Title

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Publication Date
2021-12-15

DOI
10.1016/j.envpol.2021.118208

Peer reviewed

HHS Public Access
Author manuscript
Environ Pollut. Author manuscript; available in PMC 2022 June 20.

Published in final edited form as:
Environ Pollut. 2021 December 15; 291: 118208. doi:10.1016/j.envpol.2021.118208.

Early Life Exposure to Greenness and Executive Function and Behavior: An Application of Inverse Probability Weighting of Marginal Structural Models

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Abstract

Increasingly, studies suggest benefits of natural environments or greenness on children's health. However, little is known about cumulative exposure or windows of susceptibility to greenness exposure. Using inverse probability weighting of marginal structural models (IPW/MSM), we estimated effects of greenness exposure from birth through adolescence on executive function and behavior. We analyzed data of 908 children from Project Viva enrolled at birth in 1999–2002 and followed up until early adolescence. In mid-childhood (median 7.7 years) and early adolescence (13.1 years), executive function and behavior were assessed using the Behavior Rating Inventory of Executive Function and the Strengths and Difficulties Questionnaire (SDQ).

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Greenness was measured at birth, early childhood, mid-childhood, and early adolescence, using the Normalized Difference Vegetation Index. We used inverse probability weighting of marginal structural models to estimate effects of interventions that ensure maximum greenness exposure versus minimum through all intervals; and that ensure maximum greenness only in early childhood (vs. minimum through all intervals). Results of the effects of “maximum (vs. minimum) greenness at all timepoints” did not suggest associations with mid-childhood outcomes. Estimates of “maximum greenness only in early childhood (vs. minimum)” suggested a beneficial association with mid-childhood SDQ (−3.21, 99%CI: −6.71,0.29 mother-rated; −4.02, 99%CI: −7.87,−0.17 teacher-rated). No associations were observed with early adolescent outcomes. Our results for “persistent” maximum greenness exposure on behavior, were not conclusive with confidence intervals containing the null. The results for maximum greenness “only in early childhood” may shed light on sensitive periods of greenness exposure for behavior regulation.

Keywords

Green space; Children’s health; Sensitive periods; Inverse probability weighting; Executive function

INTRODUCTION

Neuropsychiatric disorders including executive function and behavioral problems occur in 10–20% of children worldwide (Kieling et al., 2011). Executive function and behavior regulate higher order cognitive functions, including working memory, planning, initiation of activity, and cognitive flexibility (Goldstein and Naglieri, 2014). Poor executive function and behavior in childhood may lead to inadequate academic performance and difficulties in family, social life, and communication functioning through later childhood and adolescence (Zhang et al., 2019).

Green space, natural vegetation or greenness may improve executive function and behavioral development in children through more opportunities for physical activity, reducing exposure to air pollutants or through reducing mental fatigue. In particular, the Attention Restoration Theory states that access to greenness is crucial for restoring attention capacities which leads to better executive function and behavior in childhood (Kaplan and Kaplan, 1989; Kaplan, 1995). In addition, the Stress Reduction Theory (SRT) proposes that exposure to nature supports psychophysiological stress recovery (Ulrich et al., 1991), which is a predictor of attention performance for children and adolescents (Chawla et al., 2014). A number of observational studies (Amoly et al., 2014; Bijnens et al., 2020) and randomized controlled studies (Faber Taylor and Kuo, 2009; Li and Sullivan, 2016), have reported beneficial associations between residential surrounding greenness and executive function and behavioral development among school-age children. However, little is known about windows of susceptibility to greenness exposure. Early childhood (around age 3 years) has been referred to as a window of susceptibility as many aspects of development, particularly brain maturation, can be disturbed by the environment during this age (Goldman et al., 2001; Miguel et al., 2019). Further, previously published data have shown that mental health problems that emerge in early childhood are risk factors for mental health problems in adolescence and adulthood (Engemann et al., 2019). To our knowledge, this study is the first of its type to examine the association between early life exposure to greenness and executive function and behavior among children, utilizing repeated measures of greenness exposure from birth to early adolescence and exploring early childhood as a window of susceptibility to greenness exposure. We analyzed data from Project Viva, a longitudinal pre-birth cohort in eastern Massachusetts, using Inverse Probability Weighting (IPW) of Marginal Structural Models (MSM), which, unlike standard outcome regression methods, can recover effects of time-varying exposure interventions when time-varying confounders are present (Robins et al., 2000).

METHODS

Study Population

Project Viva enrolled 2670 pregnant women during their first obstetric care visit between 1999 and 2002 at Atrius Harvard Vanguard Medical Associates. More detailed information has been published elsewhere (Oken et al., 2015). Mothers and children completed in-person visits during infancy, early childhood, mid-childhood and early adolescence. The Harvard Pilgrim Health Care Institutional review approved the study protocols, mothers provided written informed consent, and children provided verbal assent at the mid-childhood and early adolescent visit. Of the 2,128 live births enrolled, 2,107 had complete information on baseline exposure (residential exposure to greenness at birth), of which 908 had complete baseline confounder data, leaving a final analytical sample size of 908 (Figure A.1).

Exposure Assessment

We used the Normalized Difference Vegetation Index (NDVI) to evaluate residential exposure to greenness at birth, early childhood (median age 3.2 years), mid-childhood (median age 7.7 years), and early adolescence (median age 13.1 years). NDVI is a satellite-based objective indicator of the quantity of ground green vegetation and has been previously used in this cohort (Jimenez et al., 2020a). Briefly, NDVI was calculated from Landsat satellite data at 30m resolution from each July from 1999 to 2017, since NDVI reaches its maximum and highest level of geographic variation during the height of the summer. NDVI ranges between −1 and 1, with negative values corresponding to water, values around zero corresponding to bare soil, and positive values represent plants and vegetation. We used average NDVI around participant's residential addresses at a 90m buffer size for our main analysis based on previous studies on this cohort (Jimenez et al., 2020a). We also conducted sensitivity analyses for larger buffer sizes of 270m and 1230m. Based on 30m Landsat data, we chose the 90m buffer as a measure of greenness directly accessible outside each home, and the 270m and 1230m buffers as a measure of greenness within walkable areas, consistent with previous literature on greenspace and health.(Casey et al., 2016; James et al., 2014) These buffer sizes allowed us to evaluate both the immediate area around residences and the walkable area as potential relevant geographic contexts.3" (Kwan, 2012).

Outcome Assessment

Executive function and behavior were assessed in mid-childhood (mother and teacher-rated), and in early adolescence (adolescent-reported). In mid-childhood, mothers (in-person or via mailed questionnaire) and teachers (via mailed questionnaire if mother's permission was granted) completed two neurobehavioral rating scale assessments about child participants: Behavior Rating Inventory of Executive Function (BRIEF) and the Strengths and Difficulties Questionnaire (SDQ). In early adolescence (mean age 13.3 years), children completed the SDQ questionnaire. The BRIEF is a validated evaluation of executive function related behaviors in children ages 5–18 years (Gioia et al., 2000). Three BRIEF indices were created by summing across eight subscales: (1) Behavioral Regulation Index, which is the sum of emotional control, shift, and inhibit subscale scores; (2) Metacognition Index, which is the sum of initiate, working memory, plan/organize, organization of materials, and monitor subscale scores; and (3) the Global Executive Composite score, which is the sum of the raw scores of all subscales (Sullivan and Riccio, 2007). All three indices were converted to T-scores (mean=50, SD=10) and represent age- and sex-standardized scores. Higher BRIEF scores indicate more executive function related behavioral dysfunction (Sullivan and Riccio, 2007), with a T-score greater than 65 considered to be clinically significant for executive dysfunction (McCandless and O' Laughlin, 2007). BRIEF scores were assessed as continuous variables in line with previous research on this cohort (Fruh et al., 2019).

The SDQ is a validated questionnaire on which parents and teachers rate behavioral difficulties in children aged 4–16 years (Goodman and Goodman, 2009), through five scales: peer relationship problems, hyperactivity, emotional problems, conduct problems, and prosocial behavior. SDQ scales range from 0 to 10 points, with higher scores indicating worse performance (prosocial behavior scale was reverse coded). The scales of peer, hyperactivity, emotional, and conduct problems were summed up to create the total difficulties score ranging from 0 to 40 points (Goodman and Goodman, 2009), with a score of 16 points or more indicating a clinically abnormal range for the US population (Bourdon et al., 2005). The total difficulties score was used as a continuous variable in line with previous research on green space and child mental well-being (Feng and Astell-Burt, 2017a).

The scales of emotional and peer problems were summed up to create the internalizing sub-scale; and the scales of conduct and hyperactivity problems were summed up to create the externalizing sub-scale. The internalizing and externalizing subscales were used as secondary outcomes based on previous research to disentangle whether greenness is associated with negative emotional states that might be internalized (e.g., anxiety, depression) or externalized problems (e.g., lack of concentration) (Feng and Astell-Burt, 2017a; Goodman et al., 2010).

Time-invariant and time-varying covariates

Time-invariant covariates accounted for in the analysis included mother's characteristics: age at enrollment (years; continuous), maternal intelligence quotient (IQ; Kaufman Brief Intelligence Test, KBIT-2; continuous), smoking during pregnancy (self-reported as former or during pregnancy vs. never), college education (yes/no), marital status (married or cohabiting yes/no); and child's characteristics: age at the time of assessment, sex (male, female), race/ethnicity (Black, Hispanic, Asian, White, Other), season of birth (winter, spring, summer, fall). We considered the following time-varying covariates: household income (>$ 70,000/year vs not), median census tract income (continuous), population density (based on the National Land Cover Data; continuous) at the census block-group level as a proxy for urbanicity (Bottino et al., 2012), derived at each visit except in early adolescence, for which only household income data was available (Table 1, Figure 1). We selected these covariates based on prior publications linking green space and executive function and behavioral development (Figure 1) (Amoly et al., 2014; Bijnens et al., 2020). For sensitivity analyses, we further adjusted for time-varying screen time as a potential confounder. In early childhood, mothers reported their children's average hours of TV/video time in the past month, separating weekdays and weekends (none, <1 hour a day, 1 to 3 hours a day, 4 to 6 hours a day, 7 to 9 hours a day, and 10+ hours a day). We computed weekly average of TV hours/day as ((weekday*5) + (weekend*2))/7. In mid-childhood and early adolescence, mothers reported their children's average hours of TV time, time spent watching videos, playing computer games, and using the internet/computer (not including homework) in the past month, separating weekdays and weekends (none, <1 hour a day, 1 to <2 hours a day, 2 to 3 hours a day, 4 to 6 hours a day, and 7+ hours/day). We computed weekly average of total screen time as described previously including TV, videos, computer games, and internet/computer.

Statistical Analysis

We used Inverse Probability Weighting of Marginal Structural Models (IPW/MSM), an approach that was explicitly developed to estimate the effects of time-varying exposure interventions on outcomes in the presence of measured time-varying confounders that may be affected by past exposure, presuming no unmeasured confounding and other assumptions hold (Robins et al., 2000). We implemented a version of this approach that replaces the actual continuous exposure with indicators of exposure being within a pre-specified level. This implementation is more stable and less susceptible to extreme weights. In this case, estimates can be interpreted as effects of time-varying exposure interventions that maintain exposure at each time within that pre-specified level; specifically such that the exposure distribution under intervention is that from the observational study among individuals with exposure in this level (Picciotto et al., 2012; Young et al., 2019). Here we considered effects of interventions that ensure greenness exposure is maintained within the highest quartile of the data ("maximum exposure") through all intervals vs. lowest ("minimum exposure") on executive function and behavior indices in mid-childhood and early adolescence, adjusting for baseline and time-varying confounders. Specifically, for outcomes in mid-childhood, we fit a weighted outcome regression model with greenness quartiles at birth, early childhood and mid-childhood as the independent variables. For outcomes in early adolescence, we fit a weighted outcome regression with greenness quartiles at birth, early childhood, mid-childhood and early adolescence as the independent variables. The details for the estimation procedure for mid-childhood outcome and for early adolescent outcomes analyses are provided in the Appendix (A.Methods).

We also estimated the effect of ensuring "maximum greenness exposure only in early childhood, while holding others at the minimum exposure" (vs. "minimum greenness exposure at all time points) by the estimated weighted regression coefficient for the highest quartile of greenness exposure in early childhood.

We used a nonparametric bootstrap with 1000 resamples to compute 99% confidence intervals. We repeated the same steps to estimate effects of time-varying greenness exposure on early adolescent executive function and behavior. We also ran sensitivity analysis among non-movers from birth to early adolescence (N=315). We use the word "somehow" to indicate that the hypothetical intervention (e.g., ensuring maximum greenness at birth, early childhood, and mid-childhood) could potentially influence executive function and behavior in a way that is not clearly defined. We defined "persistent" as having the exposure (i.e. maximum greenness) at all three age intervals (birth, early childhood, and mid-childhood), and "early childhood onset" as having the maximum greenness exposure at early childhood only, but not at birth, mid-childhood or early adolescence (Aris et al., 2021). We provide details of the estimation procedure in the Appendix (A.Methods). We conducted all analyses using in R version 3.4.0 (R Core Team, Vienna, Austria)(R Core Team, 2020).

RESULTS

At enrollment during pregnancy, the mean age of the mothers was 32.97 (SD 4.6) years, and approximately 75% reported having a college degree. At baseline, more than two-thirds (67%) of participants reported having a household income over US$70,000 per year, which increased to 83% at early adolescence. More than two thirds of the participating children identified as white (70%) and half as female (50%) (Table 2). The correlation between greenness exposures within individuals across time ranged between 0.44–0.81, while the correlation between greenness and time-varying covariates (median census tract income and population density) ranged between 0.29–0.87 and −0.63– −0.4 respectively (Figure A.2). Compared to children excluded from the study, those included were slightly younger at the mid-childhood visit and more likely to be identified as of white race/ethnicity (Table A.1). Maternal IQ of those included was higher, and the household annual income was also higher, urbanicity was lower. NDVI across time points was similar between those included and those excluded from the analysis. Finally, all outcomes at mid-childhood, and early adolescence were lower for participants included, except for teacher-rated SDQ prosocial in mid-childhood and self-rated SDQ prosocial in early adolescence (Table A.1). IP weight distribution can be found in Figure A.3.

IPW/MSM estimates of the mid-childhood BRIEF score mean difference of somehow ensuring "persistent" maximum greenness (vs. "minimum at all time points")

IPW estimates of the effect of somehow ensuring "persistent" maximum greenness on mid-childhood BRIEF scores were imprecise with wide 99%CI containing the null (Table 3). For example, the estimated total difficulties score under an intervention that ensures "persistent" maximum greenness was 4.89 (95%CI: 3.06, 6.72), while the estimated total difficulties score under an intervention that ensures "minimum greenness at all time points" was 4.09 (95%CI: 2.06, 6.12). The difference in the estimated mean total difficulties score was −0.79 (i.e., 4.09–4.89; 95%CI: −3.51, 1.92), suggesting a decrease in total difficulties when "persistently" exposed to maximum greenness, however the confidence interval included the null.

IPW/MSM estimates of the mid-childhood SDQ score mean difference of somehow ensuring “persistent” maximum greenness (vs. “minimum at all time points”)

The IPW/MSM estimates of the effect of somehow ensuring “persistent” maximum greenness on executive function and behavior at mid-childhood measured by SDQ scales were close to zero with narrow 99%CI suggesting no association, particularly for the externalizing, internalizing, and pro-social SDQ scales (Table 3).

IPW/MSM estimates of the mid-childhood BRIEF score mean difference of somehow ensuring “early childhood onset” of maximum greenness (vs. minimum at all time points)

IPW estimates of the effect of ensuring “early childhood onset” of maximum greenness vs “minimum at all time points” on mid-childhood BRIEF scores in general suggested a negative association but estimates were imprecise with wide 99%CI containing the null (Table 4).

IPW/MSM estimates of the mid-childhood SDQ score mean difference of somehow ensuring “early childhood onset” of maximum greenness (vs. “minimum at all time points)

The IPW/MSM estimates of the effect of somehow ensuring “early childhood onset” of maximum greenness vs “minimum greenness exposure at all time points” suggested a protective association with total difficulties (−3.21, 99%CI −6.71, 0.29; mother-rated; −4.02. 99%CI:−7.87, −0.17; teacher rated) (Table 4)f. The estimates for the externalizing, internalizing, and prosocial SDQ sub-scales, were close to zero with narrow 99%CI suggesting no effect, similar to the results of somehow ensuring “persistent” maximum greenness.

IPW/MSM estimates of the early adolescence SDQ score mean difference

We did not observe significant associations for executive function and behavior at early adolescence (Figures A.4 and A.5).

IPW/MSM estimates among non-movers

Non-movers represented 35% (N=315) of the analytic sample. The IPW/MSM estimates of the effect of somehow ensuring “persistent” maximum greenness on SDQ at mid-childhood were close to zero with narrow 99%CI, except for SDQ total differences, for which the estimates suggested a negative association but were imprecise with wide 99%CI containing the null (Figure A.6).

The IPW/MSM estimates of the effect of somehow ensuring “early childhood onset” of maximum greenness on SDQ at mid-childhood were also null with narrow 99%CI suggesting no association. Again, the estimate for SDQ total difficulties suggested a negative association but was imprecise with wide 99%CI containing the null, probably due to a reduced sample size (Figure A.7).

IPW/MSM estimates within 270m and 1230m buffers

The IPW/MSM estimates of the effects of somehow ensuring “persistent” maximum greenness within 270m and 1230m buffers on SDQ at mid-childhood were not statistically significant suggesting no association (Figure A.8). Similar results were observed for ensuring "early childhood onset" of maximum greenness within 270m and 1230m buffers (Figure A.9).

IPW/MSM estimates considering screen time

In analyses including screen time as a time-varying confounder we observed similar results, namely that the effect of somehow ensuring "early childhood onset" of maximum greenness vs "minimum greenness exposure at all time points" suggested a protective association with total difficulties (−4.02, 99%CI −8.0, −0.04, mother-rated; −4.11, 99%CI:−8.45, 0.23; teacher rated) (Figure A.10). The estimates for the BRIEF scores, were imprecise with wide 99%CI containing the null, similar to the results of ensuring "persistent" maximum greenness (Figure A.11).

DISCUSSION

In this study, we used IPW/MSM to analyze the relationship between repeated measures of greenness exposure across early childhood and executive function and behavior at mid-childhood and early adolescence. Our findings suggest that "persistent" exposure to maximum greenness at birth, early childhood and mid-childhood (vs. minimum) was not associated with executive function and behavior mid-childhood. Effect estimates for early childhood onset (vs minimum at all time points) suggested a protective association with the total difficulties SDQ score at mid-childhood (composed of peer, hyperactivity, emotional, and conduct SDQ sub-scales). Effect estimates for executive function and behavior at early adolescence were weaker in magnitude, with wider 99% confidence intervals containing the null.

Previous research on greenness exposure and SDQ among children between the ages of 3 and 13 has shown strong protective associations (Amoly et al., 2014; Balseviciene et al., 2014; Vanaken and Danckaerts, 2018). Our estimates of somehow ensuring "persistent" maximum greenness were imprecise with CI containing the null and not in line with previous research showing a protective effect on mother-rated behavior executive function measures or BRIEF scores at mid-childhood. This contrasting finding could be due to Project Viva being a generally economically advantaged cohort. Interestingly, the direction of point estimates of somehow ensuring "persistent" maximum greenness (vs minimum exposure) were in line with protective effect on teacher-rated behavior executive function measures at mid-childhood, but not on mother-rated behaviors. However, there was insufficient evidence to reject the null. Parents and teachers may rate students differently based on factors other than the child's behavior, and on different settings (structured classroom vs more relaxed settings at home). In both cases, outcome misclassification is possible and is a limitation of our study. Additionally, our estimates of somehow ensuring "persistent" maximum greenness on SDQ scales at mid-childhood were similar to those from a study that found no significant associations for teacher-reported SDQ outcomes among children (aged 12–13 years old) (Feng and Astell-Burt, 2017b).

Our finding on the protective effect of somehow ensuring "maximum exposure to greenness only at early childhood" (vs minimum exposure at all time points), on the total difficulties

SDQ score, may highlight early childhood as a potentially sensitive period of exposure to greenness. Findings like this may indicate that urban health policies could benefit most from additional green space as an early intervention tool. We hypothesize pathways related to noise and/or air pollution reduction at early childhood, may be significant (Engemann et al., 2019), and that during this sensitive period, the importance of playing outside can have long-term consequences for health (such as physical activity) are set (Jimenez et al., 2020b). In sensitivity analysis, the protective effect of somehow ensuring "maximum exposure to greenness only at early childhood" (vs persistent minimum exposure), on the total difficulties SDQ score remained robust to adjustment for screen time. A recent review found that in schoolchildren (5–11 years), more screen time was associated with unfavorable outcomes on measures of poor mental health, such as depression, conduct problems, emotional problems, negative affect and total difficulties, while green space was associated with favorable mental health (Oswald et al., 2020). Green spaces provide children with opportunities such as discovery, creativity, risk taking; bolstering sense of self; which in turn are suggested to positively influence different aspects of brain development (Kahn and Kellert, 2002; Kellert, 2005). Previous research has also found beneficial associations between exposure to green space and social, emotional, hyperactivity, and behavioral difficulties in early-childhood (Amoly et al., 2014; Feng and Astell-Burt, 2017a; Richardson et al., 2017). The effect estimate for the SDQ total difficulties score was comparable to that found in a longitudinal study that reported that longer higher residential surrounding greenness were associated with lower scores for SDQ total difficulties among children aged 4–5 years in Australia (Feng and Astell-Burt, 2017a). Another longitudinal study found that neighborhood greenness may reduce social, emotional and behavioral difficulties among 4–6 year olds (Richardson et al., 2017). Our effect estimates for early adolescent outcomes were not statistically significant. Collectively, these findings indicate that while exposure to greenness in early childhood may count towards well-being in mid-childhood, the well-being relevance of greenness exposure may become less relevant as children grow older, perhaps because the beneficial influence does not last through adolescence. Further, our study used data from Project Viva, a cohort is a largely suburban population that has on average high socioeconomic status. Thus, being in a generally economically advantaged cohort or having low variation in greenness may have offset the effect of greenness in the latest development. This is in contrast to the findings of a study that evaluated green space from birth to age 10 among 900,000+ Danish children, and found that living in greener spaces during childhood was associated with lower risk of psychiatric disorders during adulthood (Engemann et al., 2019).

Three strategic strengths of this study enable us to add to the current literature on greenness and childhood well-being. First, this study is among the first to examine multiple time periods of greenness exposure over a long-term follow-up period among children. Second, we used IPW/MSM methodology to estimate effects of time-varying exposures, provided all assumptions hold. The causal interpretation of our estimates relies on weaker assumptions than multivariable regression, allowing for the realistic assumption that post-baseline confounders are affected by exposure. Third, our rich covariate data allowed us to control for many important time-varying potential confounding variables.

However, our study is not without limitations. Although we adjusted for neighborhood and individual socioeconomic status at different time points, our results may be influenced by unmeasured socioeconomic factors such as lower-quality green space, higher crime rates, and fewer social advantages in deprived neighborhoods. Second, due to missing information on baseline covariates, we excluded a considerable number of children which may have led to selection bias, but we adjusted for this by using censoring weights. Third, most participants were of high socio-economic status and resided in eastern Massachusetts and all had health care, which may limit generalizability of our findings. Fourth, we performed a total of 60 comparisons which could potentially lead to multiple testing. To account for multiple comparisons, we used a conservative alpha of 0.01 to assess statistical significance. We must also consider that we did not have information on participant's exposure to green space around schools. Teacher-rated indicators of executive function and behavioral development among school-age children may be sub-optimal in studies of residential exposure to green space in which parent and/or self-rated measures might be more preferable (Feng and Astell-Burt, 2017b). Indeed, a recent study that evaluated associations between greenness and cognitive development in children, observed stronger associations for levels at school compared with those at home (Dadvand et al., 2015). This would suggest that our results on residential greenness and mental well-being might be biased towards the null. Fifth, NDVI is sensitive to season and cannot distinguish types of vegetation, which prevents us from finding out what aspects of the green space influence children's mental well-being. Additionally, the uncertainty in the relevant geographic context to evaluate greenness exposure in association with health is a fundamental problem in spatial analyses (Kwan, 2014). We examined three buffer sizes (90m, 270m and 1,230m) that yielded different results, suggesting that immediate environment around residential address is more relevant but this could also be due to exposure misclassification.

CONCLUSIONS

Our study supports prior reports of exposure to greenness on neurobehavioral outcomes (Madzia et al., 2019; Vanaken and Danckaerts, 2018) suggesting that higher greenness exposure may have the capacity to alter the developing brain. Further, the results in this study suggest that higher exposure to greenness particularly during early childhood is associated with better neurobehavioral performance on specific subscales at mid-childhood.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgements

Funding:

This work was supported by the National Institutes of Health [grants 1K99AG066949-01, and R00CA201542].

Abbreviations:

SRT	Stress Reduction Theory

IPW	Inverse Probability Weighting
MSM	Marginal Structural Models
NDVI	Normalized Difference Vegetation Index
BRIEF	Behavior Rating Inventory of Executive Function
SDQ	Strengths and Difficulties Questionnaire
IQ	Intelligence quotient

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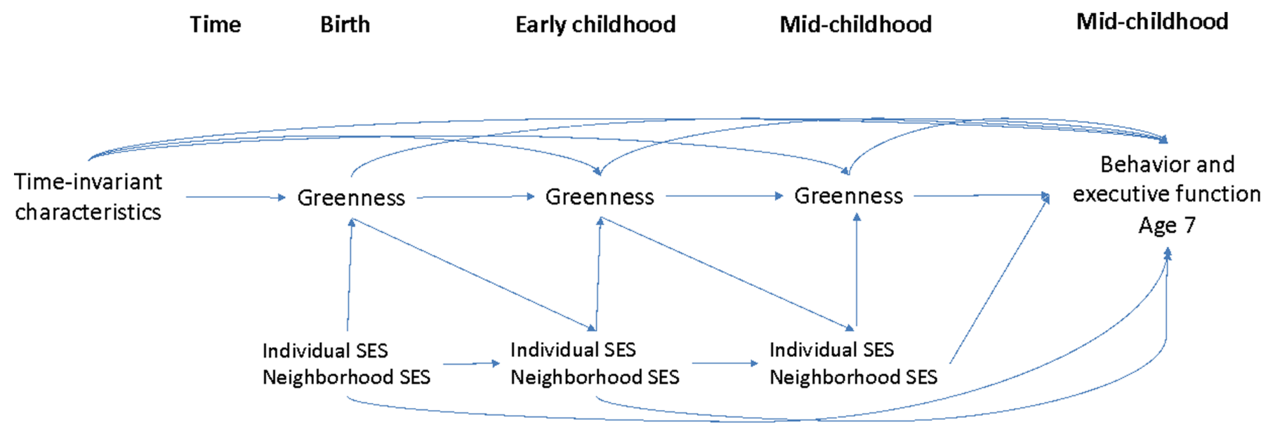

Figure 1.

Causal directed acyclic graph representing simplified assumptions on the structure of association between greenness exposure and executive function and behavior in mid-childhood among Project Viva participants [a]

[a] The desired interpretation of the IPW estimates allows the presence of unmeasured common causes of the outcome and other covariates on the DAG if they do not directly affect greenness exposure.

Table 1.

Choices of time-varying confounders

Interval (k)	**Confounders**
Birth (L_0)	Mother's characteristics: Age at enrollment, maternal IQ, smoking status during pregnancy, college education, marital status, household income Child's characteristics: Sex, race/ethnicity, season of birth Neighborhood characteristics: Median census tract income Urbanicity (population density)
Early Childhood (L_1)	Mother's characteristics: Household income Neighborhood characteristics: Median census tract income Urbanicity (population density)
Mid-childhood (L_2)	Mother's characteristics: Household income Neighborhood characteristics: Median census tract income Urbanicity (population density)
Early adolescence (L_3)	Mother's characteristics: Household income

Table 2.

Characteristics of Project Viva Children with Information on Greenness Exposures and Mid-childhood Executive Function and Behavior Outcomes (N=908)[b]

	Mean (SD) or N (%)
Maternal Characteristics	
Age at enrollment (years)	32.97 (4.6)
Maternal IQ (KBIT-2 composite), points	108.62 (14.73)
College degree, %	678 (74.67)
Smoking during pregnancy %	648 (71.37)
Married or cohabiting %	904 (99.56)
Annual Household Income Birth > $70,000, %	608 (66.96)
Annual Household Income Early Childhood > $70,000, %	595 (71.95)
Annual Household Income Mid-childhood > $70,000, %	695 (80.72)
Annual Household Income Early Adolescence > $70,000, %	634 (83.42)
Paternal Characteristics	
College degree, %	628 (69.16)
Child Characteristics	
Age at mid-childhood visit (years)	7.8 (0.73)
Sex, Female %	459 (50.55)
Race, White %	639 (70.37)
Neighborhood Characteristics	
Census Tract Median Household Income at birth (USD)	59344.3 (21153.29)
Census Tract Median Household Income at Early Childhood (USD)	64186.38 (23295.06)
Census Tract Median Household Income at Mid-childhood (USD)	67898.14 (24646.53)
Urbanicity at birth	786.9 (311.15)
Urbanicity at 3y	701.99 (330.3)
Urbanicity at 7y	656.82 (336.2)
Exposure to Greenness at Birth (NDVI)	0.54 (0.15)
Exposure to Greenness at Early Childhood (NDVI)	0.57 (0.14)
Exposure to Greenness at Mid-childhood (NDVI)	0.60 (0.13)
Exposure to Greenness at Early Adolescence (NDVI)	0.62 (0.12)
Behavior and executive function in mid-childhood	
Mother-rated	
BRIEF Global Executive Composite	48.38 (8.94)
BRIEF Behavior Regulation Index	47.89 (8.66)
BRIEF Metacognition Index	48.14 (8.52)
SDQ Total Difficulties	6.1 (4.47)
SDQ Prosocial (reverse coded)	−8.6 (1.64)
SDQ Externalizing	3.7 (3.02)
SDQ Internalizing	2.39 (2.35)

	Mean (SD) or N (%)
Teacher-rated	
BRIEF Global Executive Composite	49.65 (9.09)
BRIEF Behavior Regulation Index	49.58 (8.67)
BRIEF Metacognition Index	49.76 (9.54)
SDQ Total Difficulties	5.78 (5.44)
SDQ Prosocial (reverse coded)	−8.09 (2.13)
SDQ Externalizing	3.53 (3.8)
SDQ Internalizing	2.24 (2.68)
Behavior and executive function in early adolescence	
SDQ Total Difficulties	8.09 (5.13)
SDQ Prosocial (reverse coded)	−8.22 (1.63)
SDQ Externalizing	4.7 (3.3)
SDQ Internalizing	3.39 (2.78)

[b]Baseline variables have complete data (N=908), but the sample size may differ by outcome (N=888 with complete mid-childhood SDQ mother-reported, N=707 with complete mid-childhood SDQ teacher-reported, N=874 with complete mid-childhood BRIEF mother-reported, N=691 with complete mid-childhood BRIEF teacher-reported, and N=774 with complete early adolescence SDQ self-reported).

Table 3.

Inverse probability weighting estimates of the effect of ensuring "persistent" maximum greenness vs. "minimum greenness exposure and the mean difference on mean executive function and behavior in mid-childhood.

Outcome	Maintain minimum greenness at birth, early childhood and mid-childhood	Maintain maximum greenness at birth, early childhood and mid-childhood	Difference
Total difficulties - Mother rated	4.89 (3.06, 6.72)	4.09 (2.06, 6.12)	−0.79 (−3.51, 1.92)
Pro-social - Mother-rated	−8.73 (−9.06, −8.39)	−8.66 (−8.98, −8.34)	0.06 (−0.06, 0.19)
Externalizing - Mother-rated	3.17 (2.68, 3.65)	3.13 (2.6, 3.67)	−0.03 (−0.25, 0.19)
Internalizing - Mother-rated	2 (1.57, 2.44)	1.95 (1.55, 2.35)	−0.05 (−0.24, 0.13)
BRIEF Behavioral Regulation Index - Mother rated	44.24 (40.52, 47.97)	47.09 (43.39, 50.79)	2.85 (−2.45, 8.15)
BRIEF Metacognition index - Mother rated	45.12 (41.11, 49.13)	49.45 (45.51, 53.39)	4.32 (−1.29, 9.94)
BRIEF Global Executive Composite - Mother rated	44.52 (40.52, 48.53)	49 (44.78, 53.21)	4.47 (−1.36, 10.31)
Total difficulties - Teacher rated	5.09 (2.44, 7.74)	4.01 (2.71, 5.32)	−1.08 (−4.04, 1.88)
Pro-social - Teacher rated	−8.08 (−8.45, −7.7)	−8.07 (−8.42, −7.72)	0.01 (−0.14, 0.16)
Externalizing - Teacher-rated	3.41 (2.57, 4.24)	3.3 (2.54, 4.05)	−0.11 (−0.39, 0.17)
Internalizing - Teacher-rated	1.9 (1.4, 2.39)	1.89 (1.45, 2.33)	−0.01 (−0.2, 0.19)
BRIEF Behavioral Regulation Index - Teacher rated	49.48 (45.46, 53.5)	46.84 (44.56, 49.12)	−2.64 (−7.34, 2.07)
BRIEF Metacognition index - Teacher rated	49.63 (46.13, 53.13)	46.5 (42.88, 50.13)	−3.12 (−8.09, 1.84)
BRIEF Global Executive Composite - Teacher rated	49.52 (45.79, 53.24)	46.4 (43.4, 49.4)	−3.12 (−7.87, 1.63)

Table 4.

Inverse probability weighting estimates of the effect of ensuring "early childhood onset" of maximum greenness vs. "minimum greenness exposure at all time-points" and the mean difference on mean executive function and behavior in mid-childhood.

Outcome	Maintain minimum greenness at birth, early childhood and mid-childhood	Maintain maximum greenness only at early childhood, holding others at the minimum	Difference
Total difficulties - Mother rated	4.89 (3.06, 6.72)	1.68 (−2.05, 5.41)	−3.21 (−6.71, 0.29)
Prosocial- Mother rated	−8.71 (−9.05, −8.37)	−8.7 (−9.02, −8.38)	0.01 (−0.12, 0.13)
Externalizing - Mother-rated	3.19 (2.7, 3.68)	3.12 (2.63, 3.62)	−0.07 (−0.23, 0.1)
Internalizing - Mother-rated	2.04 (1.59, 2.49)	1.95 (1.56, 2.35)	−0.09 (−0.24, 0.07)
BRIEF Behavioral Regulation Index - Mother rated	44.24 (40.52, 47.97)	39.23 (31.97, 46.5)	−5.01 (−11.9, 1.88)
BRIEF Metacognition index - Mother rated	45.12 (41.11, 49.13)	41.03 (31.47, 50.59)	−4.09 (−12.95, 4.78)
BRIEF Global Executive Composite - Mother rated	44.52 (40.52, 48.53)	40.14 (31.62, 48.65)	−4.39 (−12.24, 3.47)
Total difficulties - Teacher rated	5.09 (2.44, 7.74)	1.07 (−3.08, 5.22)	**−4.02 (−7.87, −0.17)**
Prosocial - Teacher rated	−8.07 (−8.45, −7.69)	−8.09 (−8.45, −7.73)	−0.02 (−0.16, 0.11)
Externalizing - Teacher-rated	3.46 (2.61, 4.31)	3.3 (2.51, 4.1)	−0.16 (−0.42, 0.1)
Internalizing - Teacher-rated	1.93 (1.42, 2.43)	1.87 (1.41, 2.33)	−0.06 (−0.24, 0.13)
BRIEF Behavioral Regulation Index - Teacher rated	49.48 (45.46, 53.5)	46.21 (40.31, 52.11)	−3.27 (−9.66, 3.13)
BRIEF Metacognition index - Teacher rated	49.63 (46.13, 53.13)	46.04 (38.88, 53.21)	−3.58 (−10.29, 3.12)
BRIEF Global Executive Composite - Teacher rated	49.52 (45.79, 53.24)	45.54 (38.9, 52.18)	−3.98 (−10.45, 2.5)