Green spaces and cognitive development in primary schoolchildren

Payam Dadvand[a,b,c,1], Mark J. Nieuwenhuijsen[a,b,c], Mikel Esnaola[a,b,c], Joan Forns[a,b,c,d], Xavier Basagaña[a,b,c], Mar Alvarez-Pedrerol[a,b,c], Ioar Rivas[a,b,c,e], Mónica López-Vicente[a,b,c], Montserrat De Castro Pascual[a,b,c], Jason Su[f], Michael Jerrett[g], Xavier Querol[e], and Jordi Sunyer[a,b,c,h]

[a]Centre for Research in Environmental Epidemiology (CREAL), 08003 Barcelona, Spain; [b]Experimental and Health Sciences, Pompeu Fabra University, 08003 Barcelona, Catalonia, Spain; [c]Ciber on Epidemiology and Public Health (CIBERESP), 28029 Madrid, Spain; [d]Department of Genes and Environment, Division of Epidemiology, Norwegian Institute of Public Health, 0473, Oslo, Norway; [e]Department of Geosciences, Institute of Environmental Assessment and Water Research, Spanish National Research Council (CSIC-IDEA), 08034 Barcelona, Catalonia, Spain; [f]Environmental Health Sciences, School of Public Health, University of California, Berkeley, CA 94720-7360; [g]Department of Environmental Health Sciences, Fielding School of Public Health, University of California, Los Angeles, CA 90095; and [h]Hospital del Mar Medical Research Institute (IMIM), 08003 Barcelona, Catalonia, Spain

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Exposure to green space has been associated with better physical and mental health. Although this exposure could also influence cognitive development in children, available epidemiological evidence on such an impact is scarce. This study aimed to assess the association between exposure to green space and measures of cognitive development in primary schoolchildren. This study was based on 2,593 schoolchildren in the second to fourth grades (7–10 y) of 36 primary schools in Barcelona, Spain (2012–2013). Cognitive development was assessed as 12-mo change in developmental trajectory of working memory, superior working memory, and inattentiveness by using four repeated (every 3 mo) computerized cognitive tests for each outcome. We assessed exposure to green space by characterizing outdoor surrounding greenness at home and school and during commuting by using high-resolution (5 m × 5 m) satellite data on greenness (normalized difference vegetation index). Multilevel modeling was used to estimate the associations between green spaces and cognitive development. We observed an enhanced 12-mo progress in working memory and superior working memory and a greater 12-mo reduction in inattentiveness associated with greenness within and surrounding school boundaries and with total surrounding greenness index (including greenness surrounding home, commuting route, and school). Adding a traffic-related air pollutant (elemental carbon) to models explained 20–65% of our estimated associations between school greenness and 12-mo cognitive development. Our study showed a beneficial association between exposure to green space and cognitive development among schoolchildren that was partly mediated by reduction in exposure to air pollution.

neurodevelopment | greenness | cognition | built environment | school

Contact with nature is thought to play a crucial and irreplaceable role in brain development (1, 2). Natural environments including green spaces provide children with unique opportunities such as inciting engagement, risk taking, discovery, creativity, mastery and control, strengthening sense of self, inspiring basic emotional states including sense of wonder, and enhancing psychological restoration, which are suggested to influence positively different aspects of cognitive development (1–3). Beneficial effects of green spaces on cognitive development might accrue from direct influences such as those above, with green space itself exerting the positive influence or through indirect, mediated pathways. The ability of green spaces to mitigate traffic-related air pollution (TRAP) (4) could lead to a beneficial impact of green spaces on cognitive development, because exposure to TRAP has been negatively associated with cognitive development in children (5). Further to TRAP, green spaces can also reduce noise (6), which itself too has been negatively associated with cognitive development (7). Moreover, proximity to green spaces, particularly parks, has been suggested to increase physical activity (8), and higher levels of physical activity are related to improved cognitive development (9). Outdoor surrounding greenness has also been reported to enrich microbial input from the environment (10), which may positively influence cognitive development (10). Through these pathways, exposure to green space, including outdoor surrounding greenness and proximity to green spaces, could influence cognitive development in children, yet the available population-based evidence on the association between such exposure and cognitive development in children remains scarce.

The brain develops steadily during prenatal and early postnatal periods, which are considered as the most vulnerable windows for effects of environmental exposures (11). However, some cognitive functions closely related with learning and school achievement—such as working memory and attention—develop across childhood and adolescence as an essential part of cognitive maturation (12–14). We therefore hypothesized a priori that exposure to green space in primary schoolchildren could enhance cognitive development. Accordingly, our study aimed to assess the association between indicators of exposure to green space and measures of cognitive development, including working memory (the system that holds multiple pieces of transitory information in the mind where they can be manipulated), superior working memory (working memory that involves continuous updating of the working memory buffer), and inattentiveness in primary schoolchildren. As a secondary aim, we also evaluated the mediating role of a reduction in air pollution as one of the potential mechanisms underlying this association.

Significance

Green spaces have a range of health benefits, but little is known in relation to cognitive development in children. This study, based on comprehensive characterization of outdoor surrounding greenness (at home, school, and during commuting) and repeated computerized cognitive tests in schoolchildren, found an improvement in cognitive development associated with surrounding greenness, particularly with greenness at schools. This association was partly mediated by reductions in air pollution. Our findings provide policymakers with evidence for feasible and achievable targeted interventions such as improving green spaces at schools to attain improvements in mental capital at population level.

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[1]To whom correspondence should be addressed. Email: pdadvand@creal.cat.

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Methods

Study Setting. We undertook this study in Barcelona, Spain, a port city situated on the northeastern part of the Iberian Peninsula. It has a Mediterranean climate characterized by hot and dry summers, mild winters, and maximum precipitation and vegetation during autumn and spring. This study was conducted in the context of the brain development and air pollution ultrafine particles in school children (BREATHE) project. Of the 416 schools in Barcelona, 37 schools were initially selected to obtain maximum contrast in TRAP levels (i.e., nitrogen dioxide: NO_2), of which 36 accepted to participate and were included in the study (*SI Appendix*, Fig. S1). Participating schools were similar to the remaining schools in Barcelona in terms of the neighborhood socioeconomic vulnerability index (0.46 versus 0.50, Kruskal–Wallis test $P = 0.57$) and NO_2 levels (51.5 versus 50.9 μg/m^3, Kruskal–Wallis test $P = 0.72$).

All schoolchildren (n = 4,562) without special needs in the second to fourth grades (7–10 y) of these schools were invited to participate by letters or presentations in schools for parents, of which 2,623 (58%) agreed to take part in BREATHE. All children had been in the school for more than 6 mo (and 98% more than 1 y) before the beginning of the study. All parents or guardians signed the informed consent and the study was approved (No. 2010/41221/I) by the Clinical Research Ethical Committee of the Parc de Salut Mar, Barcelona.

Outcome: Cognitive Development. Cognitive development was assessed through 12-mo change in developmental trajectory of working memory and attention. We selected these functions because they grow steadily during preadolescence (15, 16). We used computerized *n*-back test for assessing working memory (15) and computerized attentional network test (ANT) (17) for evaluating attention.

From January 2012 to March 2013, children were evaluated every 3 mo over four repeated visits by using computerized tests in sessions lasting ∼40 min in length. Groups of 10–20 children wearing ear protectors were assessed together and supervised by one trained examiner per 3–4 children. For the *n*-back test, we examined different *n*-back loads (up to three-back) and stimuli (colors, numbers, letters, and words). For analysis here, we selected both two-back and three-back loads for number and word stimuli because they showed a clear age-dependent slope in the four measurements (4). The two-back predicts general mental abilities (i.e., working memory) whereas the three-back also predicts superior functions such as fluid intelligence (i.e., superior working memory) (18). All sets of *n*-back tests started with colors as a training phase to ensure participants' comprehension of the test. The *n*-back parameter analyzed was *d* prime (d'), a measure of detection subtracting the normalized false alarm rate from the hit rate [(Z hit rate − Z false alarm rate) ×100]. A higher d' indicates more accurate test performance. Given that our final findings for numbers and words were similar, here we only show results for numbers. Among the ANT measures, we chose hit reaction time standard error (HRT-SE) (SE of RT for correct responses), a measure of response speed consistency throughout the test (19), because it showed a clear growth during the 1-y study period. A higher HRT-SE indicates highly variable reactions related to inattentiveness.

Exposure to Green Space. Our assessment of exposure to green space was based on a comprehensive characterization of outdoor surrounding greenness (photosynthetically active vegetation) encompassing greenness surrounding home, greenness surrounding commuting route between home and school (hereafter referred to as commuting greenness), and greenness within and around school boundaries.

To assess outdoor surrounding greenness we applied normalized difference vegetation index (NDVI) derived from RapidEye data at 5 m × 5 m resolution. NDVI is an indicator of greenness based on land surface reflectance of visible (red) and near-infrared parts of spectrum (20). It ranges between −1 and 1, with higher numbers indicating more greenness. The RapidEye Imagery is acquired from a constellation of five satellites 630 km above ground in sun-synchronous orbits. We generated our NDVI map by using the image obtained on July 23, 2012, that was available for our study region during our study period (*SI Appendix*, Fig. S1).

Residential surrounding greenness. Residential surrounding greenness was abstracted as the average of NDVI in a buffer of 250 m (21, 22) around the home address of each study participant. For 174 children (5.9%) who shared two homes, we used the address where the child spent most of her/his time.

Commuting greenness. Data on the main mode of commute to and from school was obtained from parents via questionnaires. Approximately 60% of participants reported walking as the main mode of commuting, whereas the 38% reported commuting by motor vehicles (private car, bus, motorcycle, or tram). The remaining 2% reported the underground metro train as the main mode of transport, for whom we assumed no exposure to greenness during commuting. For participants reporting walking as the main mode of commuting, we identified the shortest walking route to school and for participants reporting motor vehicles as the main mode of commuting, we identified the shortest driving route to school, based on street networks (network distance) by using network analyst extension from ArcGIS software v10. We defined commuting greenness as the average of NDVI in a 50-m buffer around the commuting route.

School greenness. To assess greenness within school premises, we first digitized the school boundaries and then averaged NDVI values within those boundaries. To assess greenness surrounding schools, we averaged NDVI values across a 50 m buffer around the school boundaries.

Total surrounding greenness index. We developed a total surrounding greenness index by averaging residential surrounding greenness (250-m buffer), commuting greenness, and greenness within school boundaries weighted by the daytime (12 h a day) that children were assumed to spend at home (3 h), commuting (1 h), and school (8 h). To avoid double-counting in developing this index, we abstracted as the average NDVI over commute corridor beyond the 250-m home buffer and 50-m school buffer.

Main Analyses. Data on 9,357 tests from 2,593 (99%) children were available for analysis. Because of the multilevel nature of the data (i.e., multiple visits for each child within schools), we used linear mixed effects models with the four repeated cognitive parameters as outcomes (one test at a time), each measure of exposure to green space (one at a time) as fixed effect predictor, and child and school as random effects (5). An interaction between age at each visit and the indicator of exposure to green space was included to capture changes in 12-mo progress in cognitive trajectory associated with greenness exposure (5). The main effect of exposure to green space, which was also included in the model, captured the baseline (visit 1) differences in cognitive function that were associated with exposure to green space before the first visit. This model was further adjusted for potential confounders identified a priori*:* age (centered at visit 1), sex, and indicators of socioeconomic status (SES) at both individual and area levels. Maternal education (no or primary/secondary/university) was used as the indicator of individual-level SES and Urban Vulnerability Index (23), a measure of neighborhood SES at the census tract (median area of 0.08 km^2 for the study region) was applied as the indicator of area-level SES. Linearity of the relation between exposure to green space and cognitive tests was assumed because generalized additive mixed models did not show any nonlinearity of associations. We estimated the change in average outcome scores associated with one interquartile range (IQR) increase (based on all study participants) in average NDVI. Statistical significance was set at $P < 0.05$. R statistical package was used to carry out the analyses.

Mediating Role of Traffic-Related Air Pollution. We hypothesized that reduction in TRAP levels could be one of the potential mechanisms underlying the association between greenness exposure and cognitive development. To quantify such a mediating role, we calculated the percent of the associations between greenness and cognitive development explained by TRAP as $[1 - (\beta_{gm}/\beta_g)] \times 100$, where β_{gm} was the regression coefficient for the greenness exposure in a fully adjusted model including the mediator (i.e., TRAP) and β_g was the regression coefficient in the fully adjusted model without including the mediator (24).

We focused on the associations between school greenness and cognitive development because they were the strongest among our evaluated associations (*Results*) and also because of the availability of data on levels of air pollutants at BREATHE schools that were monitored as part of the BREATHE project. Such a high-quality monitored data were not available for TRAP levels at homes or during commuting. Among the TRAPs monitored in the BREATHE framework, we chose indoor levels of elemental carbon (EC) for this mediation analyses. EC is mainly generated by fossil fuel combustion and is considered as a tracer of road traffic emissions in Barcelona (25). In other BREATHE analyses, we had observed that indoor EC was associated with adverse impacts on cognitive development (5) and EC levels were reduced in schools with higher greenness (4). Detailed description of TRAP sampling methodology at the BREATHE schools has been published (25, 26).

Results

Children were on average 8.5 y old at baseline and 50% were girls. Regarding maternal education, 13% of mothers had no or only primary school, 29% secondary school, and 58% university education. Further characteristics of the study participants are presented in *SI Appendix*, Table S1. Average working memory increased by 22.8%, superior working memory by 15.2%, and inattentiveness decreased by 18.9% during the follow up (Table 1). At baseline, higher maternal education was associated with better cognitive function (*SI Appendix*, Table S2). For 12-mo progress, whereas higher maternal education was associated with larger reduction in inattentiveness, improvements in working memory and superior working memory were not associated with maternal education (*SI Appendix*, Table S2). The median (IQR) of our estimated surrounding greenness for all participants and across strata of maternal education are presented in Table 2 and *SI Appendix*, Table S2, respectively. The Spearman's correlation coefficient among residential, school, and commuting surrounding greenness varied from 0.46 (between surrounding greenness at home and greenness within school boundaries) to 0.80 (between commuting and school surrounding greenness) (*SI Appendix*, Table S3).

Main Analyses. We observed an enhanced 12-mo progress in working memory and superior working memory and a greater 12-mo reduction in inattentiveness associated with greenness within and surrounding school boundaries and with the total surrounding greenness index (Table 2, Fig. 1, and *SI Appendix*, Fig. S2). Commuting greenness was also associated with improved 12-mo progress in working memory and superior working memory, although the association for superior working memory was only marginally statistically significant. We did not observe any association between residential surrounding greenness and cognitive measurements (Table 2). None of the indicators of outdoor greenness were associated with baseline cognitive measurements (Table 2).

The findings for *n*-back tests with "word" stimuli were consistent with the aforementioned results for "number" stimuli (*SI Appendix*, Table S4). The association between commuting greenness and 12-mo progress in superior working memory, which had borderline statistical significance for the three-back test using number stimuli, was statistically significant for the test using word stimuli.

To explore the possibility of an impact of green space exposure on other ANT measures than inattentiveness, we repeated the main analyses by using alerting, orienting, and executive processing (one at a time) abstracted from ANT as outcome. We did not observe any statistically significant association for these outcomes with any of indicators of green space exposure (*SI Appendix*, Table S5), which was consistent with our observation that these measures did not show any clear growth during the study period.

We conducted a number of sensitivity analyses as described in *SI Appendix* that showed the robustness of our findings to alternative definition of total surrounding greenness index and commuting greenness and to including a range of relevant covariates in models (e.g., socioeconomic indicators and condition of venue at the time of cognitive tests).

Mediating Role of Traffic-Related Air Pollution. The Spearman's correlation coefficients between school EC levels and greenness within and surrounding school boundaries were −0.62 and −0.66 ($P < 0.01$), respectively. Adding EC to models explained 20–65% of associations between school greenness and 12-mo progress in cognitive functions (Table 3). Including EC reduced effect sizes in all models. EC made the associations between school surrounding greenness and superior working memory and between greenness within and surrounding school boundaries and inattentiveness much smaller and statistically nonsignificant (Table 3).

Discussion

To our knowledge, this is the first epidemiological study to report on the impact of exposure to green space on cognitive development in schoolchildren. School and total surrounding greenness index were associated with enhanced 12-mo progress in indicators of working memory and superior working memory and greater 12-mo reduction in inattentiveness. Commuting greenness was also associated with better 12-mo progress in working memory. Adding EC to our models explained 20–65% of our estimated associations between green spaces and 12-mo cognitive development.

Interpretation of Results. Over a 12-mo period, we observed that an IQR exposure increment in total surrounding greenness index was associated with a 5% increase in the progress of working memory, a 6% increase in the progress of the superior working memory, and a 1% reduction of inattentiveness. Among our assessed exposure measures, we observed the strongest associations for greenness within or surrounding school boundaries. Children spend a considerable part of their active daily time at schools and "green exercise" has been related to better mental health (27). Furthermore, the combination of physical activity in school with daily peaks of TRAPs in urban areas that often coincide with school time could result in a considerable inhaled dose of air pollutants at school. Consistently, in our other BREATHE analysis of the impact of TRAPs on cognitive development using the same measures of cognitive development as in this study, we also observed stronger associations for levels at school compared with those at home (5). Therefore, the ability of school greenness in reducing pollutant levels (4) might explain, in part, why we observed the strongest associations for school greenness.

We found some indications for an enhanced 12-mo progress in working memory associated with commuting greenness. Because of the strong correlation between greenness surrounding school boundaries and commuting greenness, it was not possible to determine the independent impact of commuting greenness (i.e., whether commuting greenness is a surrogate for school surrounding greenness). Therefore, our findings for commuting greenness should be interpreted with caution. To the best of our knowledge, this study is the first reporting on the potential impact of commuting greenness on health in general and on cognitive development in particular. We hypothesize that green exercise and visual access to greenness might underlie such an association, if any.

The beneficial associations for 12-mo progress in cognitive functions were stronger than those at baseline. Baseline estimates reflected the association between cognitive test scores at the first visit and the cumulative green space exposure preceding the study period, whereas our exposure assessment was based

Table 1. Description of the cognitive outcomes in children [median (25th–75th %)]

Visit	*n*	Age (mean), y	Working memory (WM) (two-back numbers), d′*	Superior WM (three-back numbers), d′*	Inattentiveness (ANT HRT-SE)†, ms
First visit	2,278	8.5	206 (129, 360)	112 (53, 171)	271 (205, 338)
Second visit	2,425	8.7	221 (129, 392)	112 (59, 190)	250 (186, 321)
Third visit	2,347	9.1	234 (129, 392)	128 (59, 190)	247 (183, 317)
Fourth visit	2,307	9.4	253 (152, 392)	129 (64, 210)	228 (165, 294)

*The *n*-back *d′* is a measure of detection subtracting the normalized false alarm rate from the hit rate [(Z hit rate − Z false alarm rate) × 100].
†Hit reaction time SE (HRT-SE), SE of reaction time for correct responses as a measure of response speed consistency throughout the test.

Table 2. Adjusted difference (95% confidence interval) in baseline and 12-mo progress of working memory, superior working memory, and inattentiveness per one interquartile range (IQR) change in greenness

Surrounding greenness	Median (IQR)	Working memory† (2-back number stimuli, d′)		Superior working memory† (3-back number stimuli, d′)		Inattentiveness† (HRT-SE, ms)	
		Baseline	Progress	Baseline	Progress	Baseline	Progress
Home	0.091 (0.053)	0.2 (-3.8, 4.2)	0.7 (-2.6, 4.1)	0.6 (-2.5, 3.7)	−0.1 (-2.7, 2.6)	2.0 (-1.4, 5.4)	−0.7 (-3.1, 1.7)
School							
Within	0.094 (0.085)	0.3 (−6.8, 7.4)	9.8 (5.2, 14.0)*	0.9 (−5.0, 6.8)	6.9 (3.4, 10.0)*	−4.0 (−12.0, 4.0)	−3.4 (−6.6, −0.2)*
Surrounding‡	0.100 (0.120)	3.2 (−4.3, 11)	9.5 (4.5, 15.0)*	1.5 (−4.8, 7.8)	6.3 (2.3, 10.0)*	−5.1 (−14.0, 3.6)	−3.7 (−7.3, −0.1)*
Commuting	0.100 (0.062)	1.5 (−3.5, 6.6)	4.9 (1.0, 8.8) *	3.5 (−0.6, 7.5)	3.1 (0.0, 6.1)	0.2 (−4.5, 4.9)	−1.2 (−4.0, 1.7)
Total surrounding greenness index	0.094 (0.073)	0.0 (−6.9, 6.5)	9.8 (5.0, 15.0)*	1.7 (−4.4, 7.8)	6.7 (2.8, 11.0)*	−2.4 (−9.8, 4.9)	−3.9 (−7.4, −0.4)*

*$P < 0.05$.
†Difference adjusted for age, sex, maternal education, and residential neighborhood socioeconomic status with school and subject as nested random effects.
‡Fifty-meter buffer around school boundaries.

on the home address of participants and the school they were attending during the study period, not including potential prior different addresses or schools to their current ones. Part of our observed larger estimates for 12-mo progress might therefore reflect better characterization of exposure, but it could also be due to the window of vulnerability for these high executive functions that develop significantly during the primary school age (12–14). This window of vulnerability might also explain why we observed the strongest associations for 12-mo progress in superior working memory that develops considerably during this period.

We did not observe any statistically significant difference in 12-mo progress in working memory and superior working memory (for which we found associations with green space exposure) between strata of maternal education. Moreover, further adjustment of our analyses for other indicators of SES like parental employment, marital status, and ethnicity (*SI Appendix, SI Methods*) did not change the interpretation of our findings notably. Furthermore, removing SES indicators (maternal education and neighborhood SES) from our fully adjusted models did not result in a considerable change in the interpretation of our findings (*SI Appendix*, Table S6). Additionally, we did not observe any statistically significant effect modification by maternal education or neighborhood SES for our associations ($P > 0.1$). These observations might suggest that our results were unlikely to have been affected by residual SES confounding.

Available Evidence and Potential Underlying Mechanisms. We are not aware of previous epidemiological studies on the impact of green space exposure on cognitive development in schoolchildren; therefore, it is not possible to compare our findings with those of others. Our findings, however, are consistent with several previous observations. Residential surrounding greenness has been related to better mental health including lower risk of depression and anxiety in children (28). Higher school greenness has been associated with better student performance at schools (29). Experimental studies have shown walking in nature or watching photos of nature could improve directed-attention abilities in adults (30) and have "therapeutic effects" on attention deficit hyperactivity disorder symptoms in children (31–34). Our previous cross-sectional analysis of BREATHE participants showed a protective impact of home and school greenness on behavioral problems including hyperactivity and inattention (35). That analysis was based on behavioral screening questionnaires rated by teachers and parents. In those questionnaires behavioral aspects that characterized hyperactivity/inattention were modestly correlated (Spearman's correlation coefficients ranging between 0.18 and 0.23) with the ANT inattentiveness score (at baseline) used in this study. A study by Wells (2000) reported that relocation to residences with higher "naturalness" improved cognitive function in a sample of 17 children (36). In an analysis of BREATHE schools, we observed that higher greenness inside and surrounding school boundaries was associated with lower TRAPs levels at schools (5), in line with our other study showing lower levels of personal exposure to TRAPs (based on personal monitors) associated with higher residential surrounding greenness in Barcelona (22). Another BREATHE analysis, using the same cognitive measures as the current study, demonstrated that higher levels of TRAPs at school were associated with diminished 12-mo cognitive progress (5). Thus, reduction of exposure to TRAPs associated with higher greenness could have partly underlain our observed associations. Consistently, in the current analysis we observed that including a TRAP (EC) in our models could explain one-fifth to two-thirds of the associations, suggesting that our observed beneficial associations between greenness exposure and cognitive development could have been partly mediated by reduction in exposure to TRAPs. These findings could also suggest that other mechanisms may account for 35–80% of our observed associations that was not explained by reduction in TRAP exposure. Higher ambient noise has been related with adverse impacts on cognitive development (7). The ability of green spaces to

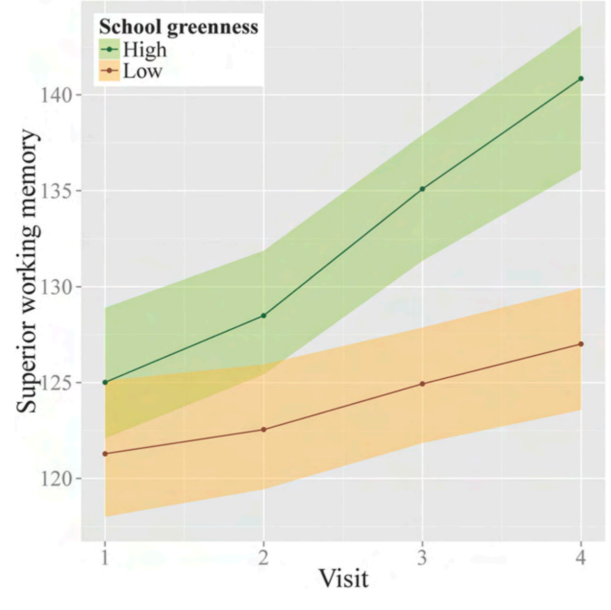

Fig. 1. Twelve-month progress (with 95% confidence bands) in superior working memory for participants with the first (low greenness) and third (high greenness) tertiles of greenness within the school boundaries.

Table 3. Difference (95% confidence interval) in 12-mo cognitive trajectory per one interquartile range change in greenness estimated by main analyses and models further including school indoor elemental carbon (EC) interaction with age

Outcomes/exposures	Main analyses[†,‡]	Further adjusted for EC[‡]	% explained
Working memory			
Within school	9.8 (5.2, 14.0)*	8.7 (2.5, 15.0)*	20.4
Surrounding school	9.5 (4.5, 15.0)*	6.9 (0.9, 13.0)*	27.4
Superior working memory			
Within school	6.9 (3.4, 10.0)*	4.9 (0.1, 9.8)*	29.0
Surrounding school[§]	6.3 (2.3, 10.0)*	3.3 (-1.5, 8.1)	47.6
Inattentiveness			
Within school	−3.4 (-6.6, -0.2)*	−1.2 (-5.6, 3.2)	64.7
Surrounding school	−3.7 (-7.3, -0.1)*	−1.8 (-6.1, 2.5)	51.4

*$P < 0.05$.
†Adjusted for age, sex, maternal education, and residential neighborhood socioeconomic status with school and subject as nested random effects.
‡Estimates per 0.085 and 0.120 change respectively in greenness within and surrounding school boundaries (i.e., 1-interquartile change).
§Fifty-meter buffer around school boundaries.

reduce noise (6) might therefore explain a part of our observed associations (37). Moreover, proximity to green spaces has been reported to increase physical activity (38), and physical activity has been associated with better cognitive function in children (9). Furthermore, parental psychological stress and depression have been reported to be adversely associated with cognitive development in their children (39) and exposure to green space has been associated with evidence of stress restorative effects and reduced depression in adults (3, 28). A growing body of evidence also suggests that a failure of the immunoregulatory pathways due to a reduced exposure to macroorganisms and microorganisms in Westernized populations might play a role in impairment of brain development (10, 40) with childhood as a particular window of vulnerability (41). Therefore, the ability of outdoor surrounding greenness to enhance immunoregulation-inducing microbial input from the environment (10) could have been another mechanism underlying our observed association between greenness exposure and cognitive development.

Implications for Policymakers. Approximately one-half of the world population lives in cities, and it is projected that by 2030, three of every five persons will live in urban areas worldwide (42). Urban areas are characterized by a network of nonnatural built-up infrastructures with increased pollutant levels and less green environments (43). Children's exposure to these pollutants such as air pollution and noise has been associated with detrimental impacts on their cognitive development. Our findings suggest for a beneficial impact of green space exposure on cognitive development, with part of this effect resulting from buffering against such urban environmental pollutants. This impact was more evident for surrounding greenness at school and for working memory and superior working memory, which are predictors of learning and academic attainment (44). Schoolchildren with a superior working memory progress of less than one-10th of a percentile (45) of the distribution can be classified as impaired superior working memory progress. Our results suggest that if schools increased greenness within their boundaries by the observed IQR (Fig. 1), then 8.8% of children with impaired superior working memory progress would move out of this category. Our findings, therefore, hold importance for policymakers when translating evidence into feasible and achievable targeted interventions such as improving greenness at schools, given that improved cognitive development in children attending schools with more greenness could result in an advantage in mental capital, which, in turn, would have lasting effects through the life-course.

Strengths and Limitations of Study. This study was based on repeated computerized tests of cognitive development to quantify different aspects of cognitive development in study participants. These tests have been reported to have acceptable internal consistency, reasonable factorial structure, and good criterion validity and statistical dependencies for use in general population (46). We applied one of the most comprehensive approaches to date to assess exposure to green space by characterizing the outdoor surrounding greenness at home and school and during commuting by using high-resolution (5 m × 5 m) satellite data on greenness, enabling us to account for small-area green spaces (e.g., home gardens, street trees, and green verges) in a standardized way.

Our study also faced some limitations. The generalizability of our findings might have been affected by selection bias in that those participants participated in BREATHE were different from those not participated with respect to SES. Approximately 58% of mothers in our study population had a university degree, which was higher that the regional average of 50% among women between 25 and 39 y old living in Barcelona (47). We did not, however, observe any indication of effect modification by maternal education in our associations. Moreover, the Urban Vulnerability Index of the schools was not associated with school participation rate (Spearman's correlation coefficient = −0.09, $P =$ 0.61); these observations might suggest that the socioeconomic status was less likely to be a major predictor of participating in the study. Similarly, school greenness was not associated with participation rate at schools (Spearman's correlation coefficients of −0.06 with P value = 0.72 for greenness within school boundaries and 0.13 with P value = 0.43 for greenness surrounding schools). Our exposure assessment focused on exposure during the school age, overlooking other potential windows of susceptibility such as prenatal and preschool periods. Investigating these windows of susceptibility presents an opportunity for future studies. By using an NDVI map obtained at a single point in time (2012), we effectively assumed that the spatial distribution of NDVI across our study region remained constant over the study period (2012). The findings of our previous studies support the stability of the NDVI spatial contrast over seasons and years (21, 48). Finally, data were not available for some potentially relevant confounders, such as parental mental health status.

Conclusions

Exposure to outdoor surrounding greenness was associated with a beneficial impact on cognitive development in schoolchildren.

ENVIRONMENTAL SCIENCES

These associations were only partly mediated by reduction in TRAP levels, suggesting that other mechanisms likely underlie this association. Our observed beneficial associations were consistent for working memory, superior working memory, and inattentiveness and were more evident for greenness at school. Further studies are warranted to replicate our findings in other settings with different climates and to investigate other cognitive functions with different windows of susceptibility such as prenatal and preschool periods.

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