Supplementary information: Benefit of natural environments particularly woodland on adolescent's cognition and mental health

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Supplementary Methods 1: longitudinal analysis

Executive function (EF)

We treated the EF as a continuous variable and we therefore modelled the outcome EF with a Gaussian distribution. We started by specifying $\mathrm{Y}_{\mathrm{ij}}^{\mathrm{EF}}$ as the measured composite score of three cognitive tests (i.e. Backward Digit Span, Spatial Working Memory and Trail Making Task) measured during the first and second visit. As the EF was characterized by tests with different scales, we z-standardized the tests to make them comparable:

$$z_i = \frac{x_i - \mu}{\sigma} \quad (1)$$

As Y_{ij}^{EF} was a continuous variable and can assume any value after standardization, it was reasonable to assume a Gaussian distribution with $j = 1, 2$ (time of first and second visit) and $i = 1, \dots, I = 3{,}568$ (total number of adolescents in this study):

$$Y_{ij}^{EF} \sim N(\mu_{ij}^{EF},\ \sigma_{EF}^2) \quad (2)$$

where σ_{EF}^2 was the variance. On μ_{ij}^{EF}, we specified a linear model:

$$\mu_{ij}^{EF} = \beta_0 + \eta_{ij} + \beta_1 X_{ij}^{age} + \beta_2 X_{ij}^{air} + \beta_3 X_{ij}^{area} + \beta_4 X_i^{ethn} + \beta_5 X_i^{gender} + \beta_6 X_{ij}^{nattyp} + \beta_7 X_i^{par} + \beta_8 X_i^{schtyp} + \varepsilon_i \quad (3)$$

where β_0 was the global intercept, $\beta_1, \dots, \beta_8$ were the regression coefficients associated with the covariates, ε_i was the random effect for adolescent i and η_{ij} was the random effect for time j nested in adolescent i. Age = adolescent's age; air = air pollution; area = area-level deprivation; ethn = ethnicity; gender = adolescent's gender; nattyp = natural environment type; par = parental occupation; schtyp = school type.

Strengths and Difficulties Questionnaire (SDQ) total difficulties score

We treated SDQ total difficulties score as count data and we therefore modeled the outcome SDQ total difficulties score with a Poisson distribution. We started by specifying Y_{ij}^{TDS} as the observed number of behavioral difficulties with $j = 1, 2$ (time of first and second visit) and $i = 1, \dots, I = 3{,}568$ (total number of adolescents in this study) and specified the Poisson model:

$$Y_{ij}^{TDS} \sim Poisson\ (\lambda_{ij}^{TDS}\ E_{ij}^{TDS}) \quad (4)$$

where E_{ij}^{TDS} represented the expected number of behavioral difficulties (included in the model as an offset in the log scale) and λ_{ij}^{TDS} represented the log relative risk of behavioral difficulties. We therefore specified a regression model on the log link transformed λ_{ij}^{TDS}:

$$log\ (\lambda_{ij}^{TDS}) = \beta_0 + \eta_{ij} + \beta_1 X_{ij}^{age} + \beta_2 X_{ij}^{area} + \beta_3 X_i^{ethn} + \beta_4 X_i^{gender} + \beta_5 X_{ij}^{nattyp} + \beta_6 X_i^{par} + \beta_7 X_i^{schtyp} + \varepsilon_i \quad (5)$$

where β_0 was the global intercept, $\beta_1, \dots, \beta_7$ were the regression coefficients associated with the covariates, ε_i was the random effect for adolescent i and η_{ij} was the random effect for time j nested in adolescent i.

KIDSCREEN-10 Health-Related Quality of Life (HRQoL) score

We modelled our binary outcome KIDSCREEN-10 Questionnaire HRQoL score with a Binomial distribution with $j = 1, 2$ (time of first and second visit) and $i = 1, \dots, I = 3{,}568$ (total number of adolescents in this study). We modelled the probability of low overall well-being p_{ij} of adolescent i at time j using the logit link function:

$$\text{logit}(p_{ij}) = log\ (\tfrac{p_{ij}}{1-p_{ij}}) = \beta_0 + \eta_{ij} + \beta_1 X_{ij}^{age} + \beta_2 X_{ij}^{area} + \beta_3 X_i^{ethn} + \beta_4 X_i^{gender} + \beta_5 X_{ij}^{nattyp} + \beta_6 X_i^{par} + \beta_7 X_i^{schtyp} + \varepsilon_i \quad (6)$$

where β_0 was the global intercept, $\beta_1, \ldots, \beta_7$ were the regression coefficients associated with the covariates, ε_i was the random effect for adolescent i and η_{ij} was the random effect for time j nested in adolescent i.

Supplementary Methods 2: cross-sectional analysis

Executive function (EF)

We specified Y_{ij}^{EF} as the measured composite score of three cognitive tests measured during the first visit at the schools. As Y_{ij}^{EF} was a continuous variable, and after standardization it can assume any value in $\mathbb{R}$, it was reasonable to assume the following Gaussian distribution with $j = 1, \dots, J = 39$ (total number of schools) and $i = 1, \dots, I =$ 6,386 (total number of adolescents):

$$Y_{ij}^{EF} \sim N(\mu_{ij}^{EF},\ \sigma_{EF}^2) \quad (7)$$

where σ_{EF}^2 was the variance. We therefore specified a linear model for μ_{ij}^{EF}:

$$\mu_{ij}^{EF} = \beta_0 + \eta_{ij} + \beta_1 X_i^{age} + \beta_2 X_i^{air} + \beta_3 X_i^{area} + \beta_4 X_i^{ethn} + \beta_5 X_i^{gender} + \beta_6 X_i^{nattyp} + \beta_7 X_i^{par} + \beta_8 X_i^{schtyp} \quad (8)$$

where β_0 was the EF global intercept, $\beta_1, \dots, \beta_8$ were the regression coefficients associated with the covariates and η_{ij} was the random effect for school j with adolescent i. Age = adolescent's age; air = air pollution; area = area-level deprivation; ethn = ethnicity; gender = adolescent's gender; nattyp = natural environment type; par = parental occupation; schtyp = school type.

Strengths and Difficulties Questionnaire (SDQ) total difficulties score

We modelled our outcome SDQ total difficulties score with a Poisson distribution. We started by specifying Y_{ij}^{TDS} as the observed number of behavioral difficulties with $j = 1, \dots, J = 39$ (total number of schools) and $i = 1, \dots, I =$ 6,386 (total number of adolescents), and treated these variables as count data to specify the Poisson model:

$$Y_{ij}^{TDS} \sim Poisson\ (\lambda_{ij}^{TDS}\ E_{ij}^{TDS}) \quad (9)$$

where E_{ij}^{TDS} represented the expected number behavioral difficulties and λ_{ij}^{TDS} represented the relative risk of behavioral difficulties. We therefore specified a regression model on the log link transformed λ_{ij}^{TDS}:

$$\log(\lambda_{ij}^{TDS}) = \beta_0 + \eta_{ij} + \beta_1 X_i^{age} + \beta_2 X_i^{area} + \beta_3 X_i^{ethn} + \beta_4 X_i^{gender} + \beta_5 X_i^{nattyp} + \beta_6 X_i^{par} + \beta_7 X_i^{schtyp} + \varepsilon_i \quad (10)$$

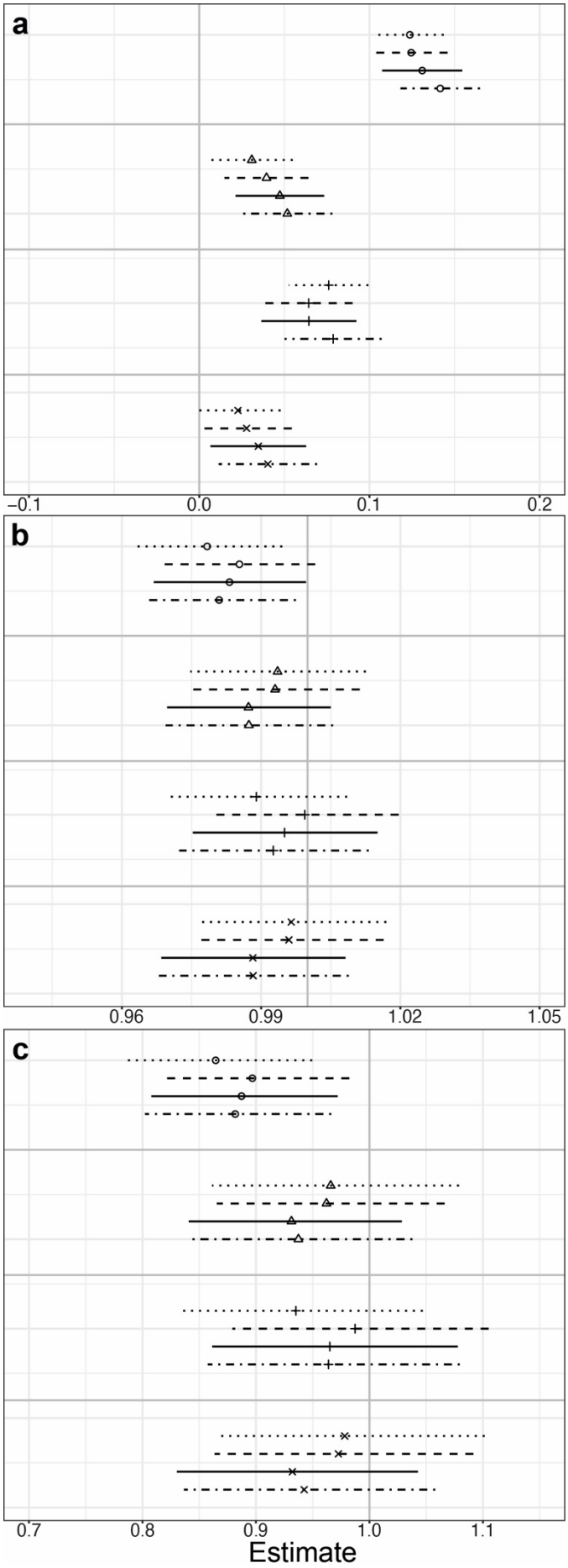
where β_0 is the global intercept, $\beta_1, \dots, \beta_7$ were the regression coefficients associated with the covariates, η_{ij} was the random effect for school j with adolescent i, and ε_i was the random effect for adolescent i. We included an additional random effect $\varepsilon_i \sim N(0, \sigma_\varepsilon^2)$ for adolescent i to account for overdispersion, which is typically present when using a Poisson model[2].

KIDSCREEN-10 Health-Related Quality of Life (HRQoL) score

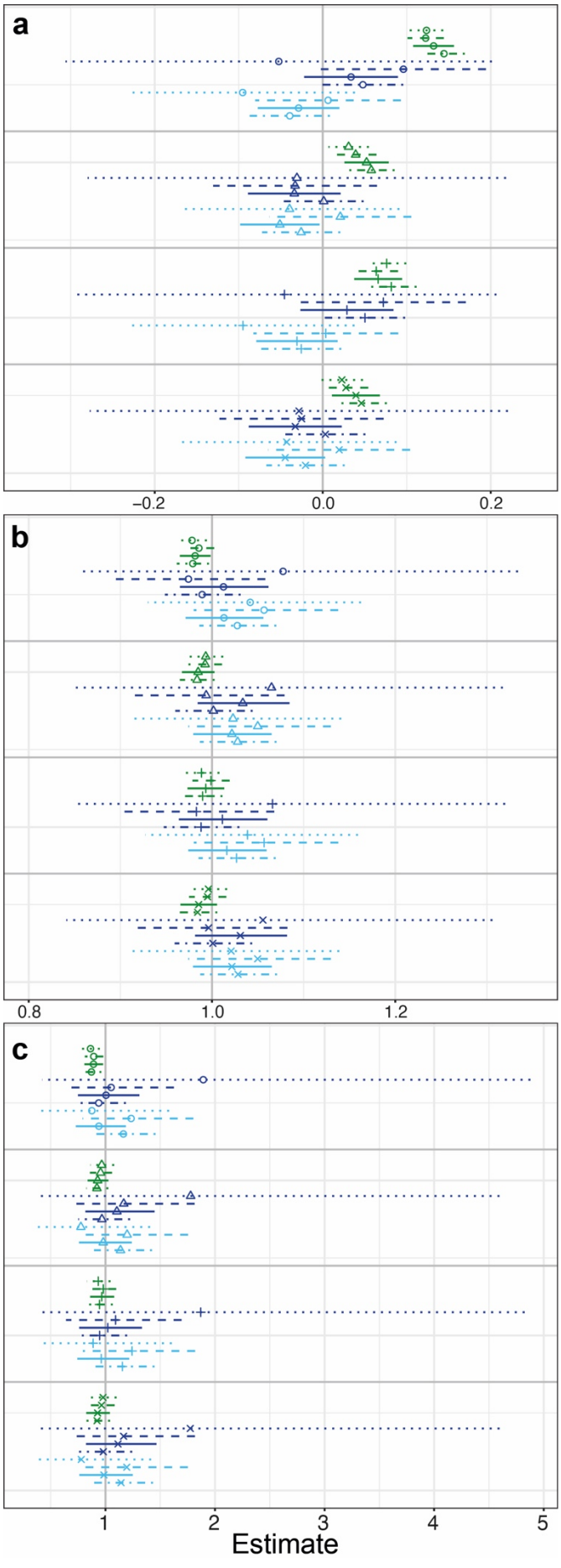
We modelled our binary outcome KIDSCREEN-10 Questionnaire HRQoL score with a Binomial distribution with $j = 1, \dots, J = 39$ (total number of schools) and $i = 1, \dots, I =$ 6,386 (total number of adolescents). We modeled the probability of low overall wellbeing p_{ij} of adolescent i at school j using the logit link function:

$$\text{logit}(p_{ij}) = log\left(\frac{p_{ij}}{1-p_{ij}}\right) = \beta_0 + \eta_{ij} + \beta_1 X_i^{age} + \beta_2 X_i^{area} + \beta_3 X_i^{ethn} + \beta_4 X_i^{gender} + \beta_5 X_i^{nattyp} + \beta_6 X_i^{par} + \beta_7 X_i^{schtyp} \quad (11)$$

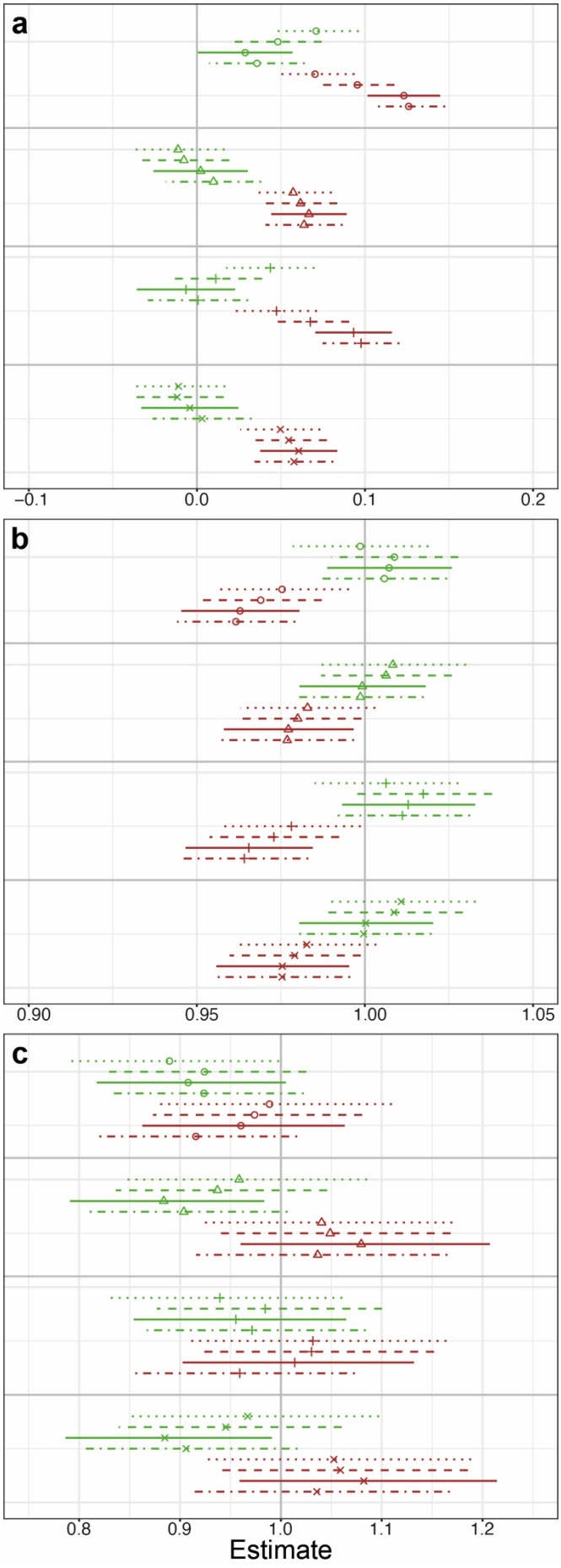
where β_0 was the global intercept, $\beta_1, \dots, \beta_7$ were the regression coefficients associated with the covariates and η_{ij} was the random effect for school j with adolescent i.



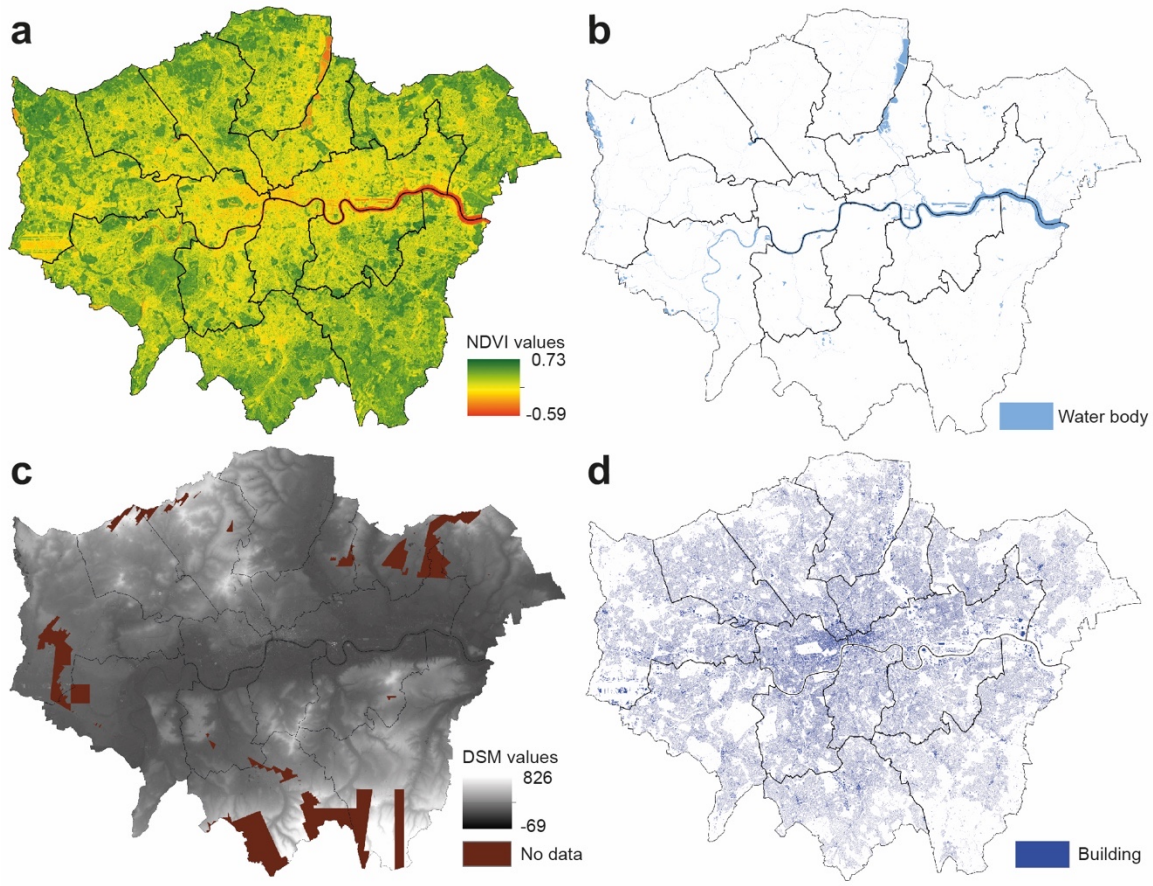
Supplementary Figure 1. Comparison of different buffer areas to investigate the association between natural space daily exposure rate (DER) and cognitive development, mental health and overall well-being during adolescence. The association between (a) executive function (EF) score, (b) Strengths and Difficulties Questionnaire (SDQ) total difficulties score (TDS) and (c) KIDSCREEN-10 Questionnaire Health-Related Quality of Life (HRQoL) score with natural space DER in buffer areas of 50 m (dotted line), 100 m (dashed line), 250 m (solid line) and 500 m (dotdash line) around the residential and school area. Four models were fitted: (○) unadjusted (△) adjusted for the effect of ethnicity and school type, (+) adjusted for socio-economic factors which includes area-level deprivation and parental occupation and (×) adjusted for all factors which includes area-level deprivation , ethnicity, parental occupation and school type. All four models were adjusted for age and gender, in the case of EF additionally adjusted for air pollution, and plotted with posterior mean and 95% credible intervals (CI). The vertical line (in grey) is the reference line and significance can be deduced when the 95% CI excludes zero for the EF, and excludes one for the SDQ TDS and HRQoL score.



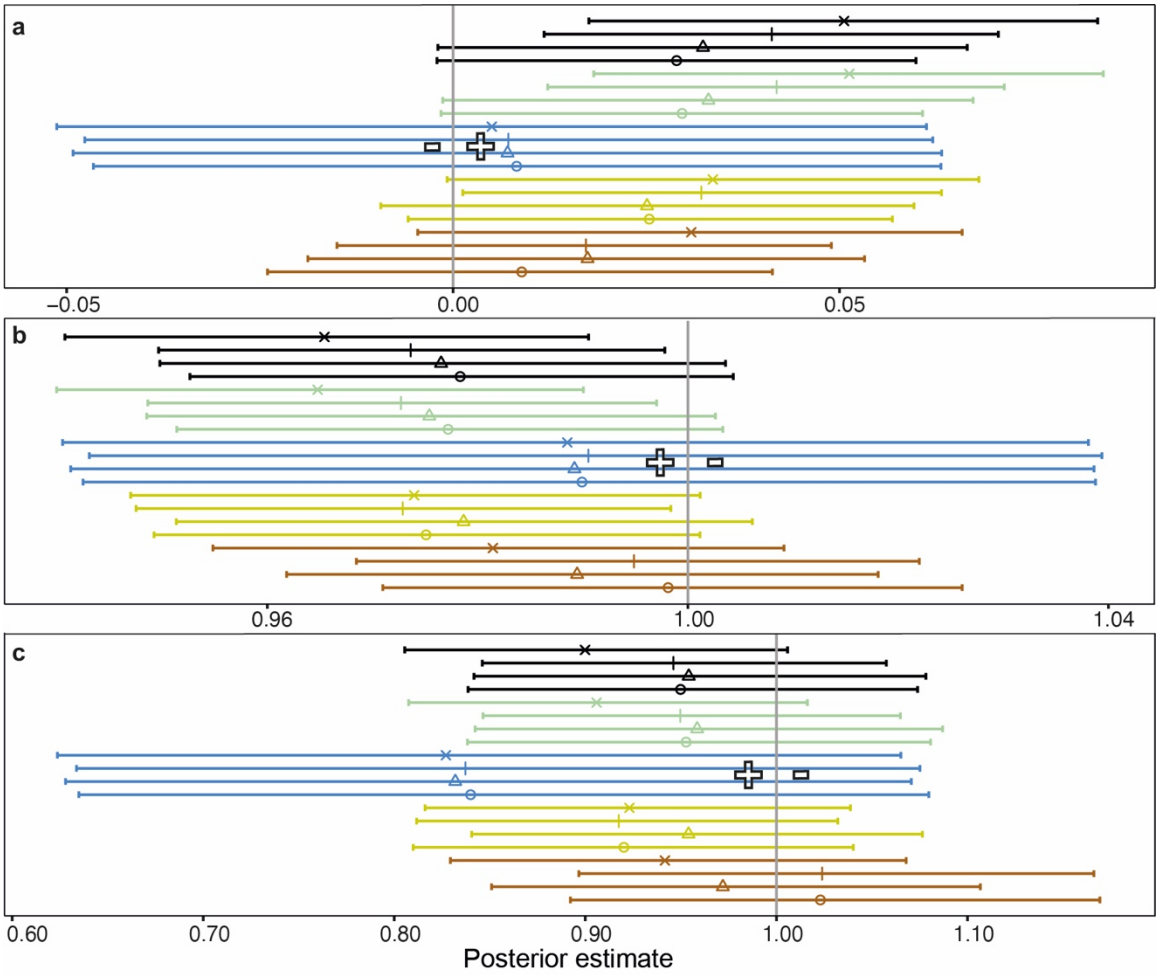
Supplementary Figure 2. Comparison of different buffer areas to investigate the association between green and blue space daily exposure rate (DER), and cognitive development, mental health and overall well-being during adolescence. The association between (a) executive function (EF) score, (b) Strengths and Difficulties Questionnaire (SDQ) total difficulties score (TDS) and (c) KIDSCREEN-10 Questionnaire Health-Related Quality of Life (HRQoL) score with the DER of green space (—●—), blue space level 2 (—●—) and blue space level 3 (—●—) in buffer areas of 50 m (dotted line), 100 m (dashed line), 250 m (solid line) and 500 m (dotdash line) around the residential and school area. Four models were fitted: (○) unadjusted (△) adjusted for the effect of ethnicity and school type, (+) adjusted for socio-economic factors which includes parental occupation and area-level deprivation and (×) adjusted for all factors which includes ethnicity, school type, parental occupation and area-level deprivation. All four models were adjusted for age and gender, in the case of EF additionally adjusted for air pollution, and plotted with posterior mean and 95% credible intervals (CI). The vertical line (in grey) is the reference line and significance can be deduced when the 95% CI excludes zero for the EF, and excludes one for the SDQ TDS and HRQoL score.



Supplementary Figure 3. Comparison of different buffer areas to investigate the association between grassland and woodland daily exposure rate (DER), and cognitive development, mental health and overall well-being during adolescence. The association between (a) executive function (EF) score, (b) Strengths and Difficulties Questionnaire (SDQ) total difficulties score (TDS) and (c) KIDSCREEN-10 Questionnaire Health-Related Quality of Life (HRQoL) score with the DER of grassland (●) and woodland (●) in buffer areas of 50 m (dotted line), 100 m (dashed line), 250 m (solid line) and 500 m (dotdash line) around the residential and school area. Four models were fitted: (○) unadjusted (△) adjusted for the effect of ethnicity and school type, (+) adjusted for socio-economic factors which includes parental occupation and area-level deprivation and (×) adjusted for all factors which includes ethnicity, school type, parental occupation and area-level deprivation. All four models were adjusted for age and gender, in the case of EF additionally adjusted for air pollution, and plotted with posterior mean and 95% credible intervals (CI). The vertical line (in grey) is the reference line and significance can be deduced when the 95% CI excludes zero for the EF, and excludes one for the SDQ TDS and HRQoL score.



Supplementary Figure 4. Environmental datasets used to quantify the type of natural environment exposure. (a) Normalised Difference Vegetation Index, (b) combined surface and tidal water body layer, (c) airborne Light Detection and Ranging layer of the Digital Surface Model and (d) buildings map (all images in this figure were restricted to the area of Greater London for visualization purposes).



Supplementary Figure 5. Cross-sectional analysis of the associations between our natural environment type daily exposure rate (DER), and cognitive performance, mental health and overall well-being across London. The association between the (a) executive function (EF) score, (b) Strengths and Difficulties Questionnaire total difficulties score and (c) KIDSCREEN-10 Questionnaire Health-Related Quality of Life score with the natural environment type DER of Model I: natural space (●), Model II: green space (●), blue space level 3 (●), and Model III: grassland (●) and woodland (●). We only represented blue space level 3 in this figure. Four models were fitted: (○) unadjusted (△) adjusted for the effect of ethnicity and school type, (+) adjusted for socio-economic factors which includes parental occupation and area-level deprivation and (×) adjusted for all factors which includes ethnicity, school type, parental occupation and area-level deprivation. All four models were adjusted for age and gender, plotted with 95% credible intervals (CI), and models with EF as the outcome were additionally adjusted for air pollution. The vertical line (in grey) is the reference line and is set to zero or one depending on the probability distribution used in each model (Supplementary Methods 2). Hollow plus or minus sign indicated whether the association had a positive or negative contribution towards high cognitive performance / good mental health vs. low cognitive performance / poor mental health.

Supplementary Table 1. Median (Q1, Q3) and Pearson's correlation coefficient between estimates of natural environment daily exposure rate (DER).

			Natural space DER	Green space DER	Blue space DER				
	n	Median (Q1, Q3)			Level 1 (ref)	Level 2	Level 3	Grassland DER	Woodland DER
Natural space DER	3,563	0.53 (0.37, 0.67)	1	0.99	-	-	-	0.94	0.63
Green space DER	3,563	0.53 (0.36, 0.67)		1	-	-	-	0.95	0.64
Blue space DER									
Level 1 (ref)	2,383	-			1	-	-	-	-
Level 2	473	-				1	-	-	-
Level 3	707	-					1	-	-
Grassland DER	3,367	0.38 (0.25, 0.49)						1	0.38
Woodland DER	3,367	0.06 (0.04, 0.11)							1

Supplementary Table 2. Comparison of fully adjusted models with the executive function (EF) score and natural environment type daily exposure rate (DER) based on daytime (12 hrs) or full day (24 hrs) weighting. We applied a different weighting on the proportionate presence of each natural environment type DER based on daytime (12 hrs) and a full day (24 hrs). We fully adjusted all models for age, air pollution, area-level deprivation, ethnicity, gender, parental occupation and school type. Model I (M I) contained natural space DER, Model II (M II) contained green and blue space DER and Model III (M III) contained grassland and woodland DER. Significance was indicated with an asterisk (*) and can be deduced when the 95% credible interval (CI) excluded zero for these models. Qn1, Qn2, Qn3, Qn4 and Qn5 represented the first, second, third, fourth and fifth quintiles of the Carstairs deprivation index, respectively; occ=occupations; emp=employers.

	Daytime weighting (12 hrs)			Full day weighting (24 hrs)		
	M I: Posterior mean (95% CI)	M II: Posterior mean (95% CI)	M III: Posterior mean (95% CI)	M I: Posterior mean (95% CI)	MII: Posterior mean (95% CI)	M III: Posterior mean (95% CI)
α (intercept)	0.33 (0.27, 0.39)*	0.35 (0.29, 0.41)*	0.31 (0.25, 0.37)*	0.27 (0.21, 0.33)*	0.29 (0.23, 0.35)*	0.25 (0.19, 0.31)*
Natural space DER	0.03 (0.006, 0.06)*	-	-	0.02 (-0.001, 0.04)	-	-
Green space DER	-	0.03 (0.01, 0.06)*	-	-	0.02 (0.01, 0.04)*	-
Blue space DER						
Level 1 (ref)	-	0 (ref)	-	-	0 (ref)	-
Level 2	-	-0.03 (-0.08, 0.02)	-	-	-0.04 (-0.10, 0.01)	-
Level 3	-	-0.04 (-0.09, 0.01)	-	-	-0.02 (-0.07, 0.01)	-
Grassland DER	-	-	-0.01 (-0.03, 0.02)	-	-	0.01 (-0.02, 0.02)
Woodland DER	-	-	0.06 (0.03, 0.08)*	-	-	0.04 (0.02, 0.06)*
Parental occupation						
Managerial/professional occ.	0 (ref)	0 (ref)	0 (ref)	0 (ref)	0 (ref)	0 (ref)
Intermediate occ.	0.01 (-0.04, 0.06)	0.01 (-0.04, 0.06)	0.01 (-0.04, 0.06)	0.03 (-0.02, 0.08)	0.02 (-0.02, 0.08)	0.03 (-0.02, 0.08)
Small emp./own-account workers	-0.01 (-0.05, 0.03)	-0.01 (-0.05, 0.03)	-0.01 (-0.05, 0.04)	-0.01 (-0.06, 0.03)	-0.01 (-0.05, 0.03)	-0.01 (-0.05, 0.03)
Lower supervisory/technical occ.	-0.09 (-0.16, -0.01)*	-0.09 (-0.10, -0.01)*	-0.08 (-0.16, -0.01)*	-0.07 (-0.15, -0.01)*	-0.07 (-0.15, -0.01)*	-0.07 (-0.15, -0.01)*
Semi-routine/routine occ.	-0.03 (-0.08, 0.02)	-0.03 (-0.08, 0.02)	-0.02 (-0.08, 0.02)	-0.01 (-0.05, 0.04)	-0.01 (-0.05, 0.04)	-0.01 (-0.05, 0.04)
Area-level deprivation						
Least deprived (Qn1)	0 (ref)	0 (ref)	0 (ref)	0 (ref)	0 (ref)	0 (ref)
Qn2	0.05 (-0.01, 0.11)	0.05 (-0.01, 0.11)	0.04 (-0.01, 0.11)	0.04 (-0.01, 0.10)	0.04 (-0.01, 0.10)	0.04 (-0.02, 0.10)
Qn3	0.03 (-0.03, 0.09)	0.03 (-0.03, 0.09)	0.02 (-0.04, 0.08)	0.01 (-0.05, 0.08)	0.01 (-0.04, 0.08)	0.01 (-0.05, 0.08)
Qn4	-0.01 (-0.07, 0.05)	-0.01 (-0.07, 0.05)	-0.01 (-0.07, 0.05)	-0.02 (-0.09, 0.04)	-0.02 (-0.09, 0.04)	-0.02 (-0.09, 0.04)
Most deprived (Qn5)	-0.03 (-0.10, 0.04)	-0.02 (-0.10, 0.04)	-0.02 (-0.09, 0.04)	-0.04 (-0.12, 0.02)	-0.04 (-0.11, 0.02)	-0.03 (-0.10, 0.03)
Gender						
Male	0 (ref)	0 (ref)	0 (ref)	0 (ref)	0 (ref)	0 (ref)
Female	0.15 (0.11, 0.19)*	0.15 (0.11, 0.19)*	0.16 (0.12, 0.19)*	0.14 (0.11, 0.18)*	0.14 (0.10, 0.18)*	0.15 (0.11, 0.19)*
Age	0.02 (0.01, 0.04)*	0.02 (0.01, 0.04)*	0.02 (0.01, 0.04)*	0.02 (0.01, 0.04)*	0.02 (0.01, 0.04)*	0.02 (0.01, 0.04)*
NO_2 DER	0.03 (0.01, 0.06)*	0.03 (0.01, 0.06)*	0.01 (-0.01, 0.04)	0.005 (0.004, 0.01)*	0.005 (0.004, 0.01)*	0.005 (0.004, 0.01)*
Ethnicity						
White	0 (ref)	0 (ref)	0 (ref)	0 (ref)	0 (ref)	0 (ref)
Black	-0.15 (-0.21, -0.09)*	-0.15 (-0.21, -0.09)*	-0.15 (-0.21, -0.09)*	-0.15 (-0.21, -0.09)*	-0.15 (-0.21, -0.09)*	-0.15 (-0.21, -0.09)*
Asian	0.07 (0.02, 0.12)*	0.06 (0.02, 0.11)*	0.06 (0.01, 0.11)*	0.06 (0.02, 0.11)*	0.06 (0.01, 0.11)*	0.06 (0.01, 0.11)*
Mixed	0.01 (-0.04, 0.08)	0.01 (-0.04, 0.08)	0.01 (-0.05, 0.07)	0.01 (-0.04, 0.08)	0.01 (-0.04, 0.08)	0.01 (-0.05, 0.07)

Other	-0.12 (-0.32, 0.08)	-0.12 (-0.32, 0.08)	-0.11 (-0.31, 0.08)	-0.11 (-0.32, 0.08)	-0.11 (-0.32, 0.08)	-0.12 (-0.32, 0.08)
School type						
Independent	0 (ref)	0 (ref)	0 (ref)	0 (ref)	0 (ref)	0 (ref)
State	-0.32 (-0.38, -0.27)*	-0.33 (-0.38, -0.28)*	-0.30 (-0.35, -0.25)*	-0.35 (-0.40, -0.30)*	-0.36 (-0.41, -0.31)*	-0.32 (-0.38, -0.27)*

Supplementary Table 3. Comparison of fully adjusted models with Strengths and Difficulties Questionnaire (SDQ) total difficulties score (TDS) and natural environment type daily exposure rate (DER) based on daytime (12 hrs) or full day (24 hrs) weighting. We applied a different weighting on the proportionate presence of each natural environment type DER based on daytime (12 hrs) and a full day (24 hrs). We fully adjusted all models for age, area-level deprivation, ethnicity, gender, parental occupation and school type. Model I (M I) contained natural space DER, Model II (M II) contained green and blue space DER and Model III (M III) contained grassland and woodland DER. Significance was indicated with an asterisk (*) and can be deduced when the 95% credible interval (CI) excluded one for these models. Qn1, Qn2, Qn3, Qn4 and Qn5 represented the first, second, third, fourth and fifth quintiles of the Carstairs deprivation index, respectively; occ=occupations; emp=employers.

	Daytime weighting (12 hrs)			Full day weighting (24 hrs)		
	M I: Posterior mean (95% CI)	M II: Posterior mean (95% CI)	M III: Posterior mean (95% CI)	M I: Posterior mean (95% CI)	M II: Posterior mean (95% CI)	M III: Posterior mean (95% CI)
α (intercept)	8.44 (8.01, 8.87)*	8.33 (7.89, 8.79)*	8.51 (8.09, 8.95)*	8.48 (8.04, 8.94)*	8.38 (7.92, 8.85)*	8.54 (8.10, 9)*
Natural space DER	0.98 (0.96, 1.01)	-	-	0.98 (0.96, 1.01)	-	-
Green space DER	-	0.98 (0.96, 1.01)	-	-	0.98 (0.96, 1.01)	-
Blue space DER						
Level 1 (ref)	-	1 (ref)	-	-	1 (ref)	-
Level 2	-	1.03 (0.98, 1.08)	-	-	1.01 (0.96, 1.06)	-
Level 3	-	1.02 (0.97, 1.06)	-	-	1.03 (0.99, 1.07)	-
Grassland DER	-	-	1 (0.98, 1.02)	-	-	0.99 (0.97, 1.01)
Woodland DER	-	-	0.97 (0.95, 0.99)*	-	-	0.97 (0.95, 0.99)*
Parental occupation						
Managerial/professional occ.	1 (ref)	1 (ref)	1 (ref)	1 (ref)	1 (ref)	1 (ref)
Intermediate occ.	0.93 (0.89, 0.98)*	0.93 (0.89, 0.98)*	0.93 (0.88, 0.98)*	0.93 (0.89, 0.98)	0.93 (0.89, 0.98)*	0.93 (0.88, 0.98)*
Small emp./own-account workers	0.99 (0.95, 1.03)	0.99 (0.95, 1.03)	0.99 (0.95, 1.03)	0.99 (0.95, 1.03)	0.99 (0.95, 1.03)	0.99 (0.95, 1.03)
Lower supervisory/technical occ.	1 (0.93, 1.07)	1 (0.93, 1.07)	0.99 (0.92, 1.06)	1.01 (0.93, 1.07)	1.01 (0.93, 1.07)	0.99 (0.93, 1.07)
Semi-routine/routine occ.	0.98 (0.93, 1.02)	0.98 (0.93, 1.02)	0.97 (0.93, 1.02)	0.98 (0.93, 1.03)	0.98 (0.93, 1.02)	0.98 (0.93, 1.02)
Area-level deprivation						
Least deprived (Qn1)	1 (ref)	1 (ref)	1 (ref)	1 (ref)	1 (ref)	1 (ref)
Qn2	0.99 (0.94, 1.05)	0.99 (0.94, 1.05)	1.01 (0.94, 1.06)	0.99 (0.93, 1.05)	0.99 (0.94, 1.05)	0.99 (0.94, 1.05)
Qn3	1.03 (0.97, 1.09)	1.02 (0.96, 1.09)	1.03 (0.97, 1.09)	1.02 (0.96, 1.08)	1.02 (0.96, 1.08)	1.02 (0.96, 1.09)
Qn4	1.02 (0.96, 1.08)	1.02 (0.95, 1.08)	1.02 (0.96, 1.08)	1.01 (0.95, 1.08)	1.01 (0.95, 1.08)	1.01 (0.95, 1.08)
Most deprived (Qn5)	1.01 (0.94, 1.07)	1.01 (0.94, 1.07)	1.01 (0.94, 1.07)	1.01 (0.93, 1.07)	1.01 (0.93, 1.07)	1.01 (0.93, 1.07)
Gender						
Male	1 (ref)	1 (ref)	1 (ref)	1 (ref)	1 (ref)	1 (ref)
Female	1.05 (1.02, 1.09)*	1.05 (1.02, 1.09)*	1.05 (1.02, 1.09)*	1.05 (1.02, 1.09)*	1.05 (1.02, 1.09)*	1.05 (1.02, 1.09)*
Age	1.01 (0.99, 1.02)	1.01 (0.99, 1.02)	1.01 (0.99, 1.02)	1.01 (0.99, 1.02)	1.01 (0.99, 1.02)*	1.01 (0.99, 1.02)
Ethnicity						
White	1 (ref)	1 (ref)	1 (ref)	1 (ref)	1 (ref)	1 (ref)
Black	1.02 (0.97, 1.08)	1.02 (0.97, 1.08)	1.02 (0.97, 1.08)	1.02 (0.97, 1.08)	1.02 (0.97, 1.08)	1.02 (0.97, 1.08)
Asian	0.91 (0.87, 0.95)*	0.91 (0.87, 0.95)*	0.91 (0.88, 0.96)*	0.91 (0.87, 0.95)*	0.91 (0.87, 0.95)*	0.91 (0.87, 0.95)*
Mixed	1.02 (0.97, 1.08)	1.02 (0.97, 1.08)	1.03 (0.97, 1.09)	1.02 (0.97, 1.08)	1.02 (0.97, 1.08)	1.03 (0.97, 1.09)
Other	1.14 (0.96, 1.35)	1.14 (0.96, 1.35)	1.14 (0.96, 1.35)	1.14 (0.96, 1.35)	1.14 (0.96, 1.35)	1.14 (0.96, 1.35)

School type						
Independent	1 (ref)	1 (ref)	1 (ref)	1 (ref)	1 (ref)	1 (ref)
State	1.10 (1.05, 1.15)*	1.11 (1.06, 1.16)*	1.09 (1.04, 1.14)*	1.10 (1.05, 1.15)*	1.10 (1.05, 1.15)*	1.09 (1.04, 1.14)*

Supplementary Table 4. Comparison of fully adjusted models with KIDSCREEN-10 Questionnaire Health-Related Quality of Life (HRQoL) score and natural environment type daily exposure rate (DER) based on daytime (12 hrs) or full day (24 hrs) weighting. We applied a different weighting on the proportionate presence of each natural environment type DER based on daytime (12 hrs) and a full day (24 hrs). We fully adjusted all models for age, area-level deprivation, ethnicity, gender, parental occupation and school type. Model I (M I) contained natural space DER, Model II (M II) contained green and blue space DER and Model III (M III) contained grassland and woodland DER. Significance was indicated with an asterisk (*) and can be deduced when the 95% credible interval (CI) excluded one for these models. Qn1, Qn2, Qn3, Qn4 and Qn5 represented the first, second, third, fourth and fifth quintiles of the Carstairs deprivation index, respectively; occ=occupations; emp=employers.

	Daytime weighting (12 hrs)			Full day weighting (24 hrs)		
	M I: Posterior mean (95% CI)	M II: Posterior mean (95% CI)	M III: Posterior mean (95% CI)	M I: Posterior mean (95% CI)	M II: Posterior mean (95% CI)	M III: Posterior mean (95% CI)
α (intercept)	0.02 (0.01, 0.04)*	0.02 (0.01, 0.04)*	0.02 (0.01, 0.03)*	0.03 (0.01, 0.04)*	0.02 (0.01, 0.04)*	0.02 (0.01, 0.03)*
Natural space DER	0.93 (0.83, 1.04)	-	-	0.93 (0.83, 1.05)	-	-
Green space DER	-	0.92 (0.82, 1.03)	-	-	0.93 (0.82, 1.04)	-
Blue space DER						
Level 1 (ref)	-	1 (ref)	-	-	1 (ref)	-
Level 2	-	1.11 (0.82, 1.46)	-	-	1.11 (0.83, 1.44)	-
Level 3	-	0.98 (0.76, 1.24)	-	-	0.98 (0.74, 1.25)	-
Grassland DER	-	-	0.88 (0.78, 0.99)*	-	-	0.88 (0.78, 0.99)*
Woodland DER	-	-	1.08 (0.95, 1.21)	-	-	1.10 (0.97, 1.24)
Parental occupation						
Managerial/professional occ.	1 (ref)	1 (ref)	1 (ref)	1 (ref)	1 (ref)	1 (ref)
Intermediate occ.	0.83 (0.56, 1.17)	0.83 (0.56, 1.17)	0.84 (0.56, 1.18)	0.83 (0.56, 1.17)	0.83 (0.56, 1.17)	0.84 (0.56, 1.18)
Small emp./own-account workers	0.99 (0.75, 1.29)	0.99 (0.75, 1.29)	1.01 (0.75, 1.30)	1.01 (0.75, 1.29)	1.01 (0.75, 1.29)	1.01 (0.76, 1.31)
Lower supervisory/technical occ.	1.42 (0.90, 2.10)	1.43 (0.90, 2.11)	1.44 (0.91, 2.13)	1.43 (0.90, 2.11)	1.43 (0.90, 2.11)	1.44 (0.91, 2.13)
Semi-routine/routine occ.	0.95 (0.67, 1.30)	0.95 (0.67, 1.30)	0.96 (0.68, 1.31)	0.96 (0.68, 1.30)	0.96 (0.67, 1.30)	0.97 (0.68, 1.32)
Area-level deprivation						
Least deprived (Qn1)	1 (ref)	1 (ref)	1 (ref)	1 (ref)	1 (ref)	1 (ref)
Qn2	1.17 (0.80, 1.65)	1.16 (0.80, 1.64)	1.16 (0.80, 1.63)	1.16 (0.80, 1.64)	1.15 (0.79, 1.63)	1.16 (0.80, 1.63)
Qn3	0.99 (0.67, 1.41)	0.98 (0.66, 1.40)	0.98 (0.66, 1.39)	0.98 (0.66, 1.41)	0.97 (0.65, 1.39)	0.99 (0.67, 1.41)
Qn4	0.91 (0.61, 1.31)	0.90 (0.60, 1.30)	0.91 (0.61, 1.31)	0.91 (0.60, 1.31)	0.90 (0.59, 1.30)	0.93 (0.62, 1.33)
Most deprived (Qn5)	1.06 (0.69, 1.55)	1.04 (0.69, 1.53)	1.06 (0.70, 1.55)	1.06 (0.69, 1.56)	1.05 (0.68, 1.54)	1.10 (0.72, 1.61)
Gender						
Male	1 (ref)	1 (ref)	1 (ref)	1 (ref)	1 (ref)	1 (ref)
Female	1.95 (1.59, 2.38)*	1.96 (1.59, 2.39)*	1.98 (1.61, 2.42)*	1.95 (1.59, 2.38)*	1.95 (1.59, 2.39)*	1.97 (1.60 ,2.40)*
Age	1.09 (0.99, 1.20)	1.09 (0.99, 1.20)	1.08 (0.98, 1.19)	1.10 (1, 1.20)*	1.10 (1, 1.21)*	1.09 (0.99, 1.19)
Ethnicity						
White	1 (ref)	1 (ref)	1 (ref)	1 (ref)	1 (ref)	1 (ref)
Black	1.68 (1.24, 2.21)*	1.67 (1.24, 2.21)*	1.68 (1.24, 2.21)*	1.68 (1.24, 2.21)*	1.67 (1.24, 2.20)*	1.68 (1.24, 2.22)*
Asian	0.88 (0.67, 1.13)	0.88 (0.67, 1.13)	0.86 (0.66, 1.10)	0.88 (0.67, 1.13)	0.88 (0.67, 1.13)	0.87 (0.66, 1.11)
Mixed	1.81 (1.33, 2.40)*	1.81 (1.33, 2.40)*	1.78 (1.31, 2.36)*	1.81 (1.33, 2.40)*	1.81 (1.33, 2.39)*	1.78 (1.31, 2.35)*
Other	2.63 (1.06, 5.23)*	2.65 (1.07, 5.27)*	2.63 (1.07, 5.23)*	2.62 (1.06, 5.20)*	2.64 (1.06, 5.26)*	2.63 (1.06, 5.23)*

School type						
Independent	1 (ref)	1 (ref)	1 (ref)	1 (ref)	1 (ref)	1 (ref)
State	1.57 (1.19, 2.04)*	1.60 (1.21, 2.09)*	1.71 (1.28, 2.24)*	1.56 (1.18, 2.03)*	1.60 (1.20, 2.09)*	1.69 (1.27, 2.22)*

Supplementary Table 5. Contribution of demographic, environmental and socio-economic factor groups based on the difference in pseudo R-squared between the full fixed-effects only Model I (M I) and M I excluding each factor group. The full fixed-effect only M I included environmental (i.e. natural space daily exposure rate [DER] and air pollution), demographic (i.e. gender, age and ethnicity) and socio-economic variables (parental occupation, area-level deprivation and school type). Mean pseudo R-squared was calculated by dividing the mean squared error between predicted and observed values by the variance of the observed values for each fold in a 10-fold cross validation. Standard error (SE) of the mean pseudo R-squared was calculated by dividing the standard deviation by the square root of the number of measurements. We did not calculate a pseudo R-squared for the Health-Related Quality of Life score because the observed value is binomial, making it impossible to measure a pseudo R-squared.

	Pseudo R-squared	Difference
Executive function score	Mean (SE)	
Full fixed-effects only model	0.102 (0.006)	-
- Environmental variables	0.101 (0.006)	0.001
- Demographic variables	0.08 (0.004)	0.022
- Socio-economic variables	0.062 (0.004)	0.04
SDQ total difficulties score		
Full fixed-effects only model	0.019 (0.003)	-
- Environmental variables	0.018 (0.003)	0.001
- Demographic variables	0.01 (0.002)	0.009
- Socio-economic variables	0.01 (0.001)	0.008

Supplementary Table 6. Cohort characteristics during the first (t_0) and second (t_1) school visit. Data from t_0 and t_1 were based on participants who took part in the computer-based assessment. This study used a subset of adolescents (*n* = 3,568) who had a known residence address during t_0 and t_1 (Table 1). Parental occupation is based on the highest National Statistics Socio-economic Classification (NS-SEC) level (five-group version) of either parent. Qn1, Qn2, Qn3, Qn4 and Qn5 of area-level deprivation represented the first, second, third, fourth and fifth quintile of the Carstairs deprivation index, respectively.

	First school visit		Second school visit	
	n = 6,612		*n* = 5,208	
	Median	IQR	Median	IQR
Age (years)	12.06	11.78-12.33	14.21	13.92-14.56
Parental occupation	*n*	%	*n*	%
Managerial/professional occupations	3270	49.45	2788	53.53
Intermediate occupations	484	7.32	283	5.43
Small employers/own-account workers	908	13.73	752	14.43
Lower supervisory/technical occupations	272	4.11	190	3.64
Semi-routine/routine occupations	693	10.48	397	7.62
Missing/not interpretable	985	14.89	798	15.32
Area-level deprivation				
Least deprived (Qn1)	919	13.89	821	15.76
Qn2	944	14.27	810	15.55
Qn3	1122	16.96	873	16.76
Qn4	1389	21	1050	20.16
Most deprived (Qn5)	2024	30.61	1495	28.70
Missing	214	3.23	159	3.05
Gender				
Female	3468	52.45	2823	54.20
Male	3144	47.54	2385	45.79
Ethnicity				
White	2719	41.12	2265	43.49
Black	980	14.82	739	14.18
Asian	1715	25.93	1354	25.99
Mixed	712	10.76	498	9.56
Other/not interpretable	54	0.81	28	0.53
Missing	432	6.53	324	6.22
Type of school				
State	5177	78.29	3918	75.23
Independent	1435	21.70	1290	24.76

Supplementary Table 7. Median (Q1, Q3) and Pearson's correlation coefficient between estimates of air pollution daily exposure rate (DER).

	n	Median (Q1, Q3)	NO_2 DER	NO_x DER	PM_{10} DER	$PM_{2.5}$ DER
NO_2 DER	3,305	35.67 (33.56, 38.26)	1	0.98	0.95	0.98
NO_x DER	3,305	63.44 (57.57, 70.48)		1	0.96	0.96
PM_{10} DER	3,305	6.93 (5.91, 8.11)			1	0.95
$PM_{2.5}$ DER	3,305	13.17 (12.85, 13.50)				1

Supplementary Table 8. Cross validation results testing different models for the executive function (EF) score. We tested Gaussian models with different random effect (RE) structures between the EF score and natural space daily exposure rate during adolescence. We used model-selection criteria to identify the best model, i.e. the Deviance Information Criterion (DIC), the Log-Pseudo Marginal Likelihood (LPML) and the pseudo R-squared from 10-fold cross validation where a lower DIC and a higher LPML and pseudo-R squared better support the data. We added penalized complexity priors to models with an asterisk (*) because the precision of the model hyperparameters was far too high with the default prior[1]. We used the standard deviation of the residuals of the fixed effects only model to specify a scale for the standard deviation of the random effects.

	Unadjusted	Adjusted for ethnicity and school type	Adjusted for socio-economic status	Adjusted for all
DIC				
No RE	12247	11900	12150	11894
RE for adolescent id	9579	9479	9567	9481
RE for school type	11958	11900	11952	11894
RE for school id	11785	11740	11792	11748
RE for adolescent id and school id	9497	9469	9501	9474
RE for time of visit	12118	11771	12020	11763
*RE for adolescent id and time of visit (2-level nested model)	6509	6451	6509	6453
*RE for school id, adolescent id, time of visit (3-level nested model)	6375	-1927	6363	-36204
LPML				
No RE	-6123	-5950	-6075	-5947
RE for adolescent id	-5157	-5075	-5142	-5076
RE for school type	-5979	-5950	-5976	-5947
RE for school id	-5892	-5870	-5896	-5874
RE for adolescent id and school id	-5070	-5052	-5074	-5056
RE for time of visit	-6059	-5885	-6010	-5881
*RE for adolescent id and time of visit (2-level nested model)	-5156	-5075	-5141	-5076
*RE for school id, adolescent id, time of visit (3-level nested model)	-5070	-5021	-5073	12822
Pseudo R-squared from 10-fold cross validation				
No RE	0.21	0.31	0.25	0.31
RE for adolescent id	0.89	0.88	0.89	0.88
RE for school type	0.29	0.31	0.30	0.31
RE for school id	0.35	0.36	0.35	0.36
RE for adolescent id and school id	0.88	0.88	0.88	0.88
RE for time of visit	0.25	0.34	0.29	0.35
*RE for adolescent id and time of visit (2-level nested model)	0.98	0.98	0.98	0.98
*RE for school id, adolescent id, time of visit (3-level nested model)	0.98	0.99	0.98	1

Supplementary Table 9. Cross validation results testing different models for the Strengths and Difficulties Questionnaire (SDQ) total difficulties score. We tested Poisson models with different random effect (RE) structures between the SDQ total difficulties score and natural space daily exposure rate during adolescence. We used model-selection criteria to identify the best model, i.e. the Deviance Information Criterion (DIC), the Log-Pseudo Marginal Likelihood (LPML) and the pseudo R-squared from 10-fold cross validation where a lower DIC and a higher LPML and pseudo-R squared better support the data.

	Unadjusted	Adjusted for ethnicity and school type	Adjusted for socio-economic status	Adjusted for all
DIC				
No RE	43009	42765	42948	42748
RE for adolescent id	35036	35033	35041	35035
RE for school type	42884	42764	42865	42748
RE for school id	42527	42462	42522	42456
RE for adolescent id and school id	35026	35025	35027	35026
RE for time of visit	42795	42542	42735	42530
RE for adolescent id and time of visit (2-level nested model)	34555	34550	34559	34553
RE for school id, adolescent id, time of visit (3-level nested model)	34542	34541	34545	34543
LPML				
No RE	-21509	-21391	-21486	-21390
RE for adolescent id	-18439	-18431	-18445	-18435
RE for school type	-21447	-21391	-21445	-21390
RE for school id	-21294	-21264	-21299	-21269
RE for adolescent id and school id	-18424	-18421	-18428	-18424
RE for time of visit	-21402	-21281	-21380	-21282
RE for adolescent id and time of visit (2-level nested model)	-18213	-18203	-18218	-18208
RE for school id, adolescent id, time of visit (3-level nested model)	-18195	-18192	-18200	-18196
Pseudo R-squared from 10-fold cross validation				
No RE	0.05	0.13	0.08	0.13
RE for adolescent id	0.87	0.87	0.87	0.87
RE for school type	0.09	0.13	0.11	0.14
RE for school id	0.18	0.19	0.18	0.20
RE for adolescent id and school id	0.87	0.87	0.87	0.87
RE for time of visit	0.12	0.17	0.13	0.17
RE for adolescent id and time of visit (2-level nested model)	0.96	0.96	0.96	0.96
RE for school id, adolescent id, time of visit (3-level nested model)	0.96	0.96	0.96	0.96

Supplementary Table 10. Cross validation results testing different models for the KIDSCREEN-10 Questionnaire Health-Related Quality of Life (HRQoL) score. We tested Binomial models with different random effect (RE) structures between the HRQoL score and natural space daily exposure rate during adolescence. We used model-selection criteria to identify the best model, i.e. the Deviance Information Criterion (DIC) and the Log-Pseudo Marginal Likelihood (LPML) where a lower DIC and a higher LPML better support the data. We did not use 10-fold cross validation because the observed value is binomial, making it impossible to calculate a pseudo R-squared. We added informative gamma priors to models with an asterisk (*) because the precision of model parameters was far too high with the default prior. We set the mean value of the gamma prior to the inverse of the variance of the residuals of the fixed-effects only model.

	Unadjusted	Adjusted for ethnicity and school type	Adjusted for socio-economic status	Adjusted for all
DIC				
No RE	4013	3970	4018	3980
RE for adolescent id	3843	3805	3840	3807
*RE for school type	3996	3970	4006	3979
*RE for school id	4004	3971	4013	3980
*RE for adolescent id and school id	3819	3789	3820	3790
*RE for time of visit	4015	3971	4020	3981
*RE for adolescent id and time of visit (2-level nested model)	3823	3787	3820	3788
*RE for school id, adolescent id, time of visit (3-level nested model)	3811	3777	3819	3788
LPML				
No RE	-2006	-1985	-2009	-1990
RE for adolescent id	-1934	-1916	-1933	-1919
*RE for school type	-1998	-1985	-2003	-1990
*RE for school id	-2002	-1985	-2006	-1990
*RE for adolescent id and school id	-1922	-1906	-1923	-1909
*RE for time of visit	-2007	-1985	-2010	-1990
*RE for adolescent id and time of visit (2-level nested model)	-1924	-1906	-1925	-1909
*RE for school id, adolescent id, time of visit (3-level nested model)	-1920	-1904	-1924	-1909

Supplementary Table 11. Results of the Moran's I test to test for spatial autocorrelation in our longitudinal models. We tested for spatial autocorrelation in our fully adjusted longitudinal models with (a) executive function (EF) score, (b) Strengths and Difficulties Questionnaire (SDQ) total difficulties score and (c) KIDSCREEN-10 Questionnaire Health-Related Quality of Life (HRQoL) score. Fully adjusted models were adjusted for all factors which includes age, area-level deprivation, ethnicity, gender, parental occupation and school type, and in the case of the EF score additionally adjusted for air pollution. Fully adjusted models included a random effect term for adolescent identifier to allow for between-adolescent variance, while we used a random effect term for tests at the time of visit (two levels: first or second visit) for each adolescent to introduce correlation among the repeated measurements If the p-value was statistically significant (< 0.05), it indicated that the data is more spatially clustered than would be expected if spatial processes were random. If the p-value was not statistically significant (> 0.05), it indicated that the spatial distribution of the data is the result of random spatial processes. P-value significance was indicated with an asterisk (*).

	Moran I test statistic	P-value
a	0.002	0.052
b	0.001	0.135
c	0.0009	0.351

Supplementary Information references

1. Simpson, D., Rue, H., Martins, T. G., Riebler, A. & Sørbye, S. H. Penalising model component complexity: A principled, practical approach to constructing priors. *Stat. Sci.* **32**, 1–28 (2017).
2. Blangiardo, M., Pirani, M., Kanapka, L., Hansell, A. & Fuller, G. A hierarchical modelling approach to assess multi pollutant effects in time-series studies. *PLoS One* **14**, e0212565 (2019).