, J. A. (eds.) *Encyclopedia of Child Behavior and Development.* Boston, MA: Springer US.

DADVAND, P., NIEUWENHUIJSEN, M. J., ESNAOLA, M., FORNS, J., BASAGAÑA, X., ALVAREZ-PEDREROL, M., RIVAS, I., LÓPEZ-VICENTE, M., DE CASTRO PASCUAL, M., SU, J., JERRETT, M., QUEROL, X. & SUNYER, J. 2015. Green spaces and cognitive development in primary schoolchildren. *Proceedings of the National Academy of Sciences,* 112**,** 7937-7942.

DADVAND, P., SUNYER, J., BASAGANA, X., BALLESTER, F., LERTXUNDI, A., FERNANDEZ-SOMOANO, A., ESTARLICH, M., GARCIA-ESTEBAN, R., MENDEZ, M. A. & NIEUWENHUIJSEN, M. J. 2012. Surrounding greenness and pregnancy outcomes in four Spanish birth cohorts. *Environmental Health Perspectives,* 120**,** 1481 - 1487.

DADVAND, P., TISCHER, C., ESTARLICH, M., LLOP, S., DALMAU-BUENO, A., LOPEZ-VICENTE, M., VALENTIN, A., DE KEIJZER, C., FERNANDEZ-SOMOANO, A., LERTXUNDI, N., RODRIGUEZ-DEHLI, C., GASCON, M., GUXENS, M., ZUGNA, D., BASAGANA, X., NIEUWENHUIJSEN, M. J., IBARLUZEA, J., BALLESTER, F. & SUNYER, J. 2017. Lifelong Residential Exposure to Green Space and Attention: A Population-based Prospective Study. *Environ Health Perspect,* 125**,** 097016.

DADVAND, P., VILLANUEVA, C. M., FONT-RIBERA, L., MARTINEZ, D., BASAGAÑA, X., BELMONTE, J., VRIJHEID, M., GRAZULEVICIENE, R., KOGEVINAS, M. & NIEUWENHUIJSEN, M. J. 2014. Risks and benefits of green spaces for children: a cross-sectional study of associations with sedentary behavior, obesity, asthma, and allergy. *Environmental Health Perspectives (Online),* 122**,** 1329.

DE KEIJZER, C., GASCON, M., NIEUWENHUIJSEN, M. J. & DADVAND, P. 2016. Long-Term Green Space Exposure and Cognition Across the Life Course: a Systematic Review. *Current Environmental Health Reports,* 3**,** 468-477.

DÖPFNER, M., DIETMAIR, I., MERSMANN, H., SIMON, K., TROST-BRINKHUES, G 2005. S-ENS – Screening des Entwicklungsstandes bei Einschulungsunter-suchungen. . Göttingen: Hogrefe. .

DORMANN, C.F., ELITH, J., BACHER, S., BUCHMANN, C., CARL, G., CARRÉ, G., MARQUÉZ, J.R.G., GRUBER, B., LAFOURCADE, B., LEITÃO, P.J., MÜNKEMÜLLER, T., MCCLEAN, C., OSBORNE, P.E., REINEKING, B., SCHRÖDER, B., SKIDMORE, A.K., ZURELL, D., LAUTENBACH, S., 2013. Collinearity: A review of methods to deal with it and a simulation study evaluating their performance. *Ecography (Cop.).* 36, 027–046. https://doi.org/10.1111/j.1600-0587.2012.07348.x

DYMENT, J. E. & BELL, A. C. 2008. Grounds for movement: Green school grounds as sites for promoting physical activity. *Health Education Research,* 23**,** 952-962.

DZHAMBOV, A. & DIMITROVA, D. 2014. Urban green spaces' effectiveness as a psychological buffer for the negative health impact of noise pollution: A systematic review. *Noise and Health,* 16**,** 157-165.

EMOND, A., BELL, J. C. & HERON, J. 2005. Using parental questionnaires to identify developmental delay. *Developmental Medicine & Child Neurology,* 47**,** 646-648.

ENGEMANN, K., PEDERSEN, C. B., ARGE, L., TSIROGIANNIS, C., MORTENSEN, P. B. & SVENNING, J.-C. Childhood exposure to green space – A novel risk-decreasing mechanism for schizophrenia? *Schizophrenia Research*.

FLEUREN, K. M., SMIT, L. S., STIJNEN, T. & HARTMAN, A. 2007. New reference values for the Alberta Infant Motor Scale need to be established. *Acta Paediatr,* 96**,** 424-7.

GASCHLER, P., HEINECKE, I. 1990. Beweglichkeit von Kindern heute und vor zehn Jahren. *Sportunterricht* 39**,** 373-384.

GASCON, M., CIRACH, M., MARTÍNEZ, D., DADVAND, P., VALENTÍN, A., PLASÈNCIA, A. & NIEUWENHUIJSEN, M. J. 2016. Normalized difference vegetation index (NDVI) as a marker of surrounding greenness in epidemiological studies: The case of Barcelona city. *Urban Forestry & Urban Greening,* 19**,** 88-94.

GEHRING, U., TAMBURIC, L., SBIHI, H., DAVIES, H. W. & BRAUER, M. 2014. Impact of noise and air pollution on pregnancy outcomes. *Epidemiology,* 25**,** 351-358.

GRACE, T., BULSARA, M., ROBINSON, M. & HANDS, B. 2016. Early life events and motor development in childhood and adolescence: a longitudinal study. *Acta Paediatrica, International Journal of Paediatrics,* 105**,** e219-e227.

HADDERS-ALGRA, M. 2007. Atypical performance: how do we deal with that? *Dev Med Child Neurol,* 49**,** 403.

HUIZINK, A. C., ROBLES DE MEDINA, P. G., MULDER, E. J. H., VISSER, G. H. A. & BUITELAAR, J. K. 2003. Stress during pregnancy is associated with developmental outcome in infancy. *Journal of Child Psychology and Psychiatry,* 44**,** 810-818.

KABISCH, N., HAASE, D. & ANNERSTEDT VAN DEN BOSCH, M. 2016. Adding Natural Areas to Social Indicators of Intra-Urban Health Inequalities among Children: A Case Study from Berlin, Germany. *International Journal of Environmental Research and Public Health,* 13**,** 783.

KABISCH, N., SELSAM, P., KIRSTEN, T., LAUSCH, A. & BUMBERGER, J. 2019. A multi-sensor and multi-temporal remote sensing approach to detect land cover change dynamics in heterogeneous urban landscapes. *Ecological Indicators,* 99**,** 273-282.

KABISCH, N., VAN DEN BOSCH, M. & LAFORTEZZA, R. 2017. The health benefits of nature-based solutions to urbanization challenges for children and the elderly - A systematic review. *Environ Res,* 159**,** 362-373.

KAHN JR, P. H., KELLERT, S. 2002. *Children and Nature Psychological, Sociocultural, and Evolutionary Investigations* Cambridge, MA, MIT Press.

KISER, B. 2015. Early child development: Body of knowledge. *Nature,* 523**,** 286-9.

KOPP, C. B. 2011. Development in the early years: Socialization, motor development, and consciousness. *Annual Review of Psychology.*

LAKES, T. & BURKART, K. 2016. Childhood overweight in Berlin: intra-urban differences and underlying influencing factors. *International Journal of Health Geographics,* 15**,** 12.

LEJARRAGA, H., PASCUCCI, M. C., KRUPITZKY, S., KELMANSKY, D., BIANCO, A., MARTÍNEZ, E., TIBALDI, F. & CAMERON, N. 2002. Psychomotor development in Argentinean children aged 0–5 years. *Paediatric and Perinatal Epidemiology,* 16**,** 47-60.

LIAO, J., ZHANG, B., XIA, W., CAO, Z., ZHANG, Y., LIANG, S., HU, K., XU, S. & LI, Y. 2019. Residential exposure to green space and early childhood neurodevelopment. *Environment International,* 128**,** 70-76.

LINGAM, R., HUNT, L., GOLDING, J., JONGMANS, M. & EMOND, A. 2009. Prevalence of developmental coordination disorder using the DSM-IV at 7 years of age: a UK population-based study. *Pediatrics,* 123**,** e693-700.

LITTLE, H. & SWELLER, N. 2015. Affordances for Risk-Taking and Physical Activity in Australian Early Childhood Education Settings. *Early Childhood Education Journal,* 43**,** 337-345.

LLOYD, J. E. V., LI, L. & HERTZMAN, C. 2010. Early experiences matter: Lasting effect of concentrated disadvantage on children's language and cognitive outcomes. *Health & Place,* 16**,** 371-380.

MA 2005. *Millennium ecosystem assessment: Ecosystems and Human Well-Being,* Washington DC, Island Press.

MAHER, B. A., AHMED, I. A., DAVISON, B., KARLOUKOVSKI, V. & CLARKE, R. 2013. Impact of roadside tree lines on indoor concentrations of traffic-derived particulate matter. *Environ Sci Technol,* 47**,** 13737-44.

MANZARDO, A. M., PENICK, E. C., KNOP, J., NICKEL, E. J., HALL, S., JENSEN, P. & GABRIELLI JR, W. F. 2005. Developmental differences in childhood motor coordination predict adult alcohol dependence: Proposed role for the cerebellum in alcoholism. *Alcoholism: Clinical and Experimental Research,* 29**,** 353-357.

MARKEVYCH, I., TESCH, F., DATZMANN, T., ROMANOS, M., SCHMITT, J. & HEINRICH, J. 2018. Outdoor air pollution, greenspace, and incidence of ADHD: A semi-individual study. *Sci Total Environ,* 642**,** 1362-1368.

MARKEVYCH, I., TIESLER, C. M. T., FUERTES, E., ROMANOS, M., DADVAND, P., NIEUWENHUIJSEN, M. J., BERDEL, D., KOLETZKO, S. & HEINRICH, J. 2014. Access to urban green spaces and behavioural problems in children: Results from the GINIplus and LISAplus studies. *Environment International,* 71**,** 29-35.

MÅRTENSSON, F., BOLDEMANN, C., BLENNOW, M., SÖDERSTRÖM, M. & GRAHN, P. 2009. Attention promoting outdoor environment for children–part of a salutogenic concept. *Health & Place,* 15**,** 1149-1157.

MCCORMICK, R. 2017. Does Access to Green Space Impact the Mental Well-being of Children: A Systematic Review. *Journal of Pediatric Nursing,* 37**,** 3-7.

MIQUELOTE, A. F., SANTOS, D. C., CACOLA, P. M., MONTEBELO, M. I. & GABBARD, C. 2012. Effect of the home environment on motor and cognitive behavior of infants. *Infant Behav Dev,* 35**,** 329-34.

PENNINGTON, B. F. 2006. From single to multiple deficit models of developmental disorders. *Cognition,* 101**,** 385-413.

PIEK, J. P., DAWSON, L., SMITH, L. M. & GASSON, N. 2008. The role of early fine and gross motor development on later motor and cognitive ability. *Human Movement Science,* 27**,** 668-681.

RAO, M., GEORGE, L. A., ROSENSTIEL, T. N., SHANDAS, V. & DINNO, A. 2014. Assessing the relationship among urban trees, nitrogen dioxide, and respiratory health. *Environmental Pollution,* 194**,** 96-104.

REUBEN, A., ARSENEAULT, L., BELSKY, D. W., CASPI, A., FISHER, H. L., HOUTS, R. M., MOFFITT, T. E. & ODGERS, C. 2019. Residential neighborhood greenery and children's cognitive development. *Social Science & Medicine*.

RUGEL, E. J., HENDERSON, S. B., CARPIANO, R. M. & BRAUER, M. 2017. Beyond the Normalized Difference Vegetation Index (NDVI): Developing a Natural Space Index for population-level health research. *Environmental Research,* 159**,** 474-483.

SEELAENDER, J., FIDLER, V. & HADDERS-ALGRA, M. 2013. Increase in impaired motor coordination in six-year-old German children between 1990 and 2007. *Acta Paediatrica, International Journal of Paediatrics,* 102**,** e44-e48.

SENSTADT. 2017. Berlin Environmental Atlas 07.05 Strategic Noise Maps. http://www.stadtentwicklung.berlin.de/umwelt/umweltatlas/edb705_01.htm. [Accessed 30 Aug 2019].

SENSTADT. 2018. Berlin Environmental Atlas 03.12 Long-Term Development of Air Quality. https://www.stadtentwicklung.berlin.de/umwelt/umweltatlas/ed312_02.htm. [Accessed 30 Aug 2019]

SENSTADT. 2019. *Geodata* [Online]. Available: http://www.stadtentwicklung.berlin.de/geoinformation/fis-broker/. 2014 [Accessed 28 May 2018].

SIERAU, S., DÄHNE, V., BRAND, T., KURTZ, V., VON KLITZING, K. & JUNGMANN, T. 2016. Effects of Home Visitation on Maternal Competencies, Family Environment, and Child Development: a Randomized Controlled Trial. *Prevention Science,* 17**,** 40-51.

SINGER, D. G., SINGER, J. L., D'AGOSTINO, H. & DELONG, R. 2009. Children's pastimes and play in sixteen nations: Is free-play declining? *American Journal of Play,* 1**,** 283-312.

SÖDERSTRÖM, M., BOLDEMANN, C., SAHLIN, U., MÅRTENSSON, F., RAUSTORP, A. & BLENNOW, M. 2013. The quality of the outdoor environment influences childrens health–a cross-sectional study of preschools. *Acta Paediatrica,* 102**,** 83-91.

SYRENGELAS, D., KALAMPOKI, V., KLEISIOUNI, P., KONSTANTINOU, D. & SIAHANIDOU, T. 2014. Gross motor development in full-term Greek infants assessed by the Alberta Infant Motor Scale: Reference values and socioeconomic impact. *Early Human Development,* 90**,** 353-357.

TAYLOR, A. F. & KUO, F. E. M. 2011. Could exposure to everyday green spaces help treat ADHD? Evidence from children's play settings. *Applied Psychology: Health and Well-Being,* 3**,** 281-303.

TIMMONS, B. W., LEBLANC, A. G., CARSON, V., GORBER, S. C., DILLMAN, C., JANSSEN, I., KHO, M. E., SPENCE, J. C., STEARNS, J. A. & TREMBLAY, M. S. 2012. Systematic review of physical activity and health in the early years (aged 0-4 years). *Applied Physiology, Nutrition and Metabolism,* 37**,** 773-792.

VAN AART, C. J. C., MICHELS, N., SIOEN, I., DE DECKER, A., BIJNENS, E. M., JANSSEN, B. G., DE HENAUW, S. & NAWROT, T. S. 2018. Residential landscape as a predictor of psychosocial stress in the life course from childhood to adolescence. *Environment International,* 120**,** 456-463.

VAN DEN BERG, A. E. & VAN DEN BERG, C. G. 2011. A comparison of children with ADHD in a natural and built setting. *Child Care Health and Development,* 37**,** 430-439.

VAN DEN BOSCH, M., BRAUER, M., BURNETT, R., DAVIES, H. W., DAVIS, Z., GUHN, M., JARVIS, I., NESBITT, L., OBERLANDER, T., RUGEL, E., SBIHI, H., SU, J. G. & JERRETT, M. 2018. Born to be Wise: a population registry data linkage protocol to assess the impact of modifiable early-life environmental exposures on the health and development of children. *BMJ Open,* 8**,** e026954.

VAN DEN BOSCH, M. & NIEUWENHUIJSEN, M. 2017. No time to lose - Green the cities now. *Environ Int,* 99**,** 343-350.

VEITCH, J., BAGLEY, S., BALL, K. & SALMON, J. 2006. Where do children usually play? A qualitative study of parents' perceptions of influences on children's active free-play. *Health and Place,* 12**,** 383-393.

VENETSANOU, F. & KAMBAS, A. 2010. Environmental Factors Affecting Preschoolers' Motor Development. *Early Childhood Education Journal,* 37**,** 319-327.

WEI, C. F., CHEN, M. H., LIN, C. C., GUO, Y. L., LIN, S. J., HSIEH, W. S. & CHEN, P. C. 2018. Household incense burning and infant gross motor development: Results from the Taiwan Birth Cohort Study. *Environment International,* 115**,** 110-116.

WHO 2016. Urban green spaces and health - a review of evidence. World Health Organization, European Regional Office, Copenhagen, Denmark.

YORIFUJI, T., KASHIMA, S., HIGA DIEZ, M., KADO, Y., SANADA, S. & DOI, H. 2016. Prenatal Exposure to Traffic-related Air Pollution and Child Behavioral Development Milestone Delays in Japan. *Epidemiology,* 27**,** 57-65.

ZHOU, Y., VON LENGERKE, T., WALTER, U. & DREIER, M. 2018. Migration background and childhood overweight in the Hannover Region in 2010–2014: a population-based secondary data analysis of school entry examinations. *European Journal of Pediatrics,* 177**,** 753-763.

ZIMMER R, V. M. 1987. *Motoriktest fur vier- bis sechsjahrige Kinder (MOT 4-6),* Weinheim: Beltz.

Supplementary material

Supplementary material table 1: Explanation of values for school education, employment education and current employment status to derive Parental social status index.

School education	Employment education	Employment Status	Points
without school graduation	without professional education	unemployed and in search for work	0
Primary education	currently in professional education/studying	unemployed other reason	1
Secondary education	finished professional education	part-time	2
Tertiary education (graduation after 12/13 years attending school qualifies to go to university)	University degree	fulltime	3

Supplementary material table 2: **Remote sensing data used for NDVI calculation by data source.**

No	Name of image	Sensor	Provider
1	150605_NDVIrad_Berlin_l7	Landsat 7	USGS: LE07_L1TP_193023_20150605_20161025_01_T1
2	150629_NDVIrad_QA_Berlin_l8	Landsat 8	USGS: LC08_L1TP_193023_20150629_20170407_01_T1
3	150707_NDVIrad_Berlin_l7	Landsat 7	USGS: LE07_L1TP_193023_20150707_20161024_01_T1
5	150917_NDVIrad_QA_Berlin_l	Landsat 8	USGS: LC08_L1TP_193023_20150917_20170404_01_T1

Note: We aimed at integrating all available and usable images for a whole vegetation period to assess fully developed vegetation. Following an automated approach by Kabisch et al. (2019) we intended to cover months April-October for the City of Berlin and could use images from May-September. Available satellite images from LANDSAT (Landsat 8 OLI sensor and Landsat 7 ETM) were downloaded from the United States Geological Survey (USGS) Landsat archive (Earth Explorer) for 2015. Landsat data were preselected for a cloud cover of less than 40%. They are provided with a QA-band (Quality Assessment (QA) band) that meets all of our needs to cover clouds and image gaps (stripes) caused by the shutter defect of Landsat 7 (NASA, 2017). The QA-channel simultaneously has different masks in binary code (USGS QA-Tools 2017, 16 classes). A transfer of the code into defined masks is implemented in the ILMS image tool (ILMSimage, Kralisch et al., 2012), which is used in the automatized approach. The NDVI was calculated by using calibrated standard Top Of Atmosphere reflectance values (for details see Kabisch et al. (2019).

Supplementary material table 3: Exemplary results of the Sensitivity analysis using data for 2015 for gross motor development and public green space (3a, 3b, 3c) and NDVI using NDIV-NO_x/NO_2 residuals (3d,3e).

3a. Adjusted associations of deficits in gross motor development with an interquartile range increase in the indicator of percentage public green and $PM_{2.5}$.

	Estimate	CI	P value	IRR	CI(IRR,95%)
(Intercept)	0.0065	(-1.4903,1.5033)	0.9932	1.0065	(0.2253,4.4966)
Percentage public green space	-0.1792	(-0.2792,-0.0793)	0.0004	0.8359	(0.7564,0.9238)
Social status (parental) SES	-0.0578	(-0.1083,-0.0074)	0.0247	0.9438	(0.8973,0.9927)
Non-German origin	-0.0019	(-0.0082,0.0045)	0.5661	0.9981	(0.9918,1.0045)
PM2.5	-0.0571	(-0.1454,0.0313)	0.2057	0.9445	(0.8646,1.0318)

3b. Adjusted associations of deficits in gross motor development with an interquartile range increase in the indicator of percentage public green and PM_{10}.

	Estimate	CI	P value	IRR	CI(IRR,95%)
(Intercept)	0.001	(-1.3561,1.3581)	0.9988	1.001	(0.2577,3.8889)
Percentage public green space	-0.1819	(-0.2807,-0.0832)	0.0003	0.8337	(0.7553,0.9202)
Social status (parental) SES	-0.057	(-0.1073,-0.0067)	0.0264	0.9446	(0.8983,0.9933)
Non-German origin	-0.0017	(-0.008,0.0047)	0.6091	0.9983	(0.992,1.0047)
PM10	-0.0405	(-0.0946,0.0136)	0.1426	0.9603	(0.9097,1.0137)

3c. Adjusted associations of deficits in gross motor development with an interquartile range increase in the indicator of percentage public green and Noise.

	Estimate	CI	P value	IRR	CI(IRR,95%)
(Intercept)	-0.228	(-1.4428,0.9868)	0.713	0.7961	(0.2363,2.6826)
Percentage public green space	-0.1551	(-0.2457,-0.0644)	0.0008	0.8564	(0.7822,0.9377)
Social status (parental) SES	-0.052	(-0.1036,-4e-04)	0.0481	0.9493	(0.9016,0.9996)
Non-German origin	-0.0016	(-0.008,0.0048)	0.6278	0.9984	(0.992,1.0048)
Noise	-0,0138	(-0.0344,0.0067)	0.188	0.9863	(0.9662,1.0068)

3d. Adjusted associations of deficits in gross motor development with an interquartile range increase in the indicator of NDVI and NDVI-NO_x residuals.

	Estimate	CI	P value	IRR	CI(IRR,95%)
(Intercept)	-1.5024	(-2.9609,-0.044)	0.0435	0.2226	(0.0691,0.7174)
NDVI	0.0024	(-0.1695,0.1744)	0.9779	1.0024	(0.8766,1.1462)
Social status (parental) SES	-0.0318	(-0.0917,0.0281)	0.2984	0.9687	(0.9162,1.0242)
Non-German origin	0.0018	(-0.0067,0.0102)	0.683	1.0018	(0.9946,1.009)
Residuals NDVI_NO_x	-0.1948	(-0.4516,0.0619)	0.1369	0.823	(0.6627,1.0221)

3e. Adjusted associations of deficits in gross motor development with an interquartile range increase in the indicator of NDVI and NDVI-NO_2 residuals.

	Estimate	CI	P value	IRR	CI(IRR,95%)
(Intercept)	-1.4607	(-2.9026,-0.0188)	0.0471	0.2321	(0.072,0.748)
NDVI	-0.0029	(-0.1724,0.1665)	0.9729	0.9971	(0.872,1.1401)
Social status (parental) SES	-0.0331	(-0.0926,0.0265)	0.2761	0.9674	(0.915,1.0228)
Non-German origin	0.0016	(-0.0068,0.01)	0.7133	1.0016	(0.9944,1.0088)
Residuals NDVI_NO_2	-0.1894	(-0.4474,0.0686)	0.1502	0.8274	(0.6662,1.0276)

Supplementary Material Table 4. Adjusted associations of deficits in fine and gross motor development 2016 with on interquartile range increase in the indicators of natural environments. (Results from the negative binominal models).

	Model 1	Model 2	Model 3
Explanatory variables	**NDVI (mean value) IRR (95% CI)**	**Percentage public green space IRR (95% CI)**	**Percentage composite nature IRR (95% CI)**
Deficits in fine motor development			
Natural environment (NDVI, green, or composite)	0.946 (0.856,1.046)	0.920 (0.852,0.993)**	0.912 (0.866,0.960)**
Social status (parental) SES	0.894(0.856,0.933)**	0.890 (0.855,0.927)**	0.892 (0.860,0.925)**
Non-German origin	0.998 (0.991,1.005)	0.998 (0.992,1.004)	0.998 (0.992,1.003)

[1] Incidence rate ratio; * significant at p<0.1; ** significant at p<0.05