

Lifelong Residential Exposure to Green Space and Attention: A Population-based Prospective Study

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BACKGROUND: Natural environments, including green spaces, may have beneficial impacts on brain development. However, longitudinal evidence of an association between long-term exposure to green spaces and cognitive development (including attention) in children is limited.

OBJECTIVES: We evaluated the association between lifelong residential exposure to green space and attention during preschool and early primary school years.

METHODS: This longitudinal study was based on data from two well-established population-based birth cohorts in Spain. We assessed lifelong exposure to residential surrounding greenness and tree cover as the average of satellite-based normalized difference vegetation index and vegetation continuous fields, respectively, surrounding the child’s residential addresses at birth, 4–5 y, and 7 y. Attention was characterized using two computer-based tests: Conners’ Kiddie Continuous Performance Test (K-CPT) at 4–5 y ($n = 888$) and Attentional Network Task (ANT) at 7 y ($n = 987$). We used adjusted mixed effects models with cohort random effects to estimate associations between exposure to greenness and attention at ages 4–5 and 7 y.

RESULTS: Higher lifelong residential surrounding greenness was associated with fewer K-CPT omission errors and lower K-CPT hit reaction time-standard error (HRT-SE) at 4–5 y and lower ANT HRT-SE at 7 y, consistent with better attention. This exposure was not associated with K-CPT commission errors or with ANT omission or commission errors. Associations with residential surrounding tree cover also were close to the null, or were negative (for ANT HRT-SE) but not statistically significant.

CONCLUSION: Exposure to residential surrounding greenness was associated with better scores on tests of attention at 4–5 y and 7 y of age in our longitudinal cohort. <https://doi.org/10.1289/EHP694>

Introduction

It has been proposed that exposure to natural environments, which include green spaces, is important for normal neurodevelopment (Kahn and Kellert 2002; Kellert 2005). Natural environments provide children with unique opportunities for engagement, discovery, risk-taking, creativity, mastery, and control, and for strengthening the child’s sense of self; in addition, they also may inspire basic emotional states (including a sense of wonder) and enhance psychological restoration, all of which may

positively influence cognitive development and attention (Kahn and Kellert 2002; Kellert 2005; Bowler et al. 2010). Proximity to green spaces also may benefit cognitive development through indirect mechanisms involving increased physical activity (James et al. 2015), reduced exposure to air pollution and noise (Gidlöf-Gunnarsson and Öhrström 2007; Davvand et al. 2012, 2015b), and exposure to an enriched microbial environment (Rook 2013), each of which may contribute to improved cognitive function in general and attention in particular (Fedewa and Ahn 2011; Klatter et al. 2013; Rook 2013; Sunyer et al. 2015). However, population-based evidence of the association between long-term exposure to green spaces and cognitive development and attention in children is limited (Dadvand et al. 2015a).

In a previous study of 2,593 children attending primary school in Barcelona (Dadvand et al. 2015a), exposure to surrounding greenness at enrollment was associated with greater progress in working memory and attention over a 12-mo period. However, children were evaluated at 7–10 years of age, after substantial cognitive development had already occurred, and we were not able to account for exposures during prenatal and early postnatal periods of rapid brain development that may be especially vulnerable to effects of environmental exposures (Grandjean and Landrigan 2014). Therefore, the aim of the present study was to evaluate longitudinal associations between

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lifelong residential exposure to greenness, including exposure during prenatal and early postnatal periods, and measures of attention during preschool and at 7 y of age.

Materials and Methods

Study Population

Our study was based on data from two well-established population-based birth cohorts that are part of the INMA (Infancia y Medio Ambiente; Childhood and Environment) network of birth cohorts in Spain. The overall goals of INMA are to identify biological, social, and environmental determinants of normal and abnormal growth, development, and health, from fetal life to adulthood (Guxens et al. 2012). The Sabadell and Valencia INMA cohorts are located in northeastern and eastern Spain, respectively. Both locations have a Mediterranean climate characterized by hot and dry summers, mild and rainy winters, and maximum vegetation between autumn and spring.

The data was collected prospectively during 2003–2013 for these two cohorts using the INMA common protocol (Guxens et al. 2012). Briefly, pregnant women who fulfilled the inclusion criteria [age ≥ 16 y, singleton pregnancy, no use of assisted reproductive techniques, intention to deliver at the reference hospital, and ability to speak and understand Spanish or a local language (e.g., Catalan)] were recruited during the first trimester of pregnancy at primary healthcare centers or public hospitals. A baseline survey was performed at enrollment (approximately 12 wk of pregnancy), and follow-up surveys were performed at 20 and 32 wk of pregnancy, at birth, and when children were 6 mo, 1 y, 2 y, 4 y, or 5 y (in Sabadell and Valencia, respectively), and 7 y of age. Additional information on the cohorts and data collection has been published elsewhere (Guxens et al. 2012). All participants gave written informed consent before enrollment in the cohorts. Each cohort obtained ethical approval from the ethical committee in its corresponding region.

Residential Surrounding Greenness

The assessment of residential surrounding greenness was based on two satellite-based indices of greenness: *a*) Normalized Difference Vegetation Index (NDVI) an indicator of greenness including all types of vegetation and *b*) Vegetation Continuous Fields (VCF), an indicator of tree canopy cover.

NDVI is based on land surface reflectance of visible (red) and near-infrared parts of spectrum (Weier 2011). Its values range between -1 and 1 , with higher numbers indicating more greenness and negative values indicating water bodies, snow, and barren areas of rock and sand. VCF indicates the percentage of land (in each image pixel) covered by the woody vegetation with a height greater than five meters (Sexton et al. 2013). To develop NDVI and VCF maps for our study regions, we used Landsat data at $30\text{ m} \times 30\text{ m}$ resolution as detailed in Supplemental Materials (see Table S1 and Figures S1 and S2).

For each participant, we derived estimates of residential surrounding greenness (NDVI) and residential surrounding tree cover (VCF) within 100 m, 300 m, and 500 m buffer areas (representing immediate, intermediate, and neighborhood areas, respectively) surrounding the residential address at birth, at the 4–5 y follow-up, and at the 7-y follow-up, resulting in 18 estimates (3 time points \times 3 buffers \times 2 indices) for (Dadvand et al. 2012, 2014, 2015a, 2016). For each greenness index and buffer area, we derived lifelong exposure estimates at 4–5 y [the mean value of the index at birth, and at 4- or 5-y (for the Sabadell and Valencia cohorts, respectively)] and at 7 y (the mean value of the index at birth, 4–5 y, and 7-y).

Assessment of Attention

We used two computer-based tests to assess attention in INMA children: Conners' Kiddie Continuous Performance Test (K-CPT) at 4 y of age for the Sabadell cohort and at 5 y of age for the Valencia cohort and Attentional Network Task (ANT) at 7 y of age for both cohorts.

The K-CPT. The K-CPT (K-CPT™ v.5) is designed to characterize attention in children aged 4 to 7 y (Conners 2000). The K-CPT has been demonstrated to be a valid tool to characterize attention in comparison with clinical (Epstein et al. 2003; Homack and Riccio 2006) and parental evaluations (Barnard et al. 2015). To conduct this task, children were instructed to press the space bar when they saw any image on the computer screen except a ball. Three main outcomes of the K-CPT were used in our analyses: *a*) omission errors (e.g., the child failed to respond when she or he should); *b*) commission errors (e.g., the child responded when she or he should not); and *c*) hit reaction time–standard error (HRT-SE) (SE of RT for correct responses), a measure of response speed consistency throughout the test (Conners and Staff 2000). A higher HRT-SE indicates highly variable reactions related to *inattentiveness*.

The ANT. The ANT is a task developed to assess attention in subjects older than 6 y (Rueda et al. 2004). To perform this test, children were asked to press the left or right key on the computer mouse, depending on whether the centrally located fish in a horizontal row of five yellow fish was pointing to the left or right. As for the K-CPT, we derived counts of omission errors and commission errors, and the HRT-SE, for each participant. We have previously shown that in a sample of $\sim 2,900$ primary schoolchildren in Barcelona, the ANT indicators have statistical dependency with age, school performance, attention deficit/hyperactivity disorder (ADHD) clinical criteria, behavioral problems, and maternal education (Forns et al. 2014).

Statistical Analysis

Because of the multilevel nature of the data (i.e., children within cohorts), we used mixed effects models with attentional parameters as outcomes (one parameter for each test at a time), measures of exposure to green spaces (one at a time) as a fixed effect predictor, and the cohort as the random effect. Random intercepts were used to account for clustering of subjects into cohorts (Chu et al. 2011). For commission and omission errors (count data), we developed negative binomial mixed effects models and for HRT-SE (continuous data), we developed linear mixed effects models. The regression coefficients of negative binomial models were exponentiated to obtain mean ratios. Separate sets of models were developed for K-CPT and ANT with 4- or 5-year exposure measures being used for K-CPT analyses and 7-y exposure for ANT analyses. All models were further adjusted for the following covariates identified *a priori*: age (at the time of 4- or 5-y follow-up for the K-CPT analyses and at the time of 7-y follow-up for the ANT analyses), sex, preterm birth (<37 weeks of gestation, yes/no), maternal cognitive performance [assessed at 4- or 5-y follow-up, using the Wechsler Adult Intelligence Scale (WAIS-IV) Similarities subscale, one of four subscales used to measure verbal comprehension], maternal smoking during pregnancy (yes/no), and exposure to environmental tobacco smoke (smoking by any resident of the child's home at 4-y follow-up for the K-CPT analyses and at 4- or 5-y as well as 7-y follow-ups for the ANT analyses, yes/no). In addition, we adjusted for maternal educational attainment at enrollment (none or primary school only, secondary school only, or university) as an indicator of individual-level socioeconomic status (SES), and for the Urban Vulnerability Index (Spanish Ministry of Public Works 2012), a

measure of neighborhood SES, at each census tract (using the address at the time of outcome assessment), as an indicator of area-level SES. We estimated the difference in average outcome scores associated with one interquartile range (IQR) increase (based on all study participants) in average lifetime NDVI or VCF at 4–5 y or 7 y.

Sensitivity Analyses

We conducted a number of sensitivity analyses to evaluate the robustness of our findings. First, we performed models with additional adjustments for parity (continuous), for whether the child had been breastfed (yes/no), for child’s birth weight (continuous), and for the following factors at the time of the outcome assessment: sleep duration (average hours per day), time spent watching TV (average hours per week), time spent on sedentary activities (average hours per week), parental marital status (single parent: yes/no), and social class [Clasificación Nacional de Ocupaciones (CNO-94) (three categories)]. In addition, we estimated associations using simple negative binomial and linear regression models with cohort as a categorical predictor, as an alternative to using mixed effects models with a random intercept for the study cohort. We used NDVI maps from two different satellite sensors to assess green-space exposure in each cohort. To explore whether differences between the sensors influenced our findings, we derived standardized NDVI estimates for each map and buffer size (100 m, 300 m, and 500 m) as follows:

$$\text{NDVI}_{\text{stan}_{ij}} = (\text{NDVI}_{ij} - \text{NDVI}_j) / \text{sd_NDVI}_j,$$

where NDVI_{ij} is the value of NDVI for subject i in center j (e.g., Sabadell or Valencia), NDVI_j is the average NDVI in center j , and sd_NDVI_j is the standard deviation of NDVI in center j . We averaged the standardized NDVI estimates for each buffer and time point (birth, 4 or 5 y, and 7 y, as appropriate) to construct alternative measures of lifelong residential exposure to green space, and we repeated the analyses. Furthermore, because the 16 May 2007 NDVI map used to estimate NDVI at birth for Valencia participants was not cloud-free, we conducted a sensitivity analysis excluding participants for whom >10% of the NDVI pixels in each buffer were affected by clouds ($n = 6, 8,$ and 9 for the 100-m, 300-m, and 500-m buffers, respectively).

Results

Study Population

Of 1,527 children with data available at birth (740 from Sabadell, 787 from Valencia), 1,199 (77.6%) and 1,044 (68.5%) participated in the 4- or 5-y and 7-y follow-ups, respectively (Figure 1 and Table S1). There were no statistically significant differences ($\alpha = 0.05$) in neighborhood SES, maternal verbal comprehension, child’s sex, or preterm birth between participants with available data at birth and those with measures of attention at 4–5 y ($n = 888, 364$ from Sabadell, 524 from Valencia) or 7 y ($n = 978, 530$ from Sabadell, 448 from Valencia) in the combined cohorts (Table 1) or individual cohorts (see Table S2). However, the children included in the analyses for 4- or 5-y and 7-y follow-ups tended to have mothers with higher educational attainment in comparison with the children participating at birth. Furthermore, the mothers of children included in the 7-y analyses were less likely to have smoked during pregnancy than all mothers with data available at birth.

Greenness Exposure

Of 888 participants with available data on K-CPT, 194 (21.8%) had changed their address of residence between birth and the 4- or 5-y follow-up. Of 978 participants with available data on ANT, 252 (25.8%) had moved home between birth and the 7-y follow-up. The description of exposure measures in each follow-up separately for participants at each center has been presented in Table 2. Participants in Sabadell generally had higher levels of residential surrounding greenness and canopy cover in comparison with participants in Valencia. As presented in Table S3, NDVI and VCF values at 500 m were moderately to strongly correlated with values of the same exposure metric at different time points (Spearman’s correlations 0.68–0.83 for NDVI, 0.83–0.94 for VCI), with stronger correlations when limited to children who had not changed addresses between the follow-ups (Table S2). Correlations between NDVI and VCF at the same time points also were moderate to strong (0.46–0.79). There was no statistically significant difference in greenness exposure between those included and excluded in each follow-up or between those included in each follow-up and participants with available data at birth (data not shown).

Attention

The description of the performance of study participants in attention tests is presented in Table 2. Median K-CPT scores for omissions and HRT-SE were lower for children from Valencia than for children from Sabadell, which may at least partly reflect the difference in the age at which children in each cohort were tested (5 y vs. 4 y, respectively) (Table 2). The ANT measures were comparable with those of our other study (Forns et al. 2014) conducted in Barcelona reporting median (IQR) of 2 (4), 5 (5), and 310.3 (122.4), respectively, for omission and commission errors and HRT-SE among a population-based sample of 7-y-old children.

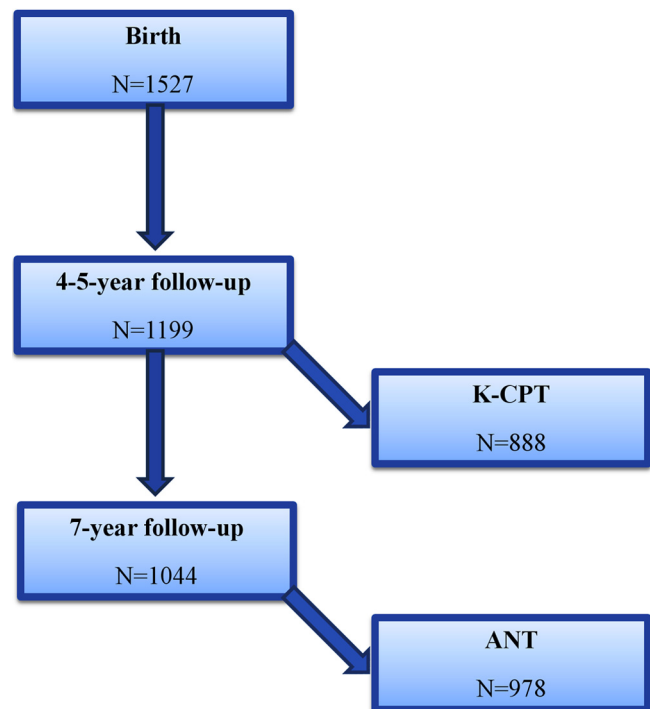


Figure 1. The number of participants in each follow-up and those with available data on attention tests in Valencia and Sabadell, Spain.

Table 1. Description of characteristics of the study participants at birth and in 4- and 7-year follow-ups.

Characteristics	4–5-y follow-up			7-y follow-up				
	Birth	Include ^a (n = 888)	Excluded ^b (n = 311)	Include ^a (n = 978)	Excluded ^b (n = 66)	p-Value ^c	p-Value ^d	p-Value ^e
Sex (Female)	48.0%	48.8%	46.1%	48.8%	40.9%	0.39	0.73	0.21
Preterm birth (yes)	4.4%	3.7%	3.9%	3.4%	7.7%	0.89	0.42	0.08
Maternal educational attainment						0.04	0.01	0.21
No or primary school	31.0%	26.1%	29.9%	24.7%	30.8%			
Secondary school	43.0%	42.7%	46.4%	43.6%	47.7%			
University	26.1%	31.2%	23.7%	31.7%	21.5%			
Maternal IQ ^f	10.5 (3.7)	10.5 (4.4)	10.5 (4.4)	10.5 (4.4)	10.5 (4.7)	0.53	0.84	0.66
Maternal smoking during pregnancy (yes)	35.6%	33.6%	33.1%	31.7%	33.3%	0.88	0.32	0.78
Exposure to environmental tobacco smoke at 4-year follow-up (yes)	***	50.2%	47.7%	51.2%	48.4%	***	***	0.67
Exposure to environmental tobacco smoke at 7-year follow-up (yes)	***	***	***	30.3%	15.2%	***	***	0.01
Neighborhood socioeconomic status ^g	0.6 (0.2)	0.6 (0.2)	0.7 (0.3)	0.6 (0.2)	0.6 (0.2)	0.33	0.22	0.12

Note: p-Values are reported for chi-squared test for categorical variables and Mann-Whitney U test for continuous variables. For continuous variables, median (IQR) and for categorical variables count (percentage) of each category has been reported.

^ap-Value for the difference between children with available data at birth and those included at the 4-year follow-up.

^bChildren participated in the 4-y follow-up but did not have data on K-CPT.

^cp-Value for the difference between children included and excluded in each follow-up.

^dp-Value for the difference between children with available data at birth and those included at the 7-year follow-up.

^ep-Value for the difference between children with available data at the 4-year follow-up and those included at 7-y follow-up.

^fWechsler Adult Intelligence Scale (WAIS-IV), Similarities subscale.

^gUrban vulnerability index.

Greenness and Attention

K-CPT. Increases in residential surrounding greenness (NDVI) in all buffer areas during the first 4–5 y of life were associated with lower K-CPT omission errors and HRT-SE (Table 3). In contrast, estimated associations between NDVI and K-CPT commission errors were essentially null. Although increases in residential surrounding tree cover (VCF) also were associated with lower average K-CPT omission errors and average HRT-SE, all estimated differences were very close to the null (Table 3).

The ANT. More residential surrounding greenness during the first seven years of life was inversely associated with ANT HRT-SE at the age of 7 y, with associations being statistically significant for the 500-m buffer (Table 3). There was little or no evidence of associations for NDVI or VCF with ANT omission or commission errors. VCF was associated with lower HRT-SE at 7 y, but associations were not significant (Table 3).

The cohort-specific associations between measures of greenness exposure and K-CPT and ANT indicators were generally consistent with the pooled analyses (see Table S3). Although there was some variation in corresponding estimates between the cohorts, estimates were imprecise, and clear differences between the regions were not evident (see Table S4).

Sensitivity Analyses

Our findings after further adjustment of analyses for the parity, breastfeeding, birth weight, sleep duration, time spent watching TV, time spent on sedentary activities, parental marital status, and social class were generally consistent with those of the main analyses in terms of direction and statistical significance (data not shown). Similarly, the results of simple negative binomial and linear regression models with cohort as a categorical predictor in the models were in line with those of the main analyses (see Table S5). Moreover, the direction and statistical significance of the associations based on standardized NDVI values were consistent with those of the main analyses (data not shown). Similarly, the associations were consistent with those of main analyses after excluding participants with more than 10% of the NDVI pixels in each buffer around their homes affected by clouds (data not shown).

Discussion

To our knowledge, this prospective study is the first to estimate associations of lifelong residential exposure to greenness with measures of attention in children, and the first to report separate estimates for associations with tree cover (VCF) and greenness (NDVI). We made use of data from two well-established population-based cohorts, utilized computerized tests (K-CPT and ANT) to assess attention, and used remote-sensing indices (NDVI and VCF) to estimate exposure to greenness. Higher lifelong residential surrounding greenness was associated with fewer K-CPT omission errors and lower K-CPT HRT-SE at 4–5 y of age, and with lower ANT HRT-SE at 7 y of age, consistent with better attention. Point estimates were close to the null for greenness (NDVI) and K-CPT commission errors and ANT omission and commission errors; and for tree cover (VCF) and all K-CPT outcomes and ANT omission and commission errors (Table 3). Tree cover was inversely associated with ANT HRT-SE, though estimates were not significant.

Interpretation of Results

Exposure to residential greenness was inversely associated with omission errors and HRT-SE, but was not associated with commission errors. K-CPT omission errors and HRT-SE may be

Table 2. Median (25th and 75th percentiles) of measures of attention [Conners' Kiddie Continuous Performance Test (K-CPT) at 4–5 y and attentional network task (ANT) at 7 y] and exposure [averages of normalized difference vegetation index (NDVI) and vegetation continuous fields (VCF, % tree cover)].

Variables	4–5-y follow-up			7-y follow-up		
	Sabadell (n = 364)	Valencia (n = 524)	p-Value ^a	Sabadell (n = 530)	Valencia (n = 448)	p-Value ^a
Attention^b						
Omissions (counts)	24 (13, 37)	10 (5, 20)	<0.01	3 (1, 7)	3 (1, 7)	0.1
Commissions (counts)	22 (15, 30)	22 (15, 29)	0.63	5 (2, 8)	4 (2, 7)	<0.01
Hit Reaction Time-Standard Error (ms)	332.8 (252.8, 441.6)	229.7 (171.9, 307.0)	<0.01	332.0 (273.8, 381.1)	326.6 (268.6, 385.3)	0.55
Residential surrounding greenness (NDVI)^b						
100-m buffer	0.20 (0.16, 0.24)	0.19 (0.17, 0.24)	0.89	0.20 (0.17, 0.25)	0.19 (0.16, 0.24)	0.01
300-m buffer	0.24 (0.18, 0.29)	0.22 (0.19, 0.27)	0.06	0.24 (0.19, 0.30)	0.22 (0.19, 0.27)	<0.01
500-m buffer	0.26 (0.21, 0.32)	0.24 (0.21, 0.29)	<0.01	0.26 (0.21, 0.32)	0.23 (0.20, 0.28)	<0.01
Residential surrounding tree cover (VCF)^b						
100-m buffer	1.6 (1.2, 2.3)	0.3 (0.1, 0.7)	<0.01	1.7 (1.3, 2.4)	0.4 (0.2, 0.8)	<0.01
300-m buffer	1.9 (1.4, 2.7)	0.6 (0.3, 1.0)	<0.01	2.0 (1.6, 2.8)	0.7 (0.4, 1.0)	<0.01
500-m buffer	2.2 (1.5, 3.0)	0.7 (0.5, 1.0)	<0.01	2.2 (1.7, 3.1)	0.8 (0.6, 1.1)	<0.01

^ap-value for Mann–Whitney U test.

^bFor the follow-up at 4 or 5 y, the NDVI was averaged for addresses at birth and 4–5 y and for the follow-up at 7 y, the NDVI was averaged for addresses at birth, 4 or 5 years, and 7-years.

measures of “focused attention,” whereas K-CPT commission errors may be more relevant to “hyperactivity-impulsivity” (Egeland and Kovalik-Gran 2010). Thus, our findings suggest that exposure to greenness might influence focused attention, rather than hyperactivity-impulsivity, consistent with attention restoration theory, as described below.

The inverse association between exposure to residential surrounding greenness and omission errors at 4–5 y of age was not present at 7 years. One explanation might be the use of different tools (K-CPT vs. ANT) to characterize attention at each time point. Furthermore, nonresidential exposure to greenness, at school or at the homes of other children, may increase with age, leading to greater exposure misclassification when exposure is estimated based only on residential address. Assessing greenness exposures at additional locations may be beneficial for future studies.

The associations for residential surrounding tree cover were close to null (with the exception of ANT HRT-SE, which showed indications of inverse associations) and none attained statistical significance. These findings might suggest that tall trees could exert fewer benefits on attention, in comparison with other types of vegetation, such as grasses and shrubs. However, the contrast in exposure to residential surrounding tree cover among our study participants was small, which could have underpowered our analyses to detect an association between this exposure and attention. Such a low contrast in exposure was not unexpected in our study regions, given their Mediterranean climate and high density of built-up areas, but it also could have resulted, at least in part, from our use of VCF to assess this exposure, which does not take account of trees shorter than five meters. The possibility that different types of greenness might have different impacts on neurodevelopment remains an open question for future studies.

Available Evidence

Surrounding greenness were associated with lower prevalence rates for depression in Dutch children <12 years of age in an ecological study based on medical records data and land use information (Maas et al. 2009). Another ecological study of 905 public schools in Massachusetts, United States, reported that higher levels of greenness surrounding the schools (measured as the average of NDVI) was associated with better student performance at schools (Wu et al. 2014). Experimental studies have suggested that walking in nature or watching photos of nature might improve directed-attention abilities in adults (Berman et al. 2008) and reduce ADHD symptoms in children (Taylor et al. 2001;

Kuo and Taylor 2004; Taylor and Kuo 2009; van den Berg and van den Berg 2011). A study by Wells (2000) reported that relocation to residences with higher “naturalness” (a combination of visual access to greenness and presence of vegetation in houses' yards) improved attention in a sample of 17 children (Wells 2000). In a previous cross-sectional analysis, we found a protective association between residential surrounding greenness and behavioral problems, including hyperactivity and inattention in primary schoolchildren in Barcelona (Amoly et al. 2014), an observation that was replicated by another cross-sectional study in Germany (Markevych et al. 2014). In another study (Dadvand et al. 2015a) based on a sample of 2,593 primary schoolchildren (aged 7–10 y) residing in Barcelona (2012–2013), we observed higher total surrounding greenness index (defined as the average of NDVI around a home, within a school, and surrounding commuting routes) between home and school was associated with reduced inattentiveness as characterized by the 12-mo trajectory of HRT-SE from four repeated ANTs measures (three months apart).

Potential Underlying Mechanisms

The Biophilia hypothesis suggests that humans have important evolutionary bonds to nature (Wilson 1984; Kellert and Wilson 1993). Accordingly, it has been proposed that contact with nature is important for brain development in children (Kahn 1997; Kahn and Kellert 2002). In addition, the theory of attention restoration proposes that contact with nature may enhance attention (Kaplan and Kaplan 1989; Kaplan 1995; Berman et al. 2008). Our findings extend the prospect of attention-restoration theory by evaluating the long-term association between lifelong exposure to green spaces and attention in children.

Greenness surrounding children's schools and residences has been associated with lower exposure to air pollution (Dadvand et al. 2012, 2015b), and school air pollution exposure was positively associated with ANT HRT-SE, indicating greater inattentiveness, in a study of Barcelona school children (Sunyer et al. 2015). Perceived access to green spaces was associated with less noise annoyance in a study of urban adults (Gidlöf-Gunnarsson and Öhrström 2007; Dadvand et al. 2012, 2015b), and performance on tests of attention is reduced when children are exposed to noise during the tests (Klatte et al. 2013; Sunyer et al. 2015). Moreover, proximity to green spaces, particularly parks, has been suggested to increase physical activity (James et al. 2015), and higher levels of physical activity are related to improved cognitive development (Fedewa and Ahn 2011). However, the body of

Table 3. Adjusted mean ratios (95% confidence interval) in omission and commission errors and regression coefficient (95% CI) for hit reaction time-standard error (HRT-SE) associated with an IQR increase in the average of normalized difference vegetation index (NDVI) and vegetation continuous fields (VCF, % tree cover) surrounding participants' residences.

Greenness exposure	Median (IQR) greenness (0 to 4–5 years)			K-CPT ^a (n = 888)			Median (IQR) greenness (0–7 years)			ANT ^b (n = 978)		
	Omission error	Commission error	HRT-SE (ms)	Omission error	Commission error	HRT-SE (ms)	Omission error	Commission error	HRT-SE (ms)	Omission error	Commission error	HRT-SE (ms)
NDVI												
100-m buffer	0.193 (0.074)	0.90 (0.85, 0.96)	1.01 (0.97, 1.04)	1.01 (0.97, 1.04)	1.01 (0.97, 1.04)	-1.0 (-2.0, -0.1)	0.194 (0.087)	1.00 (0.90, 1.11)	1.03 (0.95, 1.11)	1.00 (0.90, 1.11)	1.03 (0.95, 1.11)	-4.1 (-10.6, 2.5)
300-m buffer	0.229 (0.089)	0.88 (0.82, 0.94)	1.00 (0.96, 1.05)	1.00 (0.96, 1.05)	1.00 (0.96, 1.05)	-1.3 (-2.5, -0.2)	0.232 (0.097)	0.97 (0.87, 1.07)	1.02 (0.95, 1.11)	0.97 (0.87, 1.07)	1.02 (0.95, 1.11)	-6.6 (-13.6, 0.3)
500-m buffer	0.245 (0.091)	0.88 (0.81, 0.95)	1.01 (0.97, 1.06)	1.01 (0.97, 1.06)	1.01 (0.97, 1.06)	-1.3 (-2.5, -0.1)	0.247 (0.102)	0.95 (0.85, 1.06)	1.01 (0.93, 1.10)	0.95 (0.85, 1.06)	1.01 (0.93, 1.10)	-7.9 (-15.1, -0.8)
VCF												
100-m buffer	0.700 (1.315)	0.98 (0.94, 1.02)	1.01 (0.99, 1.04)	1.01 (0.99, 1.04)	1.01 (0.99, 1.04)	-0.2 (-0.9, 0.6)	1.162 (1.514)	1.01 (0.96, 1.06)	1.02 (0.94, 1.10)	1.01 (0.96, 1.06)	1.02 (0.94, 1.10)	-2.3 (-7.1, 2.4)
300-m buffer	0.964 (1.295)	0.99 (0.94, 1.03)	1.01 (0.98, 1.03)	1.01 (0.98, 1.03)	1.01 (0.98, 1.03)	-0.1 (-0.8, 0.6)	1.388 (1.469)	1.00 (0.95, 1.04)	1.02 (0.97, 1.09)	1.00 (0.95, 1.04)	1.02 (0.97, 1.09)	-2.6 (-6.8, 1.6)
500-m buffer	1.088 (1.372)	0.99 (0.95, 1.03)	1.00 (0.99, 1.04)	1.00 (0.99, 1.04)	1.00 (0.99, 1.04)	-0.2 (-0.9, 0.5)	1.495 (1.573)	0.99 (0.94, 1.03)	1.02 (0.96, 1.08)	0.99 (0.94, 1.03)	1.02 (0.96, 1.08)	-3.0 (-7.1, 1.2)

Note: Mixed effects models with random intercepts for cohort (binomial for omission and commission errors and linear for HRT-SE) adjusted for age at the time of attention test, sex, history of preterm birth, maternal educational attainment, maternal IQ, maternal smoking during pregnancy, exposure to environmental tobacco smoke, and neighborhood socioeconomic status.

^aConners' Kiddie Continuous Performance Test.

^bAttentional Network Task.

evidence on the effect of proximity to green spaces on physical activity is not consistent, and a notable heterogeneity exists in the reported direction and strength of associations (Timperio et al. 2008; Lachowycz and Jones 2011; Lovasi et al. 2011). Furthermore, psychological stress and depression in parents have been associated with adverse impacts on cognitive development in their children (Ramchandani and Psychogiou 2009), and residential surrounding greenness has been associated with evidence of stress-reduction effects and reduced depression in adults (Dadvand et al. 2016; McEachan et al. 2016). A growing body of evidence also suggests that a failure of the immunoregulatory pathways due to a reduced exposure to macro- and microorganisms in Westernized populations might play a role in impairment of brain development (Rook 2013; Rook et al. 2013), with childhood as a particular window of vulnerability (Rook et al. 2014). Therefore, the potential ability of surrounding greenness to enhance immunoregulation-inducing microbial input from the environment (Rook 2013) could have been another mechanism underlying our observed association between surrounding greenness and attention.

Strengths and Limitations

This prospective study was based on computerized tests to objectively characterize attention for each study participant. Our use of objective measures of attention could be considered a step forward as these computerized cognitive tests are less prone to outcome misclassification due to subjectivity in comparison with questionnaire-based methods used in previous studies (Forns et al. 2014). Questionnaire-based methods, however, have the advantage of assessing cognition in a realistic setting. Therefore, for future studies, an ideal assessment of attention could include both computerized cognitive tests and questionnaire-based methods.

We accounted for changes in residential addresses at each follow-up interview when estimating lifelong exposures, but we could not account for the timing of each address change or additional moves between study visits. Therefore we could not estimate associations with time-varying cumulative exposures, or associations with exposures during specific time windows. Also, children included in the analyses, in comparison with those children who were excluded (due to loss to follow-up or unavailability of data for attention tests) were more likely to have mothers with higher educational attainment, which could have resulted in attrition bias. Furthermore, we did not have information on the family context and support for cognitive development available to the child in the home environment, which could have been a potential source of residual confounding. Additionally, our study could not disentangle the short- and long-term associations between greenness exposure and attention.

Conclusions

We studied the association of lifelong exposure to residential surrounding greenness and tree cover with attention in children. Higher exposure to residential surrounding greenness areas was associated with fewer K-CPT omission errors and lower K-CPT HRT-SE at age 4–5 y and lower ANT HRT-SE at age 7 y, consistent with a beneficial association between this exposure and attention. The associations for residential surrounding tree cover were not conclusive; however, our analyses might have been underpowered to detect such associations. These findings warrant further replications in other settings with different climates and environments.

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