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# Availability, accessibility, and use of green spaces and cognitive development in primary school children☆

Amanda Fernandes[a,b,c,*], Norun Hjertager Krog[d], Rosemary McEachan[e], Mark Nieuwenhuijsen[a,b,c], Jordi Julvez[a,b,c,f], Sandra Márquez[a,b,c], Montserrat de Castro[a,b,c], José Urquiza[a,b,c], Barbara Heude[g], Marina Vafeiadi[h], Regina Gražulevičienė[i], Rémy Slama[j], Audrius Dedele[i], Gunn Marit Aasvang[d], Jorunn Evandt[d], Sandra Andrusaityte[i], Mariza Kampouri[h], Martine Vrijheid[a,b,c]

[a] ISGlobal, Barcelona Institute for Global Health, Barcelona, Spain
[b] Universitat Pompeu Fabra (UPF), Barcelona, Spain
[c] CIBER Epidemiología y Salud Pública (CIBERESP), Madrid, Spain
[d] Department of Air Quality and Noise, Norwegian Institute of Public Health, Oslo, Norway
[e] Bradford Institute for Health Research, Bradford Teaching Hospitals NHS Foundation Trust, Bradford Royal Infirmary, Bradford, UK
[f] Clinical and Epidemiological Neuroscience (NeuroÈpia), Institut d'Investigació Sanitària Pere Virgili (IISPV), Reus, Tarragona, Spain
[g] Université Paris Cité and Université Sorbonne Paris Nord, Inserm, INRAE, Center for Research in Epidemiology and StatisticS (CRESS), F-75004, Paris, France
[h] Department of Social Medicine, School of Medicine, University of Crete, Greece
[i] Department of Environmental Sciences, Vytautas Magnus University, Kaunas, Lithuania
[j] Institut National de la Santé et de la Recherche Médicale (Inserm) and Université Grenoble-Alpes, Institute for Advanced Biosciences (IAB), Team of Environmental Epidemiology Applied to Reproduction and Respiratory Health, Grenoble, France

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ABSTRACT

Green spaces may have beneficial impacts on children's cognition. However, few studies explored the exposure to green spaces beyond residential areas, and their availability, accessibility and uses at the same time. The aim of the present study was to describe patterns of availability, accessibility, and uses of green spaces among primary school children and to explore how these exposure dimensions are associated with cognitive development. Exposures to green space near home, school, commuting route, and other daily activity locations were assessed for 1607 children aged 6–11 years from six birth cohorts across Europe, and included variables related to: availability (NDVI buffers: 100, 300, 500 m), potential accessibility (proximity to a major green space: linear distance; within 300 m), and use (play time in green spaces: hours/year), and the number of visits to green spaces (times/previous week). Cognition measured as fluid intelligence, inattention, and working memory was assessed by computerized tests. We performed multiple linear regression analyses on pooled and imputed data adjusted for individual and area-level confounders. Availability, accessibility, and uses of green spaces showed a social gradient that was unfavorable in more vulnerable socioeconomic groups. NDVI was associated with more playing time in green spaces, but proximity to a major green space was not. Associations between green space exposures and cognitive function outcomes were not statistically significant in our overall study population. Stratification by socioeconomic variables showed that living within 300 m of a major green space was associated with improved working memory only in children in less deprived residential areas (β = 0.30, CI: 0.09,0.51), and that more time playing in green spaces was associated with better working memory only in children of highly educated mothers (β per IQR increase in hour/year = 0.10; 95% CI: 0.01, 0.19). However, studying within 300 m of a major green space increased inattention scores in children in more deprived areas (β = 15.45, 95% CI: 3.50, 27.40).

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* Corresponding author. ISGlobal, Barcelona Institute for Global Health, Barcelona, Spain Barcelona Biomedical Research Park (PRBB). Doctor Aiguader, 88 08003, Barcelona, Spain.

*E-mail address:* amanda.fernandes@isglobal.org (A. Fernandes).

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## 1. Introduction

Globally, cities are becoming denser, greyer, more polluted, and noisier, and access and exposure to green spaces are diminishing with urbanization (Gascon et al., 2016). Children are particularly vulnerable to environmental hazards, which can impact brain development during important stages of growth from birth to adolescence (Anderson, 2002; Zani et al., 2015). Green spaces may be a key resource to mitigate these urban insults and foster children's health, especially in disadvantaged neighborhoods. People living in deprived areas with lower socioeconomic status have been shown to benefit more from green spaces' health effects, however, the evidence is mixed (Marselle et al., 2020; Ward Thompson et al., 2016) and equal access remains a challenge also across European cities (Barboza et al., 2021).

Green spaces are areas covered by vegetation such as parks, community gardens, street-level trees, and forests (Markevych et al., 2017). Plausible pathways linking green space exposure to children's cognition function involve psychological, behavior, and environmental mechanisms (Markevych et al., 2017; World Health Organization. Regional Office for Europe, 2016). Possible pathways lie in greener environments inducing a short-term restful experience stimulating relaxation and physiological restoration. For instance, lifelong residential greenness was associated with better attention in children during preschool and early primary school years (Dadvand et al., 2017), and higher total intelligence quotient in a longitudinal study with twins (Bijnens et al., 2020). In the same direction, spending more time in green spaces during school hours enhanced cognition performance potentially by attention restoration effects of green spaces (Amicone et al., 2018; van Dijk-Wesselius et al., 2018).

Also, living or studying nearby green spaces may improve playtime and physical activity opportunities, which are associated with brain structure changes related to learning and memory (Hillman et al., 2008; van Dijk-Wesselius et al., 2022). Finally, by filtering proinflammatory urban hazards such as air pollutants and noise, green spaces may enhance neurocognition (Forns et al., 2016; Saenen et al., 2023). For example, green space exposure around schools has been shown to have beneficial effects on cognitive development in children which is partially explained by reduced air pollution levels (Dadvand et al., 2015).

Exposure to green spaces can be assessed using different metrics that express different aspects. For instance, the availability of green spaces can be defined as the amount of vegetation within a predefined area. The most common metric to measure availability is the normalized difference vegetation index (NDVI), which estimates surrounding vegetation. On the other hand, the accessibility dimension is usually defined as how easily parks, forests, gardens, and other green areas can be reached from home. Linear or walking distance to green spaces from different daily life locations measures potential accessibility since proximity to green spaces could act as a surrogate for access. Finally, the uses of green spaces can be expressed by the frequency of visits to and time spent in green spaces, usually measured by questionnaires, mapping tools (i.e. google maps), or tracking sensors such as GPS (Labib et al., 2020), which offers a temporal dimension of the exposure. Even though some of these metrics highly correlate, they represent different dimensions of exposure (Labib et al., 2020). A high NDVI, for instance, does not necessarily mean high accessibility (Kwan and Weber, 2003) or consequently more uses of green spaces (Andrusaityte et al., 2020). Short distances to green spaces from home and school may represent only a potential accessibility dimension considering access depends on more than physical distance (i.e., quality, safety, opening hours, etc.). Moreover, it is plausible that different mechanisms might be more linked to specific dimensions of green space exposure (accessibility vs. availability). Most previous studies have concentrated efforts on measures of availability and accessibility of green space, rather than the duration of contact (Labib et al., 2020). Moreover, few studies have explored the exposure beyond residential and school areas (Browning and Locke, 2020; Dadvand et al., 2015) to include other daily life locations (i.e.: home, school and commute route, friend's/relative's house, shops, etc.) (Kwan and Weber, 2003).

The present study aimed to describe patterns of availability, accessibility to, and uses of green spaces among primary school children from six European countries and to explore how these exposure dimensions are associated with their cognitive development. To do so, we assessed the association between availability, accessibility to green spaces around daily activity locations, number of visits to, and time playing in green spaces and children's fluid intelligence (i.e., "the ability to reason quickly, think abstractly, and problem-solve" independent of prior learning or knowledge (Happé, 2013)), inattention, and working memory. We also explored whether or not maternal education and area-level socioeconomic status modified any associations between green spaces and the outcomes.

## 2. Methods

### 2.1. Study population

This study analyzed data of mother-child pairs from the six European birth cohorts of the Human Early-Life Exposome (HELIX) project: BiB (Born in Bradford; United Kingdom), EDEN (Étude des Déterminants pré et postnatals du développement et de la santé de l'ENfant; France), INMA (INfancia y Medio Ambiente; Spain) sub-cohort conducted in Sabadell municipality in Barcelona province, KANC (Kaunas Cohort; Lithuania), MoBa (Norwegian Mother, Father and Child Cohort Study; Norway) and Rhea (The Mother-Child Cohort in Crete, Greece). The project has been described in more detail elsewhere (Maitre et al., 2018).

The HELIX Subcohort comprises 1301 mother-child pairs (around 200 children in each cohort) in which a new follow-up examination of the children between ages 6 and 11 years was carried out. The subcohort sample was selected according to the following criteria of eligibility: a) primary school ages, b) stored pregnancy blood and urine samples available, c) complete address history available, and d) no serious health problems that may affect the clinical testing or the child's safety. In addition, n = 347 extra children (n = 271 INMA, n = 26 BiB, n = 7 EDEN, n = 5 KANC, n = 21 MoBa, and n = 17 RHEA) without biomarkers available were invited and examined following the same protocols for clinical examination, sample collection, and questionnaires. The present study included n = 1607 children with complete data for the exposures and the cognitive outcomes of interest (see Supplemental Material, Figure A1).

In the follow-up, the mother-child pairs were assessed by trained personnel according to the same protocol. The assessment included a maternal computer-based main questionnaire, a geographical survey to geocode daily activity locations (i.e., home, school, commute route from/to school, and other daily life places regularly visited by the children) conducted in QGIS software© (QGIS Development Team, 2013; QGIS Geographic Information System), child computer-based cognitive tests, and clinical examination. The mothers also completed a short version of the cognitive tests. The ethics committee for each cohort approved the consent form. We obtained written informed consent for all participants, signed by the parent. The current study was approved by the HELIX Ethical committee.

### 2.2. Exposure assessment

Based on the main questionnaire, qGIS survey, and GIS data we derived multiple dimensions of the green space exposures.

*Daily activity locations measurement.* We first measured children's daily activity locations including their home, school, commuting routes from home to school and from school to home, and places other than home and school, which they visited regularly and/or in the seven days before the follow-up assessment ("*Did your child go to any place, apart from home and school, for more than 2 h in the last week?*"). Parents/carers were invited to answer an electronic survey using qGIS (Version 1.8.0) – a free and open-source Geographic Information System (GIS) software. Using different map services (such as Open Street Maps or Google Maps) with QGIS software we geocoded specific locations or paths by searching directly on the map or using a search motor. Trained researchers conducted the survey with parents/carers to geocode the child's current home(s), school(s), commuting route(s), regular places, and all places visited in the seven days before the survey (see Supplemental Material, Green space, and qGIS questionnaires).

The main home address and any secondary residence where the child spent more than two days in a usual week were recorded, as well as the school address [*What is the address of your child's school?*]. Common commuting routes between home-school and school-home were geocoded if children repeated each one more than 2 days per week. The trained researcher drew the route on the map following the information given by the parent/carer. Following the criteria, all the commuting routes from home(s) to school and from school to home(s) were geocoded (if the children had two households, both routes were geocoded; i.e., from mother's house to father's house using two distinct routes) (see Supplemental Material, Green space, and qGIS questionnaires).

Also, they were asked about places regularly visited more than once per week and other places visited by their child for more than 2 h in the last seven days before the survey [*Did your child go to any place, apart from home and school, for more than 2 h in the last week?*]. Each place reported was geocoded using the exact address or search the map visually, and then classified as (a) Friend or relatives' house, (b) Indoor shopping area, (c) Outdoor shopping area, (d) Indoor place of recreation or sport, (e) extra-curricular activity or entertainment, (f) Outdoor place specifically for recreation or sport, (g) extra-curricular activity or entertainment, (h) Garden, (i) Park, (j)Forest/Mountain area, (k) Riverside, (l) Beach, (m) Other (See Supplemental Material, Figure A2).

### 2.3. Exposure assessment across daily activity locations

(a) *Availability of green spaces* was measured by using NDVI derived from satellite images with 30 m × 30 m resolution for each place geocoded in the qGIS survey using PostgreSQL© (1996–2017, The PostgreSQL Global Development Group), PostGIS© (Creative Commons Attribution-Share Alike 3.0 License http://postgis.net), and QGIS© platforms. The imagery had been selected according to the following criteria: i) cloud cover of less than 10%, ii) Standard Terrain Correction (Level 1 T), and iii) the greenest period of the year. NDVI ranges from +1.0 to −1.0, with negative values corresponding to water and higher numbers indicating more greenness. Surrounding greenness was abstracted as the average NDVI in buffers of 100 m, 300 m, and 500 m around each location geocoded. Negative values in the images have been reclassified to null values previously. We selected *a priori* 300 m buffer for the main analysis based on WHO recommendations on residential maximum distance to the nearest green space (World Health Organization. Regional Office for Europe, 2017). In the case of multiple residences, schools, and routes, the average NDVI was assigned.

For commuting routes, we calculated the weighted average considering the time in minutes children spent to do each sub-route, the number of days of the week, and the time in minutes in each route. To assign urban exposures to the route, as the route was a line spatial feature, it was necessary to convert the line to a line of points. Then, a point was created every 10 m along the drawn path considering the speed of the transport mode reported (i.e., speed of a pedestrian: 3.5 km/h). The NDVI was measured around each path point and then an average was abstracted to the entire route. In addition, for the other places, either visited regularly and/or in the seven days before the survey, we calculated the weighted average between i) the exposure at places and ii) the exposure at home (the weight depending on the number of places geocoded for each child).

(b) *Potential accessibility to green spaces* was measured as proximity to major green spaces only from home and school. The European Commission's recommendation for access to green spaces is a 300 m distance or 5 min of walking to an open area with more than 0.5 ha (World Health Organization. Regional Office for Europe, 2017). The Europe-wide "Urban Atlas" or local layers were used to extract maps of green spaces' locations across study regions (See Supplemental Material, Table A1). Potential accessibility indicators were calculated: straight-line distance to the nearest major green space and a binary variable indicating whether the child's home and school address was within 300 m of a >0.5 ha green space.

(c) *Visits to green spaces*: The number of visits to parks, gardens, and forests/mountains in the seven days before the qGIS survey were summed up and categorized into 0, 1–2, and 3+ visits. This variable intends to represent the short-term exposure to green spaces (See Supplemental Material, Green space, and qGIS questionnaires).

(d) *Green space playing time.* As a part of the main questionnaire parents/carers answered about the average number of times per week and the average number of hours spent each time their child played in green spaces during four different periods: weekdays, weekends, New Year/Christmas, and Easter holidays during the last school period, and the previous summer. For each period, the total duration of time spent playing in green spaces was calculated by first multiplying the number of playtimes per week by the hours per playtime to obtain the weekly average time, and then multiplying these weekly average times by the number of corresponding weeks in that category per country (European Commission, 2021). We followed a previous study that used the same questionnaire (Amoly et al., 2014). Green space playing time was then defined as the annual average hours of playing in green spaces estimated by summing up the total duration of playing at green spaces during school days, weekends, New Year/Christmas and Easter holidays, and summer holidays. (See Supplemental Material, Green space, and qGIS questionnaires).

### 2.4. Cognitive measurements

Trained fieldwork technicians measured three cognitive domains of the children using a battery of computer-based tests: fluid intelligence (Raven's Coloured Progressive Matrices Test [CPM]), inattention (Attention Network Test [ANT]), and working memory (N-Back task). The CPM comprised a total of 36 items and we used the total number of correct responses as an outcome (Raven and John, 1978). For ANT, we used the outcome of hit reaction time standard error (HRT-SE), a measure of response speed consistency throughout the test. The ANT test comprised a total of 16 practice trials and four experimental blocks of 32 trials each. We compute HRT-SE for the correct answer, independently the type of the trial (congruent or incongruent) (Rueda et al., 2004; Sunyer et al., 2015). A high HRT-SE indicates highly variable reactions and is considered a measure of inattentiveness (Forns et al., 2014). In n-back test, we examined different n-back loads (up to three-back) and stimuli (colors and numbers). Each block consisted of 25 trials. For this study, we only analyzed 3-back results for number stimuli, since it requires higher working memory demands (Dadvand et al., 2015; Forns et al., 2014). As the main parameter of n-back, we used d prime ($d'$), a measure of discriminability derived from signal detection theory calculated by the subtracting the z-score of the false alarm rate from the z-score of the hit rate. In this case, a higher $d'$ indicates more accurate performance (Deserno et al., 2012; Forns et al., 2014). Further description of the outcomes can be found in the Supplemental Material, Cognitive assessment description.

### 2.5. Data pre-processing

For each exposure variable, the optimal transformation to approach normality was applied (i.e., NDVI was log-transformed and Straight line to green space square root transformed) or the variable was categorized if normality could not be achieved (i.e., visits to green spaces). Missing data for all exposures and confounders were imputed using the method of chained equations (White et al., 2011). A total of 20 imputed datasets were generated and used in all the analyses mentioned hereafter. We restricted the number of predictors in the imputation models to fewer than 25 variables while ensuring that two of the three outcomes were considered predictors (van Buuren, 2012). Rubin's rule was used to aggregate the results from the 20 imputed datasets (White et al., 2011).

### 2.6. Covariates

We identified potential confounders from a Directed Acyclic Graph drawn from DAGitty (See Supplemental Material, Figure A4): the cohort of inclusion (BiB, EDEN, INMA, KANC, MOBA, RHEA), child age at the time of tests assessment (years), child sex, and residential area-level socioeconomic status using different deprivation indexes from each country and categorized into tertiles (where 1 comprises the less deprived tertile within the sample and 3 comprises the most deprived) as was done in previous studies (Amoly et al., 2014; Dadvand et al., 2015; Julvez et al., 2021; McEachan et al., 2018). To represent individual socioeconomic status, we further adjusted for maternal education level (low = primary school, medium = secondary school, high = university degree or higher) collected during the pregnancy in all cohorts and harmonized. Analyses of "visits to green spaces" were further adjusted for season based on the date of the qGIS survey interview.

### 2.7. Statistical analyses

We explored associations between measures of green space exposure and children's fluid intelligence, inattention, and working memory test scores. For each outcome variable, we conducted separate multiple linear regression analyses on pooled data adjusted for confounders. We estimated associations with each exposure variable individually using independent regression models. To provide an easier comparison of the effects, we estimated the change in average outcome scores associated with one interquartile range (IQR) increase in average NDVI (based on all study participants). Thus, in our models, the resulting coefficient can be interpreted as the change in the mean when moving from the 1st to the 3rd quartile of NDVI and straight-line distance to the nearest major green space. To do so, we divide the transformed exposures by the interquartile range (i.e., 75th percentile (3rd quartile) minus 25th percentile (1st quartile) of the transformed variable before running the regression model. All analyses were run under 4.1.2 (The R Project for Statistical Computing, Vienna, Austria).

#### 2.7.1. Effect modification by individual, and area level SES

The modification of green space-health relationships by socioeconomic status has been reported in the literature (Markevych et al., 2017; McEachan et al., 2018). We tested socioeconomic status interactions by including exposure multiplied by maternal education or area-level socioeconomic status in the model. For the interaction tests, we used a p-value of 0.10 in order to have more power to detect potential interaction. However, we are aware that increasing the type error I may lead to false positives (Marshall, 2007) and therefore, also evaluated the stratum-specific results (and their confidence intervals) from models stratified by maternal education (low/medium, and high education levels) and area-level socioeconomic status (less, medium/more deprived areas).

#### 2.7.2. Sensitivity analysis

Several sensitivity analyses were performed for the final models. They included: 1) further adjustment for maternal working memory (Julvez et al., 2021) (n-back test, d' prime), 2) complete case analyses, 3) buffers sizes of 100 m and 500 m for the NDVI variables, 4) analyses stratified by cohort. We computed cohort-specific estimates and evaluated between-cohort heterogeneity of associations using the $I^2$ statistic (Higgins and Thompson, 2002), and finally 5) for the playing time in green spaces variable we identified 47 outliers (i.e.; reported daytime >16 h). Then, we performed a sensitivity analysis removing these outlying responses, to decide whether they should be retained.

## 3. Results

### 3.1. Study population

Of 1648 participants, 1639 answered the qGIS questionnaire and had daily activity locations geocoded. Of these, 1607 had available data on fluid intelligence (Raven's test) and on the inattention test (Attention Network Test [ANT]) (See Supplemental Material, Figure A1). Due to technical problems with the test software, the N-back test for working memory was completed by 1325 children. Descriptive statistics for the characteristics of study participants, exposures, and the prevalence of our investigated outcomes are presented in Table 1. We presented the descriptive statistics per cohort in the Supplemental Material, Table A2.

The mean age of children was higher in EDEN [11 (±0.59)], INMA [9.3 (±0.72)], and MoBA [9.0 (±0.62)], which probably explained the better cognitive test scores in these cohorts. In general, we observed better scores on all the cognitive tests among older children, Western Europeans, from highly educated mothers, who reported high family affluence or no financial difficulties, and who lived or studied in less

**Table 1**
Description of covariates and prevalence of outcomes among the study participants, Helix project (n = 1607).

| Variables | |
|---|---|
| Child & Mother characteristics | Description |
| **Child sex** (n, %) | |
| Male | 865 (53.8) |
| Female | 742 (46.2) |
| **Child Age (years)** | |
| Mean (SD) | 8.6 (±1.4) |
| **Child ethnicity**[a,b] (n, %) | |
| European | 1323 (82.3) |
| Non-European | 176 (10.9) |
| Missing | 108 (6.8) |
| **Maternal Education** (n, %) | |
| Low | 232 (14.4) |
| Middle | 525 (32.7) |
| High | 748 (46.5) |
| Missing | 102 (6.4) |
| **Residential Area level SES**[+] (n, %) | |
| 1st tertile (less deprived) | 609 (37.9) |
| 2nd tertile | 577 (35.9) |
| 3rd tertile (most deprived) | 313 (19.5) |
| Missing | 108 (6.7) |
| **Outcomes** median, (Q1-Q3) | |
| Fluid intelligence (Raven's Coloured Progressive Matrices Test)[b] | 28 (22–32) |
| Missing | 0 (0) |
| Inattentiveness (Attention Network Test)[c] | 292 (225–360) |
| Missing (n, %) | 0 (0) |
| Working Memory (N-Back test)[d] | 1.39 (0.59–1.96) |
| Missing | 282 (17.5) |

[a] The child's ethnicity was determined using questionnaire categories that included Caucasian; White-non-European; African; Asian; Pakistani; Asian; Native American; and Other, without a free-text option for specifying. [+]Area level SES: Area level Socioeconomic status.
[b] Number of correct responses.
[c] High HRT-SE indicates highly variable reactions and is considered a measure of inattentiveness.
[d] Higher d′ indicates more accurate test performance, i.e., better working memory.

deprived areas. Furthermore, boys performed better than girls only on the inattention test (Attention Network Test [ANT]) (see Supplemental Material, Table A3).

### 3.2. Patterns of availability, accessibility to, and uses of green spaces

The median of average NDVI in larger buffers around participants' daily activity locations was higher than the median in smaller buffers and similar across home [median (IQR) in NDVI 300 m: 0.47 (0.28)], school [median in NDVI 300 m: 0.46 (0.26)], commute route [median in NDVI 300 m: 0.45 (0.27)], and other daily activity locations [median in NDVI 300 m: 0.46 (0.27)] (Table 2). Overall, we observed lower surrounding vegetation in Southern European cohorts, INMA (Spain) and RHEA (Greece), while MOBA in Norway was the greenest cohort (Supplemental Material, Table A2).

With regard to potential accessibility to green spaces, the distance to a major green space from home and school varied across cohorts, with the pooled median (IQR) 127 (±259) and 135 (±240) meters, respectively. Regarding proximity to green spaces, 1167 (72.6%) participants lived and 1132 (70.4%) studied within 300 m of a green space with more than 0.5 ha (Table 2). Those living or studying within 300 m of a major green space had higher residential and school surrounding greenness compared with those living further away (see Supplemental Material, Table A4).

The median (IQR) of average green space playing time was 263 (±400) hours per year (Table 2). Hours playing in green spaces during summer holidays contributed more to the total average time (median hours (IQR) compared to other periods over the year: weekdays: 50 (125), weekends 26 (39), holidays 20 (45), and summer 110 (224). On average, older children spent more hours per year playing in green spaces [median (IQR) 9–11 years: 346.5 (447)] than younger [median (IQR) 5–6 years: 167.7 (240)], and there was no difference between sexes (see Supplemental Material, Table A5). Almost one-third of participants reported one or more visits to parks, forests, or gardens in the seven days before the interview appointment. The interviews were equally distributed across seasons (Supplemental Material, Table A2 and Figure A3). On average, one IQR increase in residential surrounding greenness over buffers of 100, 300, and 500 m was associated, respectively, with the use of green spaces during 106.9 [95% CI: 61.7, 152.0], 109.7 [95% CI: 69.4149.9], and 99.9 [95% CI: 62.4, 137.5] more hours playing in green spaces per year (see Supplemental Material, Table A6). School surrounding greenness over buffers of 100 m [beta: 46.9, 95% CI: 6.2–87.4], 300 m [beta: 80.5, 95% 42.56, 118.54], and 500 m buffer [beta: 89.2, 95% CI: 48.78, 129.66] were also associated with more hours playing in green spaces per year. For potential accessibility, the picture was less consistent. There was a tendency for more time playing in green spaces with a shorter distance to a major green space from home [beta: −26.6, 95% CI: −53.17, −0.21] and school [beta: −28.9, 95% CI: −55.32, −2.52]. We did not observe the same pattern with living or studying within 300 m of major green spaces. (See Supplement Material, Table A6).

We observed a social gradient in most of the exposure dimensions. There is a notable difference in the availability of green spaces in the activity space across strata of ethnicity and maternal education, unfavorable to most vulnerable children (see Supplemental Material, Table A5). However, no statistically significant differences were observed for residential area level socioeconomic status and green space availability. Regarding potential accessibility to green spaces, children of European ethnicity had both shorter residential and school distances to a major green space compared to the non-European category, as well as those living in less deprived socioeconomic areas (37.2% lived within 300 m of major green space vs. 19% in the 3rd tertile) (see Supplemental Material, Table A5).

In general, children of mothers with lower educational levels, non-European ethnicity, and that lived in most deprived areas reported less time playing in green spaces (see Supplemental Material, Table A5). Also, parents/carers of European children reported more visits to green spaces (28.5% vs. 21.1% at least one visit, $p = 0.008$) in the last week before the interview (see Supplement Material Figure A5).

The Spearman's correlation coefficient between NDVI averages across buffers around activity space was higher and ranged from 0.71 to 0.99. As expected, we observed a moderate inverse correlation between NDVI and linear distance to major green spaces (i.e., NDVI 300 m around home: −0.50). On the other hand, time playing in green spaces was weakly correlated with availability (i.e., NDVI 300 m around home: 0.14) and potential accessibility (i.e., Linear distance to a major green space from home: −0.07) (see Supplemental Material, Figure A6).

**Table 2**
Description of exposures among the study participants, Helix project (n = 1607).

| Variables | |
|---|---|
| Exposures | Description |
| **Green spaces availability** [a] | |
| **Home** | |
| NDVI_100 m | 0.44 (0.25–0.57) |
| NDVI_300 m | 0.47 (0.30–0.58) |
| NDVI_500 m | 0.48 (0.32–0.58) |
| Missing (n, %) | 7 (0.4) |
| **School** | |
| NDVI_100 m | 0.41 (0.26–0.50) |
| NDVI_300 m | 0.46 (0.30–0.56) |
| NDVI_500 m | 0.46 (0.31–0.57) |
| Missing (n, %) | 13 (0.8) |
| **Commute route** | |
| NDVI_100 m | 0.42 (0.27–0.53) |
| NDVI_300 m | 0.45 (0.29–0.56) |
| NDVI_500 m | 0.47 (0.31–0.57) |
| Missing (n, %) | 30 (1.8) |
| **Other daily activity locations** | |
| NDVI_100 m | 0.43 (0.26–0.56) |
| NDVI_300 m | 0.46 (0.30–0.57) |
| NDVI_500 m | 0.47 (0.32–0.58) |
| Missing (n, %) | 7 (0.4) |
| **Green space Accessibility (meters)** | |
| Distance Home [a] | 127 (52–271) |
| Missing (n, %) | 113 (7.0) |
| Distance School [a] | 135 (50–290) |
| Missing (n, %) | 123 (7.6) |
| **Green space proximity (Yes)** [b] | |
| ≤300 m major green space (home) | 1167 (72.6) |
| Missing (n, %) | 113 (7.0) |
| ≤300 m major green space (school) | 1132 (70.4) |
| Missing (n, %) | 123 (7.6) |
| **Green space use and visits** | |
| Average playing time in green spaces (hours/year) [a] | 263 (106–506) |
| Missing (n, %) | 47 (2.9) |
| Number visits Park, Gardens, or Forest Previous week for >2 h [b] | |
| 0 | 1158 (72.1) |
| 1 | 384 (23.9) |
| 2+ | 60 (3.7) |
| Missing (n, %) | 5 (0.3) |

NDVI: normalized difference vegetation index (higher scores indicate greener environments).

[a] For continuous variables, median (first and third quartile), mean (standard deviation).

[b] For categorical variables count (percentage) of each category has been reported.

### 3.3. Association between green space dimensions and cognitive function

Table 3 shows the results of the main analysis for availability, accessibility, time playing in, and visits to green spaces with the outcomes, adjusted for the selected covariates. Unadjusted results are shown in Supplement Material - Table S7. Green space availability did not show statistically significant associations with any of the outcomes. There was a tendency for better working memory scores with NDVI within a 300-m buffer around the commuting route of borderline

**Table 3**
Associations between availability, accessibility, and uses of green spaces across home, school, commute route from/to school, and other daily life locations and cognitive scores (n = 1607).

| | Raven, number of correct responses (fluid intelligence) [a] | ANT, HRT-SE (inattentiveness)[b] | 3-Back, d' (Working memory) [c, g] |
|---|---|---|---|
| | β (95% CI) | β (95% CI) | β (95% CI) |
| **Availability of green spaces** | | | |
| NDVI 300 m home [IQR = 0.28] | −0.02 (−0.51 to 0.46) | −0.36 (−8.86 to 8.14) | 0.08 (−0.03 to 0.21) |
| NDVI 300 m school [IQR = 0.25] | −0.26 (−0.72 to 0.19) | 3.03 (−4.96 to 11.03) | 0.04 (−0.07 to 0.15) |
| NDVI 300 m commute route [IQR = 0.26] | −0.01 (−0.53 to 0.52) | 2.04 (−7.15 to 11.24) | 0.12 (−0.01 to 0.25) |
| NDVI 300 m other places [IQR = 0.27] | −0.03 (−0.56 to 0.49) | 0.18 (−9.02 to 9.39) | 0.09 (−0.03 to 0.23) |
| **Accessibility of green spaces** | | | |
| Straight line green space from home (meters) [IQR = 213.66] [d] | −0.00 (−0.31 to 0.31) | −0.15 (−5.67 to 5.35) | −0.05 (−0.13 to 0.02) |
| Straight line green space from school (meters) [IQR = 228.07] [d] | 0.17 (−0.13 to 0.48) | −1.92 (−7.36 to 3.50) | −0.05 (−0.13 to 0.02) |
| Major green space within 300 m home (Reference: no) [f] | −0.26 (−0.79 to 0.25) | −1.53 (−10.71 to 7.65) | 0.12 (−0.00 to 0.26) |
| Major green space within 300 m school (Reference: no) [f] | −0.26 (−0.77 to 0.24) | 8.58 (−0.41 to 17.58) | 0.05 (−0.05 to 0.21) |
| **Green space use and visits** | | | |
| Average playing time in green spaces (hours/year) [IQR = 399.1] | −0.06 (−0.30 to 0.17) | −2.44 (−6.59 to 1.70) | 0.05 (−0.01 to 0.11) |
| Number of visits to Park, Gardens, or Forest previous week for ≥2 h (ref: no visit) | | | |
| One visit | 0.35 (−0.17 to 0.88) | −3.82 (−13.06 to 5.41) | 0.00 (−0.13 to 0.15) |
| ≥2 visits | 0.62 (−0.50 to 1.75) | −2.39 (−21.88 to 17.22) | 0.05 (−0.22 to 0.33) |

HRT-SE: hit reaction time standard error. NDVI: normalized difference vegetation index (higher scores indicate greener environments). [a]The higher the better performance in the test. [b]A high HRT-SE indicates highly variable reactions and is considered a measure of inattentiveness [c]Higher d′ indicates more accurate test performance, i.e., better working memory. Linear regression models adjusted for cohort, maternal education, child age (years), child sex, and residential area level socioeconomic status. Beta estimates were calculated per 1-interquartile range increase in exposure and as a 1-category difference in each categorical indicator. *p < 0.05. **p < 0.001.

significance (beta: 0.12 CI: −0.01, 0.25). Also, for green space accessibility, no associations with the outcomes were observed, but the presence of a major green space within 300 m of the home showed an association of borderline statistical significance with improved working memory (beta: 0.12 CI: −0.00, 0.26). Finally, more time playing in green spaces and at least one visit to green spaces in the week before the interview were also not statistically associated with any of the outcomes. Playing in green spaces showed a tendency for association with better working memory scores (beta: 0.05, CI: −0.01 to 0.11).

### 3.4. Effect modification by individual, and area level SES

Overall, the association between availability, time playing in, and visits to green spaces exposures with cognitive function outcomes showed little evidence of differences between area deprivation groups and maternal education (similar risk estimates and p-value for interaction greater than 0.1; Supplemental Material, Table A8). For fluid intelligence, the multiplicative interaction terms were not statistically significant for any of the exposures (p-value for interaction >0.1). For inattention, we found evidence for interaction between living within 300 m of a major green space and residential socioeconomic area-level (p-value for interaction = 0.07), with stronger associations for more deprived areas. Finally, for working memory models, we found evidence of interaction between distance to a major green space from home and area-level socioeconomic status, between living within 300 m of a major green space and area-level socioeconomic status, and between 300 m buffer NDVI around school and maternal education (p-value for interaction <0.1). In these cases, stronger associations were found in less deprived areas and in higher maternal education strata.

After stratifying the analysis, we found that living within 300 m of a major green space (beta: 0.30, CI: 0.09, 0.51, p-value = 0.00) was associated with higher working memory scores only in children from lower-deprived areas (Fig. 1). There was a tendency for better working memory scores with NDVI within a 300-m buffer around the commuting route (beta: 0.19, CI: 0.00, 0.39, p-value = 0.04) only in the less deprived areas. In addition, studying within 300 m of green spaces increased inattention scores (beta = 15.45, 95% CI: 3.50, 27.40, p-value = 0.01) in children living in highly deprived areas (Fig. 1). When results were stratified by maternal education, the estimate for working memory was positively associated with more playing time in green spaces in the high education category (beta = 0.10; 95% CI: 0.01, 0.19, p-value = 0.04) (Fig. 1).

### 3.5. Sensitivity analysis

Further adjustment for the mother's working memory, did not change the main results. The magnitude and direction of associations remained the same for all outcomes. Complete case analyses differed somewhat from the imputed main analysis, showing associations between NDVI around the home, commute routes, and other places with better working memory (see Supplemental Material, Table A9).

Overall, there was no notable difference between the findings for the surrounding greenness in 100 m and 500 m buffers and the outcomes and those of main analyses (300 m buffer), with a tendency for stronger within the larger buffer (see Supplemental Material, Table A10). Therefore, we observed that one IQR increase in NDVI in 500 m buffer around the home [95% CI: 0.12 (0.00–0.23), p = 0.04)] and commute route [95% CI: 0.13 (0.01–0.26), p = 0.03] was associated with better working memory scores.

The observed associations were mostly consistent between cohorts. Although, there was some variation in the estimates (i.e.; consistent positive effect of green spaces on working memory from INMA cohort, and negative effect on inattention from BIB cohort), without clear differences between regions (i.e.; southern and northern Europe). Higher heterogeneity between cohorts was observed for inattention and working memory scores (i.e., I2 > 0.6) (Higgins and Thompson, 2002) (see Supplemental Material, Figure A8).

For time playing in green spaces, we ran a sensitivity analysis removing these outlying responses and the results were not altered. These participants were thus retained (Supplemental Material, Table A11).

## 4. Discussion

This study is, to our knowledge, the first analysis of distribution and associations between availability, accessibility, and uses of green spaces

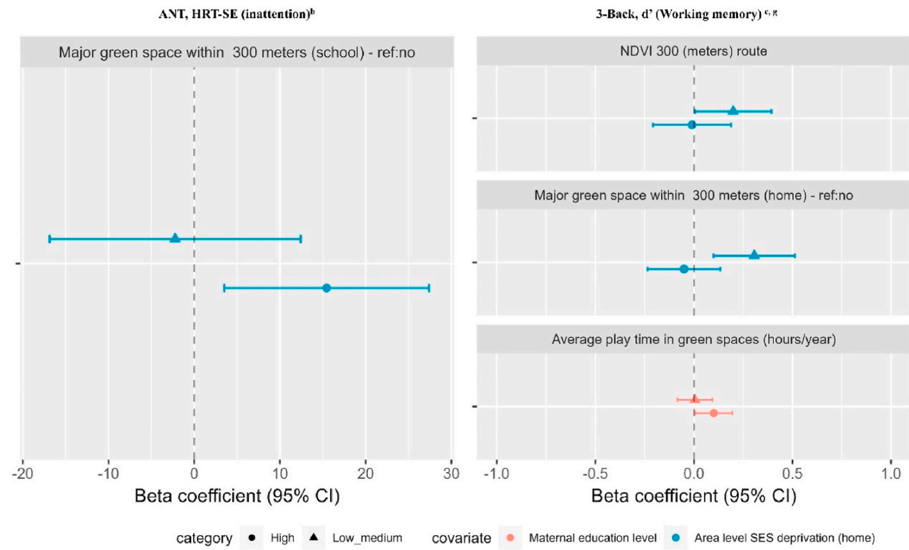


**Fig. 1.** Stratified analysis green spaces availability, accessibility and use with cognitive scores
HRT-SE: hit reaction time standard error. NDVI: normalized difference vegetation index (higher scores indicate greener environments [b]A high HRT-SE indicates highly variable reactions and is considered a measure of inattentiveness [c]Higher d′ indicates more accurate test performance, i.e., better working memory. Linear regression models adjusted for cohort, child age (years), child sex, maternal education or residential area level socioeconomic status depending on the stratified variable. Beta estimates were calculated per 1-interquartile range increase in exposure and as a 1-category difference in each categorical indicator (accessibility to green space No/Yes, reference: No). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

with child cognitive development on cohort sub-samples of six European countries. We found a social gradient in all exposure dimensions that was unfavorable in more vulnerable social groups. Also, the availability of green spaces, but not potential accessibility, seemed to foster play time in green spaces. Overall, associations between green space exposure dimensions and cognitive function outcomes were not statistically significant. Stratification by socioeconomic variables showed that living close to a major green space was associated with improved working memory only in children in less deprived residential areas and that more playing time in green spaces was associated with better working memory in children from mothers with high education levels. However, studying close to a major green space increased inattention scores in children in more deprived socioeconomic areas.

We did not find associations between multiple green space dimensions and fluid intelligence. These findings are in line with those of previous cross-sectional studies reporting no effect of 300 m home and school NDVI (Asta et al., 2021; Julvez et al., 2021) or proximity to green spaces (Almeida et al., 2022) on intelligence scores. To our knowledge, there are no previous studies on time or visits to green spaces and child intelligence tests. Intelligence is a multidimensional domain and the underlying mechanisms shaping the effects of green space on it is not fully understood (de Keijzer et al., 2016; Markevych et al., 2017). Also, it is plausible that a positive effect of green spaces depends on the intelligence subscale used (i.e., arithmetic (Asta et al., 2021), performance (Almeida et al., 2022), or global (Bijnens et al., 2020) subscales) and the buffer size selected. In the literature, longitudinal and cross-sectional associations between green spaces availability and accessibility with intelligence in children have been highly inconsistent (Luque-García et al., 2022), with some studies reporting associations only in buffers larger than 500 m (i.e.: variance heterogeneity is reduced in larger buffers) (Asta et al., 2021; Bijnens et al., 2020) or distances longer than 800 m (Almeida et al., 2022). Our results highlight the need for longitudinal follow-up of the effects of green space on fluid intelligence, as well as for a better understanding of the impact of the buffer type and size on the results.

Regarding associations between green spaces and inattention, we did not find any significant association between decreased inattention scores and any of the exposures. In the current literature linking green spaces and attention, the evidence remains inconclusive with positive associations coming from longitudinal studies (Dadvand et al., 2017; Luque-García et al., 2022). In our study, we observed inversed and stronger associations between green space and inattention scores with the 500 m buffer around home and other daily activity locations compared to the 300 m buffer, even though without statistical significance. This finding aligns with associations reported by a Spanish birth cohort study that used the same inattention test and showed a reduction in inattention in association with higher life-long estimates of residential greenness, which was only statistically significant for the 500 m buffer (Dadvand et al., 2017).

In previous studies, associations between proximity to green spaces and attention function (Amoly et al., 2014; Anabitarte et al., 2022) are less consistent than for NDVI (Amoly et al., 2014; Anabitarte et al., 2022; Dadvand et al., 2017, 2015), and show mainly null associations in primary school children in longitudinal and cross-sectional studies (Anabitarte et al., 2022), not depending on the size of the closest green area (Amoly et al., 2014). In our study, studying within 300 m of major green space was associated with higher inattention scores only in children from highly deprived socioeconomic areas. The effect of green spaces on attention function may involve a restoration of psychological capacities promoting restful experience (Markevych et al., 2017) driven by views to or time spent in these areas - and probably the quality of green space has a major role (McEachan et al., 2018). This may explain the social gradient we observed, schools in poorer areas have typically fewer green facilities and lower-quality vegetation in their surroundings (Browning et al., 2018; European Environment Agency, 2021; Hoffimann et al., 2017).

Finally, for working memory, our results, even though they mostly do not reach statistical significance, are aligned with studies that observed associations between residential (Dockx et al., 2022), neighborhood (Flouri et al., 2019), and school (Dadvand et al., 2015) availability of green spaces and three-back test using number stimuli (Dadvand et al., 2015), as well as better visual and spatial working memory in children. A previous study that evaluated home and school environments also found an increase in the 12-month progress of working memory of 5% in school and marginally significant for commute routes (Dadvand et al., 2015). It is important to note that in our study all measures of the availability of green spaces around the home, school, and commute routes were highly correlated (>0.8), making it difficult to disentangle the home-school green effect.

As in other studies, we did not find effect modification by area-level deprivation or maternal education for the association between the availability of green spaces and working memory (Dadvand et al., 2015; Flouri et al., 2019). However, we did find that potential accessibility and playing time in green spaces were associated with better working memory in population groups of higher socioeconomic status. Previous cross-sectional and longitudinal studies associated more time playing in or more visits to green spaces with children's mental well-being (Andrusaityte et al., 2020; McEachan et al., 2018). We can postulate that more time playing in and living within 300 m of green spaces may foster physical activity, which has been associated with better cognitive function in children, including memory (Markevych et al., 2017). However, again, the quality characteristics of the green spaces may explain the association we found between proximity to major green spaces and better working memory only in less deprived areas. In this direction, a longitudinal study from England found that South-Asian origin children living in a deprived urban area spent less time playing outside in green spaces compared to White British and that their parents were less satisfied with their local green spaces. This study supports our findings by showing that the quality, more than quantity, of green spaces or the short distance to green spaces alone, may be more relevant for users (McEachan et al., 2018).

Proximity to green spaces was not associated with more time playing in green spaces, perhaps indicating the importance of understanding how the quality of green spaces affects outcomes. Therefore, potential accessibility measured as linear proximity to major green spaces seemed not to work as a surrogate of real uses of green spaces, as a previous study has also shown (Amoly et al., 2014; McEachan et al., 2018). In line with our results (Amoly et al., 2014), found that children from parents with lower educational achievement spent less time playing in green spaces compared to their counterparts. Although the positive health effects of exposure to green space on cognition (Luque-García et al., 2022) can beneficiate all children from any background, particularly those more vulnerable, access to high-quality green spaces is still best accounted for by family and neighborhood socioeconomic factors (Hoffimann et al., 2017; Reuben et al., 2019). Children from more advantaged backgrounds may have both more proximity to high-quality green spaces and more access to private (i.e., garden, backyard) and green facilities outside their neighborhood (i.e.: summer vacations in the countryside). For instance, in our population, we observed that playing time in green spaces during the summer period accounted more for the total year time.

Our study has several strengths. This study was the first to account for children's multiple daily life locations going beyond residential and school places to overcome a limitation of many previous studies (Almeida et al., 2022; Amoly et al., 2014; Dadvand et al., 2015). Also, it evaluated a more comprehensive set of green space exposure variables, including a temporal dimension, that was identified as a main methodological gap in the available literature (Labib et al., 2020). In addition, the outcome assessment was based on cross-culturally validated computerized tests to objectively characterize multiple cognition functions for each study participant. A pilot was conducted in each cohort to guarantee the quality of the measures and the standardized assessment protocol. We analyzed data from six European birth cohorts, which might increase the external validity or generalizability of the present findings. Furthermore, we were able to control for the effect of maternal working memory a major confounder not addressed in previous studies (Dadvand et al., 2015; Flouri et al., 2019).

Our study also faced some limitations. We used satellite-derived NDVI to assess the availability of green spaces, an objective measure of greenness that enabled us to account for relative small-scale green spaces in a standardized way, but that did not distinguish between different types of vegetation or qualitative aspects. We did not account for the time variability of NDVI. However, there is evidence supporting the stability of greenness spatial contrast over seasons and years (Dadvand et al., 2012). We measure linear proximity to major green spaces as a proxy of potential accessibility, rather than more granulated measures such as the number of green spaces available without restrictions on size (Almeida et al., 2022). Our measure of time and visits to green spaces were self-reported which could be subject to information bias. However, for visits to green spaces, we used an innovative valid qGIS tool that was able to precisely record where the visits occurred. Future research should aim to replicate these findings with GPS data. Our questionnaires did not include measures of quality of or satisfaction with green spaces which could also be relevant. However, sensitivity analysis showed the robustness of our findings. Future studies should consider Bayesian approach when relevant to determine if there is evidence for the null hypothesis (Wong et al., 2022). Although, we assessed a wide range of potential confounders based on an acyclic causal diagram, other unmeasured variables could have contributed to residual confounding. Also, reverse causation cannot be fully ruled out by the study design. Finally, air pollution mitigation and physical activity increase might play a mediation role between green spaces and cognition (de Keijzer et al., 2016) and should be explored in future studies.

## 5. Conclusion

In conclusion, this comprehensive analysis of multiple aspects of green space exposure strengthens evidence of the social inequalities in access to green spaces and their health benefits. Our study provides some evidence that accessibility to and more time playing in green spaces are associated with better working memory in children of higher socio-economic backgrounds. Action to increase access to high-quality green spaces for children living and studying in more deprived socio-economic areas is required. These findings warrant further replications using longitudinal data, and objective and subjective measures of the quality of green spaces.

## Author statement

**Amanda Fernandes:** Conceptualization, Methodology, Formal analysis, Writing - Original Draft, Writing - Review & Editing, Visualization. **Norun Hjertager Krog:** Conceptualization, Writing - Review & Editing. **Rosemary McEachan:** Conceptualization, Writing - Review & Editing. **Mark Nieuwenhuijsen**: Conceptualization, Data Curation, Writing - Review & Editing. **Jordi Julvez:** Writing - Review & Editing. **Sandra Márquez:** Formal analysis and Writing - Review & Editing. **Montserrat de Castro:** Data Curation and Writing - Review & Editing. **José Urquiza:** Data Curation and Writing - Review & Editing. **Barbara Heude:** Writing - Review & Editing. **Marina Vafeiadi:** Writing - Review & Editing. **Regina Gražulevičienė:** Writing - Review & Editing. **Rémy Slama:** Writing - Review & Editing. **Audrius Dedele**: Writing - Review & Editing. **Gunn Marit Aasvang**: Writing - Review & Editing. **Jorunn Evandt**: Writing - Review & Editing. **Sandra Andrusaityte:** Writing - Review & Editing. **Mariza Kampouri:** Writing - Review & Editing. **Martine Vrijheid**: Conceptualization, Methodology, Writing - Review & Editing, Supervision and Funding acquisition.

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## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

The authors do not have permission to share data.

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