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Review article

Exposure to greenspace and bluespace and cognitive functioning in children – A systematic review

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ABSTRACT

Background: The field of greenspace and bluespace research in relation to cognitive outcomes is rapidly growing. Several systematic reviews have already been published on this topic but none of them are specific to cognitive outcomes in the entire age range of children. Moreover, only a few of them have examined the effects of bluespace in addition to greenspace. Also, theses reviews are focused either only on observational studies or experimental studies.

Our systematic review focuses on cognitive outcomes in relation to greenspace and bluespace in children and adolescents aged 0–18; it captures both observational and experimental studies. Cognitive outcomes are presented according to an evidence-based taxonomy of human cognitive abilities: the Cattell-Horn-Carroll (CHC) theory.

Methods: We conducted searches in the PubMed and PsychInfo databases, from their inception dates to 17 December 2021. We used three-text terms related to outcome, exposure, and population as well as MeSH terms for outcome and population. Further, the reference lists and existing reviews were searched ("snowball" search) until 21 April 2022 to detect additional studies. For the results reporting, we followed the updated guidelines of the Preferred Reporting Items for Systematic reviews and Meta Analyses (PRISMA).

We included observational and experimental studies on greenspace or bluespace exposure in relation to cognitive functioning, published in English, German, or Polish. Two reviewers independently checked study eligibility and extracted data. Two reviewers evaluated the risk of bias according to the Office of Health Assessment and Translation (OHAT) tool. At all stages, discrepancies between the two reviewers were solved via discussion with a third reviewer.

Results: Records identified from PubMed (n = 2030) and PsycINFO (n = 1168) were deduplicated and screened. Twenty one reports were first selected. The "snowball" search revealed 16 additional reports. Altogether, 39 studies (17 experimental and 22 observational) published in 37 reports were qualified. The data extraction showed that the methodology used in the studies was heterogenous and the findings were inconsistent. The majority of the studies investigated attentional functioning, which we subdivided into two categories according to the CHC theory: attentional control and reaction and decision speed (12 studies) and attentional control and processing speed (10 studies). Eleven studies investigated working memory and/or short-term memory that we categorized as CHC working memory capacity. Nine studies investigated intellectual functioning, which we categorized as CHC general ability, fluid reasoning, and comprehension-knowledge. Two studies investigated visual-spatial skills, which we categorized as CHC visual processing and psychomotor speed. One study measured parent-reported attention; two studies examined early childhood/cognitive development; three studies examined decision-making and self-regulation, which can be categorized as several CHC theory abilities.

Discussion: The heterogeneity of the included studies does not permit clear conclusions for our review. In accordance with previous systematic reviews, greenspace and bluespace were not more strongly related to a particular domain of cognitive functioning than other cognitive domains, and no effects of age or type of

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exposure assessment on the association between nature and cognition were detected. Further research is needed, including state-of-the-art of assessment of cognitive outcomes and diverse exposure assessment methods within both observational and experimental approaches. Expertise will be required in several domains, such as environmental epidemiology, cognitive psychology, and neuropsychology.
Systematic review registration number (INPLASY): 202220018.

1. Introduction

Recent years have seen rapid development in research devoted to the potential effects of nature (typically generically referred to as "greenspace" and "bluespace", respectively meaning vegetated and water feature elements of the environment) on cognitive functioning. Such research interest is justified by two well-established theories of environmental psychology: attention restoration theory (ART; Kaplan, 1995) and stress reduction theory (Ulrich et al., 1991); these are further extended by relational restoration theory (RRT) and collective restoration theory (Hartig, 2021). All four theories elaborate on different aspects of how nature enables restoration and thereby improves cognitive performance. Importantly, this restoration pathway is known to interplay with two instoration pathways (Markevych et al., 2017): physical activity and social cohesion (Dzhambov et al., 2018, 2020), which also improve cognitive functioning (Hillman et al., 2019; Peng et al., 2022).

Cognition refers to all the activities and mechanisms concerned with the acquisition, storage, retrieval, and processing of information (Bayne et al., 2019). Cognitive abilities determine what a person knows and how a person receives and interprets stimuli from the environment. Cognitive abilities are crucial to our functioning in society as they affect all areas of human life (Gerrig et al., 2015; Reed, 2012). Several factors are associated with cognition, but age (Schaie and Willis, 2010), sex (Reynolds et al., 2022), and educational attainment (Clouston et al., 2012) are considered the most meaningful. Also, the impact of other factors has received research attention, particularly, life-style (Serra et al., 2020), culture (Posner and Rothbart, 2017), and nature (de Keijzer et al., 2016).

We identified eight published systematic reviews that attempted to summarize the associations between nature and cognition (de Keijzer et al., 2016; Gascon et al., 2015; Islam et al., 2020; Luque-García et al., 2022; Ohly et al., 2016; Stevenson et al., 2018; Vanaken and Danckaerts, 2018; Vella-Brodrick and Gilowska, 2022). However, half of the existing reviews are outdated, and none of them are specific to cognitive functioning in children of all ages. Except for Gascon et al. (2015), these reviews were focused on either only observational (de Keijzer et al., 2016; Islam et al., 2020; Luque-García et al., 2022; Vanaken and Danckaerts, 2018) or only experimental research (Ohly et al., 2016; Stevenson et al., 2018). Except for Gascon et al. (2015), no previous reviews have looked into the effects of bluespace on cognition.

When looking into the search terms and domains reported in the published systematic reviews, cognitive functioning does not appear to be well understood or correctly operationalized, at least not among the environmental epidemiologists who led the majority of the reviews. As a brief example, in the only existing systematic review on specific cognitive outcomes (de Keijzer et al., 2016), studies on academic performance and attention deficit hyperactivity disorder (ADHD) were included as well, although these should be outside of the scope.

It is true that there is a lack of consensus on how many cognitive domains exist and how they are related to each other. The Cattell-Horn-Carroll (CHC) taxonomy of cognitive abilities (Carroll, 1993; Cattell, 1943, 1963; Cattell and Horn, 1978) is the most evidence-based theory on human intelligence (Jewsbury et al., 2017; van Rentergem et al., 2020). It has been used to organize meta-analyses investigating the relations between cognitive abilities and other variables across numerous studies (Schneider and McGrew, 2018), including epidemiological research (Pase and Stough, 2014; Stough and Pase, 2015). Briefly, the CHC theory is a hierarchical model that organizes human cognitive abilities on three strata, with one general ability (g) on stratum III, 17 broad abilities on stratum II, and approximately 70 narrow abilities on stratum I (McGrew, 2009; Schneider and McGrew, 2018). Fig. 1 presents a selection of broad and narrow CHC theory abilities that are relevant to the research summarized in this review. Since there is no commonly used nomenclature for cognitive outcomes within environmental epidemiology, we suggest the implementation of a taxonomy based on CHC theory.

The objective of our systematic review is to examine the association between cognitive functioning and greenspace and bluespace in children aged 0–18 years across observational and experimental studies.

The following questions are addressed in this review:

(1) Is there an association between exposure to greenspace or bluespace and cognitive functioning in children?
(2) Is exposure to greenspace or bluespace more strongly related to a particular domain of cognitive functioning than to other domains of cognitive functioning?
(3) Does the association between exposure to greenspace or bluespace and cognitive functioning in children differ across ages?
(4) Does the association between greenspace and bluespace differ depending on the types and methods of exposure assessment?

To provide a broader perspective on the topic, an interdisciplinary team of environmental epidemiologists and psychologists specialized in greenspace and bluespace, cognition, and systematic reviews contributed to the review.

2. Methods

2.1. Registered protocol

We followed the updated guidelines (Page et al., 2021) of the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA; Moher et al., 2009; for the PRISMA checklist, see Supplementary 1). The systematic review and its study protocol were preregistered on the International Platform of Registered Systematic Review and Meta-Analysis Protocols (INPLASY) (Buczyłowska et al., 2022). The present work was conducted in line with the registered protocol, to which we made only a few minor changes. In the protocol, we stated that "assessed cognitive functioning using an objective measure such as standardized psychometric tasks" is required for a study to be included. While screening the literature, we decided to also accept subjective standardized measures, as they are commonly used within the cognitive assessment of children. According to the registered protocol, the main outcomes should be cognitive functioning, including attention, memory, executive functioning, intelligence, etc.; however, in the review we decided to be more specific and stick to the CHC theory when presenting the results. We also extended the list of study characteristics to be extracted, specifically the model's adjustment, data analysis, and the assessor of cognitive measures.

2.2. Eligibility criteria

We formulated our inclusion and exclusion criteria according to the PECOS (Population, Exposure, Comparator, Outcome, Study) statement (Division of the National Toxicology Program National Institute of Environmental Health Sciences, 2019), as described below:

(P) general (non-clinical) human population of children 0–18 years of age;
(E) assessed greenspace or bluespace exposure using objective (e.g., normalized difference vegetation index (NDVI), proportion of greenspace or bluespace, distance to greenspace or bluespace), or subjective measures (e.g., self-reported frequency of visits to greenspaces or bluespaces, quality of green space or blue space);
(C) exposed to more greenspace or bluespace compared to those exposed to lower levels;
(O) assessed cognitive functioning using objective and subjective measures, such as standardized psychometric tasks and parent, teacher or self-report questionnaires;
(S) original observational human studies, including longitudinal, case-control or cross-sectional studies, and quasi-experimental or experimental studies, published in peer-reviewed scientific journals, in English, German, or Polish. Studies focused on behavior only (i.e., without cognition) were excluded. Also, studies focused on cognitive disorders or/and clinical populations were excluded. If studies included both clinical and non-clinical populations, only results regarding non-clinical populations are reported. There were no restrictions on the basis of the publication date.

2.3. Information sources and search strategy

We conducted searches of two databases: PubMed and PsycInfo via EBSCO. The number of databases searched is in accordance with the recommendations of the AMSTAR 2 tool (https://www.bmj.com/content/358/bmj.j4008). PubMed is the main database for epidemiological studies, whereas PsycInfo covers psychological research. We believe that by searching these two databases, we were able to identify the majority of peer-review studies relevant for the topic of this review. The searches were done on 17 December 2021. We also conducted a "snowball" search to detect additional studies by searching through the reference lists of publications eligible for full-text review and by using Google Scholar to identify studies citing them. The "snowball" search was finished on 23 March 2022. Further, by April 2022, we had manually searched the reference lists of previously published reviews.

We used terms, which have frequently been used in previous research and capture all relevant facets of the domains investigated. We combined terms related to outcomes (e.g., cognition, cognitive, intelligence) and exposure (e.g., greenspace, bluespace, urban environment) with terms related to population (e.g., child, boy, girl). Additionally, we used Medical Subject Headings (MeSH) terms for outcome (cognition, intelligence, attention, memory, executive function) and population (child, adolescent, puberty, infant, newborn) for the PubMed search. After formulating a search strategy, we adapted it to each of the two databases. We applied language (English, German, and Polish) restrictions. The complete search strategy is depicted in Supplementary 2 Fig. 1.

2.4. Selection and data collection process

To deduplicate and screen the results, we used the scanning online software tool Rayyan (https://www.rayyan.ai/; Ouzzani et al., 2016). After deduplication, two reviewers (AJ and AS) independently scanned titles and abstracts according to the eligibility criteria. They further reviewed the full-text publications to decide which publications met the eligibility criteria for inclusion in the review. If there were differences between the reviewers' opinion regarding the eligibility of a publication, they were resolved by discussion with a third reviewer (DB).

Two independent reviewers conducted the data extraction (NS and IM). The reviewers checked each other's extractions and confirmed their accuracy. A Microsoft Word document was used for data extraction. Any discrepancies in data extraction between the two reviewers were resolved by discussion with a third reviewer (DB).

Eligible outcomes to be extracted were categorized as specific domains of cognitive functioning according to the CHC theory. The outcomes were extracted if they were measured using standardized psychometric tools designed to assess cognition. If multiple outcomes were reported, only those derived from cognitive measures were extracted. If multiple outcomes assessing different cognitive domains were reported, all of them were extracted and accordingly assigned to specific cognitive domains.

The following study characteristics were extracted from each report: the report (author(s), year of publication, country); sample characteristics (age, type of school/type of population, sample size); study design/project/study, outcome assessment (outcomes, cognitive measure,

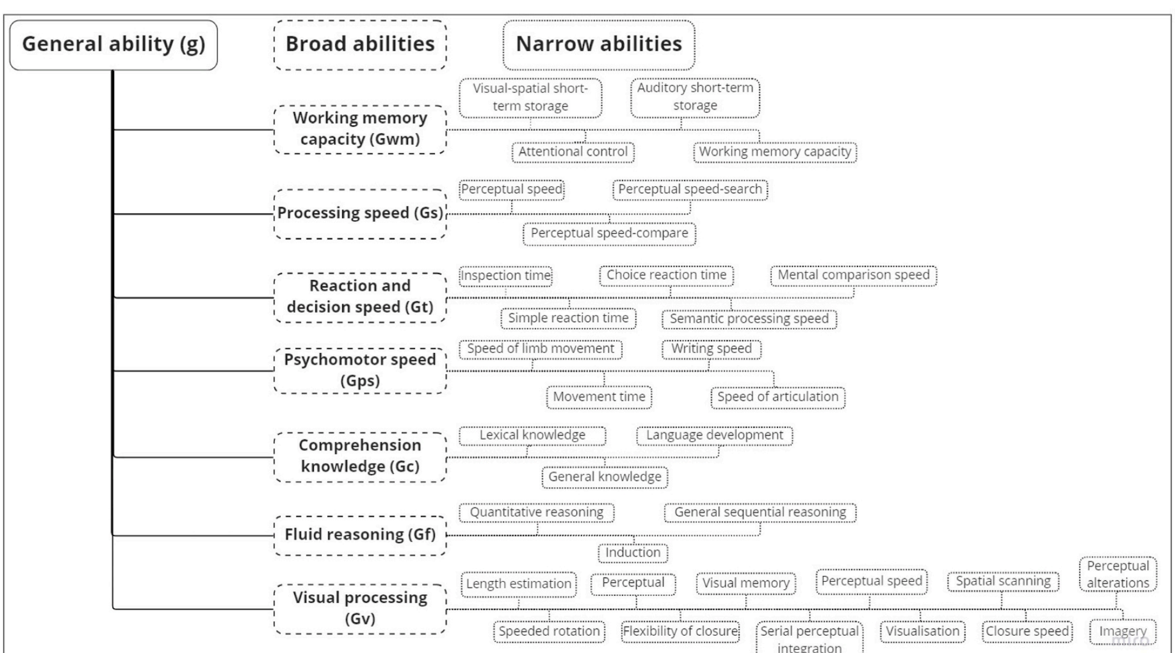

Fig. 1. Cattel-Horn-Carroll (CHC) theory three strata of cognitive abilities.

assessor), exposure assessment (greenspace and bluespace metric/intervention), and analysis (model's adjustment, data analysis, results).

2.5. Study risk of bias assessment

We evaluated the risk of bias (RoB) of the included studies according to the Office of Health Assessment and Translation (OHAT) tool (Lam et al., 2016; OHAT, 2015; Woodruff and Sutton, 2014; Zhao et al., 2018). The evaluation covered three key criteria: exposure assessment, outcome assessment, and confounding bias. Other criteria were included, such as selection bias, attrition/exclusion bias, selective reporting bias, conflict of interest, and statistical methods and other sources of bias. Each of these domains was classified as "low", "probably low", "probably high", or "high" risk based on specifically tailored criteria (Supplementary 2 Table 1). RoB assessment was done by two reviewers: DB handled outcome assessment and TZ performed other assessments. A third reviewer (IM) rechecked all the results. Indetermination was solved via discussion between the three reviewers.

3. Results

3.1. Study selection

The study selection process is depicted by Fig. 2. Altogether 39 studies (17 experimental and 22 observational) published in 37 reports were selected. Table 1 gives a brief overview of relevant study characteristics for all included reports. Four studies appeared eligible to meet the inclusion criteria during the full text reading, but they were excluded after extraction of relevant study characteristics. Allah Yar and Kazemi (2020) failed to provide sufficient information regarding outcome assessment; based on the available information, we could identify shortcomings in the construction of the used cognitive measure. Barbiero et al. (2021) presented only descriptive statistics without any inferential statistical analysis. In the study by Carrus et al. (2012), there was insufficient information on the standardization procedure and the description of cognitive measures; moreover statistical analysis that included all relevant outcomes was missing. In the study by Ward et al. (2016), descriptions of cognitive measures and information on how outcomes were calculated were missing.

3.2. Risk of bias evaluation

Fig. 3 illustrates the results of the RoB assessment for the selected studies; the detailed assessment is listed in Supplementary 2. We did not further exclude studies based on the RoB results since meta-analysis was not our intention. Looking into the included studies, regardless of observational or experimental research, we found some RoBs in common; therefore, we collectively summarize the RoB results below, and there are no exhaustive descriptions in the following subsections.

Regarding the exposure assessment, none of the included studies were rated as "low risk". The observational studies usually adopted NDVI or distance to greenspace but lacked other possible metrics like tree cover. Although 27 studies considered individual-level or different exposure buffers as well as life-long or multiple time-point exposures, only one study (Bakir-Demir et al., 2019) simultaneously performed objective and perceived/subjective measurements of greenspace. In contrast, the experimental studies with a shorter duration and a smaller sample of participants had more detailed exposure assessments. Nevertheless, these studies cannot provide individual-level exposure, but they normally expose a group of participants in a setting.

As for outcome assessment, nine studies were rated as "low risk" and 22 studies were rated as "probably low risk". None of the studies were assessed as "high risk" and only four studies were rated as "probably high risk". 22 studies were given a lower rating in the RoB because they lacked information on who conducted the assessments, or the information was not sufficient (i.e., "trained staff", "experimenters"), or the assessors were rated as not sufficiently prepared (i.e., "teachers"). Although we consider information on assessors as significant, based solely on this one criterion the majority of studies were given a lower rating in the RoB and were therefore rated as "probably low risk" in the RoB for outcome assessment. Seven studies did not provide necessary details that would allow proper identification of the cognitive assessment tools applied, such as author names, year and country of publication. Four studies were given a lower rating because they applied

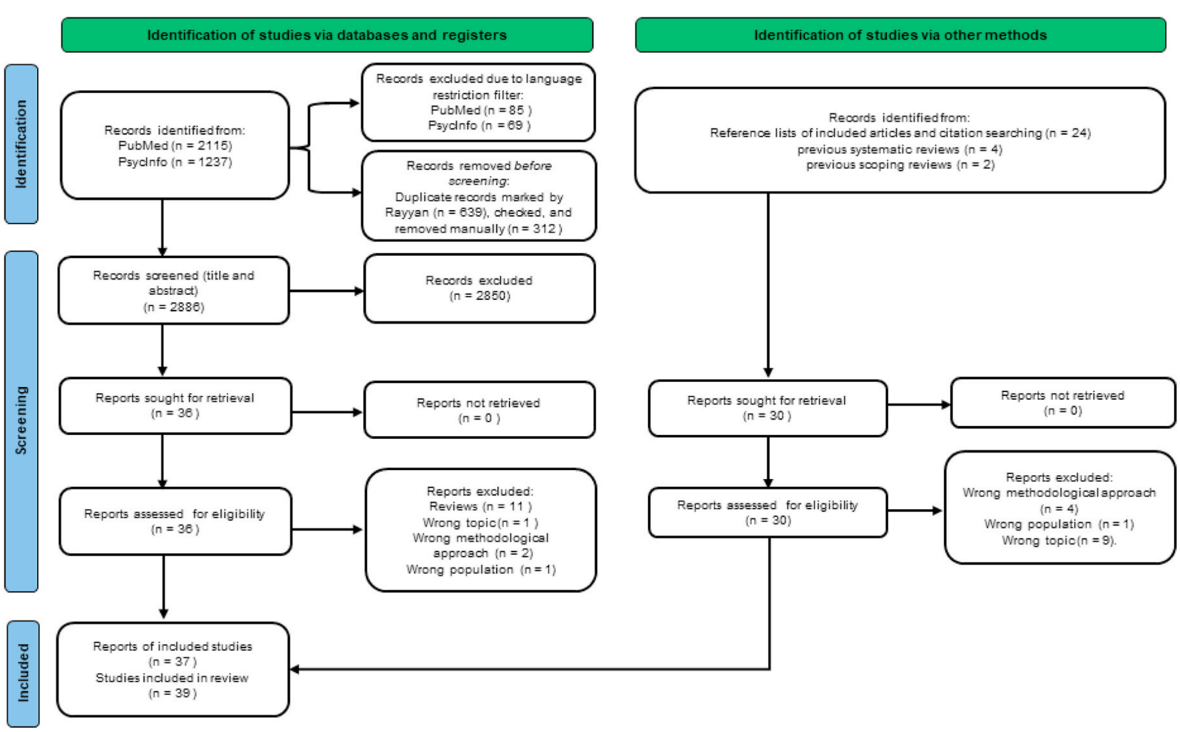

Fig. 2. Study selection process.

Table 1
Study characteristics of included reports.

Characteristic of report	Report count	References (first author and year)
Sample size		
<50	7	Amicone et al., 2018 (study 2); Berto et al., 2015; Mygind et al., 2018; Schutte et al., 2017b; Stevenson et al., 2019; Torquati et al., 2017; Wells 2000
50–100	7	Amicone et al., 2018 (study 1); Bernardo et al., 2021; Johnson et al., 2019; Kelz et al., 2013; Li and Sullivan, 2016; Mancuso et al., 2006; Wallner et al., 2018
101–500	7	Anabitarte et al., 2021; Anabitarte et al., 2022; Asta et al., 2021; Bakir-Demir et al., 2019; Dockx et al., 2022; Lee et al., 2021; van den Berg et al., 2016
501–1000	6	Bijnens et al., 2020; Bijnens et al., 2022; Jimenez et al., 2021a; Jimenez et al., 2021b; Lindemann-Matthies et al., 2021; van Dijk-Wesselius et al., 2018
1001–5000	9	Almeida et al., 2022; Dadvand et al., 2015; Dadvand et al., 2017; Flouri et al., 2019; Flouri et al., 2022; Julvez et al., 2021; Liao et al., 2019; Maes et al., 2021; Reuben et al., 2019
>5000	2	Binter et al., 2022; Jarvis et al., 2021
Study design		
Observational	22	Almeida et al., 2022; Anabitarte et al., 2022; Asta et al., 2021; Bakir-Demir et al., 2019; Bijnens et al., 2020; Bijnens et al., 2022; Binter et al., 2022; Dadvand et al., 2015; Dadvand et al., 2017; Dockx et al., 2022; Flouri et al., 2019; Flouri et al., 2022; Jarvis et al., 2021; Jimenez et al., 2021a; Jimenez et al., 2021b; Julvez et al., 2021; Lee et al., 2021; Liao et al., 2019; Lindemann-Matthies et al., 2021; Maes et al., 2021; Reuben et al., 2019; Wells 2000
Experimental/quasi experimental	15	Amicone et al., 2018; Anabitarte et al., 2021; Bernardo et al., 2021; Berto et al., 2015; Johnson et al., 2019; Kelz et al., 2013; Li and Sullivan, 2016; Mancuso et al., 2006; Mygind et al., 2018; Stevenson et al., 2019; Schutte et al., 2017b; Torquati et al., 2017; van den Berg et al., 2016; van Dijk-Wesselius et al., 2018; Wallner et al., 2018
Sample age		
Children (0–10 years)	15	Almeida et al., 2022; Amicone et al., 2018; Anabitarte et al., 2021; Asta et al., 2021; Bernardo et al., 2021; Binter et al., 2022; Dadvand et al., 2017; Dockx et al., 2022; Jimenez et al., 2021b; Julvez et al., 2021; Lee et al., 2021; Liao et al., 2019; Mancuso et al., 2006; Mygind et al., 2018; Schutte et al., 2017b
Adolescents (11–18 years)	5	Bijnens et al., 2022; Flouri et al., 2019; Kelz et al., 2013; Li and Sullivan, 2016; Wallner et al., 2018
Both	17	Anabitarte et al., 2022; Bakir-Demir et al., 2019; Berto et al., 2015; Bijnens et al., 2020; Dadvand et al., 2015; Flouri et al., 2022; Jarvis et al., 2021; Jimenez et al., 2021a; Johnson et al., 2019; Lindemann-Matthies et al., 2021; Maes et al., 2021; Reuben et al., 2019; Stevenson et al., 2019; Torquati et al., 2017; van den Berg et al., 2016; van Dijk-Wesselius et al., 2018; Wells 2000
Year of publication		
2000–2010	2	Wells 2000; Mancuso et al., 2006
2011–2015	3	Berto et al., 2015; Dadvand et al., 2015; Kelz et al., 2013
2016–2020	16	Amicone et al., 2018; Bakir-Demir et al., 2019; Bijnens et al., 2020; Dadvand et al., 2017; Flouri et al., 2019; Johnson et al., 2019; Li and Sullivan, 2016; Liao et al., 2019; Mygind et al., 2018; Reuben et al., 2019; Stevenson et al., 2019; Schutte et al., 2017b; Torquati et al., 2017; van den Berg et al., 2016; van Dijk-Wesselius et al., 2018; Wallner et al., 2018
2021+	16	Almeida et al., 2022; Anabitarte et al., 2021; Anabitarte et al., 2022; Asta et al., 2021; Bernardo et al., 2021; Bijnens et al., 2022; Binter et al., 2022; Dockx et al., 2022; Flouri et al., 2022; Jarvis et al., 2021; Jimenez et al., 2021a; Jimenez et al., 2021b; Julvez et al., 2021; Lee et al., 2021; Lindemann-Matthies et al., 2021; Maes et al., 2021
Geographic region		
Europe	27	Almeida et al., 2022; Amicone et al., 2018; Anabitarte et al., 2021; Anabitarte et al., 2022; Asta et al., 2021; Bakir-Demir et al., 2019; Bernardo et al., 2021; Berto et al., 2015; Bijnens et al., 2020; Bijnens et al., 2022; Binter et al., 2022; Dadvand et al., 2015; Dadvand et al., 2017; Dockx et al., 2022; Flouri et al., 2019; Flouri et al., 2022; Julvez et al., 2021; Kelz et al., 2013; Lindemann-Matthies et al., 2021; Maes et al., 2021; Mancuso et al., 2006; Mygind et al., 2018; Reuben et al., 2019; Stevenson et al., 2019; van den Berg et al., 2016; van Dijk-Wesselius et al., 2018; Wallner et al., 2018
North America	8	Jarvis et al., 2021; Jimenez et al., 2021a; Jimenez et al., 2021b; Johnson et al., 2019; Li and Sullivan, 2016; Schutte et al., 2017b; Torquati et al., 2017; Wells 2000
Asia	2	Lee et al., 2021; Liao et al., 2019
Green/bluespace inclusion		
Greenspace only	34	Amicone et al., 2018; Anabitarte et al., 2021; Anabitarte et al., 2022; Asta et al., 2021; Bakir-Demir et al., 2019; Bernardo et al., 2021; Berto et al., 2015; Bijnens et al., 2020; Bijnens et al., 2022; Dadvand et al., 2015; Dadvand et al., 2017; Dockx et al., 2022; Flouri et al., 2019; Flouri et al., 2022; Jarvis et al., 2021; Jimenez et al., 2021a; Jimenez et al., 2021b; Julvez et al., 2021; Johnson et al., 2019; Kelz et al., 2013; Lee et al., 2021; Li and Sullivan, 2016; Liao et al., 2019; Lindemann-Matthies et al., 2021; Mancuso et al., 2006; Mygind et al., 2018; Reuben et al., 2019; Stevenson et al., 2019; Torquati et al., 2017; Schutte et al., 2017b; van den Berg et al., 2016; van Dijk-Wesselius et al., 2018; Wallner et al., 2018; Wells 2000
Greenspace and bluespace	3	Almeida et al., 2022; Binter et al., 2022; Maes et al., 2021
Greenspace metric type		
Observational studies		
GIS-derived	19	Almeida et al., 2022; Anabitarte et al., 2022; Asta et al., 2021; Bijnens et al., 2020; Bijnens et al., 2022; Binter et al., 2022; Dadvand et al., 2015; Dadvand et al., 2017; Dockx et al., 2022; Flouri et al., 2019; Flouri et al., 2022; Jarvis et al., 2021; Jimenez et al., 2021a; Jimenez et al., 2021b; Julvez et al., 2021; Lee et al., 2021; Liao et al., 2019; Maes et al., 2021; Reuben et al., 2019
GIS-derived and perceived	1	Bakir-Demir et al., 2019
Expert rating	2	Lindemann-Matthies et al., 2021; Wells 2000
Experimental studies	15	Amicone et al., 2018; Anabitarte et al., 2021; Bernardo et al., 2021; Berto et al., 2015; Johnson et al., 2019; Kelz et al., 2013; Li and Sullivan, 2016; Mancuso et al., 2006; Mygind et al., 2018; Stevenson et al., 2019; Schutte et al., 2017b; Torquati et al., 2017; van den Berg et al., 2016; van Dijk-Wesselius et al., 2018; Wallner et al., 2018
Cognition domain		
Attentional control/reaction and decision speed	13	Anabitarte et al., 2021; Anabitarte et al., 2022; Bijnens et al., 2022; Dadvand et al., 2015; Dadvand et al., 2017; Dockx et al., 2022; Johnson et al., 2019; Julvez et al., 2021; Kelz et al., 2013; Reuben et al., 2019; Schutte et al., 2017b; Stevenson et al., 2019; Torquati et al., 2017

(*continued on next page*)

Table 1 (*continued*)

Characteristic of report	Report count	References (first author and year)
Attentional control/processing speed	11	Amicone et al., 2018; Bernardo et al., 2021; Berto et al., 2015; Bijnens et al., 2022; Lindemann-Matthies et al., 2021; Mancuso et al., 2006; Mygind et al., 2018; van den Berg et al., 2016; van Dijk-Wesselius et al., 2018; Wallner et al., 2018; Wells 2000
Working memory capacity	11	Bernardo et al., 2021; Bijnens et al., 2022; Dadvand et al., 2015; Dockx et al., 2022; Flouri et al., 2019; Julvez et al., 2021; Li and Sullivan, 2016; Maes et al., 2021; Reuben et al., 2019; Schutte et al., 2017b; Torquati et al., 2017
Visual processing and psychomotor speed	2	Binter et al., 2022; Jimenez et al., 2021b
Intelligence	9	Almeida et al., 2022; Asta et al., 2021; Bijnens et al., 2020; Binter et al., 2022; Flouri et al., 2022; Jimenez et al., 2021b; Julvez et al., 2021; Lee et al., 2021; Reuben et al., 2019
Early childhood/cognitive development	2	Jarvis et al., 2021; Liao et al., 2019
Decision-making, self-regulation, and emotional intelligence	3	Bakir-Demir et al., 2019; Flouri et al., 2022; Jimenez et al., 2021a

questionnaires, which are considered less valid than objective measures for the assessment of cognition. Two studies (Binter et al., 2022; Dadvand et al., 2017) were given a lower rating because they used different cognitive measures at different time points and assumed that the assessed cognitive functions were the same.

In terms of confounding bias, most of the observational studies (18 out of 22) considered more than three important covariates, including age, sex, education level, household income and regional social-economic status data. Some experimental studies had a relatively higher risk of bias because of imbalanced grouping (four studies, e.g., no control group) and mixed exposure of greenspace and physical activity (three studies).

Twelve studies were rated as “low” or “probably low” in the domains of Selection bias, Attrition/exclusion bias, Selective reporting bias, and Conflict of interest. Typically, studies were given a lower rating in the RoB because they included non-randomly selected participants (15 experimental studies), failed to elaborate on the reasons for the exclusion of participants (six studies), and had a potential conflict of interest or did not report conflicts of interest in the manuscript (12 studies).

In addition, statistical methods were inappropriate or insufficiently described in five studies. Specifically, two studies (Jarvis et al., 2021; Liao et al., 2019) adopted Baron and Kenny’s method (Baron and Kenny, 1986) for mediation analysis, but the use of more robust methods is recommended (Dzhambov et al., 2020). Also, more than half of the experimental studies (11 out of 17) had no sample calculations or reported no study protocols.

3.3. *Characteristics of individual studies*

The characteristics of individual studies are depicted in Table 2 for observational research and Table 3 for experimental research. We assigned the extracted results to specific domains of cognitive functioning according to the CHC theory as follows (please also see Table 1).

3.3.1. *Attentional control and reaction and decision speed*

The majority of the observational studies on the association between the natural environment and cognition examined different facets of attention as outcomes. Attention refers to the processes that supervise which percepts arise in consciousness; it interfaces with many other cognitive domains, therefore it is crucial for many cognitive tasks (Schneider and McGrew, 2018). Most of the reviewed studies used computerized measures such as the Attention Network Test (ANT; Rueda et al., 2004) or the Continuous Performance Test (CPT; Conners, 2000). According to the CHC theory, measures of this kind involve reaction and decision speed (often referred to as reaction time (RT) and RT variability) as well as attentional control, often referred to as inhibition, executive/cognitive/impulse control, or selective attention. Reaction and decision speed are defined as the average speed of making simple decisions when items are presented individually and the examiner or a computer controls the pace at which the next item is presented. Attentional control is defined as the ability to flexibly manipulate the spotlight of attention in order to focus on task-relevant stimuli and ignore task-irrelevant stimuli (Schneider and McGrew, 2018).

3.3.1.1. Experimental studies. Among the experimental studies, three found a positive association with at least one outcome, and one found no association at all. In a study conducted in Canada, Johnson et al. (2019) demonstrated the effects of a 30-min walk in a natural environment in 8- to 15-year-old children on two computerized measures of endogenous attention derived from the Combined Attention Systems Test (CAST), but not on any measures of exogenous attention. In a study by Schutte et al. (2017b) conducted in the USA, 4- to 17-year-olds responded faster on the CPT after a 20-min nature walk than after an urban walk. School-aged children performed significantly better on the attention task than preschoolers following the nature walk, but not the urban walk. Walk type did not affect inhibitory control (go/no-go task). In a Danish study (Stevenson et al., 2019), a 30-min nature walk was associated with faster reaction times and improved stability of performance derived from ANT executive attention score for 10- to 14-year-olds.

On the other hand, researchers from Spain (Anabitarte et al., 2021) found no association in 7-year-olds between ANT-derived attention outcomes (hits, accuracy, reaction time, reaction time variability) and collected post-play activities in green space compared to grey spaces. Also, researchers from Austria (Kelz et al., 2013) observed no difference in ANT executive network performance between 13- to 15-year-olds attending school after adding more greenery to the schoolyard and those attending control schools. Further, in a study conducted in the USA (Torquati et al., 2017) there was no difference in performance between a natural outdoor area and an indoor laboratory room on attention and inhibitory control (go/no-go and CPT).

3.3.1.2. Observational studies. Five observational studies found a positive association with at least one outcome, whereas one study found a negative association, and another found no association. Cross-sectional analyses by Anabitarte et al. (2022) showed a protective association between NDVI within 300 m around residential address and inattentiveness (standard error of reaction time from ANT) at 11–13 years, but not for hit reaction time. In a study by Belgian researchers (Bijnens et al., 2022) green space in a 2000 m radius around the residence and school was associated with a faster reaction time in 14- to 17-year-olds as measured by the Stroop test and CPT. Vegetation higher than 3 m was associated with a faster reaction when measured with CPT. The presence of accessible greenspace in a district, small urban green, urban green, and urban forest was associated with faster reaction time. Also, researchers from Spain (Dadvand et al., 2015) showed a greater reduction in inattentiveness in 7- to 13-year-olds (12-mo change in developmental trajectory of hit reaction time standard error from ANT) related to school greenness (NDVI) and to combined school-home greenness, but not to home greenness. Importantly, adding elemental carbon to models explained 20–65% of associations between school greenness and 12-mo progress in attention. In another study by Dadvand et al. (2017), NDVI in

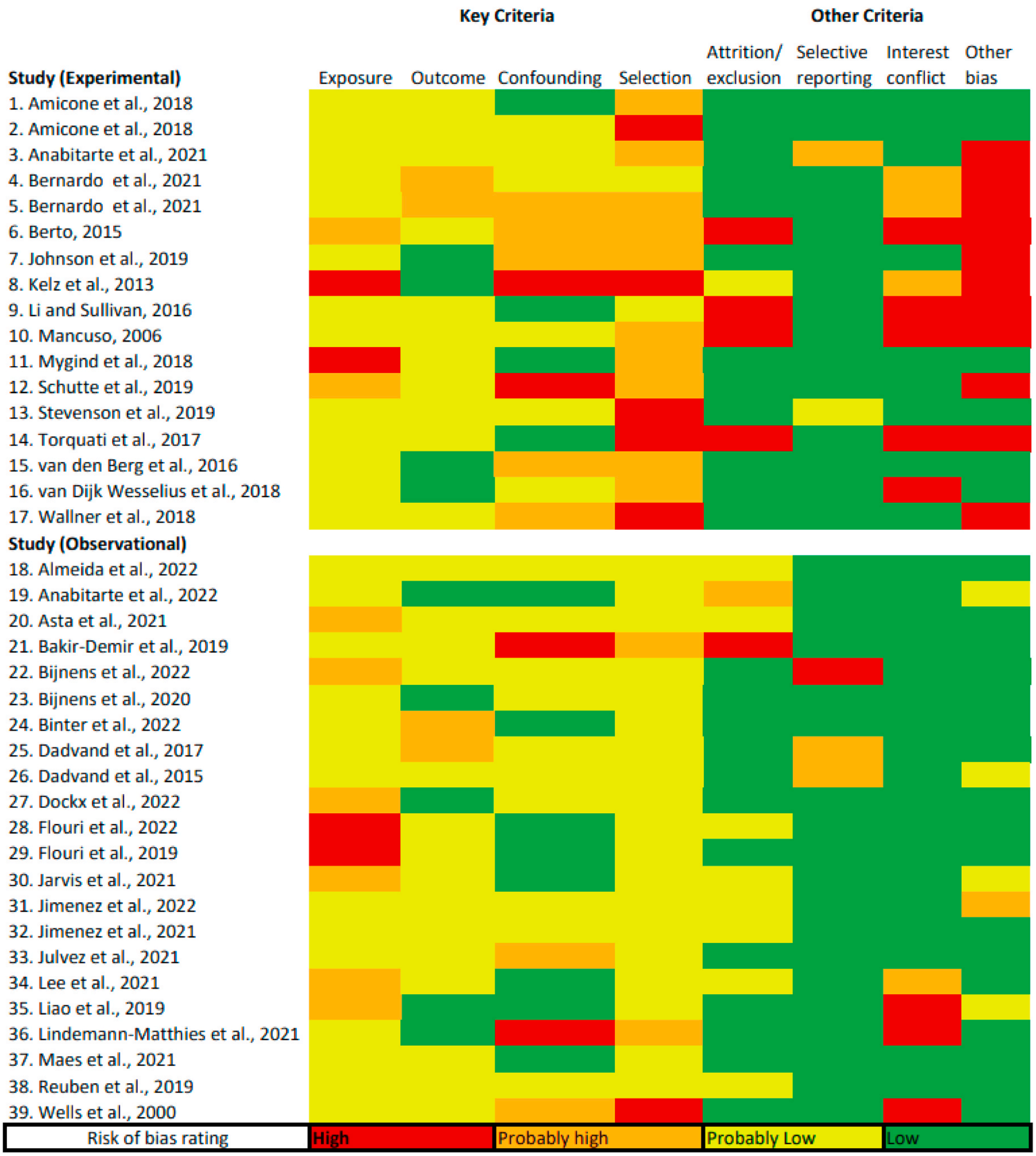

Fig. 3. Results of the risk of bias assessment.

all buffers was associated with a lower number of omission errors (Conners' Kiddie Continuous Performance Test (K-CPT)) at age 4–5 years but not 7 years (ANT). No associations with commission errors were observed. NDVI in all buffers was inversely associated with hit reaction time standard error at ages 4 to 5 (K-CPT) and 7 (ANT). Vegetation Continuous Fields (VCF) were not associated with attention outcomes. A study conducted in Belgium (Dockx et al., 2022) demonstrated an association in 4- to 6-year-olds between total natural non-agricultural space and attention and psychomotor speed (the Motor Screening Task from Cambridge Neuropsychological Test Automated Battery (CANTAB) within 50 m and 100 m buffers around the residence. In contrast, in a study conducted in the USA (Julvez et al., 2021), higher NDVI within a 100 m buffer during pregnancy was associated with higher inattentiveness (hit reaction time standard error from ANT); nevertheless, this association was not significant after multiple testing correction. Also, in a study from the UK (Reuben et al., 2019) attention (Rapid Visual Information Processing subtest from CANTAB) at age 18 was not associated with average lifelong residential NDVI when confounding by neighborhood and family SES was taken into account.

3.3.2. Attentional control and processing speed

Several studies have investigated the association between natural environment and attention using paper-pencil tasks. According to the CHC theory, besides attentional control, tasks of this kind involve processing speed, which is defined as the ability to control attention and to quickly and fluently perform relatively simple repetitive cognitive tasks. In contrast to reaction and decision speed, all processing speed items are presented at once, and the examinee determines when the next item will be attempted (Schneider and McGrew, 2018).

3.3.2.1. Experimental studies. Among eight experimental studies, seven found a positive association with at least one outcome, and one found no

Table 2
Main characteristics of observational studies included.

#	Author, year, country	Study design, project/study	Age/ population, sample size	Outcome, cognitive measure, assessor	Green- and bluespace metric/ intervention	Model's adjustment	Data analysis	Results
1	Almeida et al. (2022), Portugal	Cross-sectional, the Generation XXI birth cohort	10 years, N = 3827	Verbal IQ, performance IQ, and global IQ: Wechsler Intelligence Scale for Children - the third edition. Assessor: trained professionals in a controlled environment.	- Greenness: Landsat NDVI in 100, 250 and 500 m buffers around residence and 50, 100, 250, 500 m buffers around school. - Urban Green Spaces (UGC): Public and free access, as availability and number of available UGS in 400 and 800 m buffers around residence and school and minimum distance to the nearest UGS. - Blue spaces: Nearest bluespace distance from residence and school.	Sex, type of school, mother's education, household monthly income, urbanicity, neighborhood socioeconomic deprivation and population density.	Generalized mixed models fitted with schools and neighborhoods as random effects. Mediators (physical activity and air pollution) treated as additional adjustment.	- NDVI 100 m buffer around school negatively associated with verbal IQ, performance IQ, and global IQ. - NDVI in 50 m negatively associated with performance IQ. - No association when looking at NDVI around the current residence. - UGS in 800 m around the residence associated with higher performance and global IQ. - No association with the number of UGS around residence or school. - No associations regarding blue spaces. - No meaningful mediation effect by physical activity or air pollution.
2	Anabitarte et al. (2022), Spain	Cross-sectional and longitudinal within a population-based INMA cohort	8 years, N = 75 and 11–13 years, N = 598	Attention: ANT (Fan et al., 2002; Rueda et al., 2004) measured twice at ages 8 and 11–13 years: hit RT median and hit RT standard error. Assessor: person prepared for this purpose.	Four indicators of greenspace exposure at current home: 1) Landsat-NDVI, 2) Vegetation Continuous Field (VCF) in buffers of 100, 300, and 500 m, 3) availability of a green space within 300 m, 4) residential distance to green spaces from Urban Atlas and EUNIS for Asturias and Gipuzkoa, respectively.	Neighborhood SES, age, sex, preterm, maternal IQ/ smoking during pregnancy. Mediator: NO2.	- General linear models for the cross-sectional analyses. - Linear mixed effects model for the longitudinal analyses.	- In cross-sectional analyses one significant protective association between average NDVI at 300 m and inattentiveness at 11–13 years. - No associations in longitudinal analysis. - No significant indirect effect for NO2.
3	Asta et al. (2021), Italy	Cross-sectional, GAS-PII cohort	7 years, N = 465	Intelligence: WISC-III: composite and subtest scores. Assessor: psychologists.	Landsat NDVI around residences at birth in 300 and 500 m buffer.	Child's age in months, gender, maternal and parental education, SES at birth, maternal age at delivery, maternal smoking during pregnancy, number of older siblings, and the psychologist. Mediator: NO_2	- Weighed multiple regressions. - Causal mediation analysis (Baron and Kenny method extended by counterfactual approach).	- No associations between NDVI in 300 m buffer and any of the IQ scores. - Association between NDVI in 500 m buffer and arithmetic subtest (partly mediated by reductions in NO2 - 35% of estimated association).

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Table 2 (*continued*)

#	Author, year, country	Study design, project/study	Age/ population, sample size	Outcome, cognitive measure, assessor	Green- and bluespace metric/ intervention	Model's adjustment	Data analysis	Results
4	Bakir-Demir et al. (2019), Turkey	Cross-sectional	8–11 years (M = 9,28), N = 299	- Emotional, behavioral, and cognitive self-regulation: Cognitive Emotion Regulation Questionnaire (CERQ-k; Garnefski et al., 2007), Emotion Regulation Questionnaire for Children and Adolescents (ERQ-CA; Gullone and Taffe, 2012), Childhood Executive Functioning Inventory (CHEXI; Thorell and Nyberg, 2008), Barratt Impulsiveness Scale-11 (BIS-11; McCoy et al., 2011; Patton et al., 1995) - Nature connectedness: Connection to Nature Index (CNI; Cheng and Monroe, 2010), Inclusion of Nature in Self Scale (INS; Schultz, 2002), and Nature Relatedness Scale (NR; Nisbet et al., 2008). - Children's temperament: Temperament in Middle Childhood Questionnaire, Version 3.0 (TMCQ; Simonds and Rothbart, 2004). Assessor: researchers.	- Landsat NDVI in 100 m buffer around home. - Mothers' and children's perceptions of levels of nearby green areas assessed by a single 4-point scale question. - Composite variable of greenery (sum of z-scores of the three variables).	Nature connectedness as mediator and perceptual sensitivity as moderator of indirect effect.	SEM moderated mediation analyses to test the associations among greenery, perceptual sensitivity, nature connectedness, and regulation skills.	- Emotional regulation not directly predicted by greenery, the relationship indirectly mediated by nature connectedness but not moderated by perceptual sensitivity. - Higher greenery and perceptual sensitivity predicted higher nature connectedness, which was in turn associated with better cognitive regulation. - Behavioral regulation not mediated by nature connectedness. The direct, total, and indirect effects of greenery on behavioral regulation problems through nature connectedness not significant.
5	Bijnens et al. (2022), Belgium	Cross-sectional, FLEHS program	13–17 years, N = 596	- Selective attention: Stroop Test - Dutch version (Xavier Educational Software Ltd), Continuous Performance Test (Conners, 2000). - Short-term memory: Digit Span Test. - Visual information processing speed: Digit-Symbol Test and Pattern Comparison Test from the Neurobehavioural Evaluation System 3 (NES3; Letz, 2000; White et al., 2003). Assessor: Field workers.	- Green space (1 m^2 resolution land cover) in 50, 100, 300, 500, 1000, and 2000 m) around residence/ school (combined) in three measures: high green (higher 3 m), low green (lower 3 m), and total vegetation (the sum of the other two). - Presence of accessible green space by road classified based on minimum area size and maximum distance.	- Age, sex, maternal education, area deprivation index. - Black carbon and road noise exposure treated as confounders.	- Multiple linear regression models. - Logistic models used for RT longer than 90th percentile.	- Green space in a 2000 m radius associated with faster RT (Stroop test and CPT). - High green associated with faster RT (CPT). - Accessible green space associated with faster RT. - Residential green space not associated with short-term memory and visual information processing speed. - No confounding by black carbon or noise.

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#	Author, year, country	Study design, project/study	Age/ population, sample size	Outcome, cognitive measure, assessor	Green- and bluespace metric/ intervention	Model's adjustment	Data analysis	Results
6	Bijnens et al. (2020), Belgium	Cross-sectional, EFPTS program	7–15 years, N = 620 (310 twin pairs)	Verbal IQ, performance IQ and total IQ: WISC - Revised (WISC-R; Wechsler, 1986). Assessor: 2 trained research workers.	Seminatural, forested, blue, and urban green areas (green space) in 5000, 4000, 3000, 2000, 1000, and 500 m buffers around the prenatal and childhood residential address (CORINE land cover). High green (higher 3 m), within 2000, 1000, 500, 300, 100, and 50 m buffers around the residence (1 m^2 dataset).	- Childhood: sex, age, parental education, neighborhood household income, year of assessment, zygosity, andchorionicity. - Pregnancy: birth weight, gestational age, birth year, cord insertion, and maternal smoking during pregnancy. - NO_2 and distance to major road treated as confounders.	- Multilevel regression analysis. - Greenspace variables categorized into tertiles to allow for nonlinearity,. Stratification by urbanicity.	- Urban green space, both during pregnancy and childhood in 1000 m–5000 m buffer associated with total and performance IQ and in 2000 m–5000 m buffer with verbal IQ. - No associations in suburban and rural areas. - High green associated with verbal and total IQ in buffer sizes larger than 500 m. - No confounding by air pollution and noise.
7	Binter et al. (2022), UK, France, Spain, and Greece	Cross-sectional, HELIX project −4 cohorts: BiB (UK), EDEN (France), INMA (Spain), and RHEA, (Greece)	4–5 years, N = 5403	- BiB cohort: verbal abilities (the British Picture Vocabulary Scale), fine motor function (the Clinical Kinematic Assessment Tool). - EDEN cohort: verbal and non-verbal abilities (Wechsler Preschool and Primary Scale of Intelligence), fine motor function (the Peg moving task). - INMA and RHEA cohorts: verbal and non-verbal abilities, gross and fine motor (the McCarthy Scales of Children's Abilities). Assessor: trained psychologists.	- Landsat NDVI within 100, 300, 500 m buffers around pregnancy and childhood address. - Straight-line distance from the home to nearest green or blue space with an area greater than 5000 m^2.	Area of inclusion, deprivation index, season of birth, native parents, maternal and paternal age at recruitment and education level, maternal smoking during pregnancy/pre-pregnancy body mass index, paternal body mass index at recruitment, parity, child sex/ age at assessment.	- Pooled linear regressions. - Area-specific meta-analyses. - NO_2 and $PM_{2.5}$ as mediators in causal mediation analysis (only BiB cohort).	- Higher greenness exposure within 300 m and 500 m during pregnancy (but not during childhood) associated with higher verbal abilities (74% of the association mediated by air pollution). - Green and blue space distance not related to verbal abilities. - No associations with nonverbal abilities, gross motor, and fine motor skills.
8	Dadvand et al. (2015), Spain	Longitudinal, BREATHE project	7–13 years, N = 2593	- 12-mo change in developmental trajectory of working memory and superior working memory: n-back test (Jaeggi et al., 2010), inattentiveness: hit RT standard error from ANT (Rueda et al., 2004). Assessor: one trained examiner per 3–4 children.	RapidEye NDVI- in 250 m buffer around residence, 50 m buffer around commuting route, 50 m buffer around school. - Total surrounding greenness index: weighted average of residential,	- Age, sex, maternal education and area level SES. - Mediation by elemental carbon checked by additional adjustment.	- Mixed linear models with repeated outcomes, child/ school as random effects. - Interaction term between age at visit and greenness to capture trajectory.	- Progress of working memory, superior working memory and greater 12-mo reduction in inattentiveness related to school greenness and to total surrounding greenness index (elemental carbon explained 20–65% of the associations). - No association with home greenness.

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#	Author, year, country	Study design, project/study	Age/ population, sample size	Outcome, cognitive measure, assessor	Green- and bluespace metric/ intervention	Model's adjustment	Data analysis	Results
					commuting and school.			
9	Dadvand et al. (2017), Spain	Cross-sectional study at two time points and lifelong exposure to greenness	4–5 years, N = 888 and 7 years, N = 978	Attention: Conners' Kiddie Continuous Performance Test (K-CPT v.5; Conners, 2000) at 4 years of age for the Sabadell cohort and at 5 years of age for the Valencia cohort; ANT (Rueda et al., 2004) at 7 y of age for both cohorts). Assessor: no information.	Landsat NDVI and Landsat Vegetation Continuous Fields (VCF), an indicator of tree canopy cover within 100, 300 and 500 m buffer around lifelong residential address.	Age, sex, preterm birth, maternal education/ cognitive performance/ smoking during pregnancy, exposure to environmental tobacco smoke, neighborhood, individual-level and area-level SES.	- Mixed models with cohort as random effects, for 4–5 years and 7 years separately. - Negative binomial models for errors and linear for SD of RT. Weighting was used to account for attrition.	- VCF were not associated with attention outcomes. - NDVI in all buffers was inversely associated with SE of RT at both ages. - NDVI in all buffers was associated with lower omission errors at age of 4–5 but not 7. - No associations with commission errors.
10	Dockx et al. (2022), Belgium	Prospective birth cohort study, ENVIRONAGE birth cohort	4–6 years, N = 430	CANTAB (2019): attention and psychomotor speed (the Motor Screening Task and Big/Little Circle), visual recognition/working memory (the Spatial Span Test and Delayed Matching to Sample). Assessor: A trained examiner.	Greenspace (natural elements, identified as all non-agricultural vegetation) around residential address in 50, 100, 300, 500, and 1000 m buffers in 1 m resolution (Groenkaart Vlaanderen - Green Map of Flanders).	Child's age, sex, maternal education, average daily screen time and time of examination, $PM_{2.5}$ and NO2	Values of the first two principal components of principal component analyses applied to the variables assessing the same cognitive domain were used as dependent variables in a multivariable linear regression model.	- The Motor Screening Task: significant inverse association between green space and the pixel distance from the target only in 50 and 100 m buffers; increase in residential green space associated with a decrease pixel unit distance from target within the 50 m and 100 m buffers. - The Delayed Matching to Sample task: increase in green space within all buffers associated with a decrease of probability of an error; positive association between green space and percentage of correct trials in all buffers but 50 m buffer.
11	Flouri et al. (2019), UK	Cross-sectional, UK's Millennium Cohort	11 years, N = 4758	Spatial working memory (Spatial Working Memory (SWM) task from CANTAB (Robbins et al., 1994)). Assessor: no information.	Ward-level proportion of greenspace (deciles) as a combination of CORINE and GLUD datasets to capture larger and smaller greenspace.	Poverty, parental education, sports participation, computer gaming, neighborhood deprivation, and residential stability.	- Mixed linear models used to account for sampling wards. - Weighting used to account for attrition.	- More greenspace associated with better spatial working memory. - Lower quantity of greenspace related to poorer spatial working memory similarly in deprived and non-deprived neighborhoods.
12	Flouri et al. (2022), UK	Cross-sectional, Millennium Cohort Study (MCS)	5 and 11 years, N = 1701	At age 5: General cognitive ability - IQ: British Ability Scales (BAS; Elliott et al., 1996). At age 11: Decision-making and risk-taking behavior (CANTAB Cambridge Gambling Task (CGT; Cambridge Cognition, 2006). Assessor: No information.	- Neighborhood greenspace (2001 Generalized Land Use Database (GLUD). - The percentages of neighborhood greenspace per Lower Layer Super Output Area (LSOA)	Domestic garden, area deprivation, maternal education, pubertal status, sex, neighborhood physical/home physical environment, overcrowding, second-hand smoke, poverty, ethnicity, IQ, exact age,	Multiple linear regression models.	- No difference between two greenspace area types (lowest decile of greenspace yes vs. no) and IQ at age 5. - Children in the least green urban areas showed higher sensitivity to reward than other urban children.

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#	Author, year, country	Study design, project/study	Age/ population, sample size	Outcome, cognitive measure, assessor	Green- and bluespace metric/ intervention	Model's adjustment	Data analysis	Results
					converted to deciles.	internalising and externalising problems.		
13	Jarvis et al. (2021), Canada	Cross-sectional analysis within a population-based cohort	5–12 years (M = 5,6), N = 27372	Early childhood development: Early Development Instrument (EDI; Janus and Offord, 2007): (1) physical health and wellbeing, (2) social competence, (3) emotional maturity, (4) language and cognitive development and (5) communication skills and general knowledge. Assessor: Kindergarten teachers.	- The annual percentage of vegetation derived from spectral unmixing of Landsat satellite image composite calculated for each year from birth to time of EDI assessment. - Lifetime residential exposure to greenspace calculated within a 250, 100 and 500 m buffers around postal code centroid.	- Covariates: sex, birth season, lone-parent household, English as a second language, maternal age, material deprivation, and urbanicity. - Moderators: sex and area-level SES - Mediators: NO2, $PM_{2.5}$ and noise.	- Multilevel regression models with teachers as random effect. - Causal mediation analysis.	- Positive association between lifetime residential greenspace and total EDI score (mediated through reductions in NO2 (97.1%), PM2·5 (29.5%), and noise (35.2%). - No association between lifetime residential greenspace and the language and cognitive development domain score. - No evidence of moderation.
14	Jimenez et al. (2021b), USA	Cross-sectional, Viva project	Early childhood (Me = 3.1 years) and mid-childhood (Me = 7.8 years), N = 857	Early childhood: vocabulary comprehension: Peabody Picture Vocabulary Test (PPVT-III; Dunn et al., 1965), visual-motor, fine-motor and visuospatial skills: Visual-Motor Subtest of the Wide Range Assessment of Visual-Motor Abilities (WRAVMA; Adams and Sheslow, 1995). Mid-childhood: crystalized and fluid intelligence: verbal and non-verbal IQ from the Kaufman Brief Intelligence Test (KBIT-2; Kaufman, 2004), visual-motor skills: the Visual-Motor Subtest from the WRAVMA and visual memory: Visual Memory Index of the Wide Range Assessment of Memory and Learning (WRAML2; Sheslow	Landsat NDVI within 90 m and 270 m buffers around residence at birth, early childhood and mid-childhood.	Age, sex, race, income, neighborhood SES, maternal intelligence and parental education. Mediators: black carbon and physical activity.	- Pearson correlation and generalized additive models for continuous exposures. - Causal mediation.	- No associations between greenness and early childhood outcomes. - Greenness exposure at early childhood nonlinearly associated with increase in non-verbal intelligence (partially mediated by black carbon, but not observed after further adjusting for early childhood cognition) and visual memory (also after adjusting for early childhood cognition and across different methodologies) in mid-childhood. - Associations were stronger for 90 m compared to 270 m buffer.

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#	Author, year, country	Study design, project/study	Age/ population, sample size	Outcome, cognitive measure, assessor	Green- and bluespace metric/ intervention	Model's adjustment	Data analysis	Results
				and Adams, 2003). Assessor: "trained staff".				
15	Jimenez et al. (2021a), USA	Cross-sectional, Viva project	Mid-childhood (Me = 7.7 years) and early adolescence (Me = 13.1 years), N = 908	Executive function and behavior: Behavior Rating Inventory of Executive Function (BRIEF; Gioia et al., 2000) assessed in mid-childhood (mother and teacher-report) and early adolescence (self-report). Three BRIEF indices: (1) Behavioral Regulation Index, (2) Metacognition Index, (3) the Global Executive Composite score (the sum of the raw scores of all subscales). Assessor: no information.	- Landsat NDVI within 90 m, 270 m and 1230 m buffers around residence at birth, early childhood, mid-childhood and early adolescence treated as quartiles. - Effects of maximum (greenness exposure maintained within the highest quartile of the data) vs. minimum exposure (greenness exposure maintained within the lowest quartile of the data).	- Time-invariant covariates: Maternal age/IQ/ smoking during pregnancy/ education/ marital status. Child age/sex/ race/ethnicity/ season of birth. - Time-varying covariates: household/ median census tract income, urbanicity.	Inverse Probability Weighting of Marginal Structural Models (IPW/ MSM).	Effects of "maximum (vs. minimum) greenness at all timepoints" not associated with mid-childhood or early adolescence executive function and behavior.
16	Julvez et al. (2021), UK, France, Spain, Lithuania, Norway, Greece	Cross-sectional within established birth cohorts (BiB, EDEN, INMA, KANC, MoBa, Rhea)	6–11 years, N = 1298	- Fluid intelligence: Raven's Coloured Progressive Matrices test (CPM; Raven and Raven, 1998). - Attention: ANT (hit RT standard error). - Working memory: N-Back task (d'). Assessor: Trained fieldwork technicians.	Green exposure (NDVI) in 100 m, 300 m, or 500 m buffer around current school and home address during pregnancy.	Cohort, maternal age, and education level, trimester of the year of conception, child age at cognitive examination and child sex.	Two approaches to build multi exposure model: 1) Exposome-wide association study considering each exposure independently; 2) deletion-substitution-addition algorithm considering all exposures simultaneously.	- Associations between higher NDVI in 100 m buffer during pregnancy and lower fluid intelligence and higher inattentiveness (not significant after multiple testing correction). - No association with working memory.
17	Lee et al. (2021), South Korea	Cross-sectional study, the Environment and Development of Children Cohort	6 years, N = 189	Total IQ, verbal IQ, and performance IQ from Korean Educational Developmental Institute's WISC (Park et al., 1996). Assessor: no information.	Percentage of total greenness, natural greenness and built greenness (Landsat-derived) in 100, 500, 1000, 1500 and 2000 m buffers around residence.	Children's sex, maternal IQ, exposure to environmental tobacco smoke, NO2, proportions of road densities in each radius during pregnancy and at age 6, subjective noise level, distance of main road from house, child's physical activity duration at age 6, personal and neighborhood SES.	Mixed models with district as random effect.	- Higher prenatal (500 m and 1000 m buffers) and postnatal built greenness associated with higher total IQ. - Prenatal and postnatal built greenness (1000 m and 1500 m buffers) associated with verbal IQ. - Prenatal exposure to total greenness (100 m and 500 m buffers) or built greenness in 500 m buffer associated with performance IQ. - Postnatal exposure in 500 m buffer to total and built greenness associated with performance IQ.

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#	Author, year, country	Study design, project/study	Age/ population, sample size	Outcome, cognitive measure, assessor	Green- and bluespace metric/ intervention	Model's adjustment	Data analysis	Results
								- IQ not associated with natural greenness.
18	Liao et al. (2019), China	Cross-sectional study, a birth cohort	2 years old, N = 1312	Childhood neurodevelopment: Mental development index (MDI) and psychomotor development index (PDI) from Bayley Scales of Infant Development (Yi et al., 1993) for each child at about 24 months. Assessor: certified psychologists.	MODIS NDVI (500 m × 500 m resolution) within a 300 m buffer area surrounding residential address at birth.	Residence area, maternal age/ education/pre-pregnancy BMI, passive smoking/ outdoor physical activities in leisure time during pregnancy, infant gender, gestational age and birth weight.	- Linear regression models - Causal mediation analysis with traffic-related air pollution and maternal physical activity during pregnancy as mediators.	- Exposure to higher levels of residential surrounding green spaces associated with both indicators of better early childhood neurodevelopment. - Reduced levels of traffic-related air pollution explained 13.6% – 28.0% of the association between exposure to green space and PDI score.
19	Lindemann-Matthies et al. (2021), Germany	Cross-sectional	8–11 years (4th grade), N = 634, in 41 classes/ 29 schools)	Attention and concentration, visual scanning speed and accuracy: d2-revision test (Brickenkamp et al., 2010). Assessor: investigator.	- Natural window views (natural elements could be seen outside. - Natural interior views (the number of plants in a classroom). - Both measures scored on 7-step scale from not natural to very natural.	Space per child, wall color, comfort and learning, stress, social wellbeing, time spent in nature, time spent on plant care.	Linear mixed models with class and school as random effects.	- Performance in the d2-revision test not significantly associated with the naturalness of the window or interior classroom views. - Time spent in natural places and on plant care also not significantly associated with any of the variables in the d2-rvevision test.
20	Maes et al. (2021), UK	Longitudinal	9–15 years, N = 3568	Executive function (composite score using computerized backwards digit span, spatial working memory and trail-making task (Luciana and Nelson, 2010; Tombaugh, 2004; Wechsler, 1944)). Assessor: no information.	- Greenspace (NDVI): woodland higher 1 m, grassland 0–1 m. - Bluespace (Ordnance Survey Open Map). - Daily exposure rate around residence/ school (50, 100, 250, 500 m): 1) natural space, 2) green vs. blue	Age, area-level deprivation, ethnicity, gender, parental occupation and school type, and models with the executive function score were additionally adjusted for air pollution.	Multilevel longitudinal regression models using Bayesian statistics. Clustering by school and spatial autocorrelation were checked but discarded.	- Higher daily exposure to woodland, but not grassland associated with higher composite executive function score during adolescence - stronger effect estimates for the two larger buffers. - No association between daily exposure to blue space and executive function.

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#	Author, year, country	Study design, project/study	Age/ population, sample size	Outcome, cognitive measure, assessor	Green- and bluespace metric/ intervention	Model's adjustment	Data analysis	Results
					space, 3) grassland versus woodland.			
21	Reuben et al. (2019), UK	Longitudinal study, cross-sectional analyses, E-Risk Longitudinal Study	5, 12, and 18 years, N = 1658	IQ as crystallized and fluid ability: - Age 5: short form of Wechsler Preschool and Primary Scale of Intelligence Revised (WPPSI-R; Buckhalt, 1990); - Age 12: short form of WISC-IV; - Age 18: short form of Wechsler Adult Intelligence Scale–IV (WAIS-IV). Executive function, working memory, and attention at Age 18: Spatial Span subtest, Spatial Working Memory subtest, and Rapid Visual Information Processing subtest from CANTAB). Assessor: no information.	- MODIS NDVI in 1 mile radius buffers around residential address at age 5, 7, 10, 12 and 18. MODIS images at years of IQ assessment were selected. - Average childhood greenness was calculated to lifelong exposures at every timepoint of IQ assessment.	- Sex, child genotype, family SES (composite of parental education, occupation, and income), neighborhood SES (Index of Multiple Deprivation, child GWAS-derived polygenic score for educational attainment).	- Full information maximum likelihood (FIML) estimated regression models for all cross-sectional analyses. - Analysis of covariance for longitudinal analyses.	- No cross-sectional nor longitudinal associations between residential greenness and overall IQ, crystallized ability or fluid ability in fully adjusted models. - No associations with executive function, working memory, and attention at 18 were observed neither (due to confounding by neighborhood and family SES).
22	Wells (2000), USA	Longitudinal study (Premove/ Postmove)	7–12 years, N = 17	Directed attention capacity: Attention Deficit Disorder Evaluation Scale (ADDES; McCarney, 1995) - mother-reported questionnaire applied pre- and post-move. Assessor: trained research assistant.	Naturalness scale of the residential environment was developed (rated by a trained research assistant pre- and post-move.	No model's adjustment.	Hierarchical regression analyses with ADDES score postmove as dependent variable, corresponding score in the prior year as independent variable, and change in naturalness as second predictor variable.	Change in the naturalness of the home significanty predicted the postmove attentional capacity: Children whose homes improved the most in terms of greenness had the highest levels of attention.

Note. RT = reaction time, SES = socioeconomic status, NO2 = nitrogen dioxide, PM2.5 = fine particulate matter, SD = standard deviation, ANT = Attention Network Test, CANTAB = Cambridge Neuropsychological Test Automated Battery, WISC = Wechsler Intelligence Scale for Children, IQ = intelligence quotient.

association at all. Researchers from Italy (Amicone et al., 2018) observed a greater increase in sustained and selective attention (Bells test) in 10-year-old children after a break in natural environment as compared to a break in built environment. However, there was no increase in impulse control (go-no-go test from the Battery for the Assessment of Children with ADHD (BIA)) in either natural or built environment. In a study conducted in Portugal (Bernardo et al., 2021) with 3rd-grade primary school children, sustained and selective attention (Bells test) did not significantly improve after introducing a green wall into the classroom, but it did after the second intervention, which involved children planting vegetables in pots. In an Italian study (Berto et al., 2015) with 9- to 11-year-olds, the best performance in sustained attention and inhibition (paper-and-pencil version of the CPT) was achieved within assessments after a walk in the alpine wood as compared to assessments in the classroom after practicing Mindful Silence and in the school playground after play-time. In another Italian study (Mancuso et al., 2006), 8- and 10-year-old children performed better on attention (Trail Making Test (TMT)) when the test was taken in a garden as compared to a classroom. Austrian researchers (Wallner et al., 2018) reported that selective attention (d2-Revision test) was significantly higher in 16- to 18-year-olds after spending time in green spaces of different types (small urban park, large urban park, forest) but the highest increase of performance was found for the large urban park. In a study conducted in the Netherlands (van den Berg et al., 2016), 7- to 10-year-old children scored better on selective attention (the Sky Search task from the Everyday Attention for Children) in classrooms with a green wall as compared to children in classrooms without a green wall. Processing speed performance (Digit Letter Substitution Test) was not affected by the green wall. In another Dutch study (van Dijk-Wesselius et al., 2018) conducted in 7- to 11-year-old children, attention restoration based on performance in information processing speed (Digit Letter Substitution Test) and selective attention (Sky search task) improved during a break in a greened schoolyard, but only after the schoolyard had already been greened for two years. In contrast to other experimental studies, in a Danish study (Mygind et al., 2018) no differences were found in attention performance (d2 test) in 10-year-old children between natural and indoor learning environments.

3.3.2.2. Observational studies. Only two observational studies have found a negative association between greenspace exposure and

Table 3
Main characteristics of experimental studies included.

#	Author, year, country	Study design, project/study	Age/ population, sample size	Outcome, cognitive measure, assessor	Green- and bluespace metric/intervention	Model's adjustment	Data analysis	Results
1.	Amicone et al. (2018) Italy	Study 1 Quasi-experimental, within-subjects design	4–5th grade (M = 10.1 years), N = 82	- Sustained and selective attention: Bells test (Biancardi and Stoppa, 1997a; 1997b). - Working memory: digit span test in WISC-IV (Wechsler et al., 2003). - Impulse control: go-no-go test from Battery for the Assessment of Children with ADHD (BIA; Marzocchi et al., 2010). Assessor: no information.	Natural environment (school garden, 1303 m^2) vs built environment (courtyard, 139 m^2)	No adjustment.	2 × 2 repeated-measures analyses of covariance to test the effect of condition (natural vs. built) and time (pretest vs. posttest) while controlling for the presentation order of conditions.	- Greater increase in sustained and selective attention and working memory from pretest to posttest only in the natural environment condition. - No increase of impulse control neither in the natural, nor in built-up environment.
		Study 2 Quasi-experimental between-subjects	Primary school children (5th grade), M = 10.8 years, N = 36	Sustained and selective attention: Bells test (Biancardi and Stoppa, 1997a). Assessor: no information.	Natural environment and built environment of approximately same size (460m^2)	No adjustment.	2 × 2 mixed model ANOVA to test the interaction effect of condition (natural vs. built) and time (pretest vs posttest).	Increase in sustained and selective attention after the time in natural environment vs. built environment break.
2	Anabitarte et al. (2021), Spain	Quasi-experimental, pretest and posttest in green vs. grey space	7 years, N = 167	Attention: ANT (Rueda et al., 2004): test scores, accuracy, RT, RT variability and impulsivity. Assessor: 3–4 instructors for 19 children on average.	Green space with trees bigger than 5000 m^2. Grey spaces – paved squares or schoolyards.	No adjustment as randomization was used.	Linear mixed models used for each of four schools separately. Effect sizes summarized using meta-analysis.	No association between exposure to green vs. grey spaces and ANT performance.
3	Bernardo et al. (2021), Portugal	Study 1 Quasi-experimental: within-/ between subjects design.	3rd grade primary school, N = 95	- Sustained and selective attention: Bells test (Biancardi and Stoppa, 1997a). -Working memory: Digital span test from WISC-IV. Assessor: no information.	- Three times outcome measurements within three months: before 1 intervention (green wall), before 2 intervention (planting lettuce in pots) and after the 2 intervention. - Two randomly selected intervention groups vs. two control groups.		One-way analysis of variance (ANOVA) of repeated measurements performed to identify the pairs of measures that differ from each other.	- Sustained and selective attention significantly improved in the intervention with vegetable pots. - Working memory significantly improved after introducing a green wall but not after vegetable pots activity.
		Study 2 Quasi-experimental: between-subjects design	3rd grade primary school, N = 75	- Sustained and selective attention: Bells test (Biancardi and Stoppa, 1997a). - Working memory: Digital span test from WISC-IV. Assessor: no information.	Two different SES schools were compared with the same type of intervention.		One-way analysis of variance (ANOVA) of repeated measurements performed to identify the pairs of measures that differ from each other.	Significant differences between the group of medium SES and the group of low SES in working memory but not in sustained and selective attention.
4	Berto et al. (2015), Italy	Within subject experimental design	9–11 years, N = 48	Sustained attention and inhibition: number of correct responses and RT from the paper-and-pencil version of the Continuous Performance test (Cornoldi et al., 1996). Assessor: teachers.	Children assessed in three different conditions: 1) in the classroom after practicing Mindful Silence, 2) in the school playground after play-time, 3) in the alpine wood after a walk.	Gender.	Repeated and mixed analyses of variance (ANOVAs), with condition as a within-subjects factor and gender as the between-subjects factor.	Best performance on sustained attention and inhibition achieved in the alpine wood after a walk as compared to assessments in the classroom after practicing Mindful Silence and in the school playground after play-time.

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Table 3 (*continued*)

#	Author, year, country	Study design, project/study	Age/ population, sample size	Outcome, cognitive measure, assessor	Green- and bluespace metric/intervention	Model's adjustment	Data analysis	Results
5	Johnson et al. (2019b), Canada	Quasi-experimental	8–15 years, M = 60	Exogenous and endogenous attention: Combined Attention Systems Test (CAST; Lawrence, 2018). Assessor: researchers (presumably psychologists).	30-min walk in natural environment (Shubie Park in Dartmouth, Nova Scotia) vs. urban environment (a busy section of downtown Halifax, Nova Scotia). Participants blindly assigned to two locations.	No adjustment.	Bayesian hierarchical modeling of both response time (RT) and error rate (ER) to evaluate the fixed effect of attentional measures and interactions with session and group.	Effects of the nature intervention on two measures of endogenous attention (alerting RT and orienting ER), but not on any of the measures of exogenous attention.
6	Kelz et al. (2013), Austria	Pre-test/post-test quasi-experiment (school with intervention vs. two control schools)	13–15 years (4th grade, M = 14,4), N = 133 including 61 controls	Executive functioning: conflict network from ANT (Fan et al., 2002). Assessor: Two experienters.	Renovated schoolyard (test group) with more greenery implemented along with enhanced seating, sports opportunities, and a drinking fountain vs. two schools without renovation (control group). Time of measurement: baseline - a month before vs. 6–7 weeks after intervention.	No adjustment.	Two-way mixed ANOVA with group as the between-subject factor (test vs. control school) and time of measurement as the within-subject factor.	- Significant interaction between group and time of measurement. - significant increase in executive functioning from pre- to post-measurement in the test school and the control schools. - Between schools a significant difference for the first time of measurement, but not the second time of measurement.
7	Li and Sullivan (2016), USA	Randomized controlled experiment	High school students, N = 94, age range not reported	- Summary attention score of attentional capacity, short-term memory and working memory: Digit Span Forward and the Digit Span Backward tests (Wechsler, 1981). - Stress: EKG, Blood Volume Pulse, Skin Conductance Level, and body temperature. Assessor: two examiners.	All students randomly assigned to three types of classrooms: 1) with no windows, 2) with windows that opened onto a built space, 3) with windows that opened onto a greenspace. All tests were conducted pre and post task in each type of room after a 30min classroom activity.	Age, gender, race, grade, health information, self-reported chronic stress levels, self-reported chronic mental fatigue, and preference for their school landscape.	- Repeated-measures ANOVA during the baseline, after class activities and after the break. - Pearson's correlation to test whether stress recovery is a pathway for attention restoration.	- Better performance on attention and working memory tests in the green window view room than in rooms without views to greenspaces. - No evidence of stress mediated the relation between view to greenspace and attention restoration.
8	Mancuso et al. (2006), Italy	Between group experimental design	8 and 10 years, N = 80	Attention: Trail Making Test (TMT; Partington and Leiter, 1949), Part A and Part B (done only by 10 year-olds). Assessor: teacher and an "operator", who timed the trials.	Garden dominated by green vegetation vs. classroom lacking natural elements.	No model adjustment.	ANOVA conducted separately for two different age groups.	Significant correlations between the time needed to solve the test (TMT part A and Part B) and the place where the test was taken - garden exposure significantly improved performance.
9	Mygind et al. (2018), Denmark	Quasi-experimental, within-subjects design	5th-6th grade (M = 10,9 years), N = 47	Complex scanning, visual tracking, and sustained attention: d2 test (Brickenkamp, 1994) Assessor: no information.	- Natural learning environment: forested area with a grassy slope overlooking a lake. - Indoor learning environment: classroom with no plants and limited view to greenery.	Covariates: condition sequence, age and sex.	- Generalized estimating equations. - Estimated marginal means calculated to illustrate differences in adjusted means.	No differences in d2 test performance conducted in natural vs. indoor learning environment.

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Table 3 (*continued*)

#	Author, year, country	Study design, project/study	Age/ population, sample size	Outcome, cognitive measure, assessor	Green- and bluespace metric/intervention	Model's adjustment	Data analysis	Results
10	Schutte et al. (2017), USA	Quasi-experimental, within-subjects design	4 years (M = 4,53), N = 17 5 years (M = 5,48), N = 16; 7 years (M = 7,4), N = 17; 8 years (M = 8,5), N = 17	- Verbal working memory: digit span backwards (DSB; Wechsler, 1955). - Spatial working memory: spatial working memory task (SWM; Schutte et al., 2017a; Schutte and Spencer, 2002). - Inhibitory control: Go/No go (Wiebe et al., 2012). - Attention: continuous performance task (CPT; Wiebe et al., 2011; 2012). Assessor: an experimenter.	Nature vs. urban 20-min walk after attention fatigue task (order was randomly assigned). No talking was encouraged during the walk but parents were invited to accompany their child and experimenter.	No adjustment.	- ANOVA conducted for each Go/No go, CPT and DSB measure with age and gender as between-participants variables and type of walk as a within-participants variable. - Mixed models with a compound symmetry covariance structure conducted on SWM measures.	- Children responded faster on the attention task after a nature walk than an urban walk. - School-aged children performed better on the attention task than preschoolers following the nature walk, but not urban walk. - Inhibitory control or verbal working memory not affected by walk type. - Preschoolers' spatial working memory more stable following the nature walk.
11	Stevenson et al. (2019), Denmark	Semi-randomized crossover trial	10–14 years 3rd grade (M = 12,03 years), N = 33	- Attention: ANT (Rueda et al., 2004): the executive attention score, standard error of RT, mean RT and total accuracy. - Eye tracking (Tobii Pro 2 Mobile Eye-Tracking Glasses). Assessor: no information.	Natural walking environment: rolling grass fields, walking tracks through young pine trees and rocks, farmland, and forest containing beech and birch.	Age, gender, order of environment, restoration tendency score, number of fixations per minute, and average fixation length.	- Linear mixed models to analyze how post-test cognitive performance varied as a function of environment, while controlling for pre-test scores.	- 30-min natural walk associated with faster RTs on correct responses, and improved stability of performance. - No influence of confounders.
12	Torquati et al. (2017), USA	Within-subject experimental design	6–11 years, N = 10	- EEG recorded during behavioral tasks. - Working memory: digit span backward. - Spatial working memory: spatial working memory task (Schutte et al., 2017a; Schutte and Spencer, 2002). - Attention and inhibitory control: go/no-go and continuous performance task (CPT; Wiebe et al., 2011; 2012). Assessor: Two experimenters.	A natural outdoor area vs. an indoor laboratory room. The order of sessions was counterbalanced (i.e., the same number of participants completed the outdoor session or indoor session first).	Gender.	Mixed linear model, ANOVA with gender as a between-participants variable and environment (indoors, outdoors) as a within-participants variable, paired *t*-test.	- No difference in performance across environments on either go/no-go or CPT but two EEG markers larger indoors than outdoors - more cognitive resources were needed. - Better performance on the spatial working memory task outdoors compared to indoors.

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Table 3 (*continued*)

#	Author, year, country	Study design, project/study	Age/ population, sample size	Outcome, cognitive measure, assessor	Green- and bluespace metric/intervention	Model's adjustment	Data analysis	Results
13	van den Berg et al. (2016), Netherlands	Controlled, prospective design	7–10 years (5–7 grades), N = 170, including 86 controls	Questionnaires adapted from test materials used in previous studies: - information processing speed: Digit Letter Substitution Test (DLST; Pradhan, 2013). - Selective attention: the Sky Search task from the Everyday Attention for Children (Manly et al., 2001). Assessor: Research assistants.	Green wall in intervention classrooms vs. control ones.	Baseline scores, school, and grade level.	Effects of the green walls were tested using repeated measures ANCOVAs, with time as a within-subjects factor, condition (green wall, control) as between-subjects factor.	- Better performance on selective attention (the Sky Search task) in classrooms with a green wall than in a classroom without a green wall. - Processing speed (Digit Letter Substitution Test) not affected by the green wall.
14	van Dijk-Wesselius et al. (2018), Netherlands	Longitudinal prospective intervention study with two follow-ups within two-years.	7–11 years, N = 700, in 9 schools	Attention restoration (the difference between the performance before and after recess) in: - information processing speed: Digit Letter Substitution Test (DLST; Natu and Agarwal, 1995). - Selective attention: Sky search task (SST, Manly et al., 2001) Assessor: three researchers accompanied by ten trained students.	Green schoolyard intervention in five out of nine schools - natural elements (such as trees, flowers, sand, water, grass, hills and bushes) are combined to create a more appealing schoolyard and improve the quality of children's (play) experiences.	Group (control and intervention school) and gender. Moderator: grade and gender.	- Multilevel analysis to control for the clustering of measurements within children (repeated measures) and the clustering of children within schools. - Effects of greening at first and second follow-up estimated by specifying interaction-terms between the follow-up measurement (time) and condition.	- At baseline, scores on the two attentional tasks improved after recess, both in intervention and control schools. - For both tasks no significant interactions between time and condition at first follow-up, no moderation by gender and grade. - At second follow-up, an improvement in DLST after recess and a trend for the improvement in SST.
15	Wallner et al. (2018), Austria	Cross-over experiment	16–18 years, N = 64	Selective attention: d2-R (Brickenkamp et al., 2010). Assessor: no information.	- Inner urban small and heavily used park surrounded by heavily used streets and dense residential areas. - Larger park with some trees. - larger forest with some scattered meadows and low visitor numbers.	No adjustment.	Differences after-before stay at the site evaluated by ANOVA to the self-condition scale except for the time factor.	Selective attention significantly better after the stay in green spaces for all sites (small urban park, large urban park, and forest). The highest increase of performance found for the larger park type.

Note. RT = reaction time, EKG = Electrocardiography, SES = socioeconomic status, ANT = Attention Network Test, WISC = Wechsler Intelligence Scale for Children.

attentional control and processing speed. In a study conducted in Belgium (Bijnens et al., 2022) with 13- to 17-year-olds, residential green space was not associated with visual information processing speed (Pattern Comparison Test from the Neurobehavioural Evaluation System 3.). Also, German researchers (Lindemann-Matthies et al., 2021) showed that attention measured by the d2-Revision test in 8- to 11-year-old children was not associated with the naturalness of their window or interior classroom views. Time spent in natural places and on plant care was not associated with d2-revision test performance either.

3.3.3. *Parent-reported attention*

One observational study on greenspace exposure and attention that was conducted in the USA (Wells, 2000) used a mother-reported questionnaire (Attention Deficit Disorder Evaluation Scale) to assess directed attention capacity in 7- to 12-year-old children. This study is listed separately as it cannot be easily assigned to any of the CHC theory abilities - it used a subjective measure that likely covered both cognitive and behavioral aspects of attention. The researchers were interested in the impact of pre-postmove greenness levels on attention and reported that children whose homes improved the most in terms of greenness following relocation tended to have the highest levels of attention.

3.3.4. *Working memory capacity*

Ten studies investigated working memory and/or short-term memory, which can be categorized as CHC broad ability working memory capacity. Working memory capacity can be defined as the ability to maintain and manipulate information in active attention. Narrow abilities within working memory capacity include auditory short-term storage, visual-spatial short-term storage, and attentional control (Schneider and McGrew, 2018). In seven studies (three experimental) a positive association between greenspace and working memory capacity was observed, whereas in four studies (one experimental) a negative association was found. In one observational study (Maes et al., 2021), bluespace exposure was considered in addition to greenspace exposure, but no association was observed.

3.3.4.1. Experimental studies. Three experimental studies found a positive association between greenspace and working memory capacity, whereas a negative association was observed in one study. In a study conducted with 3rd-grade primary school children (Bernardo et al., 2021), working memory (Digital span test from WISC-IV) significantly improved after introducing a green wall into the classroom but not after the second intervention, which involved children planting vegetables in pots. Also, in a study conducted in the USA (Li and Sullivan, 2016) high-school students scored significantly higher on attentional capacity, short-term memory and working memory (Digit Span Forward and the Digit Span Backward tests) after a 30min activity in a classroom with a green window view than their peers who were assigned to rooms without views to greenspaces. There was no evidence that stress mediated the relation between the green window view and attention restoration. In another study (Torquati et al., 2017), 6- to 11-year-olds performed significantly better on a spatial working memory task (Schutte et al., 2017a; Schutte and Spencer, 2002) outdoors compared to indoors. In contrast, Schutte et al. (2017b) reported that in 4- to 17-year-olds a 20min nature walk as compared to an urban walk did not affect verbal working memory (digit span backwards). However, preschoolers remained more stable on spatial working memory tasks following the nature walk compared to the urban walk.

3.3.4.2. Observational studies. In four observational studies, a positive association between greenspace and working memory capacity was observed, whereas a negative association was found in three studies. Dadvand et al. (2015) demonstrated 12-mo progress in working memory and superior working memory (n-back test) in 7- to 13-year-olds as being related to school greenness (NDVI) and total home-school greenness. Elemental carbon explained 20–65% of associations between school greenness and progress in working memory. Also, Dockx et al. (2022) reported an association in 4- to 6-year-olds between residential green space in all buffers with the exception of the 50 m buffer and visual recognition/working memory (the Delayed Matching to Sample subtest from CANTAB). Flouri et al. (2019) conducted a study in the UK and reported that 11-year-olds living in greener urban neighborhoods (ward-level proportion of greenspace) had better spatial working memory as measured by the Spatial Working Memory task from CANTAB, similarly in deprived and non-deprived neighborhoods. In another study conducted in the UK (Maes et al., 2021) with 9- to 15-year-olds, higher daily exposure to woodland, but not grassland, was associated with higher composite executive function scores (computerized backwards digit span, spatial working memory, and trail-making task). No association between daily exposure to bluespace and executive function was detected.

In contrast, Bijnens et al. (2022) reported that residential green space was not associated with short-term memory (Digit Span Test) in 13- to 17-year-olds. Also, Julvez et al. (2021) reported no association between NDVI in different buffers around school and home during pregnancy and working memory (N-Back task). Further, in a study by Reuben et al. (2019), average lifelong residential greenness exposure (NDVI) was not associated with spatial working memory (Spatial Span subtest and Spatial Working Memory subtest from CANTAB) at age 18 when confounding by neighborhood, and family SES was taken into account.

3.3.5. Visual processing and psychomotor speed

Visual processing can be defined as the ability to make use of simulated mental imagery to solve problems based on perceiving, discriminating, manipulating, and recalling nonverbal images. Psychomotor speed can be defined as the ability to perform physical body motor movements (e.g., movement of fingers, hands, legs) with precision, coordination, fluidity, or strength (Schneider and McGrew, 2018).

3.3.5.1. Observational studies. Only two studies investigated the association between greenspace and visual processing and psychomotor speed. Both were observational. In a study conducted by Binter et al. (2022) there were no associations between greenness exposure (NDVI) nor green and blue space distance and gross motor and fine motor skills (the McCarthy Scales of Children's Abilities and the Peg moving task) in 4- to 5-year-old children. Also, in a study by Jimenez et al. (2021b) there were no associations between greenness (NDVI) and visual-motor, fine-motor and visuospatial skills (Visual-Motor Subtest of the Wide Range Assessment of Visual-Motor Abilities (WRAVMA)) in early childhood. Greenness exposure at early childhood was nonlinearly associated with an increase in visual memory (Visual Memory Index of the Wide Range Assessment of Memory and Learning (WRAML2)) in mid-childhood and this association was observed after further adjusting for early childhood cognition as well as across different methodologies.

3.3.6. Intelligence: general ability, fluid reasoning, and comprehension–knowledge

Nine studies investigated the association between exposure to natural environment and intellectual functioning. All of them were observational. Only two of them considered bluespace in addition to greenspace exposure (Almeida et al., 2022; Binter et al., 2022). All the studies employed standardized intelligence tests to assess intellectual functioning. According to the CHC theory, intelligence test subtests measure CHC narrow abilities that can be assigned to several broad abilities. However, the main CHC broad abilities usually examined within intelligence tests include fluid reasoning and comprehension–knowledge. Fluid reasoning can be defined as the use of deliberate procedures to solve novel problems that cannot be solved by using previously learned schemas. Comprehension–knowledge can be defined as the ability to comprehend and communicate culturally valued knowledge; it includes skills such as language, words, and general knowledge developed through experience and learning. In addition, intelligence tests usually provide estimations of general ability (g) best represented by full scale intelligence quotient (IQ), with which all broad and narrow abilities are substantially correlated (Schneider and McGrew, 2018).

3.3.6.1. Observational studies. Five studies reported a positive association between natural environment and intelligence regarding at least one outcome. Four studies reported no association. The results are not consistent across studies nor across methodologies as follows. In a study by Almeida et al. (2022) conducted in Portugal in 10-year-old children, greenness (NDVI) in a 100 m buffer around school was negatively associated with verbal, performance, and global IQ scores (Wechsler Intelligence Scale for Children - third edition (WISC-III)); greenness in a 50 m buffer around school was negatively associated with performance IQ score. No association was found when looking at NDVI around the current residence. However, freely available Urban Green Spaces (UGS) in 800 m around the residence was associated with higher performance and global IQ scores. There was no meaningful mediation effect of physical activity or air pollution. No associations were observed with blue spaces. In a study conducted in Italy (Asta et al., 2021) with 10-year-olds, there was no association between residential greenness (NDVI) in a 300 m buffer and any of the measured IQ scores (WISC-III). However, there was an association between NDVI in a 500 m buffer and Arithmetic subtest, but 35% of the estimated association was mediated by reductions in NO_2. Researchers from Belgium (Bijnens et al., 2020) reported that, in 7- to 15-year-olds, urban residential green space, both during pregnancy and childhood in 1000 m–5000 m buffers, was associated with total and performance IQ scores (Wechsler Intelligence Scale for Children - Revised (WISC-R)), and in 2000m–5000 m buffers with verbal IQ. No associations were observed in suburban and rural areas. High green (vegetation higher than 3 m) was associated with verbal and total IQ in buffer sizes larger than 500 m. There was no confounding by air pollution and noise. In a study conducted in four European countries including UK, France, Spain, and Greece (Binter et al., 2022) with 4- to 5-year-olds, higher greenness (NDVI) within 300 m and 500 m buffers during pregnancy was associated with higher verbal abilities (the British Picture Vocabulary Scale; Wechsler Preschool and Primary Scale of Intelligence), but this was not the case for postnatal exposure. Air pollution mediated 74% of the association between NDVI and verbal scores. Green and blue space distances were not related to verbal abilities. No associations were found with nonverbal abilities (Wechsler Preschool and Primary Scale of Intelligence) either. Researchers from South Korea (Lee et al., 2021) reported that Landsat-derived built greenness, but not natural greenness, was associated with verbal, performance, and total IQ scores (Korean Educational Developmental Institute's Wechsler Intelligence Scale for Children (Park et al., 1996)) in 6-year-olds. Postnatal greenness was more strongly associated with IQ scores than prenatal greenness.

Researchers from the UK (Flouri et al., 2022) reported no difference between two greenspace area types (residing in the lowest decile of greenspace in a ward) at age 5 in general cognitive ability (IQ) based on three subscales (Naming Vocabulary, Pattern Construction, and Picture Similarities) of the British Ability Scales (BAS). In a study conducted in the USA (Jimenez et al., 2021b), there were no associations between greenness (NDVI) and vocabulary comprehension (Peabody Picture Vocabulary Test (PPVT-III)) in early childhood. However, greenness exposure in early childhood was nonlinearly associated with an increase in nonverbal intelligence (Kaufman Brief Intelligence Test (KBIT-2)) in mid-childhood, but this association was not observed after further adjusting for early childhood cognition nor across different methodologies. Black carbon partially mediated the association between early life greenness and nonverbal IQ. In a study conducted in UK, France, Spain, Lithuania, Norway, and Greece (Julvez et al., 2021) in 6- to 11-year--olds, higher NDVI in a 100 m buffer during pregnancy was associated with lower fluid intelligence (Raven's Coloured Progressive Matrices test (CPM) but this association was not significant after multiple testing correction. In a study from the UK (Reuben et al., 2019) there were neither cross-sectional nor longitudinal associations between residential NDVI and overall IQ, crystallized ability or fluid ability in 5-year-olds (Wechsler Preschool and Primary Scale of Intelligence Revised (WPPSI-R)), 12-year-olds (Wechsler Intelligence Scale for Children-IV (WISC-IV)), and 18-year-olds (Wechsler Adult Intelligence Scale–IV (WAIS-IV)) in models adjusted by neighborhood and family SES.

3.3.7. Early childhood/cognitive development

Developmental tests are usually employed in early childhood to depict the stage of overall psycho-emotional development; consequently, they measure several domains including cognition. Scores on cognitive domains inform about general rather than specific skills; thus, they can be assigned to several CHC theory abilities.

3.3.7.1. Observational studies. Two observational studies investigated the association between greenspace and early childhood development including cognitive development. One of them found a positive association and the other found no association. In a study conducted in China (Liao et al., 2019), exposure to higher levels of residential greenness (NDVI) was associated with indicators of better early childhood neurodevelopment (Mental Development Index (MDI)) and Psychomotor Development Index (PDI) from Bayley Scales of Infant Development for children at 24 months. Mediation analyses indicated that reduced levels of traffic-related air pollution explained 13.6%–28.0% of the association between exposure to greenness and early childhood PDI score. Researchers from Canada (Jarvis et al., 2021) found no evidence of an association between lifetime residential exposure to percentage of vegetation derived by spectral unmixing of Landsat images and language and cognitive development (Early Development Instrument) in 5- to 12-year-old children.

3.3.8. Decision-making, self-regulation including, and emotional intelligence

Three observational studies cannot be clearly assigned to one of the CHC theory abilities as they measure several abilities across different CHC domains. One of them (Bakir-Demir et al., 2019) examined self-regulation, which likely involves fluid reasoning, working memory capacity, and attentional control. Two other investigated decision-making (Flouri et al., 2022) and executive function and behavior (Jimenez et al., 2021a), which involve similar abilities. However, compared to the other studies presented in this review, the three studies are unique as they involve emotional intelligence, specifically emotion management and emotion utilization. Emotional intelligence can be defined as the ability to perceive emotional expressions, understand emotional behavior, and solve problems using emotions (Schneider and McGrew, 2018).

3.3.8.1. Observational studies. In a study by Bakir-Demir et al. (2019), conducted in Turkey in 8- to 11-year-olds, greenery (NDVI and child- and mother-perceived greenery) did not directly predict children's emotional regulation skills (Cognitive Emotion Regulation Questionnaire (CERQ-k) and Emotion Regulation Questionnaire for Children and Adolescents (ERQ-CA)). However, the relationship was mediated by nature connectedness, but this was not moderated by perceptual sensitivity. There was no direct effect of greenery on behavioral self-regulation (Childhood Executive Functioning Inventory (CHEXI) and the Barratt Impulsiveness Scale-11 (BIS-11), nor on cognitive self-regulation (CHEXI subscales: regulation, planning, and working memory). The indirect effect of greenery on behavioral regulation problems through nature connectedness was not significant, but higher greenery and perceptual sensitivity predicted higher nature connectedness, which was in turn associated with better cognitive regulation. In a study by Jimenez et al. (2021a), there were no associations between the effects of "maximum vs. minimum greenness" (NDVI) at all timepoints with executive function and behavior (Behavior Rating Inventory of Executive Function (BRIEF)) in mid-childhood or early adolescence. In a study by Flouri et al. (2022), 11-year-old children in the least green urban areas (lowest decile of green space in wards) showed higher sensitivity to reward or scored higher on risk-taking than other urban children.

4. Discussion

4.1. Summary of evidence

We reviewed 39 studies; based on outcome assessment, we assigned them to seven cognitive domains according to the CHC theory. We present the results separately for 17 experimental and 22 observational studies. We included in our searches both greenspace and bluespace exposures; however, only three studies considered bluespace in addition to greenspace, and these studies demonstrated that there was no association with cognition. The majority of the studies investigated attentional functioning, which we subdivided into two categories according to the CHC theory: attentional control and reaction and decision speed (12 studies) and attentional control and processing speed (10 studies). Regarding attentional control and reaction and decision speed, eight of 12 studies were observational and used computerized outcome measures. The majority (66.6%) found a positive association with at least one outcome. Regarding attentional control and processing speed, the vast majority of the studies were experimental (eight studies) and used paper-pencil tests for outcome assessment. The majority (70%), all of which were experimental, found a positive association in at least one outcome. Although a trend is visible for a positive impact of natural environment on attentional functioning in children, the heterogeneity of methodological approaches does not permit clear conclusions. As an example, within experimental studies exposure to natural environment was considered within a variety of settings, such as garden/planting vegetables (two studies), walking in a natural environment (three studies), a stay in a natural outdoor area/forest/schoolyard (six studies), a stay in classroom with a green wall (2 studies) and trees bigger than 5,000 m^2 (one study). In observational research, NDVI (five studies) and land cover (three studies) exposure measures were used most commonly. Also, a variety of cognitive measures was employed, including a variety of scores derived from the same cognitive measures. For example, from ANT scores such as executive attention score, hits, accuracy, reaction time, reaction time standard error were used as outcomes, but this was inconsistent across studies.

Eleven studies investigated working memory and/or short-term memory functions, which we assigned to working memory capacity according to the CHC theory. Seven studies were observational. More than half (64%) of the studies found a positive association. Similarly to studies on attention, various nature exposure measures/interventions were used. Observational studies used NDVI (three studies) and land cover (four studies), whereas experimental studies implemented stay in classroom with green wall (one study), classroom natural window view (one study), walk in a natural environment (one study), and a stay in a natural outdoor area (one study). Cognitive outcome measures often employed Digit Span Forward and the Digit Span Backward tests, the n-back test, and the visual recognition/working memory subtest from the CANTAB. Nevertheless, due to the low number of studies and diversity in the methodological approach, no clear conclusions can be made.

Nine studies investigated the association between exposure to natural environment and intellectual functioning, which we assigned to general ability, fluid reasoning, and comprehension-knowledge, according to the CHC theory. All of them were observational; 56% observed a positive association in at least one outcome. Six studies used NDVI within exposure assessment; three studies used land cover/land use data. Within outcome assessment, several versions of Wechsler intelligence tests (five studies) were frequently employed, but also the British Picture Vocabulary Scale, British Ability Scales, Kaufman Brief Intelligence Test, and Raven's Coloured Progressive Matrices test. The five studies that found a positive association used a Wechsler test. Three of them used NDVI within exposure assessment, and two others used green space from land cover/use images.

Two studies investigated visual-spatial abilities, which we assigned to visual processing and psychomotor speed, according to the CHC theory. One study reported no association and another reported mixed findings. Both studies used NDVI as an exposure measure but applied different outcome assessment tools and examined children of different age ranges; thus, the two studies cannot be compared. Similarly, the low number of studies, the different age groups examined and the different outcome assessment tools applied prevent us from forming any conclusion in the domains of early childhood/cognitive development with two observational studies (NDVI vs. spectral unmixing of Landsat images as exposure measures) and decision-making and self-regulation with three observational studies (two studies used NDVI and one study used land cover as exposure measures).

Clear conclusions cannot be reached not only due to heterogeneity within exposure and outcome assessment, but also due to "high" or "probably high" RoB in some studies, heterogeneity within the methodological approaches or inappropriate use of statistical methods.

As our RoB assessment revealed, none of the included studies was rated as "low risk" regarding exposure assessment. Four studies had high RoB and eight studies had probably high RoB. As for outcome assessment, nine of the included studies were rated as "low risk", but four studies were rated as probably high RoB. In terms of confounding bias, four studies were rated as "high risk" and seven studies were rated as "probably high" risk of confounding bias. Regarding selection bias, six studies had "high" and 12 studies had "probably high" RoB. Consequently, when there is "probably high" or "high" RoB in one of the aforementioned key RoB criteria, caution is warranted with the interpretation of study findings.

In terms of statistical methods, most of the studies used an appropriate approach, with the exception of mediation analysis. In observational studies, regression or a mixed-models approach was usually chosen within the main analysis, whereas analysis of variance/covariance was most frequently used in experimental research. Nevertheless, mediators were treated as confounders in seven studies and were adjusted using wrong statistical procedures, such as correlation or regression.

Regarding sample sizes, in observational studies the number of participants ranged from 17 to 27372. In the majority of the studies, the data of several hundred participants were analyzed, which is considered sufficient to detect patterns suggesting a potential association between exposure and outcome. In the experimental studies, the sample size ranged from 10 to 700 participants but in most of the studies sample sizes were below 100 participants. Due to the specific requirements of the experimental settings, often only smaller numbers of participants could be examined; however, sample size calculations should be conducted a priori under consideration of the number of variables being analyzed.

4.2. Comparison to previous systematic reviews

Our review demonstrates that further research is required to determine whether the natural environment impacts cognitive functioning in children and adolescents. Eight systematic reviews have been previously published in relation to the association between nature and cognition (de Keijzer et al., 2016; Gascon et al., 2015; Islam et al., 2020; Luque-García et al., 2022; Ohly et al., 2016; Stevenson et al., 2018; Vanaken and Danckaerts, 2018; Vella-Brodrick and Gilowska, 2022). The studies included in these reviews most frequently examined the association between exposure to nature and attentional functioning (16 studies). We identified six more studies within that domain: attentional control and reaction and decision speed (12 studies) and attentional control and processing speed (10 studies).

According to our findings, which suggest a short-term effect of nature exposure, previous systematic reviews of experimental research (Ohly et al., 2016; Stevenson et al., 2018) summarized some evidence supporting the Attention Restoration Theory (Kaplan, 1995) and identified three cognitive domains (working memory, cognitive flexibility, attentional control) that are sensitive to the restoration effect. Also, a recent systematic review (Vella-Brodrick and Gilowska, 2022) showed that selective attention, sustained attention, and working memory are benefited by nature interventions. However, due to the heterogeneity in the methodology and the low number of studies providing evidence for each of the cognitive domains, caution is warranted in the interpretation of these results. In contrast, the authors of previous systematic reviews of observational research (de Keijzer et al., 2016; Islam et al., 2020; Luque-García et al., 2022) are rather cautious with drawing clear conclusions. In line with our judgment, the heterogeneity in the methodology, the limited number of studies, and the insufficient quality of studies are frequently pointed out. Only Vanaken and Danckaerts (2018) concluded that the evidence from observational research consistently suggests a beneficial association between greenspace exposure and children's neurocognitive development.

In accordance with previous systematic reviews, we could not identify any effects of age or type of exposure assessment on the association between nature and cognition.

4.3. Cognitive outcome assessment

Due to heterogeneity within outcome assessments and the inappropriate use of cognitive measures in the studies included, the current review cannot provide clear conclusions regarding the potential association between nature exposure and cognition. Consequently, the main principles of cognitive assessment should be considered. First, cognitive measures can differ regarding the target population. On the one hand, some of them are designed to detect cognitive disorders and are mainly used in clinical settings. Importantly, these measures are sensitive to cognitive impairments in clinical populations and are less able to assess cognitive performance in normal individuals. On the other hand, some intelligence and achievement tests are designed to estimate the highest possible level of cognitive performance; these measures may be less sensitive to cognitive impairments, but are better indicated for use in the general population. Although of a different nature, both types of measures are used across populations; for example, individual intelligence test subtests are frequently used to assess specific abilities in patients (e.g., the Digit Span subtest from the Wechsler Intelligence Scale for Children as a measure of working memory capacity). Similarly, neuropsychological measures are used in healthy individuals (e.g., the Continuous Performance Test as a measure of attention). Nevertheless, the primary application for an assessment tool should be always considered and researchers using cognitive measures within observational studies should take into account whether these measures were validated for the population of interest. Second, in line with psychometric criteria (Lezak et al., 2012; Strauss et al., 2006), assessment tools should be standardized for the country where they are applied. This includes sufficient levels of reliability as well as appropriate norming when taking into consideration specific age ranges, sex, and socioeconomic status and/or educational attainment. Third, when reporting on employed cognitive measures, the information that is necessary to properly identify the measures should be provided, such as the specifics of the original version and potential adaptations including the names of the authors, year, and country of standardization.

5. Limitations

5.1. Limitations of the evidence included in the review

Huge heterogeneities exist in the studies included in our review. The different study designs, greenspace or bluespace metrics, exposure buffers and durations, as well as outcome definitions, preclude the potential of meta-analyzing the results and also hinder comparisons and summarizations of the studies. Therefore, it is challenging to derive evidence from these studies.

We may take greenspace as an example. Although NDVI and distance to greenspace are commonly used in observational studies, they cannot provide information on the quality of greenspace. Various effects of grass, trees (Astell-Burt et al., 2020), and allergenic plants (Lai and Kontokosta, 2019; Markevych et al., 2020) should be expected, and having information on visual access (Wang et al., 2021) or the frequency or duration of visits to greenspace (Dzhambov et al., 2018) would help in the further evaluation of associations. We tried to cover the different outcomes reported by studies according to the CHC theory, and seven domains were grouped in our review; however, other domains from the remaining ten CHC broad abilities have not yet been investigated. Also, in our review, “visual processing and psychomotor speed” and “early childhood/cognitive development”, respectively, are examined by only two studies. Similarly, decision-making, self-regulation including, and emotional intelligence were investigated by only three studies; thus, no conclusions can be made. Further, the extraction of outcome-related data is prone to false decisions. Frequently, cognitive measures were not properly described, outcomes derived from these measures not properly assigned to cognitive domains, and information on assessors were missing. All the above could additionally bias our results.

Currently, experimental studies are constrained to a relatively small number of participants. On the one hand, the findings of experimental studies are complementary to observational results; on the other hand, well-designed experimental studies are needed to better verify the effects of exposure to greenspace or bluespace.

Further, the included studies are based in Europe and North America, except two from Asia. Considering the geographic and climatic differences, our current results may have problems when extrapolated to other areas.

5.2. Strengths and limitations of the current review

To our knowledge, this is the first systematic review analyzing the association between greenspace and bluespace exposure and cognitive functioning in children and adolescents of the entire age range including both observational and experimental research. The review was prepared according to the PRISMA statement and preregistered at INPLASY. An interdisciplinary team comprised of environmental epidemiologists and cognitive psychologists contributed to the review during the entire preparation process. The searches were conducted on PubMed and PsycInfo in order to include both epidemiological and psychological studies. Further, the “snowball” search approach was used, and previously published reviews were manually searched to detect additional studies. The results are presented according to the CHC theory that is the most evidence-based theory of human cognitive abilities. Consequently, the current work has substantial strengths and can be considered novel from various perspectives.

Nevertheless, several limitations should be considered. First, we conducted our searches in only two databases, but using more than two databases could reveal more results. Further, we imposed language constraints including research only in English, German, and Polish. As a result, potential studies that would have been identified via other databases or in different languages were excluded. We also did not consider grey or non-peer-reviewed research, which might have revealed further evidence. Adding grey literature could increase the total number of studies within each cognitive domain, thus helping to verify the potential association between nature exposure and cognition.

Another potential limitation might be the search strategy and search terms used. A specialized librarian was not involved in the development of our search strategy. Moreover, due to the lack of consensus on cognitive abilities, a selection of the most common cognitive terms was utilized, but a selection of different search terms would potentially have revealed different results.

Taking into consideration the substantial heterogeneity within outcome assessment among the studies, the CHC theory was chosen to present the results. Nevertheless, the implementation of different theories and approaches to presenting cognitive outcomes might have led to different conclusions. Some outcome assessments might be questionable because of an inappropriate method, and we might have mismatched the outcomes due to the limited information included in the reports.

Lastly, due to the heterogeneity among the included studies, we failed to answer two research questions: whether some measures of greenspace or bluespace exposure show more consistent associations with cognition, and whether these associations differ across ages. Nor were we able to meta-analyze the results.

6. Implications for future research

Based on the results of the present systematic review, implications for future studies can be formulated to help improve the quality of research. In particular, proper selection of outcome assessment tools appears crucial.

As previously described in paragraph 4.3., the use of standardized cognitive measures with high reliability ratings that are validated for the target population, and normed for the country of application is recommended.

Regarding exposure assessment, the application of diverse methods is recommended within both observational and experimental approach. In addition to objective exposure measures, perceived measures should be implemented to help capture the exposure from different angles. Use of different methods for exposure to nature could change the results. It is especially important to consider different aspects of exposure: availability, accessibility, use, and visibility (Labib et al., 2020). Bluespace exposure is even less standardized than greenspace exposure, and the characteristics of bluespace might be crucial: freshwater vs. saltwater, types of bluespace, time at bluespace, activities conducted.

Regarding methodological approaches, future studies should implement state-of-the-art statistical analysis methods. In particular, appropriate adjustment for confounder variables that are considered meaningful for cognition, such as sex, age, and educational attainment, is crucial. Identifying and testing indirect effects of nature exposure on cognition, including potential mediators such as physical activity or social cohesion (Dzhambov et al., 2018, 2020), would be of additional value. We recommend conducting mediation analyses according to recent methodological advances (Dzhambov et al., 2020).

In general, we recommend planning and conducting studies within interdisciplinary teams as knowledge and skills from several disciplines are required. In particular, experts from environmental epidemiology, cognitive psychology, and neuropsychology should be involved in all stages of research.

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Authors' contributions

Dorota Buczyłowska conceived, designed, and coordinated the review; coordinated data collection, data management and screening of data; extracted and interpreted data; conducted the risk of bias assessment; drafted manuscript, revised the draft, and approved the final manuscript. Tianyu Zhao conceived and designed the review; conducted the risk of bias assessment; drafted the manuscript, revised the draft, and approved the final manuscript. Nitika Singh conceived the review; extracted data; designed the graphical abstract, tables and illustrations; and approved the final manuscript. Anna Jurczak collected and screened data; prepared tables and illustrations; and approved the final manuscript. Agnieszka Siry collected and screened data,\; prepared tables and illustrations; and approved the final manuscript, Iana Markevych conceived and designed the review; extracted and interpreted data; conducted the risk of bias assessment; drafted the manuscript, revised the draft, and approved the final manuscript.

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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

Data will be made available on request.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envres.2023.115340.

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