Does exposure to nature make children more intelligent? Analysis in Polish children with and without ADHD

Dorota Buczyłowska (dorota.buczyłowska@uj.edu.pl)  
Jagiellonian University

Clemens Baumbach  
Jagiellonian University

Jakub Bratkowski  
Institute of Environmental Protection-National Research Institute

Yarema Mysak  
Jagiellonian University

Maja Wierzbą–Łukaszyk  
Jagiellonian University

Krzysztof Skotak  
Institute of Environmental Protection-National Research Institute

Katarzyna Sitnik-Warchulska  
Jagiellonian University

Małgorzata Lipowska  
University of Gdansk

Bernadetta Izydorczyk  
Jagiellonian University

Marcin Szwed  
Jagiellonian University

Iana Markevych  
Jagiellonian University

Research Article

Keywords: Nature, green space, blue space, children, epidemiology, cognition, physical activity

Posted Date: March 24th, 2023

DOI: https://doi.org/10.21203/rs.3.rs-2724128/v1
Abstract

Previous studies have shown that exposure to nature and physical activity (PA) may be associated with higher intelligence in children. We examined whether there is an association between lifelong exposure to greenspace and bluespace and intelligence in children aged 10–13 with and without attention deficit hyperactivity disorder (ADHD), and whether PA mediates this association. The sample (N = 714) was collected within the NeuroSmog case-control study, where children with (N = 206) and without ADHD (N = 508) were recruited from 18 towns in southern Poland. Nature exposure was estimated as the sum of the z-scores of the objective and perceived measures. Objective greenspace exposure was defined as the percentage of grass and tree cover in 500 m and 1 km buffers around lifelong residential addresses, respectively. Objective bluespace exposure was defined as the percentage of water cover in 500 m and 1 km buffers. Perceived greenspace/bluespace was measured as the parent-rated availability, quality, and use of greenspace/bluespace. Intelligence was assessed using the Polish version of the Stanford-Binet Intelligence Scales, 5th edition (SB5). SB5 Full Scale intelligence quotient (IQ), Nonverbal IQ, Verbal IQ, five factor and ten subtest scores were analysed as outcomes. The associations between nature and IQ scores were assessed by linear regressions separately for cases and controls, adjusting the models for sex, parental education, and urbanicity. Structural equation modeling was implemented to test whether PA mediated the association between nature and intelligence. None of the greenspace or bluespace measures were consistently associated with intelligence. PA was not found to be a mediator. We did not find evidence that higher lifelong nature exposure is associated with higher intelligence in Polish schoolchildren with or without ADHD. This casts doubts on whether exposure to nature has relevant influence on IQ.

1. Introduction

According to a United Nations report (United Nations Department of Economic and Social Affairs, 2018), 55% of the world's population lives in urban areas. Living in cities is associated with higher risks for both physical and mental health issues (Nieuwenhuijsen et al., 2017).

Air and noise pollution and limited access to natural environments are frequently mentioned factors that contribute to higher health risks for urban populations. Therefore, the beneficial health effects of population exposure to nature (typically referred to as “greenspace” and “bluespace”, respectively meaning vegetated and water feature elements of the environment) have become the focus of an emerging field in environmental epidemiology, including research across various disciplines, such as ecology, urban planning, medicine, psychology, and neurosciences. Consequently, there is a growing body of evidence on the positive impact of greenspace and bluespace on human health and well-being (Yang et al., 2021). Previous research also suggests associations between exposure to the natural environment and cognitive functioning in both adults and children (Buczyłowska et al., 2023; de Keijzer et al., 2016; Luque-García et al., 2022), but the number of studies is limited and their findings are inconclusive. This topic should be more investigated in children, since crucial stages of cognitive development occur during childhood and adolescence. These developmental stages are also considered critical windows of
vulnerability (Davis, 2011; Rice & Barone, 2000), and sensitive periods for exposure to environmental neurotoxicants (Miodovnik, 2011); thus, children and adolescents may also be more strongly affected by greenspace and bluespace exposure than adults.

The beneficial effects of nature on children's cognition might occur through multiple pathways that can be presented in three domains according to their function: reducing harm (e.g. reducing exposure to air pollution, noise, and heat), restoring capacities (e.g. attention restoration and physiological stress recovery), and building capacities (e.g. encouraging physical activity [PA] and facilitating social cohesion) (Hartig et al., 2014; Markevych et al., 2017).

The function of restoring capacities is represented by two well-established theories of environmental psychology: attention restoration theory (ART; Kaplan, 1995) and stress reduction theory (SRT; Ulrich et al., 1991), which are further extended by relational restoration theory (RRT) and collective restoration theory (T. Hartig, 2021). All four theories elaborate on the different ways nature enables restoration, thereby improving cognitive functioning. Importantly, the domain of restoring capacity is considered to interact with two other restoration domains (Markevych et al., 2017). The interrelations among different restoration pathways, including PA and social cohesion, should be further examined (Dzhambov et al., 2020; Dzhambov, Hartig, et al., 2018). In particular, the indirect effect of nature on cognition through the PA pathway requires further investigation, as the effects of PA on cognition in children have frequently been demonstrated (Bidzan-Bluma & Lipowska, 2018; Hillman et al., 2019).

The focus of research devoted to the potential association between exposure to nature and cognition has been on greenspace and/or bluespace, and several different cognitive abilities. In a recently published systematic review on exposure to greenspace and bluespace and cognitive functioning in children (Buczyłowska et al., 2023), the majority of the included studies investigated attentional control and reaction and decision speed (12 studies), and attentional control and processing speed (10 studies). Eleven studies investigated the working memory capacity. Eight studies examined visual processing and psychomotor speed, parent-reported attention, early childhood/cognitive development, and decision-making and self-regulation. Nine of the studies focused on intellectual functioning.

Investigating the association between nature exposure and intellectual functioning appears particularly meaningful, as intelligence is considered one of the best predictors of several crucial life outcomes such as educational attainment, job performance, income, health, and longevity (Deary et al., 2004; Gottfredson & Deary, 2004; Sternberg et al., 2001). Moreover, intelligence test scores usually depict the highest level of cognitive capacity and are correlated with all essential cognitive functions (McDonough et al., 2018).

All nine studies that previously examined the association between exposure to nature and intelligence in children were observational. All employed standardised intelligence tests to assess intellectual functioning. Only two studies considered bluespace in addition to greenspace exposure (Almeida et al., 2022; Binter et al., 2022) but their results showed no associations.
The results of these studies are rather inconsistent. Five studies reported a positive association in at least one outcome (Almeida et al., 2022; Asta et al., 2021; Bijnens et al., 2020; Binter et al., 2022; Lee et al., 2021). These studies applied various versions of the Wechsler intelligence test for outcome assessment, and one of them used the British Picture Vocabulary Scale in addition to the Wechsler test (Binter et al., 2022). For exposure assessment, two studies used normalised difference vegetation index (NDVI) (Asta et al., 2021; Lee et al., 2021), two studies implemented both NDVI and nature availability/distance (Almeida et al., 2022; Binter et al., 2022), and one study used land cover data (Bijnens et al., 2020). Four studies reported no association (Flouri et al., 2022; Jimenez et al., 2021; Julvez et al., 2021; Reuben et al., 2019). These studies used the British Ability Scales, Kaufman Brief Intelligence Test, Raven's Coloured Progressive Matrices test, and Wechsler intelligence tests for outcome assessment. For exposure assessment, three studies applied NDVI, whereas one study used land cover data (Flouri et al., 2022).

The inconsistency in the results is most likely due to the heterogeneity of the methodological approaches, including both exposure and outcome assessments. Moreover, the findings within these studies appear to be inconsistent, too. In a study by Almeida et al. (2022), only residential availability of structured green spaces was positively associated with higher intelligence quotient (IQ) scores, whereas NDVI in different buffers around school was negatively associated with all IQ scores. In a study by Asta et al. (2021), NDVI was positively associated with only one subtest score for one buffer size, whereas no associations were detected between NDVI and the remaining test scores. In a study by Lee et al. (2021), the percentage of total, natural, and built prenatal and postnatal greenness was measured in four different buffer sizes around residences; however, the measured IQ scores were inconsistently associated with one, two, or three different buffer sizes of built and total greenness, but not natural greenness. In addition, the findings sometimes suggest unexpected associations. In the aforementioned study by Almeida et al. (2022), NDVI in two different buffer sizes around school was negatively associated with IQ scores. Furthermore, in a study by Julvez et al. (2021), a higher NDVI during pregnancy was associated with lower intelligence.

Consequently, the low number of studies, heterogeneity of methodological approaches, and inconsistency in the results across and within the studies do not allow for clear conclusions about the association between nature exposure and intelligence. It is not possible to determine whether some measures of greenspace or bluespace exposure show more consistent associations with cognition than others, and whether associations differ across age groups. Thus, further research using diverse state-of-the-art methodological approaches is required (Buczyłowska et al., 2023).

Nature exposure has also been examined in association with attention-deficit/hyperactivity disorder (ADHD) (de Keijzer et al., 2016; Luque-García et al., 2022), which is the most common neurodevelopmental disorder in school-aged children with an estimated worldwide prevalence approximately 5–7% (Polanczyk et al., 2007, Thomas et al., 2015). However, studies focusing on nature exposure and intelligence in ADHD are lacking. Based on evidence suggesting that ADHD is associated with deficits across a variety of cognitive domains, including intelligence (Pievsky & Mcgrath, 2018), the potential impact of nature exposure should also be investigated in ADHD.
The current study aimed to examine the associations between lifelong exposure to greenspace and bluespace and intelligence in schoolchildren with and without ADHD. Another objective was to test the indirect effect of nature exposure on intelligence through PA. We hypothesised associations between greenspace and bluespace exposure and intelligence on individual subtest level rather than on the overall intelligence test score level. Further, we expected an indirect effect of greenspace exposure on intelligence through PA. We assumed differences in both the direct and indirect examined effects between children with and without ADHD.

2. Methods

2.1. Sample, recruitment, and testing procedure

The current analysis is a spin-off of the case-control NeuroSmog study, which aims to explore the associations between long-term air pollution and neurodevelopment in children with ADHD (cases) and their ADHD-free counterparts (controls). The data used in the current analysis were collected from October 2020 to July 2022 in 18 towns in southern Poland. Children without ADHD were randomly sampled from randomly selected schools. A team of 25 field clinical psychologists with at least five years of clinical experience was responsible for recruiting potential cases and conducting psychological assessments of all children. Children at risk of ADHD were referred to field psychologists by cooperating schools, psychological-educational counselling centres, and mental health centres, or parents applied for participation on their behalf. A two-step model was used to verify ADHD diagnosis in cases and controls, respectively. Firstly, a comprehensive psychological assessment was conducted and evaluated by field psychologists. Secondly, three consultant clinical psychologists reviewed the assessments to verify the diagnoses according to the International Classification of Diseases 11th Revision (ICD-11) criteria (WHO, 2019).

The included children were fluent Polish speakers, aged between 10 and 13 years (born between 2007 and 2011), with average or above-average intelligence, and attending a school in the selected towns. To be enrolled, children had to be born at $\geq 35$ weeks of gestation with a birth weight of $\geq 2500$ g and Apgar score $\geq 8$. Children with severe comorbidities, such as diagnosed intellectual disability, neurological or psychiatric disorders, or other serious medical conditions were excluded. Excluded were also children with contraindications to magnetic resonance imaging (MRI), or those not residing in Poland for at least the previous year.

Clinical psychologists were trained in administering the psychological measures utilised in the study. Psychological assessments, including cognitive and behavioural tasks, were conducted in three meetings with a field psychologist. Each meeting lasted for approximately two hours. The intelligence assessment was conducted on one occasion during the first meeting. Additionally, children were invited for one session of MRI scanning within three months of the psychological evaluation. For more details on recruitment and testing procedure, please refer to the NeuroSmog study protocol (Markevych et al., 2022).
The sample size was not based on previous power analysis. According to the main goal of the NeuroSmog project, the sample was collected based on the feasibility of MRI scanning. Initially, 756 participants were recruited and tested. Our analytic sample comprised 714 participants: 206 cases and 508 controls with outcome, exposure, main confounder, and mediator data (for details, see Supplement 1 Figure S1).

The current residential addresses of the study participants superimposed over the study area, as well as the locations of the study area in Poland and Europe, are depicted in Fig. 1.

2.2. Intelligence assessment

For intelligence assessment Stanford-Binet Intelligence Scales, Fifth Edition (SB5) – Polish version (Roid, Sajewicz-Radtke, et al., 2017) was used. SB5 is an individually administered intelligence test battery designed to assess cognitive abilities in individuals between 2 and 85 years of age.

The SB5 was revised according to the Cattell-Horn-Carroll (CHC) theory (Carroll, 1993; Cattell, 1943, 1963; Cattell and Horn, 1978), representing three levels of cognitive ability: general ability (stratum III), broad ability (stratum II), and narrow ability (stratum I). Narrow and broad ability scores are obtained from the individual subtests: Fluid Reasoning, Knowledge, Quantitative Reasoning, Visual-Spatial Reasoning, and Working Memory. Each of the subtests is available in both nonverbal and verbal versions; as a result, for each cognitive domain, a composite factor score based on verbal and nonverbal subtests can be calculated. Based on five nonverbal subtests and five verbal subtests, Nonverbal Intelligence Quotient (NVIQ) and Verbal Intelligence Quotient (VIQ) composite scores are calculated. The Full Scale Intelligence Quotient (FSIQ) score representing CHC general ability is derived from the administration of all 10 subtests.

For the Polish version of SB5, the following reliability coefficients were reported: split-half-reliability across age groups for the FSIQ ranged from .97 to .99, and for the NVIQ and VIQ from .93 to .98. Internal consistency reliability across age groups for the FSIQ ranged from .95 to .98, and for the NVIQ and VIQ, they ranged from .91 to .95 (Roid, Jurek, et al., 2017). The standardised mean for the SB5 composite scores is 100, and the standard deviation is 15. The standardised mean for the SB5 subtests is 10 and the standard deviation is 3. Within the current analysis, SB5 composite scores (FSIQ, NVIQ, and VIQ, Fluid Reasoning, Knowledge, Quantitative Reasoning, Visual-Spatial Reasoning, and Working Memory), as well as subtest scores, were treated as outcomes.

2.3. Residential greenspace and bluespace exposure assessment

The lifelong addresses of the NeuroSmog participants were collected using a NeuroSmog-specific paper-and-pencil Address Questionnaire that was then digitalised, and validated. Google's Geocoding application programming interface (API) was used to geocode the addresses in the World Geodetic System 84 (WGS 84) coordinate system, as implemented in the R (R Core Team, 2021) ggmap package (function geocode()) (Kahle & Wickham, 2013).
The land cover data set for 2018 (Geoportal, 2022) from the Poland-wide database of topographic objects 10k (BDOT10k) was used to derive information on tree, grass/shrub, and water cover in square meters (Supplement 1, Figure S2). First, the relevant vector layers were transformed into rasters with a resolution of 20 m x 20 m using the gdal_rasterise function of GDAL version 3.0.4. Second, the focal sum in ArcGIS Pro 2.5.1 (ESRI, Redlands, CA) was used to calculate the areas of each land cover category within a circular 500 m and 1 km buffer for each residential address starting at birth. The assignments were performed in Python version 3.9.6 using the tiffile package version 2022.5.4. Lifelong exposures to greenspace and bluespace were calculated by averaging exposures over all residential addresses, while weighing living duration at each residence. The areas of the land cover categories were then transformed into percentages.

Percentage tree and grass/shrub cover were used as objective greenspace measures, and percentage water cover was used as an objective bluespace measure. In addition, perceived greenspace and bluespace measures were used. Perceived greenspace/bluespace exposure was assessed by parents on a seven-point Likert scale (strongly agree [1] to strongly disagree [7]) with five questions covering the following aspects: (1) greenspace/bluespace usage in the neighbourhood, (2) visible greenspace/bluespace from window view, (3) quality of greenspace/bluespace, (4) greenspace/bluespace neighbourhood use, and (5) use of greenspace/bluespace outside of the neighbourhood. The exact questions can be found in Supplement A of Markevych et al. (2022). The mean score of the responses across the five items for each greenspace and bluespace variable was used as a proxy for the perceived greenspace/bluespace. The internal consistency of the scales was acceptable for both greenspace (Cronbach's alpha = 0.77) and bluespace scores (Cronbach's alpha = 0.70). Lifetime greenspace exposure was calculated as the sum of z-scores derived from percentage tree cover in the 500 m buffer, grass cover in the 500 m buffer, and perceived greenspace measure. Lifetime bluespace exposure was calculated as the sum of z-scores derived from percentage water cover in a 1 km buffer and perceived bluespace measure. These buffer sizes were selected based on previous research showing that children aged 10–12 years travel no further than 500 m to access greenspace and 1 km to access other common activity spaces (Hand et al., 2018; Loebach & Gilliland, 2016).

## 2.4. Covariates

We considered several covariates as potential confounders, mediators, and effect modifiers. A directed acyclic graph (DAG), as implemented in dagitty.net (Textor et al., 2016), was used to select a minimum sufficient set of confounders (Greenland et al., 1999) to avoid over-adjustment and to identify potential mediators. Sex, parental education, and urbanicity were identified as confounders, whereas PA was identified as a potential mediator (Supplement 1, Figure S3).

Sex, minimum education of both parents (low vs. medium vs. high), and PA were reported by parents via a questionnaire. The three levels of parental education were defined as follows: “low” – primary school or/and vocational training, “medium” – high school or/and vocational training after high school, and “high” – bachelor’s degree or higher. The level of urbanicity was estimated via proxy which was the
percentage of sealed soil in 1000 m buffer around home; these data were derived from the Imperviousness Density for the year 2018 (European Environment Agency, 2020).

To estimate the duration of children's PA per week (None; <1 h; 1–2 h; 3–4 h; 5–6 h; >6 h), the parents were asked the following question: “Approximately how many hours per week does your child usually do strenuous PA outside of school that makes her or him get out of breath or sweat more than usual (e.g., playing team sports, dancing, swimming)?” This question was adopted from the RHINESSA study (Ekström et al. 2022; Lindberg et al. 2020).

As an additional confounder, we considered the presence of learning disabilities such as dyslexia, dyscalculia, and dysorthographia, as they may have an impact on intelligence assessment results. The diagnosis of learning disabilities was verified by clinical psychologists who conducted the psychological assessments.

2.5. Analytic strategy

2.5.1. Main analysis

Data pre-processing and statistical analysis were performed using the statistical software R, version 4.0.4 (R Core Team, 2018). Descriptive characteristics of the entire sample (i.e., children with and without ADHD) are presented as frequencies and percentages for categorical variables, and as means and standard deviations for continuous variables. The distributions of the exposure variables were tested using histograms. One outlier was identified by visual inspection of the scatter plots and was removed.

All regression analyses were conducted separately for the cases and controls. Linear regression was used to examine the associations among residential lifetime greenspace/bluespace exposure, and intelligence. Regressions were performed separately for each exposure-outcome pair. SB5 composite scores (FSIQ, NVIQ, VIQ, Fluid Reasoning, Knowledge, Quantitative Reasoning, Visual-Spatial Reasoning, and Working Memory) were used as outcomes. All models were adjusted for DAG-selected confounders including sex, minimum parental education, and urbanicity. The results are presented as b coefficients and their corresponding 95% confidence intervals (CIs). Residual diagnostics were performed using the DHARMa package (F. Hartig, 2022). Non-linearity of exposure-outcome relationships was checked using generalised additive models (GAMs; Hastie & Tibshirani, 1986).

2.5.2. Sensitivity analyses

To verify the impact of the confounding factors, we conducted unadjusted analyses. In addition, we restricted the main model to children without learning disabilities (cases, N = 204; controls, N = 500). To test whether there were associations between greenspace and bluespace exposure and SB5 performance at the subtest level, we used subtest scores separately from the nonverbal and verbal domains. To test whether there was an association between the single exposure measures and intelligence, we separately regressed each of the residential tree cover, grass/shrub, and water cover in 500 m and 1 km buffers and perceived greenspace and bluespace scores on each of the outcome variables. For this analysis, water
cover was dichotomised into the presence or absence of water bodies in line with other analyses in landlocked areas (Dzhambov, Markevych, et al., 2018) as the data were extremely right-skewed.

2.5.3. Testing effect modification

To check for the presence of effect modification, we stratified our main models by changing place of residence in “movers” (participants who changed their place of residence at least once) vs “non-movers” (participants who never changed their place of residence), minimum parental education in low vs. medium vs. high, and median urbanicity in rural vs. urban place of residence. We concluded an effect modification if 95% CIs of the strata-specific associations did not overlap, disregarding formal statistical significance.

2.5.4. Mediation analyses

To investigate whether PA is involved in the association between greenspace and intelligence, we used structural equation modelling (SEM). We used a robust diagonally weighted least squares (DWLS) estimator (Muthén, 1993) with bootstrapping (1000 draws) to estimate standard errors. SEM modelling was performed using the R lavaan v. 0.6–12 package (Rosseel, 2012). A p-value of < 0.05 was selected as a threshold for statistical significance.

3. Results

The main characteristics of the participants are listed in Table 1. The majority of the case subsample were boys (74.27%). In the control subsample, the proportion of both sexes was almost equal (51.48% boys). The cases and controls were similar with respect to age, urbanicity, and presence of learning disabilities. In 75.33% of the cases and 84.81% of the controls, at least one parent had a medium or high level of education. There were also differences in the proportion of low parental education levels between the cases (24.27%) and controls (15.19%). There were no substantial differences in the proportion of medium parental education levels between the cases (40.29%) and controls (43%). The proportion of participants performing PA for more than six hours per week was higher in cases (21.36%) than in controls (9.86%). Moreover, the proportion of participants who never performed PA was higher in the controls (12.23%) than the cases (4.37%). No substantial differences were observed in the remaining PA duration levels. As presented in Table S1 (Supplement 1), there were differences in SB5 composite scores with controls outperforming the cases. In general, participants with ADHD showed SB5 performance levels closer to the mean of the norming sample (i.e. FSIQ = 100) than did participants without ADHD. As shown in Table S2 (Supplement 1), there were also differences between the two subsamples with respect to exposure to greenspace and bluespace, such that controls were more exposed to greenspace than cases, whereas cases were more exposed to bluespace than controls.
Table 1. 
Descriptive characteristics of the study sample (N = 714)

<table>
<thead>
<tr>
<th>Variable</th>
<th>Cases (with ADHD, N = 204)</th>
<th>Controls (without ADHD, N = 508)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sex</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Female</td>
<td>53 (24.73)</td>
<td>246 (48.52)</td>
</tr>
<tr>
<td>Male</td>
<td>153 (74.27)</td>
<td>261 (51.48)</td>
</tr>
<tr>
<td>Age (years)</td>
<td>11.15 ± 0.9 (9.28-13.32)</td>
<td>11.32 ± 0.75 (9.32-13.23)</td>
</tr>
<tr>
<td>Minimum parental education</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low</td>
<td>50 (24.27)</td>
<td>77 (15.19)</td>
</tr>
<tr>
<td>Medium</td>
<td>83 (40.29)</td>
<td>218 (43)</td>
</tr>
<tr>
<td>High</td>
<td>73 (35.4)</td>
<td>212 (41.81)</td>
</tr>
<tr>
<td>Dyslexia (n = 704)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>No</td>
<td>195 (95.59)</td>
<td>485 (96.6)</td>
</tr>
<tr>
<td>Yes</td>
<td>9 (4.41)</td>
<td>17 (3.4)</td>
</tr>
<tr>
<td>Dyscalculia (n = 704)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>No</td>
<td>202 (99.02)</td>
<td>483 (96.6)</td>
</tr>
<tr>
<td>Yes</td>
<td>2 (0.98)</td>
<td>2 (0.4)</td>
</tr>
<tr>
<td>Dysorthographia (n = 704)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>No</td>
<td>201 (98.53)</td>
<td>492 (98.4)</td>
</tr>
<tr>
<td>Yes</td>
<td>3 (1.47)</td>
<td>8 (1.6)</td>
</tr>
<tr>
<td>Changing place of residence</td>
<td></td>
<td></td>
</tr>
<tr>
<td>No</td>
<td>84 (40.78)</td>
<td>254 (50.1)</td>
</tr>
<tr>
<td>Yes</td>
<td>122 (59.22)</td>
<td>253 (49.9)</td>
</tr>
<tr>
<td>Urbanicity* (continuous variable, %)</td>
<td>21.53 ± 13.07 (1-59)</td>
<td>19.57 ± 11.3 (1-56)</td>
</tr>
<tr>
<td>Urbanicity (categorical variable)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Urban</td>
<td>102 (49.51)</td>
<td>247 (48.72)</td>
</tr>
<tr>
<td>Rural</td>
<td>104 (50.49)</td>
<td>260 (51.28)</td>
</tr>
<tr>
<td>Physical activity</td>
<td></td>
<td></td>
</tr>
<tr>
<td>&gt; 6 h per week</td>
<td>44 (21.36)</td>
<td>50 (9.86)</td>
</tr>
</tbody>
</table>
In both cases and controls, no consistent associations were found between residential lifetime exposure to greenspace (Figure 2) and bluespace (Figure 3) and SB5 composite scores. Excluding participants with learning disabilities, stratification by changing place of residence (movers vs non-movers), urbanicity (rural vs urban), and parental education level (low vs medium vs high) did not reveal any consistent associations. In controls, several significant negative b coefficients in regression models for bluespace, Quantitative Reasoning, and Visual-Spatial Processing indicated an association in an unexpected direction.

Further, no consistent associations were found when looking at greenspace, bluespace, and performance on SB5 individual subtests from the nonverbal and verbal domains (Supplement 1, Figure S4). In addition, no associations were detected with SB5 composite scores and greenspace and bluespace single exposures, including those within a 1 km buffer around residence, and perceived greenspace and bluespace (Supplement 1, Figure S5). All the numerical regression results are presented in Supplement 2.

The mediation analysis did not reveal any significant results for PA as a mediator in the pathway between lifelong exposure to greenspace and FSIQ, NVIQ, and VIQ for cases or controls (Supplement 1, Table S3). Furthermore, there were no direct effects of PA on IQ scores. Nevertheless, the association between greenspace and physical activity was significant.

4. Discussion

Considering the conflicting results derived from previous research, our goal was to analyse the association between nature exposure and intelligence using a state-of-the-art methodology. We conducted a comprehensive analysis of the associations between lifelong residential exposure to greenspace and bluespace and intelligence in schoolchildren. We used a sample composed of randomly selected healthy controls and children with ADHD as cases, whose diagnoses were verified by clinical psychologists. We used land cover data and lifetime addresses to estimate the lifelong exposure to greenspace and bluespace. In addition, perceived greenspace and bluespace exposure measures were applied. In the outcome assessment, we implemented SB5, a comprehensive intelligence test battery used worldwide that allows the assessment of both overall intelligence and domain-specific cognitive abilities. Our analysis showed that in both cases and controls, none of the greenspace and bluespace measures were consistently associated with intelligence, either on the overall performance level or on a domain-
specific level. Considering confounders and modifiers did not change the results. PA was not found to be a significant mediator, either.

Comparing the results of our study with those of previous studies is possible only to a limited extent due to differences in the methodology and heterogeneity within previous research. To the best of our knowledge, this study is the first to use SB5 in relation to nature exposure and intelligence. Therefore, meaningful comparisons with previous studies are limited. Although all previous studies have employed standardised intelligence tests, there might be differences in the aspects of intellectual functioning being assessed, as well as in the reliability and validity of these measures. Generally, the application of full versions of intelligence test batteries is recommended (Strauss et al., 2006). Studies that reported positive associations between nature exposure and intelligence used a full version of a Weschler intelligence test; however, in one study (Binter et al., 2022) different cognitive measures in four different cohorts were used and study conclusions were formulated based on the results derived from these different measurements, which is not in line with the standards of cognitive assessment (Lezak et al., 2012). Studies that reported negative or no associations used short versions of intelligence test batteries (Jimenez et al, 2021; Reuben et al., 2019), measures composed only of three subtests (Flouri et al., 2022) or assessing only one facet of intelligence (Julvez et al., 2021). Another aspect that should be considered relates to who conducted intelligence assessments (Buczyłowska et al. 2023). Frequently, studies do not report this information, but it is crucial to know whether the assessments were conducted by psychologists, who are best qualified to conduct intelligence assessments and interpret their results.

Furthermore, the heterogeneity of exposure assessment, including the quality of greenspace or bluespace metrics, should be considered. Our greenspace and bluespace measures were derived from land cover data. Additionally, we used parent-rated availability, quality, and frequency of greenspace and bluespace use; on the contrary, none of the previous studies implemented perceived exposure measures. Two previous studies used land cover data, five used only NDVI as a greenspace measure, and two used both NDVI and nature availability/distance to nature. However, these metrics do not provide information on the quality of green spaces. Moreover, information on the frequency and duration of visits to green spaces is essential (Dzhambov et al., 2018) as it would help evaluate potential associations with intelligence.

As pointed out in the introduction, three of the five previous studies that reported positive associations between exposure to greenspace and intelligence in children had rather inconsistent results. Moreover, in two studies, the associations were opposite to the expected direction (Almeida et al., 2022; Julvez et al. (2021). In our study, bluespace exposure was negatively associated with the two SB5 factors in controls; nevertheless, there seems to be no plausible explanation for these results. Two previous studies that considered bluespace exposure (Almeida et al., 2022; Binter et al., 2022) reported no association with intelligence. Examining the association between cognition and bluespace exposure seems to be even more challenging than is the case with greenspace as bluespace assessment is less standardized than greenspace. Thus, future research should consider the specific characteristics of bluespace, such as bluespace types, duration of time spent around bluespace, and activities conducted in or around bluespace.
In the current study, we were also interested in whether greenspace would have an indirect effect on intelligence through increased PA. Similar to previous research (Almeida et al., 2022; Jimenez et al., 2021; Lee et al., 2021), the mediation analysis did not reveal any significant results for the three main IQ scores for either cases or controls. PA had no direct effect on IQ scores. These results are not surprising. Although previous research (Bidzan-Bluma & Lipowska, 2018; Hillman et al., 2019) has shown positive effects of PA on cognition, these findings mainly included attention, memory, language, and executive functions. Consequently, PA may be positively associated with cognition. However, IQ scores represent the highest level of cognitive performance and are likely to be affected by several lifelong factors. Thus, lifelong data for variables considered meaningful for the development of intelligence, including PA are required to answer this research question.

5. Limitations

Several limitations of this study should be considered when interpreting its results. Although we calculated lifelong objective greenspace and bluespace, the information was derived from the land cover data referring to a single year (2018), and thus, no land use changes over time were reflected. In addition, we did not have well-resoluted land use data, but only land cover data, thus, we could not differentiate greenspace by its functionality (i.e. natural, urban, agricultural).

Although we used lifelong nature exposure data, intelligence assessments were conducted at only one time point. Using a longitudinal study design with several consecutive outcome assessments at different time points to capture several stages of cognitive development would strengthen future studies. Our intelligence assessments were conducted by qualified clinical psychologists according to the standards of psychological assessment; however, as there were 25 individuals involved in the assessments, individual characteristics of the assessing psychologist might have contributed to the measurement error and decreased the objectivity of assessments.

Furthermore, we used both objective and perceived exposure measures, but unlike objective measures of greenspace and bluespace, our perceived exposures were cross-sectional and parent-reported, and the same concerns PA. In addition, we did not consider specific characteristics of nature exposure, such as the type of greenspace/bluespace or the type of activities conducted therein.

6. Conclusions

We could not find evidence that higher lifelong exposure to greenspace and bluespace is associated with higher intelligence in Polish schoolchildren with or without ADHD. PA did not mediate the association between greenspace and intelligence. The current results raise doubts on whether exposure to nature has relevant influence on IQ.

Declarations
Ethics approval and consent to participate

NeuroSmog was approved by the Ethics Committee of the Institute of Psychology, Jagiellonian University, Kraków, Poland (# KE_24042019A). Written informed consent was collected from the legal guardians of the participants, and written informed assent was collected from the participants themselves. The clinical trial identifier was NCT04574414.

Consent for publication

Not applicable

Availability of data and materials

Data were obtained from the NeuroSmog study, which is bound to the local ethical and legal restrictions with respect to the study data. The informed consent provided by the NeuroSmog study participants did not include data posted in public databases. However, all data used for this publication are available upon request. Contact persons are Dr Dorota Buczyłowska (Dorota.buczylowska@uj.edu.pl), and Dr Iana Markevych (iana.markevych@uj.edu.pl).

Competing interests

The authors declare that they have no competing interests.

Funding

1. “NeuroSmog: Determining the impact of air pollution on the developing brain” (Nr. POIR.04.04.00-1763/18-00), project, which is implemented as part of the TEAM-NET program of the Foundation for Polish Science, co-financed from EU resources, obtained from the European Regional Development Fund under the Smart Growth Operational Programme.

2. Grant from the Faculty of Philosophy under the Strategic Programme "Excellence Initiative" at the Jagiellonian University.

Authors' contributions

Conceptualisation: Dorota Buczyłowska, Iana Markevych

Methodology: Dorota Buczyłowska, Clemens Baumbach, Iana Markevych,

Software: Dorota Buczyłowska, Clemens Baumbach, Iana Markevych, Jakub Bratkowski

Formal analysis: Dorota Buczyłowska, Clemens Baumbach, Iana Markevych,

Resources: Dorota Buczyłowska, Jakub Bratkowski, Katarzyna Sitnik-Warchulska, Krzysztof Skotak, Małgorzata Lipowska, Bernadetta Izydorczyk, Marcin Szwed, Iana Markevych
Acknowledgments

We are very grateful to all children and parents for their participation in the study, partner schools for helping with the recruitment of study participants, field psychologists for recruiting children with ADHD and performing psychological testing of all children, and the project team for technical, logistic, administrative, and communication efforts.

We would like to thank Angel M. Dzhambov for his training in the application of structural equation modeling in environmental epidemiology.

References


six European countries. *Environmental Pollution, 284*, 117404.
https://doi.org/10.1016/j.envpol.2021.117404


https://doi.org/10.1016/j.scitotenv.2020.143561


https://doi.org/10.3390/ijerph19010310


**Figures**

**Figure 1**

Study area location and current residential addresses of the study participants superimposed over the study area.
**Figure 2**

B coefficients and their corresponding 95% confidence intervals for the associations between lifetime *greenspace* exposure and SB5 IQ and factor scores in cases and controls.

*Note.* FSIQ = Full Scale Intelligence Quotient, NVIQ = Nonverbal Intelligence Quotient, VIQ = Verbal Intelligence Quotient. Statistically significant results are indicated by filled circles.
**Figure 3**

B coefficients and their corresponding 95% confidence intervals for the associations between lifetime bluespace exposure and SB5 IQ and factor scores in cases and controls.

*Note.* FSIQ = Full Scale Intelligence Quotient, NVIQ = Nonverbal Intelligence Quotient, VIQ = Verbal Intelligence Quotient. Statistically significant results are indicated by filled circles.

### Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- Buczyłowskaetal.Supplement1.docx
- Buczyłowskaetal.Supplement2.xlsx