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Review article

Does exposure to greenness improve children's neuropsychological development and mental health? A Navigation Guide systematic review of observational evidence for associations

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ABSTRACT

Background: Contact with nature may have a key role in child brain development. Recent observational studies have reported improvements in children's neuropsychological development and mental health associated with greenness exposure. In a rapidly urbanizing word, researchers, policymakers, healthcare workers and urban planners need to work together to elaborate evidence-based policies and interventions to increase the availability of quality green space with the potential to enhance childhood development.
Objective: To review the observational evidence assessing the effect of exposure to greenness on children's neuropsychological development and mental health.
Methods: The protocol for the review was preregistered at PROSPERO (CRD42020213838). The Navigation Guide systematic review methodology was followed. Search strategies were formulated and adapted to each database. Searches were performed in PubMed, Scopus, Web of Science and EBSCO's GreenFILE on October 5, 2021. Additional articles were further identified by hand-searching reference lists of included papers.
Results: A systematic search of 4 databases identified 621 studies, of which 34 were included in the review. The studies included investigated diverse domains within neuropsychological development and mental health, such as attention, working memory, intelligence, cognitive development, academic performance, well-being, attention-deficit/hyperactivity disorder symptoms, and behavior. Most of the studies were rated as having high or probably high risk of bias in the assessment.
Discussion: Although nearly all studies showed a positive association between greenness exposure and the outcomes studied, the heterogeneity in the methods used to assess exposure and the diversity of domains within each main outcome has made it difficult to draw clear conclusions. Future studies should adopt a longitudinal design to confirm the causality of the associations and include measures to determine which characteristics of greenness have the greatest influence on each domain. Researchers should also try to explore pathways linking exposure to greenness with the neuropsychological development and mental health, by implementing mechanistic studies.

1. Introduction

Mental health problems affect 10–20% of children worldwide (Belfer, 2008; Kieling et al., 2011). Importantly, while such disorders may emerge in early life, they can have major implications for people's wellbeing throughout their lives (The Lancet, 2016; Morabito et al., 2021; Navarro-Pardo et al., 2012). Similarly, the problems derived from poor neuropsychological development in childhood may have an impact on not only current but also future generations, related to children not fully benefiting from education and corresponding productivity losses

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(Daelmans et al., 2017). Undoubtedly, this poses a burden for both individuals and society due to the magnitude of impact it may have in the long term, making it an issue of great importance in public health.

Contact with nature may have a key role in child brain development (Wilson, 1986, Kahn Jr, 1997; Dadvand et al., 2018; Islam et al., 2020; Jimenez et al., 2021a). On the other hand, urbanization threatens to weaken the close link there has been between humans and nature throughout the history of humankind, hindering people's access and exposure to green space (Hartig et al., 2014). Urban population will increase exponentially: 7 out of 10 people will live in cities by 2050 (United Nations, 2018). The growing urbanization modifies the environmental factors to which large parts of the population are exposed, decreasing the amount of green space due to a dominance of concrete and favoring, in turn, exposure to air and noise pollution resulting from industrial and commercial activity, road traffic and overcrowding (UNICEF, 2012). Children are particularly sensitive to such environmental factors, their brain being vulnerable as it develops in the prenatal and early postnatal period (Grandjean and Landrigan, 2014), and during dynamic behavioral, cognitive and emotional changes throughout childhood and adolescence (Calderón-Garcidueñas et al., 2008; Rice and Barone Jr, 2000). Consequently, a secure environment that protects people's health is key to safeguarding child development and minimizing life-long deficiencies and dysfunctions (Grandjean and Landrigan, 2014, UNICEF, 2012).

According to the biophilia hypothesis, humans have an innate tendency to seek connections with other forms of life as a result of evolution (Wilson, 1986). Greenness refers to landscapes dominated by vegetation, and people's exposure to it has been associated with a wide range of health benefits (Twohig-Bennett and Jones, 2018). In the last decade, scientific interest in the potential benefits of exposure to greenness has increased substantially, as reflected in numerous scientific papers (Zhang et al., 2020a). Several studies have reported improvements in children's neuropsychological development and mental health associated with greenness exposure. In particular, better early childhood neurodevelopment has been associated with residential exposure to green space (Liao et al., 2019), better emotional and behavioral regulatory skills with more tree canopy around children's homes and/or schools (Scott et al., 2018) and better mental health with spending more of time in green areas (Andrusaityte et al., 2020, Van Den Berg et al., 2016). Further, neighborhood natural space may reduce social, emotional and behavioral difficulties in 4- to 6-year-olds (Richardson et al., 2017) in line with the finding that greater neighborhood availability of parks, from childhood to adulthood, may help to reduce the rate of cognitive deterioration in old age (Cherrie et al., 2018).

While the mechanisms underlying these positive effects remain unclear, they may be related to three potential domains of pathways linking exposure to green space and health outcomes (Markevych et al., 2017), namely, mitigation, restoration and instoration (Fig. 1).

Green spaces help to reduce exposure to harmful conditions through the mitigation pathway by influencing three different environmental factors (air pollution, noise, and heat). Plants can reduce CO2 levels due to their capacity to convert CO2 into oxygen through photosynthesis (Singhal et al., 1999). Further, levels of traffic-related air pollution and noise are lower in green spaces, as a consequence of the lack of traffic in these areas (Su et al., 2011). And finally, vegetation has a cooling effect through evapotranspiration (Venter et al., 2020). Greenness can also contribute to the reduction of heat by absorbing direct solar radiation and changing the albedo of background surfaces (Markevych et al., 2017; Gunawardena et al., 2017; Venter et al., 2020).

Concerning the restoration pathway, two major theories have described the mechanism through which exposure to greenness might improve human health, Attention Restoration Theory (ART) and Stress Reduction Theory (SRT). According to the ART, green spaces offer a place to relieve neurocognitive load while attracting and recovering attention effortlessly. As suggested by this theory, overcoming mental fatigue is enabled because natural spaces stimulate involuntary

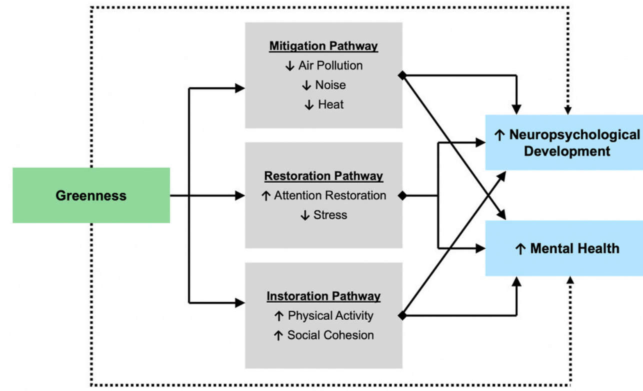

Fig. 1. Theoretical domains of pathways linking greenness to neuropsychological development and mental health outcomes. Dashed arrows represent a direct effect, while solid line arrows represent hypothetical mediating patterns of influence related mitigation, instoration, or restoration.

attentional processes, and consequently, voluntary attentional processes are restored (Kaplan and Kaplan, 1989; Kaplan, 1995). On the other hand, SRT states that due to the innate tendency humans have to seek connection with nature, spending time surrounded by vegetation might influence feelings or emotions by activating the parasympathetic nervous system to reduce stress and autonomic arousal (Ulrich, 1983; Ulrich et al., 1991).

Lastly, greenness promotes physical activity and social cohesion through the instoration pathway. Green spaces are likely to create opportunities to conduct exercise (Mccormack et al., 2010), many studies have observed associations between higher levels of greenery and increased physical activity (Almanza et al., 2012, De La Fuente et al., 2020; Mytton et al., 2012; Astell-Burt et al., 2014a). Similarly, the social cohesion of a community can be enhanced by greenness, because green spaces can provide safe, attractive, and accessible settings for contact with neighbors (Weinstein et al., 2015; Kuo et al., 1998; Hartig et al., 2014; Jennings and Bamkole, 2019).

Although there are several reviews of observational studies that have analyzed the effect of greenness on cognition throughout life (De Keijzer et al., 2016) and in adulthood (Wu et al., 2015), no systematic reviews have yet analyzed its effect on the neuropsychological development of children. On the other hand, there are systematic reviews on the relationship between green space and mental health (Zhang et al., 2021), but most of the reviews analyzing mental health on children have not assessed the quality of the studies included (Mccormick, 2017; Vanaken and Danckaerts, 2018), hindering the interpretation of results, and those that did (Gascon et al., 2015; Mygind et al., 2021) concluded that the evidence for children was of inadequate quality or limited. In contrast, a recently published scoping review analyzed the diverse methods employed in literature for measuring attention, stress, and green space, by focusing on the methodological framework to guide future research (Barger et al., 2021). While a systematic review following the Navigation Guide methodology assessed the long-term impacts of four distinct spatially correlated urban environmental exposures, including natural spaces, by evaluating studies with measures of at least two such exposures relating to physical health. However, this review evaluated the impact on the general population (Rugel and Brauer, 2020).

In recent years, many observational studies have analyzed the effect of greenness exposure on various domains of neuropsychological development and mental health in children (Putra et al., 2020, 2021a; Lee et al., 2019, 2021; Julvez et al., 2021; Jimenez et al., 2021b; Hartley et al., 2021; Asta et al., 2021; Sajady et al., 2020; Poulain et al., 2020; Nordbø et al., 2020; Bijnens et al., 2020; Yang et al., 2019; Weeland et al., 2019; Reuben et al., 2019; Madzia et al., 2019; Flouri et al., 2019;

Van Aart et al., 2018; Tallis et al., 2018). Consequently, there is a clear need to synthesize and assess the evidence relating greenness with domains of neuropsychological development beyond cognition and with mental health in childhood.

As it may be key to supporting recommendations on which to base future policy decisions related to urban planning and environmental interventions, we concluded the need for an up-to-date, explicit, and accurate systematic review. For this aim, we decided to follow the Navigation Guide systematic review methodology. This approach was first described in 2011 to bridge the gap between the clinical sciences and the field of environmental health. The Navigation Guides methodologically rigorous, explicit, and transparent approach is appropriate for supporting policy development and other forms of translation and therefore aligns with the aim of this review (Woodruff and Sutton, 2014). The children of today will drive the growth and development of our societies of tomorrow, and hence, it is crucial to analyze the factors that may help them to develop to their full potential (Chan et al., 2017).

The objectives of this systematic review were to gather, synthesize and assess the observational evidence available concerning the effect of greenness exposure on neuropsychological development and mental health in 6- to 12-year-olds. We decided to focus only on the school (6–12 years) developmental stage considering that the variability on the characteristics, needs and clinical manifestation through the different developmental stages (preschool 0–6, school 6–12 and adolescence 12–18) could lead to errors in interpretation and conclusions. The school stage could be the most representative period, as it is a stage in which the evaluation can already be carried out with greater reliability, allowing the detection of both clinical and subclinical symptoms (Ollendick, 2013). The results of the papers selected are discussed stratifying findings by the area where the greenness was measured (home, neighborhood or school, among others) and examining potential explanatory pathways.

2. Methods

The methods used in this systematic review are described in a protocol registered on PROSPERO (reference CRD42020213838 available from: https://www.crd.york.ac.uk/prospero/). We conducted the review following the guidelines of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement (Moher et al., 2009).

2.1. Study question

The primary aim of this systematic review was to evaluate whether exposure to greenness is beneficial for children's neuropsychological development and mental health, based on observational evidence. The PECOS statement described below has been developed around this main objective:

- **Population:** Children between 6 and 12 years old (inclusive) at the assessment of the outcome, to obtain studies representative of primary school children, accepting studies in which the mean age was in this range when the study used a different range.
- **Exposure:** Exposure to landscapes dominated by vegetation assessed via objective (vegetation indices, land use/land cover data, etc.) or subjective (scales, questionnaires, surveys, etc.) methods.
- **Comparator:** Comparatively lower levels of exposure or lack of exposure.
- **Outcome:** Neuropsychological development and mental health assessed via validated tools, excluding any studies that assessed outcomes in terms of medical diagnoses. The nosographyc view of neuropsychological development and mental health problems hiders understanding the issue from an epidemiological perspective. For this reason, we decided to look at the problem as a continuum, based on symptomatology, rather than as a discrete categorical variable, to better understand the real magnitude and dimension of the problem on the general population without classifying children by diagnosis (Dell'osso et al., 2019; Fernández-Jaén et al., 2017).
- **Study design:** Observational studies.

2.2. Search strategy

We used terms related to exposure (green space, greenness, etc.), neuropsychological development (neuropsychology, neurodevelopment, cognition, intelligence, attention, working memory, and executive function, among others), mental health (mental health, behavior, etc.) and the population (child, schoolchildren, etc.). We formulated a search strategy and, subsequently, we adapted it to each database. After applying language (English and Spanish) and source type (journal article) restrictions we performed searches in PubMed, Scopus, Web of Science and EBSCO's GreenFILE **(**detailed search strategies in Supplementary Material, S1**)** on October 5, 2021. We further identified additional articles by hand-searching reference lists of included papers, also referred to as snowballing.

The complete search string used for PubMed was: (Neuropsychology [mh]) OR (Neuropsycholog* [tiab]) OR (Neuropsychological development* [tiab]) OR (Neurodevelopment* [tiab]) OR (Cognition [mh]) OR (Cogniti* [tiab]) OR (Intelligence [mh]) OR (Intell*[tiab])OR (attention [mh]) OR (attention [tiab]) OR (Executive function [mh]) OR (Executive function* [tiab]) OR (Memory, Short-Term [mh]) OR (Working Memory [tiab]) OR (Mental health [mh]) OR (Child behavior [mh]) OR (Child behavior disorders [mh]) OR (Problem behavior [mh]) OR (Motor development [tiab]) AND (Greenness [tiab]) OR (Greenery [tiab]) OR (Green space* [tiab]) OR (Greenspace [tiab]) OR (Green area* [tiab]) OR (Residential green [tiab]) OR (Parks, Recreational [mesh]) OR (Natural environment* [tiab]) OR (Natural space* [tiab]) OR (NDVI [tiab]) OR (Normalized Difference Vegetation Index [tiab]) OR (Tree canopy [tiab]) AND (Child [mh]) OR (Child* [tiab]) OR (Schoolchildren* [tiab]) NOT (Letter [Publication Type]) OR (Comment [Publication Type]) OR (Preprint [Publication Type]) OR (Editorial [Publication Type]) OR (meta-analysis [Publication Type]) OR (review [Publication Type]) OR (Letter [ti]) OR (Comment [ti]) OR (Preprint [ti]) OR (Editorial [ti]) OR (meta-analysis [ti]) OR (review [ti]).

2.3. Eligibility criteria

We restricted the inclusion criteria to original research articles with an observational design written in English or Spanish. Further, the eligibility was based on the PECOS statement described below (Table 1).

Table 1
Eligibility criteria based on the PECOS statement.

	Inclusion Criteria	Exclusion Criteria
Population	School aged children (6–12 years), accepting studies in which the mean age was in this range when the study used a different range	Preschool children (0–6 years) Teenagers (12–18 years) Adults (18 years ≤)
Exposure	Exposure to greenness (trees, shrubs, grass, parks, forest, gardens, etc.) assessed via objective (vegetation indices, land use/land cover data, etc.) or subjective (scales, questionnaires, surveys, etc.) methods	Exposure to indoor vegetation
Comparator	Comparatively lower levels of exposure or lack of exposure	–
Outcome	Neuropsychological development or mental health assessed via validated tools	Medical diagnosis
Study Design	Observational	Experimental

2.4. Study selection and data extraction

After removing duplicate publications, three reviewers (LL, AC and SD) examined the articles included on the list independently, applying the aforementioned eligibility criteria. The articles were screened first by their titles and then by their abstracts, and subsequently, after reading the full text. Any disagreement was resolved by discussion. When no consensus was reached, a fourth researcher (JI) also assessed the articles.

Two reviewers (AC and SD) extracted data from the articles selected and independently confirmed them before there were checked by a third researcher (LL). Again, any disagreement was resolved by discussion. When needing missing data, our protocol determined to contact the corresponding author. Yet, since all data were reported, we did not require to contact the authors. The data extracted included: characteristics of the study (author, year, design, study name), characteristics of the population (geographical location, sample size and age at assessment of the exposure and outcome), characteristics of the greenness exposure (type of exposure to greenness and data source), characteristics of the outcome (domain and tool used), type of data analysis, main results (after adjustment) and confounders and mediators in the adjusted model, as well as information for assessing research quality (details related to recruitment strategy, blinding, confounding, exposure assessment, incomplete outcome data, selective outcome reporting, conflicts of interest, etc.). We also extracted numerical data for both outcomes examined, namely, neuropsychological development and mental health, but given the heterogeneity between studies, opted for a narrative review.

The cases in which studies analyzing the same outcome account for the same population will be communicated, since some studies may share the same study sample. Those studies will be treated as one data point on the qualitative synthesis. Nevertheless, partial overlapping between studies will also be communicated on the text, but studies will be treated as different data points. In this regard, the results and the tables will be presented with the study names to facilitate contrasting the evidence and the study samples through the different domains.

2.5. Risk of bias in individual studies

We assessed the quality and strength of the evidence following the Navigation Guide methodology, an approach that has been specifically developed for research in the environmental health field. The Navigation Guide approach to systematic review was first described to frame a robust method to synthesize what is known about environmental health in a transparent and systematic manner (Woodruff and Sutton, 2014; Johnson et al., 2014).

Based on the protocol from a previous systematic review applying the Navigation Guide methodology (Uwak et al., 2021), we assessed the risk of bias in individual studies across the following domains: Recruitment strategy, blinding, confounding, exposure assessment, incomplete outcome data, selective outcome reporting, conflicts of interest, or other problems that could put the study at risk of bias. Ratings for each domain were “low,” “probably low,” “probably high,” or “high” risk of bias, **(**Supplementary Material, S2**).** We personalized instructions for each of the eight domains; for instance, we assessed the exposure following a scoring list formed by six questions evaluating characteristics that may influence the quality of the exposure assessment (number of exposure metrics, the ability of metrics to differentiate between types of greenness, exposure assessed more than once, consideration of different buffer distances/areas, green space quality/accessibility evaluation, measures of use of green space) by modifying the criteria from a previous systematic review (Gascon et al., 2015). Moreover, on the confounding domain, we determined for a study to be rated “low” risk of bias if both pre-determined potential confounders were accounted for; namely, individual-level and neighborhood-level socioeconomic status (SES). A study was rated “probably low” when accounting for only one of the two potential confounders. Similarly, when a study accounted for one or both potential confounders while including potential mediators (air pollution, noise, heat, physical activity, social cohesion, stress, or attention) in the model, the study was rated as “probably high”, as overadjustment of the model may have introduced substantial bias. Finally, a study was rated as “high” when not accounting for any of our listed potential confounders.

Two reviewers (AC and SD) independently determined the risk of bias across all domains with narrative justifications of the ratings, and a third reviewer (LL) validated the information. Any disagreement was resolved by discussion. When no consensus was reached, a fourth researcher (AL) also assessed the risk of bias. Ultimately, overall risk of bias rating was assigned to each of the included studies. Looking at the individual domain ratings, if any were “high” or “probably high,” the overall rating was automatically rated as “high” or “probably high,” respectively. If most domains were rated as “low” or “probably low,” the overall rating was determined to be “low” or “probably low,” respectively.

2.6. Risk of bias across studies

The Navigation Guide integrates the GRADE approach, therefore, ratings for the overall body of evidence quality were classified as “high,” “moderate,” “low,” or “very low.” In line with the Navigation Guide methodology, we rated the quality beginning from an initial rating of “moderate" (Johnson et al., 2014; Woodruff and Sutton, 2014; Balshem et al., 2011). Subsequently, we carried downgrades and upgrades of the ratings based on a previously described Navigation Guide approach rationale (Johnson et al., 2014). “Downgrades” to the quality rating were deliberated based on five categories of considerations: Risk of bias, indirectness, inconsistency, imprecision, and potential for publication bias. In turn, “upgrades” were considered for a large magnitude of effect, dose-response, and whether residual confounding would minimize the overall effect estimate. Optional downgrades or upgrades were: 0 (no change from initial quality rating), −1 (1 level downgrade) or – 2 (2 level downgrade), +1 (1 level upgrade) or + 2 (2 level upgrade) (Balshem et al., 2011). Again, we based our quality rating on a previous systematic review’s protocol (Uwak et al., 2021) **(**Supplementary Material, S3**).** Two reviewers (LL and AC) rated the evidence individually and then compared ratings together to reach a final decision. Any disagreement was resolved by discussion.

3. Results

3.1. Study selection

Our searches retrieved 901 records, 621 remaining after removing duplicates. Screening by title and abstract identified 66 articles for full-text review. Having read the papers in detail, a further 35 were discarded **(**Supplementary Material, S4**).** Finally, and after including 3 studies identified through snowballing, we used 34 studies for this systematic review (Fig. 2).

3.2. Description of studies included

We grouped the studies included by outcome of interest, in two different tables, separating those that assessed neuropsychological development (Tables 2 and 4) from those focused on mental health (Tables 3 and 5), and summarized their characteristics. Two studies that report both types of outcomes are included in both tables (Bijnens et al., 2020; Lindemann-Matthies et al., 2021).

Seventeen of the studies included had been conducted in Europe (n = 17; 50%), nine in the United States of America (n = 9; 26%), four in Australia (n = 4; 12%), two in South Korea (n = 2; 6%), and one each in Canada and China (n = 1; 3%). All of them had been published since 2002, although most (n = 28; 82%) were from the last 5 years

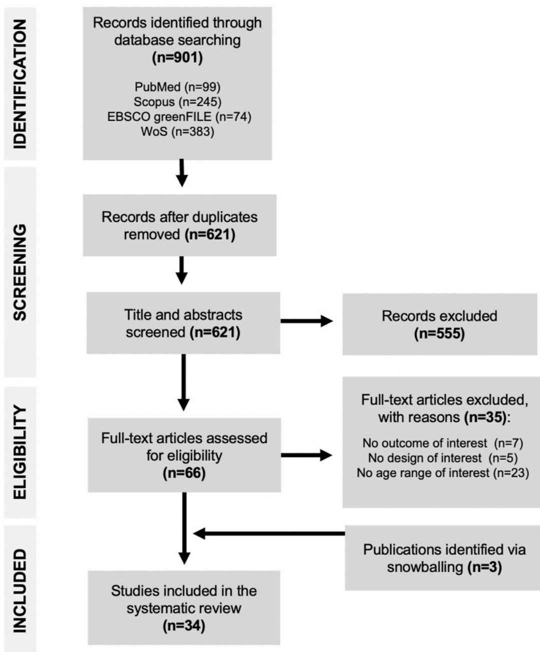

Fig. 2. Flow chart as a description of the study selection process.

(2017–2021). Regarding the design, seventeen were longitudinal (n = 17; 50%), twelve cross-sectional (n = 12; 45%) and five ecological (n = 5; 15%). The sample size ranged from 169 (Taylor et al., 2002) to 59,754 (Yang et al., 2019).

3.3. Greenness exposure assessment

Greenness exposure was measured very differently across the studies. The most widely used locations to analyze exposure to surrounding greenness were the participants' home, school, and neighborhood. One study assessed greenness along the route from home to school, using a 50-m buffer around the route (Dadvand et al., 2015), while another assessed greenness in the school attendance catchment area (i.e., where its student body lived), composed of two non-overlapping zones, the school itself and the neighborhood (Kuo et al., 2018), and a third study analyzed exposure by assessing the greenness in the attendance area of each school (Hodson and Sander, 2017).

The Normalized Difference Vegetation Index (NDVI) was the objective measure most widely used to quantify surrounding greenness, being employed in 15 studies (Amoly et al., 2014; Asta et al., 2021; Dadvand et al., 2015, 2017, 2018; Hartley et al., 2021; Jimenez et al., 2021b; Julvez et al., 2021; Madzia et al., 2019; Markevych et al., 2014, 2018; Reuben et al., 2019; Tallis et al., 2018; Wu et al., 2014; Yang et al., 2019), grass or shrub cover (Hodson and Sander, 2017; Kuo et al., 2018), vegetation continuous fields (Dadvand et al., 2017), the soil-adjusted vegetation index (SAVI) (Yang et al., 2019) or modified soil-adjusted vegetation index (Lee et al., 2019), the total area of green space in the neighborhood (Nordbø et al., 2020) and/or tree cover density (Markevych et al., 2018), as well as the percentage of green space, natural areas or vegetation of certain characteristics in a given area (Bijnens et al., 2020; Feng and Astell-Burt, 2017; Flouri et al., 2019; Lee et al., 2021; Markevych et al., 2018; Poulain et al., 2020; Sajady et al., 2020; Sivarajah et al., 2018; Tallis et al., 2018; Van Aart et al., 2018; Weeland et al., 2019).

Various studies measured access to greenness. A study in Barcelona (Spain) (Amoly et al., 2014) assessed the proximity of the home address to green space, using an ecological map of the city, generating a binary variable (yes/no) indicating whether a child's home was <300 m from a major green space, and also, seeking to assess contact with greenness, recorded the number of times and average number of hours participants spent time playing in green spaces, using parent-completed questionnaires. Likewise, a study conducted in Germany measured the shortest distance from the home to urban green space (Markevych et al., 2014). With the same objective, another study (Nordbø et al., 2020) used binary variables (yes/no) to assess the presence of parks, within 800- and 5000-m buffers around the home. One last study (Zach et al., 2016) asked parents about access to public parks and green spaces using a binary response variable (available/not available).

On the other hand, some studies used subjective measures to assess exposure to greenness. A cross-sectional study published in 2002 (Taylor et al., 2002)assessed natural spaces in the residential area by asking adult participants to rate the views from the windows of their high-rise apartments in relation to natural and man-made features using 5-point scales. Further, four studies conducted in Australia (Feng and Astell-Burt, 2017; Putra et al., 2020, 2021a, 2021b) requested parents/caregivers to rate on a Likert scale how strongly they agreed with the following statement: "There are good parks, playgrounds and play space in this neighborhood" (recording responses as strongly disagree, disagree, agree, and strongly agree), to assess the quality of the greenness. Finally, a German study (Lindemann-Matthies et al., 2021) asked students. to evaluate the naturalness of window view and interior view on 7-step scale (1: not natural at all; 7: very natural). Additionally, this study also assessed connectedness to nature by accounting for the weekly amount of time spent in nature and plant care on a 5-step scale (ranging from 1: very little to 5: very much).

3.4. Risk of bias in individual studies

In our assessment, nine studies were rated as having a low risk of bias (n = 9; 26%), fourteen were rated with a probably high risk of bias (n = 14; 41%), while the remaining eleven were deemed to have a high risk of bias (n = 11; 33%). We have summarized the rating for individual studies across the eight domains below (Fig. 3). The overall risk of bias ratings (Tables 2 and 3) **(**Supplementary Material, S5**)**, and the narrative justifications for each have been detailed **(**Supplementary Material, S6**)**. Exposure assessment was the domain with the higher risk of bias rating since the methods used to measure exposure to greenness did not differentiate between types of vegetation in many studies. Further, numerous studies did not assess green space quality or accessibility, while almost none of the studies accounted for green exposure time or use.

3.5. Risk of bias across studies

A rationale for risk of bias assessment across studies has been specified (Supplementary Material, S3), together with a table with the risk of bias rating details **(**Supplementary Material, S7**)**. The overall quality ratings by outcome have been presented in two different tables (Tables 2 and 3), next to the outcome domain. We classified studies in different groups, by outcome domain. Brain volume and self-discipline were assessed independently, as did not fit with the rest of the groups. Most of the domains for neuropsychological development (brain volume, attention, working and visual memory, intelligence, cognitive development, and self-discipline) (86%; n = 6) obtained "very low" quality ratings, while the remaining (academic performance) (14%; n = 1) received a "low" rating. In contrast, regarding mental health, each of the three outcome domains (well-being, ADHD symptoms, and behavior) received a different rating; "moderate", "low" and "very low".

Table 2

Summary of risk of bias ratings and adjusted associations between greenness exposure and outcomes within each neuropsychological development domain. In studies with a positive (↑) or negative association (↓), the table only shows measures in which the association was found.

Outcome domain (Quality of evidence)	Study/ Project	Sample Size	Design	Greenness measurement	Area	Buffer	Outcome Assessment	Direction	Overall Risk Of Bias
Brain Volume (Very Low)									
Dadvand et al. (2018)	BREATHE	N = 253	Longitudinal	NDVI	Residence	100-m	3D MRI	↑	HIGH
Attention (Very Low)									
Julvez et al. (2021)	HELIX	N = 1298	Longitudinal	NDVI	Residence	100-m	ANT	**NA**	HIGH
Dadvand et al. (2017)	INMA	N = 978	Longitudinal	NDVI	Residence	500-m	ANT	↑	LOW
Dadvand et al. (2015)	BREATHE	N = 2593	Longitudinal	NDVI	School	50-m	ANT	↑	HIGH
Lindemann-Matthies et al. (2021)	–	N = 634	Cross-sectional	Naturalness Connectedness to nature	School	–	D2-revision test	**NA**	HIGH
Visual and Working Memory (Very Low)									
Jimenez et al. (2021b)	VIVA	N = 857	Longitudinal	NDVI	Residence	90-, 270-m	WRAML2	↑	Probably HIGH
Julvez et al. (2021)	HELIX	N = 1298	Longitudinal	NDVI	Residence	100-m	N-back	**NA**	HIGH
Dadvand et al. (2015)	BREATHE	N = 2593	Longitudinal	NDVI	School Commuting route Total	50-m 50-m –	2-back test 3-back test	↑	HIGH
Flouri et al. (2019)	Millennium	N = 4758	Cross-sectional	% Of greenness	Neighborhood	–	CANTAB SWM task	↑	HIGH
Intelligence (Very Low)									
Jimenez et al. (2021b)	VIVA	N = 857	Longitudinal	NDVI	Residence	90-, 270-m	KBIT-2	↑	Probably HIGH
Julvez et al. (2021)	HELIX	N = 1298	Longitudinal	NDVI	Residence	100-m	CPM	**NA**	HIGH
Lee et al. (2021)	EDC	N = 189	Longitudinal	% Built greenness density	Residence	100-, 500-, 1000-, 1500-, 2000-m	WISC	↑	Probably HIGH
Bijnens et al. (2020)	EFPTS	N = 620	Longitudinal	% Of seminatural, forested, blue, and urban green areas	Residence (Urban area)	1-, 2-, 3-, 4-, 5-Km	WISC-R	↑	LOW
Cognitive Development (Very Low)									
Asta et al. (2021)	GASPII	N = 465	Longitudinal	NDVI	Residence	500-m	WISC-III	↑	Probably HIGH
Jimenez et al. (2021b)	VIVA	N = 857	Longitudinal	NDVI	Residence	90-, 270-m	KBIT-2 WRAML2	↑	Probably HIGH
Julvez et al. (2021)	HELIX	N = 1298	Longitudinal	NDVI	Residence	100-m	CPM ANT n-back test	**NA**	HIGH
Dadvand et al. (2015)	BREATHE	N = 2593	Longitudinal	NDVI	School Total	50-m –	2-back 3-back ANT	↑	HIGH
Reuben et al. (2019)	E-Risk	N = 2232	Longitudinal	NDVI	Neighborhood	1-mile	WISC-IV	**NA**	HIGH
Academic Performance (Low)									
Markevych et al. (2018)	GINIplus and LISA	N = 2429	Longitudinal	NDVI, tree cover density, proportions of green spaces	Residential School	500-, 1000-m	German Mathematics	**NA**	LOW
Tallis et al. (2018)	–	N = 495 schools	Ecological	% Of tree/shrub	School	750-, 1000-m	Composite indicator of different standardized test scores	↑	LOW
Kuo et al. (2018)	–	N = 318 public schools	Ecological	TCC	School Neighborhood Catchment	–	Reading Mathematics	↑	Probably HIGH
Sivarajah et al. (2018)	–	N = 387 schools	Ecological	TCC	School	–	Reading Writing	↑	HIGH
Hodson and Sander (2017)	–	N = 222 primary schools	Ecological	TCC	School	–	Reading	↑	Probably HIGH
Wu et al. (2014)	–	N = 905 public schools	Ecological	NDVI in March	School	250-, 500-, 1000-, 2000-m	English Mathematics	↑	Probably HIGH
Self- Discipline (Very Low)									
Taylor et al. (2002)	–	N = 169	Cross-sectional	Near-home nature from apartment views	Residential	–	Concentration, inhibition of initial impulses, and delaying gratification	↑	HIGH

Abbreviations: (BREATHE) BRain dEvelopment and Air polluTion ultrafine particles in scHool childrEn; (NDVI) Normalized Difference Vegetation Index; (MRI) Magnetic Resonance Imaging; (HELIX) Human Early-Life Exposome; (ANT) Attentional Network Task; (NA) No association; (INMA) INfancia y MedioAmbiente; (WRAML2) Wide Range Assessment of Memory and Learning; (CANTAB) Cambridge Neuropsychological Automated Battery; (SWM) Spatial Working Memory; (KBIT-2) Kaufman Brief Intelligence Test; (CPM) Raven's Coloured Progressive Matrices test; (EDC) Environment and Development of Children; (WISC) Wechsler Intelligence Scale for Children; (EFPTS) East Flanders Prospective Twins Survey; (WISC-R) Wechsler Intelligence Scale for Children Revised; (GASPII) Gene and Environment Prospective Study on Infancy in Italy; (WISC-III) Wechsler Intelligence Scale for Children-Third edition; (E-Risk) Environmental Risk; (WISC-IV) Wechsler Intelligence Scale for Children-Fourth edition; (GINIPlus) German Infant Study on the influence of Nutrition Intervention plus Environmental and Genetic Influences on Allergy Development; (LISA) Influence of life-style factors on the development of the immune system and allergies in East and West Germany; (TCC) Tree Canopy Cover.

3.6. Neuropsychological development outcomes

Eighteen studies analyzed the effect of exposure to greenness on various domains of neuropsychological development (Tables 2 and 4).

3.6.1. Brain volume

The only study assessing brain volume found positive results. This study, which had a cohort design and a high risk of bias (Dadvand et al., 2018), analyzed the association between lifelong residential exposure to greenness, using the NDVI and the volume of various brain regions, using 3D magnetic resonance imaging. The authors observed that several brain region volumes were significantly associated with lifelong exposure to greenness. Additionally, they found that clusters associated with residential greenness exposure partly overlapped with more numerous and spatially extensive clusters that were positively associated with measures of working memory in the adjusted model. Specifically, they showed that the tissue volume of the left premotor cortex was positively correlated with working memory (4.3, 95% CI: 1.2, 7.4) and superior working memory (3.8, 95% CI: 1.2, 6.5). The tissue volume from the right prefrontal cortex's superior cluster was also positively correlated with working memory (3.0, 95% CI: 0.4, 5.6), and inferior cluster with superior working memory (1.6, 95% CI: 0.2; 3.1), while tissue volume of the left premotor region was positively correlated with working memory (3.1, 95% CI: 0.2, 6.0).

3.6.2. Attention

We observed inconsistency among the results concerning the effect of exposure to greenness on attention. Two out of four studies that assessed this finding reported positive associations (Dadvand et al., 2015, 2017). While the remaining two did not find significant associations between children's exposure to greenness and attention (Julvez et al., 2021; Lindemann-Matthies et al., 2021).

Both studies conducted by Dadvand et al., and deemed to have a low (Dadvand et al., 2017) and a high (Dadvand et al., 2015) risk of bias, found significant associations of lifelong exposure to greenness and attention with lower hit reaction time standard error (HRT-SE; an indicator of inattention), leading to better attention. The first study (Dadvand et al., 2015), conducted in Barcelona, found that children with greater total exposure to surrounding greenness measured using the NDVI had lower HRT-SE after 12 months (−3.9, 95% CI: −7.4, −0.4), and the same trend for greenness within (−3.4, 95% CI: −6.6, −0.2) and surrounding (−3.7, 95% CI: −7.3, −0.1) school boundaries. The second study (Dadvand et al., 2017), with data from the Sabadell and Valencia INMA cohorts, concluded that more residential greenness during the first years of life was associated with lower HRT-SE, although the associations were only significant for NDVI in the 500-m buffer. No association was found for vegetation continuous fields.

In contrast, a German cross-sectional study (Lindemann-Matthies et al., 2021) with a high risk of bias did not find associations between students' evaluation of the naturalness of the window and interior classroom views and performance in the d2-division test (a standardized attention and concentration test). Time spent in natural places and on plant care was neither significantly associated. Remarkably, test performance was negatively associated with children's perceived level of stress in class in terms of speed ($p = 0.001$) and concentration ($p = 0.008$). Finally, a study with a high risk of bias (Julvez et al., 2021) including mother-child pairs selected from six European birth cohorts (BiB, N = 204; EDEN, N = 198; INMA, N = 221; KANC, N = 204; MoBa, N = 272; Rhea,n = 199) found no associations between residential greenness exposure during childhood and attention but concluded that higher green space exposure during pregnancy was associated with higher inattentiveness scores (15.52, 95% CI: 3.24, 27.80).

It is important to note that since (Julvez et al., 2021) includes participants from INMA (N = 221) in the study sample, there may be partial double counting of the evidence with Dadvands' study (N = 978) (Dadvand et al., 2017).

3.6.3. Visual and working memory

Two out of three studies assessing the effect of exposure to greenness on working memory found a positive impact. A previously mentioned longitudinal study with a low high risk of bias (Dadvand et al., 2015) that used n-back tests, a 2-back version to measure working memory and a 3-back version to measure superior working memory, showed that both total exposure to surrounding greenness and greenness within and surrounding school grounds were related to greater working memory (9.8, 95% CI: 5.0, 15.0; 9.8 95% CI: 5.2, 14.0; and 9.5, 95% CI: 4.5, 15.0, respectively) and greater superior working memory (6.7, 95% CI: 2.8, 11.0; 6.9, 95% CI: 3.4, 10.0; and 6.3, 95% CI: 2.3, 10.0, respectively). It also found working memory to be associated with greenness along the route from home to school (4.9, 95% CI: 1.0, 8.8). The other study (Flouri et al., 2019), with a cross-sectional design and a high risk of bias, concluded that children living in wards with more green space had a better spatial working memory as they made fewer total errors in the Cambridge Neuropsychological Automated Battery spatial working memory task (−0.793, 95% CI -1.545, −0.041). In turn, an European study (Julvez et al., 2021) did not find associations between residential greenness exposure during childhood and working memory.

Regarding visual memory, a cohort study from project Viva (Jimenez et al., 2021b) deemed to have a probably high risk of bias rating found that early childhood greenness was nonlinearly associated with higher mid-childhood visual memory. At lower levels of greenness (NDVI <0.6), children with higher levels of residential greenness during early childhood had a better performance in the visual memory index of the WRAML2 (Wide Range Assessment of Memory and Learning) in mid-childhood.

3.6.4. Intelligence

Results differed concerning the effect of exposure to greenness on intelligence. Two of the studies that investigated this association used versions of the Wechsler Intelligence Scale for Children (WISC) to assess intelligence and observed a positive impact (Bijnens et al., 2020; Lee et al., 2021), whereas a third study (Jimenez et al., 2021b) also found a positive association employing the Kaufman Brief Intelligence Test. The remaining study did not find associations measuring fluid intelligence with Raven's Coloured Progressive Matrices test (Julvez et al., 2021).

The first, a cohort study with a low risk of bias (Bijnens et al., 2020) found that, for children living in urban areas, an IQR increase in residential greenness, within a 3000-m radius, was associated with a 2.6-point increase (95% CI: 1.4, 3.9; $p < 0.001$) in the total Intelligence Quotient (IQ), with increases of 2.2 points in verbal IQ (95% CI: 0.9, 3.4; $p = 0.0008$) and 2.4 points in performance IQ (95% CI: 1.0, 3.8; $p = 0.0014$). No associations were found in children living in rural or suburban areas. The second cohort study (Lee et al., 2021), conducted in South Korea and classified as having a probably high risk of bias,

Table 3
Summary of risk of bias ratings and adjusted associations between greenness exposure and outcomes within each mental health domain. In studies with a positive (↑) or negative (↓) association, the table only shows measures in which the association was found.

Outcome domain (Quality of evidence)	Study/ Project	Sample Size	Design	Greenness measurement	Area	Buffer	Outcome Assessment	Direction	Overall Risk Of Bias
Well-being (Moderate)									
Hartley et al. (2021)	CCAAPS	N = 339	Longitudinal	NDVI	Residential	400-, 800-m	SCAS, Separation Anxiety subscale	↑	Probably HIGH
Van Aart et al. (2018)	–	N = 172	Longitudinal	Surrounding semi-natural, forested, and agricultural areas	Residence	2000-m	Emotional status (0–10 Likert scale)	↑	LOW
Feng and Astell-Burt (2017)	LSAC	N = 4968	Longitudinal	% Of parkland Green space quality	Neighborhood	–	SDQ TDS, and internalizing and externalizing subscales	↑	LOW
Lindemann-Matthies et al. (2021)	–	N = 634	Cross-sectional	Naturalness Connectedness to nature	School	–	19 item questionnaire to assess subjective well-being	↑	HIGH
Nordbø et al. (2020)	MoBa	N = 21,019	Cross-sectional	Total km2 of green spaces Access to parks	Residential	800-, 5000-m	Short Mood Feelings Questionnaire	↓	LOW
ADHD symptoms (Low)									
Yang et al. (2019)	–	N = 59,754	Cross-sectional	NDVI SAVI	School	100-m, 500-, 1000-m	ADHD/DSM-IV	↑	Probably HIGH
Amoly et al. (2014)	BREATHE	N = 2111	Cross-sectional	NDVI	Residence Home-School	100-m 100-m	ADHD/DSM-IV	↑	LOW
Behavior (Very Low)									
(Putra et al., 2021a) (Putra et al., 2020)	LSAC	N = 4969 N = 24,418	Longitudinal	Green space quality	Neighborhood	–	SDQ prosocial scale	↑	Probably HIGH
Bijnens et al. (2020)	EFPTS	N = 620	Longitudinal	% Of seminatural, forested, blue, and urban green areas	Residence (Urban area)	0.5-,1-, 2-, 3-, 4-km	CBCL (total scores, internalizing and externalizing subdomains)	↑	LOW
Poulain et al. (2020)	LIFE	N = 398	Longitudinal	% Of green spaces	Residential	50-, 100-, 400-m	SDQ	**NA**	LOW
Sajady et al. (2020)	Minnesota Student Survey	N = 21,378	Cross-sectional	% Of grass/shrub cover	School	300-, 500-m	Global Appraisal of Individual Needs Short Screener, externalizing symptoms	↑	Probably HIGH
Madzia et al. (2019)	CCAAPS	N = 562, 7 years N = 313, 12 years	Cross-sectional	NDVI	Residence	200-, 400-, 800-m	Behavioral Assessment System for Children	↑	Probably HIGH
Lee et al. (2019)	KorEHS-C	N = 1817	Cross-sectional	MSAVI	Neighborhood	1.6-km	CBCL	↑	HIGH
Weeland et al. (2019)	TRAILS	N = 715	Cross-sectional	% Of public green space	Neighborhood	–	CBCL	**NA**	HIGH
Zach et al. (2016)	–	N = 6206	Cross-sectional	Availability of public parks or green spaces	Neighborhood	–	SDQ TDS	↑	HIGH
Amoly et al. (2014)	BREATHE	N = 2111	Cross-sectional	NDVI Time spent in green spaces	Residential School	100-, 250-, 500-m 100-m	SDQ	↑	LOW
Markevych et al. (2014)	GINIplus and LISAplus	N = 1932	Cross-sectional	Access to green spaces	Residential	Within 500-m	SDQ	↑	Probably HIGH

Abbreviations: (CCAAPS) Cincinnati Childhood Allergy and Air Pollution Study; (NDVI) Normalized Difference Vegetation Index; (SCAS) Spence Children's Anxiety Scale; (LSAC) Longitudinal Study of Australian Children; (SDQ) Strengths and Difficulties Questionnaire; (TDS) Total Difficulties Score; (MoBa) Norwegian Mother and Child Cohort Study; (ADHD) Attention-Deficit/Hyperactivity Disorder; (SAVI) Soil-Adjusted Vegetation Index; (BREATHE) BRain dEvelopment and Air polluTion ultrafine particles in scHool childrEn; (DSM-IV) Diagnostic and Statistical Manual of Mental Disorders, Fourth Edition; (EFPTS) East Flanders Prospective Twins Survey; (CBCL) Child Behaviour Checklist; (NA) No association; (KorEHS-C) Korean Environmental Health Survey in Children and Adolescents; (TRAILS) TRacking Adolescents' Individual Lives Survey; (GINIPlus) German Infant Study on the influence of Nutrition Intervention plus Environmental and Genetic Influences on Allergy Development; (LISAplus) Influence of Life-Style Factors on the Development of the Immune System and Allergies in East and West Germany plus the Influence of Traffic Emissions and Genetics.

Table 4
Main characteristics of the studies assessing neuropsychological development included.

Reference, geographical location	Design, sample size, and project/study	Age at exposure and type of greenness	Greenness data source	Neuropsychological domain	Assessment tool	Age at evaluation	Data analysis	Confounders adjusted for in the model	Main results
Asta et al. (2021) Rome, Italy	Longitudinal N = 465 Gene and Environment Prospective Study on Infancy in Italy	Birth-7 years Residential 300- and 500-m buffers around address at birth	NDVI	Cognitive development	WISC-III	7 years	Multiple linear regression models Pearson correlation coefficients	Gender, child age at the cognitive test, maternal and paternal educational level, SES at birth, maternal age at delivery, maternal smoking during pregnancy, number of older siblings, psychologist who administered the cognitive test and inversely weighted for the probability of participation at baseline and follow-up	For an IQR increase in NDVI in the 500-m buffer, there was a 0.39-point increase (90% CI: 0.11, 0.60) in the Arithmetic subtest scores that evaluate attention, concentration, and numerical reasoning. This association was partly mediated by reduction in NO2, since adding this pollutant to the model explained 35% (90% CI: 7%–62%) of the estimate
Bijnens et al. (2020) East Flanders, Belgium	Longitudinal N = 620 (310 twin pairs) East Flanders Prospective Twins Survey	During pregnancy and at IQ evaluation Residence was categorized into urban, suburban, and rural % Of seminatural, forested, blue, and urban green areas (5, 4,3,2,1, and 0.5 km) around home address Vegetation height higher than 3 m within several radii (2000, 1000, 500, 300, 100, and 50 m) around the residence	Flemish Government–Department Environment map CORINE Land Cover 1990 High-resolution land cover data set (Green Map of Flanders, 2012)	Intelligence	WISC-R (total, verbal and performance IQ)	7–15 years	Mixed modelling Multilevel regression analysis	Sex, age, parental education, neighborhood household income, year of WISC-R assessment, and zygosity and chorionicity	Residential green space within a 1000- to 5000-m buffer was significantly associated with total IQ and performance IQ, while verbal IQ was significant in a 2000- to 5000-m buffer. An IQR increase in residential green space within a 3000-m radius was associated with a 2.6-point (95% CI: 1.4, 3.9; $p < 0.001$) higher total IQ, 2.2-point higher (95% CI: 0.9, 3.4; $p = 0.0008$) verbal IQ, and 2.4-point higher (95% CI: 1.0, 3.8; $p = 0.0014$) performance IQ among children residing in an urban environment. High green vegetation (>3 m in height) was also positively associated with verbal and total IQ in large buffer sizes (>500 m)
Dadvand et al. (2015) Barcelona, Spain	Longitudinal N = 2593	7–10 years Residential (250-m buffer), within	NDVI	Cognitive development: Working memory	*Computerized tests every 3 months:* 2-back test	7–11 years (12 month)	Linear mixed effects models Spearman's	Age, sex, maternal education, and residential	Total surrounding greenness was associated with

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Table 4 (*continued*)

Reference, geographical location	Design, sample size, and project/study	Age at exposure and type of greenness	Greenness data source	Neuropsychological domain	Assessment tool	Age at evaluation	Data analysis	Confounders adjusted for in the model	Main results
	The BREATHE project	and surrounding school (50-m buffer) and commuting route between residence and school (50-m buffer around)		Superior working memory Attention	3-back test ANT		correlation coefficients	neighborhood SES with school and subject as nested random effects	increased 12-month progress in working memory (9.8, 95% CI: 5.0, 15.0) and superior working memory (6.7, 95% CI: 2.8, 11.0), and a 12-month reduction in inattentiveness (−3.9, 95% CI: −7.4, −0.4), as well as greenness within and surrounding school. Commuting greenness was also associated with improved 12-month progress in working memory (4.9, 95% CI: 1.0, 8.8) and superior working memory (3.1, 95% CI: 0.0, 6.1). Adding elemental carbon to our models explained 20–65% of our estimated associations.
Dadvand et al. (2017) Sabadell and Valencia, Spain	Longitudinal N = 978 INMA project	Birth, 4–5 and 7 years Residential (within 100-, 300-, and 500-m buffer areas)	NDVI Vegetation continuous fields	Attention	ANT	7 years	Mixed effects models	Age at the attention test, sex, preterm birth, maternal educational attainment, maternal IQ, maternal smoking during pregnancy, exposure to environmental tobacco smoke, and neighborhood SES	Residential surrounding greenness during the first 7 years of life, measured with NDVI within the 500-m buffer, was associated with lower ANT HRT-SE at the age of 7 (- 7.9, 95% CI: −15.1, −0.8), consistent with better attention
Dadvand et al. (2018) Barcelona, Spain	Longitudinal N = 253 The BREATHE project	Birth-MRI evaluation Residential (within 100-m buffer)	NDVI	Brain volume Working memory Inattention	3D MRI *Computerized tests every* 3 months *for a year:* 2-back test 3-back test ANT, HRT-SE	7–10 years	Regression analysis Linear mixed effect models	Sex, age, and maternal education	Several brain region volumes significantly correlated with lifelong exposure to greenness, including clusters mapped to gray matter in the right and left prefrontal cortex and in the left premotor cortex (all p < 0.0005), and white matter in the right prefrontal regions' superior (p = 0.017) and inferior clusters (p < 0.0005), in the left

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Table 4 (*continued*)

Reference, geographical location	Design, sample size, and project/study	Age at exposure and type of greenness	Greenness data source	Neuropsychological domain	Assessment tool	Age at evaluation	Data analysis	Confounders adjusted for in the model	Main results
									premotor region ($p < 0.006$), and in both cerebellar hemispheres ($p < 0.0005$). Additionally, clusters associated with the residential greenness exposure partly overlapped with more numerous and spatially extensive clusters associated with cognitive test scores; after adjustment, peak volumes in these regions predicted better working memory
Flouri et al. (2019) Scotland and Northern Ireland, United Kingdom	Cross-sectional N = 4758 Millennium Cohort Study	11 years Neighborhood	% of greenery in the child's ward using CORINE and Generalized Land Use Database data	SWM	CANTAB SWM task	11 years	Two-level regression model	Family poverty, parental education, sports participation, and neighborhood deprivation	Children residing in wards with more green space had fewer SWM total errors (−0.793 95% CI: 1.545, −0.041)
Hodson and Sander (2017) TCMA of Minnesota, USA	Ecological N = 222 primary schools	8–9 years School (school attendance area)	Grass cover Shrub cover TCC	Academic performance	% Of students exceeding the basic standard on reading and mathematics Minnesota Comprehensive Assessment test scores	8–9 years	OLS regression Spatially-simultaneous autoregressive models	% of students eligible for free or reduced-price lunch, and % of English language learners	Schools with higher levels of TCC had higher mean reading test scores. Mean TCC was positively related to mean reading score ($\beta = 0.1211$, $p < 0.05$)
Jimenez et al. (2021b) Massachusetts, USA	Longitudinal N = 857 Project Viva	Birth, early childhood (median age 3.1 years), and mid-childhood (median age 7.8 years) Residential (within 90- and 270-m buffers)	Average NDVI	***Cognition*** Intelligence (verbal & non-verbal IQ) Motor abilities Visual memory	KBIT-2 Visual-Motor subtest of the WRAVMA Visual Memory Index of the WRAML2	Mid-childhood (median age 7.8 years)	Pearson correlation Linear regression models Generalized additive models	Sex, race, age at cognitive testing, mother's intelligence, parents' education, annual household income at enrollment, and neighborhood median annual income	At NDVI levels below the median of 0.6, greenness exposure at early childhood was associated with a 0.48% increase in nonverbal intelligence and a 2.64% increase in visual memory in mid-childhood. The association between early-childhood greenness and mid-childhood visual memory was observed after further adjusting for early childhood cognition and across different methodologies, while the association with

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Table 4 (*continued*)

Reference, geographical location	Design, sample size, and project/study	Age at exposure and type of greenness	Greenness data source	Neuropsychological domain	Assessment tool	Age at evaluation	Data analysis	Confounders adjusted for in the model	Main results
									nonverbal intelligence was not
(Julvez et al., 2021) Europe	Longitudinal N = 1298 Human Early-Life Exposome (HELIX) project	Pregnancy and childhood (6–11 years) Residential (within 100-m buffer)	NDVI	Fluid intelligence Attention Working memory	CPM ANT, HRT-SE N-Back	6–11 years	Linear regression models Multi-exposure regression models	Cohort, maternal education, maternal age, child age, sex, and trimester of conception	No statistically significant associations were found between greenness exposure during childhood and intelligence, attention or working memory. Nonetheless, higher green space exposure during pregnancy was associated lower fluid intelligence scores (−0.72, 95% CI: 1.42, −0.02
Kuo et al. (2018) Chicago, United States	Ecological N = 318 public schools	8–9 years Catchment, and its components: school, and neighborhood	TCC Grass/shrub cover	Academic performance	% of students meeting or exceeding expectations in reading and math on the Illinois Standardized Assessment Test	8–9 years	Bivariate correlations Generalized linear mixed models	Income and race/ethnicity combined in a single variable: Disadvantage	School trees were strongly correlated with both reading and math. TCC was significantly related to academic achievement. Each of the three geographic areas considered (catchment, school and neighborhood) predicted better reading performance (each with $p < 0.001$), as well as better math performance ($p < 0.01$, $p < 0.001$, $p < 0.01$ respectively). Grass and shrub cover was not related to academic achievement
Lee et al. (2021) Seoul, South Korea	Longitudinal N = 189 mother-child pairs Environment and Development of Children	Prenatal and 6 years Residential (within 100-, 500-, 1000-, 1500-, and 2000-m buffers)	% Of greenness density Differenced between built and natural greenness	Intelligence	Korean Educational Developmental Institute's WISC (total, verbal and performance IQ)	6 years	Student's t Analysis of variance Regression Least-squares means	Maternal age, child sex, maternal education level, maternal IQ, exposure to environmental tobacco smoke at age 6, 3-year average NO2 in residential area at age 6, household income, residential deprivation, subjective noise level, distance of main road from the home at age 6, proportion of road	Built greenness affected children's IQ more effectively than natural greenness. Children living in neighborhoods with more built greenness tended to score higher on total IQ, the association being significant for all buffer sizes but strongest for the 2000-m buffer (5.32, 95% CI: 2.35, 8.29)

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Table 4 (*continued*)

Reference, geographical location	Design, sample size, and project/study	Age at exposure and type of greenness	Greenness data source	Neuropsychological domain	Assessment tool	Age at evaluation	Data analysis	Confounders adjusted for in the model	Main results
								density within each radius at age 6, physical activity time at age 6 and the administrative district as random effect	
Lindemann-Matthies et al. (2021) State of Baden-Württemberg, Germany	Cross-sectional N = 634	8–11 years The naturalness of window and interior classroom views Connectedness to nature	Students were asked to evaluate the naturalness of window view and interior view on 7-step scale (1: not natural at all; 7: very natural) Weekly amount of time spent in nature and on plant care (5-step scales, ranging from 1: very little to 5: very much)	Attention & concentration Subjective well-being in class	D2-revision test A questionnaire comprising 19 questions (children had to state their opinion on 5-step Likert scales, ranging from 1: strongly disagree to 5: strongly agree)	8–11 years	Pearson correlation Linear mixed models	Wall color, naturalness of window and interior classroom views, social density, amount of time spent in nature, amount of time spent on plant care, comfort and learning satisfaction, stress, and social well-being scores	Children's performance in the d2-revision test was not significantly associated with the naturalness of their window or interior classroom views (all p > 0.168). Time spent in natural places and on plant care was neither significantly associated with any of the variables in the d2-revision test
Markevych et al. (2018) Wesel and Munich, Germany	Longitudinal N = 2429 GINIplus and LISA	10–15 years Residential and school (within 500- and 1000-m buffers)	NDVI (May to August) Tree cover density Proportions of agricultural land, forest, and urban green space (in Munich only)	Academic performance	Report of the latest certificate grades in German and mathematics	10 and 15 years	Logistic mixed effects models	Parental education, net equivalent income at follow-up, and urbanicity at follow-up (Munich only)	A small proportion of associations between green space in 500-m buffer and academic performance reached formal statistical significance in Munich children, though not in Wesel children, but they were inconsistent in sensitivity analyses
Reuben et al. (2019) England and Wales, United Kingdom	Longitudinal N = 2232 Environmental Risk Longitudinal Twin Study	5–12 years Neighborhood (within 1-mile buffers around the home)	NDVI	Cognitive development	WISC-IV (IQ computed based on Information and Matrix Reasoning scores)	12 years	Multiple linear regression models	Fully adjusted model included sex, child polygenic score for educational attainment, family SES, and neighborhood SES	Children living in greener neighborhoods tended to score slightly higher on measures of cognitive ability (β = 0.09; 95% CI: 0.02, 0.15; p = 0.007) at 12 years, but after adjustment, exposure to greenness was not a significant predictor of longitudinal increases in IQ across childhood
Sivarajah et al. (2018) Toronto, Canada	Ecological N = 387 schools	8-9 and 11–12 years School	TCC Tree diversity and species	Academic performance	% of students at or above the provincial standard in reading, writing, and mathematics	8-9 and 11–12 years	Multiple regression models Generalized linear models	Learning opportunity index	Tree cover positively affected children's academic performance in grade 6 (11–12 years), significant associations being found with mean test

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Table 4 (*continued*)

Reference, geographical location	Design, sample size, and project/study	Age at exposure and type of greenness	Greenness data source	Neuropsychological domain	Assessment tool	Age at evaluation	Data analysis	Confounders adjusted for in the model	Main results
									scores ($p = 0.027$). Tree species diversity did not significantly influence academic performance
Tallis et al. (2018) California, United States	Ecological N = 495 schools	10–11 years School (within 10-, 50-, 100-, 300-, 500-, 750-, and 1000-m circular buffers)	NDVI Agricultural percent cover % Of tree and shrub	Academic performance	Composite indicator of science, mathematics, and English scores in standardized tests	10–11 years	Pearson correlations Linear regression models	SES, gender, ethnicity, student: teacher ratio, urban versus rural settings, and solar irradiance	A significant positive association was found between test scores and tree and shrub cover within 750 and 1000 m of urban schools. Average tree- and shrub-cover schools performed 4.2% (CI 95%:3.9, 4.4) better in terms of standardized test scores than low tree-cover urban schools. This association was not found in rural schools
Taylor et al. (2002) Chicago, United States	Cross-sectional N = 169 adult-child pairs	7–12 years Residential	Adult participants rated the views from their apartment windows on a five-point scale, to assess near-home nature	Self-discipline	*Concentration:* SDM, DSB, ABK, and NCPC *Inhibition of initial impulses:* MFF, Stroop, and CM *Delaying gratification:* challenge to resist an immediate, smaller reward in favor of a delayed but larger reward	7–12 years	OLS regression	Gender	A greener view from home strongly positively predicts girls' scores on this combined self-discipline measure ($p < 0.0001$), for each point difference in greenness of view, scores increase by roughly a quarter of a standard deviation, $\beta = 0.274$
Wu et al. (2014) Massachusetts, United States	Ecological N = 905 public schools	8–9 years School (within 250-, 500-, 1000-, and 2000-m buffers)	NDVI in March, July and October	Academic performance	% of students above proficient in English and Math based on Massachusetts Comprehensive Assessment System standardized tests	8–9 years	Spatial generalized linear mixed models	Race, gender, language ability, income level, student/ teacher ratio, attendance, and place	Surrounding greenness in March showed a significant ($p < 0.01$) association with school academic performance in English and Math regardless of which buffer distance was considered

Abbreviations: (NDVI) Normalized Difference Vegetation Index; (SES) socioeconomic status; (WISC-III) Wechsler Intelligence Scale for Children-Third edition; (NO2) nitrogen dioxide; (IQR) interquartile range; (CI) confidence interval; (IQ) Intelligence Quotient; (CORINE) Coordination of Information on the Environment; (WISC-R) Wechsler Intelligence Scale for Children Revised; (BREATHE) Brain dEvelopment and Air polluTion ultrafine particles in scHoolchildrEn; (ANT) Attentional Network Task; (INMA) INfancia y MedioAmbiente; (HRT-SE) Hit Reaction Time-Standard Error; (MRI) Magnetic Resonance Imaging; (CANTAB) Cambridge Neuropsychological Automated Battery; (SWM) Spatial Working Memory; (TCC) Tree Canopy Cover; (OLS) Ordinary Least Squares; (KBIT-2) Kaufman Brief Intelligence Test; (WRAVMA) Wide Range Assessment of Visual-Motor Abilities; (WRAML2) Wide Range Assessment of Memory and Learning; (CPM) Raven's Coloured Progressive Matrices test; (GINIPlus) German Infant Study on the influence of Nutrition Intervention plus Environmental and Genetic Influences on Allergy Development; (LISA) Influence of life-style factors on the development of the immune system and allergies in East and West Germany; (WISC-IV) Wechsler Intelligence Scale for Children-Fourth edition; (SDM) Symbol Digit Modalities; (DSB) Digit Span Backwards; (ABK) Alphabet Backwards; (NCPC) Necker Cube Pattern Control; (MFF) Matching Familiar Figures; (CM) Category Matching.

measured the effect of greenness density (as a percentage) on 6-year-olds in buffers around their home. Analyzing natural and built greenness separately, it found that children living in neighborhoods with more built greenness tended to have better total IQ scores. The association was significant for all radii considered (100, 500, 1000, 1500 and 2000 m), but strongest for the 2000-m buffer (5.32, 95% CI: 2.35, 8.29). No significant associations were reported for natural greenness. The third study (Jimenez et al., 2021b), a previously mentioned cohort study from project Viva, observed that at lower levels of residential greenness (NDVI <0.6), an increase from the 25th to the 50th NDVI percentile was associated with a 0.48% increase in mid-childhood nonverbal IQ.

Although the fourth study (Julvez et al., 2021), which has been previously mentioned, did not find statistically significant associations between fluid intelligence and childhood residential greenness, concluded that higher green space exposure during pregnancy was associated lower fluid intelligence scores (−0.72, 95% CI: 1.42, −0.02). This result points in the opposite direction in contrast with the previously mentioned research.

3.6.5. *Cognitive development*

Regarding cognitive development, findings differed between studies. Out of the five studies that analyzed this outcome, two used versions of WISC adapted for assessing cognitive development in children (Asta et al., 2021; Reuben et al., 2019), while a third (Dadvand et al., 2015) was based on computerized attention and working memory tasks. Meanwhile, the fourth study (Jimenez et al., 2021b) used intelligence, motor abilities and visual memory to assess cognition in mid-childhood. Finally, the fifth study (Julvez et al., 2021) evaluated children's' cognitive function measuring fluid intelligence, attention and working memory.

A cohort study with a probably high risk of bias mentioned earlier (Asta et al., 2021) reported a 0.39-point increase (90% CI: 0.11, 0.60) in the arithmetic subtest score of the third edition of the WISC (WISC-III), used to assess cognitive development, for every IQR increase in NDVI in a 500-m buffer around the home. Modeling with NO2 level as a mediator explained 35% (90% CI: 7%–62%) of the effect of exposure to greenness within the 500-m buffer. No associations were observed for the 300-m buffer. In contrast, another cohort study (Reuben et al., 2019) with a high risk of bias, conducted in the United Kingdom, did not find significant associations in the adjusted model between neighborhood greenness, measured using the NDVI in a 1-mile buffer around the home, and cognitive development at 12 years of age, assessed using the fourth edition of the WISC (WISC-IV). Another study using data form different European cohorts (Julvez et al., 2021) also found no association between residential surrounding greenness and cognitive function.

A longitudinal study with a high risk of bias mentioned above (Dadvand et al., 2015) observed that exposure to greenness has a beneficial impact on cognitive development. This study measured changes in attention, working memory and superior working memory scores after 12 months to assess cognitive development, and it found associations of total surrounding greenness with increases in working memory (9.8, 95% CI: 5.0, 15.0) and superior working memory (6.7, 95% CI: 2.8, 11.0), and decreases in inattentiveness (−3.9, 95% CI: 7.4, −0.4), all consistent with an improvement in cognitive development.

Finally, a previously mentioned high risk of bias study (Jimenez et al., 2021b) analyzed the effect of early-childhood residential greenness exposure on cognitive functioning using longitudinal data from the Project Viva cohort. A nonlinear relationship of exposure to greenness at early childhood with cognition at mid-childhood was observed; at NDVI levels below the median of 0.6, higher greenness was associated with higher levels of mid-childhood nonverbal IQ and with higher visual memory. No evidence of consistent improvement was observed at NDVI levels above 0.8. The association for mid-childhood visual memory was also observed in the fully adjusted linear regression analysis, with a minimal set of confounders, and further adjusting for early childhood cognition, while the association with mid-childhood nonverbal IQ was not.

3.6.6. *Academic performance*

Results differed concerning the effect of exposure to greenness on academic performance. A study with a low risk of bias that included data from two German cohorts (Markevych et al., 2018) did not find consistent associations between home and school exposure to greenness and academic performance in German language and mathematics.

Out of the six studies that measured this outcome, five have an ecological design (Hodson and Sander, 2017; Kuo et al., 2018; Sivarajah et al., 2018; Tallis et al., 2018; Wu et al., 2014). Among these studies, one study with a probably high risk of bias conducted in Chicago (Kuo et al., 2018) found significant associations between academic performance and TCC, but not grass and shrub cover. For all the areas considered (catchment, school and neighborhood), TCC predicted better performance in mathematics ($p < 0.01$, $p < 0.001$, $p < 0.01$ respectively) and reading ($p < 0.001$ in all cases). Similarly, they concluded that school tree cover was more strongly correlated with academic performance than catchment or overall neighborhood tree cover. Similarly, another ecological study with a probably high risk of bias, conducted in Minnesota (Hodson and Sander, 2017) used the same measures to assess exposure, and observed positive associations only for TCC. It concluded that mean marks in standardized tests for reading, though not mathematics, were higher in schools with greater TCC ($\beta = 0.1211$, $p < 0.05$).

A third study, with a high risk of bias, conducted in Toronto (Sivarajah et al., 2018), found positive associations of TCC with mean performance across all academic tests ($p = 0.027$) and two out of the three components of the tests (reading, $p = 0.017$, writing $p = 0.029$, and mathematics $p = 0.064$). Additionally, it found that the impact of TCC on academic performance was more marked in schools with the highest level of external challenges. A fourth study (Tallis et al., 2018), with a low risk of bias, conducted in California, found that exam marks were higher in urban schools with more trees and shrubs in 750- and 1000-m buffers. Schools with average tree and shrub cover showed 4.2% better performance (95% CI: 3.9, 4.4) in standardized test scores than schools with a low cover. This association was not found for rural schools. Neither NDVI nor agricultural area was associated with academic performance in any of the buffers analyzed. Finally, a fifth ecological study with a probably high risk of bias (Wu et al., 2014) analyzed the effect of NDVI of school surroundings in March, July and October on academic performance in English and mathematics, concluding that students with greater exposure to greenness over the year had better academic performance. In particular, highly significant associations were found between greenness in March and academic performance in English and mathematics ($p < 0.01$) in all the buffers considered. Noting that most standardized exams used to assess academic performance were taken in the spring, greenness in March was the most closely linked to academic performance.

3.6.7. *Self-discipline*

The only study evaluating self-discipline found a positive association. A cross-sectional study from Chicago (Taylor et al., 2002), rated with a high risk of bias, analyzed the association between near-home nature, based on apartment window views rated on a five-point scale, and self-discipline. The researchers assessed children's self-discipline measuring concentration, inhibition of initial impulses and delaying gratification. This study found that a greener view form home strongly predicted girls' scores on the combined self-discipline measure ($p < 0.0001$).

3.7. *Mental health outcomes*

The effect of exposure to greenness on mental health was assessed in eighteen studies (Tables 3 and 5).

3.7.1. *Well-being*

We found differences in the results regarding the effect of exposure to

Table 5
Main characteristics of the studies assessing mental health included.

Reference, geographical location	Design, sample size, and project/study	Age at exposure and type of greenness	Greenness data source	Mental health domain	Assessment tool	Age at evaluation	Data analysis	Confounders adjusted for in the model	Main results
Amoly et al. (2014) Barcelona, Spain	Cross-sectional N = 2111 The BREATHE project	7–10 years Residential (100-, 250- and 500-m buffers) and school (100-m buffer) greenness Proximity to green spaces (living within 300 m of a major green space, yes/no) Time spent in green spaces and on beaches (hours/year)	Average NDVI Ecological map of Barcelona Questionnaire	Behavioral development ADHD symptoms	Parent-rated SDQ ADHD/DSM-IV from teachers	7–10 years	Quasi-Poisson mixed effects model	Child's sex, school level, ethnicity, preterm birth, breastfeeding, exposure to environmental tobacco smoke, maternal smoking during pregnancy, responding person, parental educational achievement, parental employment status, parental marital status, and neighborhood SES	An IQR increase in green space playing time was associated with lower total difficulties (−4.8, 95% CI: 8.6, −0.9), emotional symptoms (−8.2, 95% CI: 13.9, −2.2), and peer relationship problems (−15.4, 95% CI: 22.7, −7.4) scores. An IQR increase in mean NDVI around participants' homes was also associated with decreased total difficulties in 100- (−3.6, 95% CI: 6.6, −0.6), 250- (−3.8, 95% CI: 6.4, −1.2), and 500-m buffers (−4.0, 95% CI: 6.7, −1.2), as well as with combined home and school greenness (−4.5, 95% CI: 8.6, −0.1). ADHD symptoms (−6.0, 95% CI: 11.3, −0.2) and inattention (−6.2, 95% CI: 11.6, −0.4) scores decreased significantly with an IQR increase in residential greenness in a 100-m buffer
Bijnens et al. (2020) East Flanders, Belgium	Longitudinal N = 620 (310 twin pairs) East Flanders Prospective Twins Survey	During pregnancy and at IQ evaluation Residence was categorized into urban, suburban, and rural Seminatural, forested, blue, and urban green areas (5, 4,3, 2,1, and 0.5 km) around home address Vegetation height greater than 3 m within several radii (2000, 1000,	Flemish Government–Department Environment map CORINE Land Cover 1990 High-resolution land cover data set (Green Map of Flanders, 2012)	Behavior	Parent-rated CBCL (total scores and externalizing and internalizing subdomains)	7–15 years	Mixed modelling Multilevel regression analysis	Sex, age, parental education, neighborhood household income, year of CBCL assessment, and zygosity and chorionicity	For twins living in an urban area, percentage of residential green space within a 1000- to 3000-m radius was significantly associated with a reduction in total problem behavior, green space within a 500- to 4000-m radius with a reduction in externalizing problem behavior (including attention problems and aggressive behavior) and green space in a 3000-m radius with

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Table 5 (*continued*)

Reference, geographical location	Design, sample size, and project/study	Age at exposure and type of greenness	Greenness data source	Mental health domain	Assessment tool	Age at evaluation	Data analysis	Confounders adjusted for in the model	Main results
		500, 300, 100, and 50 m) around the residence							lower internalizing problem behavior (including anxiety and withdrawal). An IQR increase in residential green space within a 3000-m radius was associated with decreased CBCL total (−2.0, 95% CI: −3.6, −0.4; p = 0.015) and externalizing (2.0, 95% CI: −3.5, −0.4; p = 0.017) scores among urban-living children. No association was found in children living in rural or suburban settings
Feng and Astell-Burt (2017) Australia	Longitudinal N = 4968 LSAC cohort	4–13 years Neighborhood green space quantity and quality	% Of parkland within each statistical area 2 Parent-rated Likert scale to measure green space quality	Well-being	SDQ TDS SDQ Internalizing and externalizing subscales	4–13 years	Linear regressions	Gender, age, indigenous status, green space quantity, quality parks, SEIFA index, and ARIA index	Gains in well-being appeared to top out for participants with 21%–40% of the residential land use designated as green space for TDS (β = −0.54, 95% CI: 0.86, −0.22), the internalizing subscale (β = −0.29, 95% CI: 0.47, −0.10) and the externalizing subscale (β = −0.25, 95% CI: 0.45, −0.06)
(Hartley et al., 2021) Cincinnati, USA	Longitudinal N = 339 CCAAPS	At three time periods: Birth, 12 years and averaged across childhood Residential (200-, 400-, and 800-m radius around home address)	Average NDVI	Self-reported symptoms of anxiety Self-reported symptoms of depression	SCAS (6 subscales: Panic and Agoraphobia, Separation Anxiety, Social Phobia, Obsessive Compulsive Disorder, Physical Injury Fears, and Generalized Anxiety Disorder) CDI 2, Short-Form	12 years	Linear regressions	Household income, traffic-related air pollution, neurological hazard exposure, blood lead, and community deprivation	NDVI was generally not associated with self-reported anxiety and depression symptoms, except for the SCAS separation anxiety subscale at 400 m (β = − 0.97, 95% CI: − 1.86, −0.07) and 800 m (β = − 1.33, 95% CI: − 2.32, −0.34)
Lee et al. (2019) South Korea	Cross-sectional N = 1817 Korean Environmental Health Survey in Children and Adolescents	6–18 years Neighborhood (1.6-km radius around residence)	Modified Soil-Adjusted Vegetation Index	Neurobehavioral health	Parent/guardian-rated CBCL	6–18 years	Regression models	Age, sex, body mass index, monthly household income, exposure to second-hand smoke, number of vigorous physical activity per week, exposure to NO2, and	Living in a highly green neighborhood was associated with lower CBCL total scores (−2.33, 95% CI: 4.10, −0.57), than those of children living in low green areas, and

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Table 5 (*continued*)

Reference, geographical location	Design, sample size, and project/study	Age at exposure and type of greenness	Greenness data source	Mental health domain	Assessment tool	Age at evaluation	Data analysis	Confounders adjusted for in the model	Main results
								blood lead level (mg/dL)	especially with lower externalizing behavior (−1.90, 95% CI: −3.52, −0.27), attention problems (−1.32, 95% CI: −2.58, −0.06) and ADHD problems (−1.27, 95% CI: −2.43, −0.12) scores
Lindemann-Matthies et al. (2021) State of Baden-Württemberg, Germany	Cross-sectional N = 634	8–11 years The naturalness of window and interior classroom views Connectedness to nature	Students were asked to evaluate the naturalness of window view and interior view on 7-step scale (1: not natural at all; 7: very natural) Weekly amount of time spent in nature and on plant care (5-step scales)	Subjective well-being in class	A questionnaire comprising 19 questions (children had to state their opinion on 5-step Likert scales)	8–11 years	Pearson correlation Linear mixed models	Wall color, naturalness of window and interior classroom views, social density, amount of time spent in nature, and amount of time spent on plant care	Children felt more relaxed and attentive during class, the higher the naturalness of the window views (p = 0.011). The weekly time spent in nature was positively associated with children's feelings of comfort and learning satisfaction, and social integration (p = 0.009) and negatively associated with stress and lack of concentration during lessons (p = 0.002)
Madzia et al. (2019) Cincinnati, United States	Cross-sectional N = 562, 7 years N = 313, 12 years CCAAPS	7 and 12 years Residential (200, 400, and 800 m around home address)	Average NDVI	Behavior	Behavioral Assessment System for Children, Parent Rating Scale, Second Edition	7 and 12 years	Pearson correlation Logistic regression models Linear regression models	Sex, race, maternal education, and neighborhood deprivation	At age 7 years, a 0.1-unit increase in NDVI within a 200-m buffer was associated with lower conduct scores (β = −1.10, 95% CI: 2.14, −0.06). At age 12 years, a 0.1-unit increase in NDVI was associated with lower anxiety scores considering an 800-m buffer only (β = −1.83, 95% CI: −3.44, −0.22) and was also associated with lower depression scores for both 200- (β = −1.36, 95% CI: −2.61, −0.12) and 800-m (β = −1.63, 95% CI: −3.00, −0.26) buffers and with lower somatization scores for 200- (β = −1.83, 95% CI: −3.22, −0.44) and 400-m (β = −1.69, 95%

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Reference, geographical location	Design, sample size, and project/study	Age at exposure and type of greenness	Greenness data source	Mental health domain	Assessment tool	Age at evaluation	Data analysis	Confounders adjusted for in the model	Main results
									CI: −3.08, −0.30) buffers
Markevych et al. (2014) Munich, Germany	Cross-sectional N = 1932 GINIPlus and LISAplus longitudinal studies	10 years Residential (500-m buffer around) Access to green spaces	NDVI Local Bavarian land use dataset to calculate the shortest distance between residence at 10 years and the nearest urban green space in meters	Behavioral problems	Parent-rated SDQ	10 years	Logistic regression	Study, sex, age, parental level of education, age of mother at time of birth, single-parent status at the 10-year follow-up, time spent in front of a screen and time spent outdoors	Children living further than 500 m away from urban green spaces had overall more behavioral problems than those living within this range (proportional OR 1.41, 95% CI: 1.06, 1.87). A longer distance to the nearest urban green space was associated with an increased risk of hyperactivity and inattention problems (OR 1.20, 95% CI: 1.01–1.42) and peer relationship problems (OR 1.20, 95% CI: 1.02, 1.40). After stratifying by sex, the association with hyperactivity/ inattention was only significant among boys. Behavioral problems were not associated with the distance to a forest or with residential NDVI
Nordbø et al. (2020) Norway	Cross-sectional N = 21,019 Norwegian Mother and Child Cohort Study cohort	8 years Neighborhood and local community (800- and 5000-m radius around home address)	Total Km2 of green spaces (forests, marshland, parks, and golf courses) at the 800-m radius Access to parks within 800- and 5000-m radius (yes/no)	Subjective well-being	Short Mood and Feelings Questionnaire	8 years	Logistic regression	Child's gender, mother's age and level of education, hours spent on watching TV, hours spent on other screen-based activities, after- school care and population density	Depressive and emotional symptoms among the children increased when they had more parks (within 800 m) β = 0.162 (95% CI: 0.25, −0.08) and playgrounds/sports fields (800 and 5000 m) β = 0.127 (95% CI: 0.21, −0.04) in the neighborhood, and when they lived in more densely populated areas β = 0.140 (95% CI: 0.23, −0.05)
Poulain et al. (2020) Leipzig, Germany	Longitudinal N = 398 LIFE Child study	3–10 years Residential (within 50-, 100-, and 400-m radius around the home)	% Of green spaces (sum of agriculture, lawn, bushes/young trees, and trees) and streets (sum of railways and streets)	Emotional problems	Parent-rated SDQ	3–10 years	Logistic regression	Child age, child gender, SES, and the rate of social benefit recipients in the local district	No association was found between the percentage of green spaces and emotional problems
Putra et al. (2020) Australia		4–5 years to 14–15 years (biannually		Prosocial behavior	Parent-rated SDQ prosocial scale	4–5 years to 14–15 years		Age, sex, ethnicity, child speaking a	Prosocial behavior was higher among children

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Reference, geographical location	Design, sample size, and project/study	Age at exposure and type of greenness	Greenness data source	Mental health domain	Assessment tool	Age at evaluation	Data analysis	Confounders adjusted for in the model	Main results
	Longitudinal N = 24,418 LSAC cohort	followed-up) Neighborhood	Parent rated Likert scale to measure green space quality				Multilevel linear regression	language other than English at home, family SES, SEIFA and neighborhood safety	whose parents agreed (β = 0.10, 95% CI: 0.04, 0.16) and strongly agreed (β = 0.20, 95% CI: 0.13, 0.27) that there was quality green space in their neighborhood
(Putra et al., 2021b) Australia	Longitudinal N = 4969 LSAC cohort	4–5 years to 14–15 years (biannually followed-up) Neighborhood	Caregivers were asked to rate (strongly disagree, disagree, agree, and strongly agree) on the following statement: "There are good parks, playgrounds and play spaces in this neighborhood"	Prosocial behavior **5 candidate mediators:** Physical activity Social interaction Child mental health Child health-related quality of life Caregiver mental health	Caregiver-rated SDQ prosocial scale Child-rated SDQ prosocial scale Weekday and weekend physical activity (time-use diaries), the choice for free time (caregiver reported), and physical activity enjoyment (caregiver reported) Children's contacts with neighbors (caregiver reported) SDQ TDS (child & caregiver rated) PedsQL 4.0 K6	4–5 years to 14–15 years	Causal mediation analysis: Standard regression models	Sex, Indigenous status, language spoken at home, caregiver education, family weekly income, family structure, number of siblings, neighborhood safety, area disadvantage, area accessibility, and prosocial behavior from the baseline wave	Only physical activity enjoyment from physical activity indicators was found as a mediator with moderate consistency, suggesting very weak evidence that physical activity mediated the association between green space quality and prosocial behavior. Child social interaction and caregiver mental health were found to have low mediation consistency. In addition, indicators of child mental health and HRQOL served as mediators on the pathway from green space quality to prosocial behavior with low-to-high mediation consistency
(Putra et al., 2021a) Australia	Longitudinal N = 4969 LSAC cohort	4–5 years to 14–15 years (biannually followed-up) Neighborhood	Caregivers were asked to rate (strongly disagree, disagree, agree, and strongly agree) on the following statement: "There are good parks, playgrounds and play spaces in this neighborhood"	Prosocial behavior	Caregiver-rated SDQ prosocial scale	4–5 years to 14–15 years	Latent class analysis Multinomial logistic regression Multilevel linear regression	Age, sex, Indigenous status, language spoken at home, caregiver education, family weekly income, family structure, number of siblings, neighborhood safety, area disadvantage, and area accessibility	Higher quality green space perceived by caregivers accumulated over time was associated with better prosocial behavior. Children with consistently very good quality green space had higher prosocial behavior (β = 0.35, 95% CI: 0.23, 0.47) than those with low quality green space. Better prosocial behavior was also observed among children whose caregiver perception of

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Reference, geographical location	Design, sample size, and project/study	Age at exposure and type of greenness	Greenness data source	Mental health domain	Assessment tool	Age at evaluation	Data analysis	Confounders adjusted for in the model	Main results
									green space quality trended from good to very good (β = 0.23, 95% CI: 0.11, 0.35) and from very good to good (β = 0.31, 95% CI: 0.20, 0.42) compared to children with consistently low quality green space
Sajady et al. (2020) Metropolitan areas in Minnesota, USA	Cross-sectional N = 21,378 Minnesota Student Survey	10–11 years (Fifth grade students) School (within 300- and 500-m radius areas from the center of each school)	% Of tree canopy cover, grass/shrub cover	Internalizing symptoms (depression and anxiety) Externalizing symptoms (problematic behaviors)	Pediatric Symptom Checklist, SDQ Global Appraisal of Individual Needs Short Screener	10–11 years (Fifth grade students)	Multilevel linear regression Logistic regressions	Sex, race/ethnicity groups, free/reduced-price lunch	Students attending schools with a higher % of grass/shrub cover within 500-m buffers had significantly lower odds of engaging in externalizing behaviors (OR 0.93, 95% CI: 0.87, 0.99) than students attending schools with lower amounts of grass and shrub cover. Higher % of tree canopy within 300- and 500-m buffers and higher grass/shrub cover within 300 m buffers around schools were not significantly associated with internalizing or externalizing behaviors
Van Aart et al. (2018) Aalter, Belgium	Longitudinal N = 172	9–15 years Residential surrounding (100-, 300-, 500-, 1000-, 2000-, 3000-, 4000- and 5000-m buffers) semi-natural, forested, and agricultural areas, and residential and industrial areas	CORINE database land cover 2000	Psychosocial stress	Children were questioned about recent feelings of happiness, sadness, anger, and anxiousness using a 0- to 10-point Likert scale Parent-rated SDQ Hair cortisol as stress biomarker	9–15 years	Linear regression models Linear mixed-effect regression models	Age, sex, and parental SES	Natural landscapes within a 2000-m buffer were positively associated with better emotional status (greater happiness and less sadness, anxiousness, and total negative emotions, $p < 0.05$) and agricultural areas within 300 m were associated with lower hyperactivity problem scores ($p = 0.02$). In longitudinal analyses, natural landscape within a 2000-m buffer predicted more happiness ($p = 0.049$) and industrial areas within 4000-m

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Reference, geographical location	Design, sample size, and project/study	Age at exposure and type of greenness	Greenness data source	Mental health domain	Assessment tool	Age at evaluation	Data analysis	Confounders adjusted for in the model	Main results
									predicted more negative emotions (p = 0.013)
Weeland et al. (2019) The Netherlands	Cross-sectional N = 715 Tracking Adolescents' Individual Lives Survey cohort	11–16 years Neighborhood	% Of public green space	Externalizing problems	Parent-rated CBCL	11 years	Bivariate correlations	Sex, age at T1, externalizing behavior at T1, urbanization, and SES	No association was found between % of public green space in the neighborhood between 11 and 16 years (T1-T3) and externalizing problems at 11 years (T1)
Yang et al. (2019) Lianoning province, China	Cross-sectional N = 59,754	2–17 years Schools and kindergartens (within 100-, 500- and 1000-m buffers)	NDVI SAVI	ADHD symptoms	Parent/guardian-rated: ADHD/DSM-IV survey Conner's Abbreviated Symptom Questionnaire (To assess robustness)	2–17 years	Generalized linear mixed models Regression models	Age, sex, parental education level, household income level, type of home district, and dog ownership	Higher greenness levels were associated with lower odds of ADHD symptoms. A 0.1-unit increase in NDVI and SAVI in the 500-m buffer was significantly associated with a lower odds of ADHD symptoms (OR 0.87, 95% CI: 0.83; 0.91, and 0.80, 95% CI: 0.74, 0.86, respectively; p < 0.001 for both). The direction of the associations was consistent across the other buffer sizes
Zach et al. (2016) Bavaria, Germany	Cross-sectional N = 6206	5–7 years Availability of public parks or green spaces (available/not available)	Parents' answers concerning crowding in their home, traffic load and accessibility of green space	Mental health	Parent-rated SDQ TDS	5–7 years	Logistic regression	Sex, parental education, household income, parental occupational status, crowding, traffic load, and accessibility of green space	Children with no access to green spaces (weighted, OR 3.17, 95% CI: 1.76–5.70) and unweighted, OR 1.84, 95%: 1.26–2.69) were at greater risk of mental health problems

Abbreviations: (BREATHE) BRain dEvelopment and Air polluTion ultrafine particles in scHool childrEn; (NDVI) Normalized Difference Vegetation Index; (ADHD) Attention-Deficit/Hyperactivity Disorder; (SDQ) Strengths and Difficulties Questionnaire; (DSM-IV) Diagnostic and Statistical Manual of Mental Disorders, Fourth Edition; (SES) socioeconomic status; (IQR) interquartile range; (CI) confidence interval; (IQ) Intelligence Quotient; (CORINE) Coordination of Information on the Environment; (CBCL) Child Behaviour Checklist; (LSAC) Longitudinal Study of Australian Children; (TDS) Total Difficulties Score; (SEIFA) Socio-Economic Index For Areas; (ARIA) Accessibility-Remoteness Index of Australia; (CCAAPS) Cincinnati Childhood Allergy and Air Pollution Study; (SCAS) Spence Children's Anxiety Scale; (CDI 2) Children's Depression Inventory 2; (NO2) nitrogen dioxide; (GINIPlus) German Infant Study on the influence of Nutrition Intervention plus Environmental and Genetic Influences on Allergy Development; (LISAplus) Influence of Life-Style Factors on the Development of the Immune System and Allergies in East and West Germany plus the Influence of Traffic Emissions and Genetics; (OR) odds ratio; (PedsQL) The Pediatric Quality of Life Inventory; (K6) Kessler 6 Psychological Distress Scale; (SAVI) Soil-Adjusted Vegetation Index.

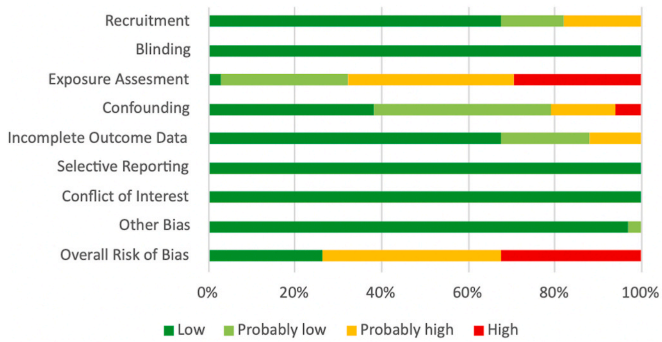

Fig. 3. Summary of risk of bias rating for individual studies.

greenness on well-being. An Australian study with a cohort design and a low risk of bias (Feng and Astell-Burt, 2017) explored the association of the quantity and quality of residential green spaces with well-being during childhood using Goodman's Strengths and Difficulties Questionnaire (SDQ). The SDQ is a behavioral screening tool used to assess well-being that covers children's behavior, emotions, and peer relations, with 25 items divided into five 5-item subscales: emotional symptoms, conduct problems, hyperactivity/inattention, peer relationships problems, and prosocial behavior. The study considered two secondary outcomes: (1) the internalizing subscale score, the sum of emotional symptoms and peer problems scores, and (2) the externalizing subscale score, the sum of conduct problems and hyperactivity scores. It found that while more green space tended to be associated with better well-being, the gains in well-being were greatest for children with 21–40% of residential green space coverage, improvements plateauing beyond this range. For this amount of greenness, the study reported markedly lower internalizing ($\beta = -0.29$, 95% CI: 0.47, −0.10) and externalizing ($\beta = -0.25$, 95% CI: 0.45, −0.06) subscale scores.

A second longitudinal study with a low risk of bias conducted in a suburban area in Belgium (Van Aart et al., 2018) analyzed the effect of residential landscape on psychosocial stress. Children's emotional state and behavioral problems were respectively assessed with a 0- to 10-point Likert scale and the SDQ completed by their parents, and hair cortisol levels were measured as an objective biomarker of stress. The cross-sectional analysis found residential exposure to semi-natural and forested areas within a 2000-m buffer correlated positively with happiness and negatively with sadness, anxiousness, and total negative emotions ($p < 0.05$, in all cases). Similarly, a 0.50-point decrease in hyperactivity problem score was observed for every IQR increase in agricultural area within the 300-m buffer ($p = 0.02$) and a 16.01% decrease in hair cortisol level for every IQR increase in agricultural area in the 100-m buffer ($p = 0.03$). In contrast, longitudinal analyses revealed that the presence of semi-natural and forested areas within a 2000-m buffer predicted better scores in happiness ($p = 0.049$, pseudo-$R2 = 3.31\%$). In turn, cohort study from Cincinnati (Hartley et al., 2021) with a probably high risk of bias rating observed that residential NDVI was largely not associated with self-reported anxiety and depression symptoms, except for the Spence Children's Anxiety Scales separation anxiety subscale at 400- and 800-m (0.1 unit increase mean NDVI 400-m: $\beta = -0.97$, 95% CI: − 1.86, −0.07; 800-m: $\beta = -1.33$, 95% CI: − 2.32, −0.34).

Additionally, a third aforementioned cross-sectional study from Germany a high risk of bias (Lindemann-Matthies et al., 2021) concluded that Children felt more relaxed and attentive during class, the higher the naturalness of the window views ($p = 0.011$). The weekly time spent in nature was positively associated with children's feelings of comfort and learning satisfaction, and social integration ($p = 0.009$) and negatively associated with stress and lack of concentration during lessons ($p = 0.002$). Finally, a cross-sectional study with a low risk of bias mentioned earlier (Nordbø et al., 2020) analyzed the influence of characteristics of the built environment (total area of green space, access to parks, and population density) on mood and feelings of 8-year-olds, using the Short Mood and Feelings Questionnaire to assess their subjective well-being. Additionally, the authors examined the mediation effect of participation in leisure activities in these relationships. More depression and emotional symptoms were observed in children with more parks (in an 800-m radius) ($\beta = -0.162$, 95% CI: 0.25, −0.08) and playgrounds/sports fields (in 800- and 5000-m radii) ($\beta = -0.127$, 95% CI: 0.21, −0.04) around their home. The results of this study point in the opposite direction to others described above. On the other hand, participation in leisure-time physical activity, organized activities and social activity with friends mediated these relationships and helped counterbalance some of the negative associations observed.

3.7.2. ADHD symptoms

Results found concerning the effect of exposure to greenness on symptoms of attention-deficit/hyperactivity disorder (ADHD) were consistent, the two studies that analyzed this association reporting a positive impact. A cross-sectional study with a low risk of bias conducted in Barcelona as part of the Brain dEvelopment and Air polluTion ultrafine particles in scHoolchildrEn (BREATHE) project (Amoly et al., 2014) measured the effect of greenness on ADHD symptoms using the ADHD Diagnostic and Statistical Manual of Mental Disorders, Fourth Edition (DSM-IV) checklist rated by teachers. For each IQR increase in residential greenness within the 100-m buffer, scores for ADHD symptoms decreased by 6.0% (95% CI: 11.3, −0.2) and for inattention decreased by 6.2% (95% CI: 11.6, −0.4). The combination of greenness at home and school was also associated with 7.7% lower ADHD symptoms scores (95% CI: 14.5, −0.3).

The second study, with a cross-sectional design and a probably high risk of bias, conducted in China (Yang et al., 2019), assessed the association of ADHD symptoms, assessed using the ADHD DSM-IV survey, with greenness surrounding schools and nurseries. In addition, they used a 10-item version of Conner's Abbreviated Symptom Questionnaire, a tool used to measure ADHD symptoms, to assess the effect of outcome misclassification. A greater level of greenness around schools and nurseries was associated with a lower likelihood of children developing ADHD symptoms. Notably, 0.1-point increases in NDVI or SAVI in the 500-m buffer were significantly associated with a lower likelihood of ADHD symptoms (NDVI, OR 0.87, 95% CI: 0.83, 0.91; and SAVI, 0.80, 95% CI: 0.74, 0.86, $p < 0.001$ in both cases). Further, the direction of the associations was consistent for NDVI and SAVI in the 100-m (OR 0.92, 95% CI: 0.89–0.97; and OR 0.90, 95% CI:0.83–0.95, respectively) and 1000-m (OR 0.84, 95% CI: 0.80–0.88; and OR 0.76, 95% CI: 0.70–0.82; respectively) buffers ($p > 0.001$ in all cases).

3.7.3. Behavior

Results concerning the effect of exposure to greenness on behavior differed between studies. A Belgian cohort study with a low risk of bias (Bijnens et al., 2020) used the Achenbach Child Behavior Checklist (CBCL) to examine the extent to which children have behavioral and emotional problems. It observed a 2.0-point decrease (95% CI: −3.5, −0.4; $p = 0.017$) in the externalizing behavioral score with an IQR increase in greenness within 3000 m of children's home, in those living in urban areas, while no associations were found for children in rural or suburban areas.

Another longitudinal study using data from the Longitudinal Study of Australian Children with a probably high risk of bias conducted in Australia (Putra et al., 2020) concluded that parents' perception of the quality of neighborhood green space was positively associated with the prosocial behavior among children, measured using the SDQ prosocial scale. This result aligns with another research conducted by the same author with identical population, exposure and outcome characteristics (Putra et al., 2021a). Additionally, a third longitudinal study from Putra et al. (2021b), analyzed the mediating effect of physical activity, social interaction, and mental health on the association between green space quality and child prosocial behavior. This study observed that only physical activity enjoyment was found as a mediator with moderate consistency, suggesting very weak evidence that physical activity mediated the association. On the other hand, child social interaction and caregiver mental health were found to have low mediation consistency. Moreover, indicators of child mental health and HRQOL served as mediators on the pathway from green space quality to prosocial behavior with low-to-high mediation consistency. Finally, the last longitudinal study, which was conducted in Germany (Poulain et al., 2020), analyzed the association between the percentage of residential green spaces (within 50-, 100-, and 400-m radius around the home) and children's emotional well-being employing parent-rated SDQ, but found no association.

Regarding cross-sectional studies, we should highlight one cohort study with a high risk of bias (Weeland et al., 2019) from which we extracted cross-sectional data corresponding to the age range of interest, that did not find associations between the amount of public green space in the neighborhood and externalizing problems at 11 years assessed using the CBCL.

All other studies found pointed in the same direction. A study mentioned earlier (Markevych et al., 2014), with a cross-sectional design and a probably high risk of bias, found that children living more than 500 m from urban green space had more behavioral problems (proportional OR 1.41, 95% CI: 1.06, 1.87), measured using the parent-rated SDQ. Another cross-sectional study with a high risk of bias (Lee et al., 2019) concluded that living in a neighborhood with greater greenness was associated with a lower total CBCL score (−2.33, 95% CI, −4.10 to−0.56). Further, a third low risk of bias study mentioned earlier (Amoly et al., 2014), observed that children that spent more time playing in green spaces and those with a greater mean NDVI around their home obtained lower scores for total difficulties. Meanwhile, a fourth cross-sectional study with high risk of bias (Zach et al., 2016) concluded that children with no access to green spaces (weighted, OR 3.17, 95% CI: 1.76–5.70) were at greater risk of mental health problems. A fifth, cross-sectional study (Sajady et al., 2020) with a probably high risk of bias rating analyzed the association between the percentage of school tree canopy and grass/shrub cover and student adjustment via internalizing and externalizing symptoms. The authors found only one significant association; students attending schools with a higher percentages of grass/shrub cover within 500-m buffers had significantly lower odds of engaging in externalizing behaviors (OR 0.93, 95% CI: 0.87, 0.99) than students attending schools with lower amounts of grass and shrub cover. Finally, a cross-sectional study with a probably high risk of bias conducted in Cincinnati (Madzia et al., 2019) concluded that a 0.1-point increase in NDVI was associated with lower behavior scores in 7-year-olds ($\beta = -1.10$, 95% CI: 2.14, −0.06), and similarly, with lower anxiety, depression and somatization scores in 12-year-olds.

4. Discussion

The objective of this systematic review was to summarize the observational evidence assessing the effect of exposure to greenness on school children's neuropsychological development and mental health. Based on the 34 studies included that met our selection criteria, exposure to greenness seems to have a predominantly beneficial effect on the neuropsychological development and mental health of children. Nonetheless, the heterogeneity in the methods for assessing exposure and the diversity of domains considered within each primary outcome hinder comparisons between studies. Further, most of the studies were deemed to have a probably high or high risk of bias, and hence, their results should be interpreted with caution.

To facilitate the interpretation of how greenness around homes, schools and neighborhoods may influence the outcomes of interest, we discuss the main findings here by the area in which the greenness was measured. Although many studies select the home address as the reference to measure greenness, buffers beyond 500 m, in practice, correspond to the neighborhood rather than areas adjacent to the home. For this reason, we decided to base our discussion on these distances rather than the point of reference itself for stratifying exposure by residential area or neighborhood. We have not taken this approach for the school area, however, given that no matter how large the buffer, the areas surrounding children's schools are not necessarily similar to those around their homes.

The studies analyzing the effect of the exposure to greenness in the residential area have reported that children whose home is surrounded by more greenness have larger tissue volumes in various brain regions (Dadvand et al., 2018), higher scores on self-discipline (Taylor et al., 2002), in attention (Dadvand et al., 2017) and on intelligence (Jimenez et al., 2021b; Lee et al., 2021; Bijnens et al., 2020). Studies also observed improvements in cognitive development (Asta et al., 2021; Jimenez et al., 2021b) and well-being (Hartley et al., 2021), and fewer ADHD symptoms (Amoly et al., 2014) and behavioral problems (Amoly et al., 2014; Madzia et al., 2019; Markevych et al., 2014; Bijnens et al., 2020).

Regarding the school area, it has been observed that children at schools with more greenness show improved well-being (Lindemann-Matthies et al., 2021) and better scores for working memory, superior working memory, and attention (Dadvand et al., 2015), which is, in turn, consistent with better cognitive development, and fewer ADHD symptoms (Yang et al., 2019). Similarly, several studies indicate that students at schools with more tree cover have better academic performance than those at schools with less tree cover (Hodson and Sander, 2017; Kuo et al., 2018; Sivarajah et al., 2018; Tallis et al., 2018; Wu et al., 2014).

After classifying exposure as "corresponding to the neighborhood" in studies that used >500-m buffers to measure greenness and the residential address as a reference, we found that children living in greener neighborhoods had better scores on spatial working memory (Flouri et al., 2019) and intelligence (Bijnens et al., 2020; Lee et al., 2021) tests, higher academic performance (Kuo et al., 2018) and fewer behavioral (Bijnens et al., 2020; Lee et al., 2019; Madzia et al., 2019) and emotional problems (Van Aart et al., 2018). Further, better quality greenness in the neighborhood was associated with more prosocial behavior (Putra et al., 2020, 2021a). Similarly, it has been shown that a greater quantity and quality of greenness around the residential address predicts better well-being (Feng and Astell-Burt, 2017).

In studies using buffers to measure exposure to greenness, the most significant associations were found with the widest buffers (Bijnens et al., 2020; Tallis et al., 2018). This occurs when the buffer is large enough to reflect neighborhood, which often includes the greenness around the school as well as around the home (Asta et al., 2021; Dadvand et al., 2017). For example, both a study that assessed the effect of greenness on intelligence (Lee et al., 2021) and another assessing its effect on academic performance (Wu et al., 2014) reported stronger associations when using the largest buffer (2000 m). Nonetheless, buffers do not allow us to assess the impact of the different areas that potentially act on a given outcome. The approach by Kuo et al. (2018) is promising to clarify this issue, these authors opting to define the areas of interest (overall catchment and within it, the school and the neighborhood) independently, with no overlap between the components, and assessed the relationship between the greenness in each area and academic performance. This study concluded that having trees on school grounds was most strongly correlated with exam results.

Like Kuo et al. (2018), there were other ecological studies assessed the effect of greenness at school on academic performance across groups of schools (Hodson and Sander, 2017; Sivarajah et al., 2018; Tallis et al., 2018; Wu et al., 2014). Interestingly, while all studies that measured tree cover (Hodson and Sander, 2017; Kuo et al., 2018; Sivarajah et al., 2018; Tallis et al., 2018) reported significant associations between TCC at school and academic performance, no associations were found for shrub or grass cover in the two studies that assessed these variables (Hodson and Sander, 2017; Kuo et al., 2018). Although it is important to highlight that the only study with a longitudinal design that analyzed the effect of greenery on academic performance did not find any association (Markevych et al., 2018), both the methodology and the findings of the aforementioned studies are consistent. In order to avoid ecology fallacy, ecological study data cannot be used to make assumptions about associations. For this reason, future research should seek to confirm the causality of the association and clarify what mechanisms are involved in children benefiting from trees since current knowledge does not allow us to attribute such a benefit to a mitigation, instoration or restoration pathway or a combination of thereof (Markevych et al., 2017).

Concerning the different pathways, a study (Dadvand et al., 2015) observed improvements on 12-month cognitive development and found that adding elemental carbon to the models explained 20–65% of the estimated associations. Similarly, a study assessing the effect of exposure to greenness on cognitive development (Asta et al., 2021) concluded that the association between residential greenness and scores on subtests evaluating attention, concentration and numerical reasoning was partially mediated by lower NO2 levels, these explaining 35% of the effect. A third study (Van Aart et al., 2018) observed that natural landscapes were associated with a better emotional status, and that this was partly explained by reductions on residential noise. Lower air pollution and noise levels may be due to the capacity of greenery to improve air quality and reduce noise annoyance through the mitigation pathway (Dzhambov et al., 2018; Markevych et al., 2017). Nonetheless, not all types of vegetation have the same pollution mitigation capacity (Tomson et al., 2021; Zhang et al., 2020b; Mori et al., 2018; Xing et al., 2019; Kumar et al., 2019; Han et al., 2020; Diener and Mudu, 2021; Barwise and Kumar, 2020). For this reason, it is important to use objective measures in future research that allow us to differentiate between types of vegetation; for example, the currently widely used NDVI does not differentiate between a golf course and a forest, and the mitigation capacity of the latter is greater given its scale and the amount of foliage. Another study (Lindemann-Matthies et al., 2021) concluded that the weekly time spent in nature was positively associated with children's feelings of comfort and learning satisfaction, and social integration and negatively associated with feelings stress and lack of concentration during lessons ($p = 0.002$). These results support the SRT and ART mechanisms behind the restoration pathway (Kaplan and Kaplan, 1989; Kaplan, 1995; Ulrich, 1983; Ulrich et al., 1991).

On the other hand, several studies have reported differences between children in urban and rural areas. A cohort study (Bijnens et al., 2020) with a low risk of bias found intelligence test scores and behavioral problems to only be significantly associated with greenness in children living in urban areas. In line with this, Tallis et al. (2018) reported associations for greenness around urban schools, but strikingly, none in the case of rural schools. It has been suggested that children in urban areas may benefit more from exposure to greenness because unlike those living in rural areas, they are more likely to use active transport, which facilitates exposure to greenness in their neighborhood on their route to school (Richardson et al., 2012).

Along similar lines, two studies with a moderate risk of bias suggest that built greenness is more beneficial than natural greenness. One of these studies concluded that built greenness had a greater impact on children's intelligence than natural greenness (Lee et al., 2021). Similarly, the second study (Markevych et al., 2014) which assessed the influence of access to green spaces, found that children living more than 500 m from an urban green space had more behavioral problems. No associations were found for total greenness or distance to the nearest forested area, suggesting that the presence of urban green space is more important than greenness per se in children. A potential explanation is that built greenness favors children benefiting from greenness because it offers easier opportunities than natural greenness, as it includes areas that have been designed to actively encourage exposure of the population, and in general, tends to be easy to access, relatively well-lit and well maintained and have facilities for sports or other leisure activities. These characteristics help children and their parents to view these spaces as safer, favoring their use. In contrast, we should note that another study, with a cross-sectional design and a moderate risk of bias (Nordbø et al., 2020), reported more depressive and emotional symptoms with greater availability of parks and playgrounds/sports fields in the neighborhood. Nonetheless, participation in physical, organized and social activities with friends was a mediator in this relationship and helped counterbalance the negative associations observed. This evidence suggests that the benefits obtained from urban green spaces may be the result of the physical activity and social interactions they promote through the instoration pathway.

Regarding quality, the two Australian studies with a low risk of bias that used a Likert scale to assess neighborhood green space showed well-being (Feng and Astell-Burt, 2017) and prosocial behavior (Putra et al., 2020, 2021a) to be strongly positively associated with parents' perception of quality of greenness. Further, another study by Putra et al. (2021b) analyzed mediation of the associations between green space quality and prosocial behavior and concluded that green space quality may indirectly influence prosocial behavior via several pathways; improving the quality of neighborhood green space may support physical activity enjoyment, social interaction, mental health among children, which in turn, may potentially foster the development of prosocial behavior.

Finally, in most of the studies included, the associations found between exposure to greenness and the domains studied remained significant after adjusting for socioeconomic characteristics. Similarly, we should highlight that several studies have confirmed inequalities associated with access to green space, with more disadvantaged neighborhoods having less green space (Camargo et al., 2018; Astell-Burt et al., 2014b; Schüle et al., 2019; Wolch et al., 2014). Considering the evidence of the benefits of greenness for children's development, it could be used as a tool for decreasing social inequalities through urban design interventions targeting the most disadvantaged neighborhoods (Badland and Pearce, 2019).

4.1. Strengths and limitations

To our knowledge, this is the first systematic review analyzing the relationship of children's neuropsychological development and mental health with exposure to greenness. We conducted this review following the PRISMA statement guidelines and documented the methods in a protocol registered on PROSPERO before starting the review, strengthening the process and trustworthiness of the results. This systematic review followed the Navigation Guide approach, adding rigorousness and transparency to the methodology. For the search, no limits were placed on publication date and studies written in either English or Spanish were included, enabling us to retrieve a large number of studies. Further, we obtained additional studies by examining the reference lists of the studies included and previous systematic reviews. To facilitate interpretation of results, we detailed the characteristics of the studies included in tables, specifying the type of greenness and tools or methods used for assessing exposure and outcomes and listing the main results of each study together with any potential confounders for which the results were adjusted. Additionally, almost all the associations observed remained after adjusting for socioeconomic variables. Lastly, following the Navigation Guide approach, we assessed studies' risk of bias in individual studies and across studies. The Navigation Guide integrates the GRADE approach, one of the most widely adopted tool for grading the quality of evidence.

The limitations of this review include the fact that most of the studies were cross-sectional, a design that is prone to bias, and consistent with this, the majority of studies found were considered to have a high or probably high risk of bias. Further, our use of just four databases for the search may have led to us missing some relevant publications, not listed in these databases. On the other hand, all the studies have been conducted in developed countries, and this means that policies or interventions based on the findings may not apply to developing countries. Notably, this systematic review covered a range of cognitive domains, neuropsychological developmental disorders, and mental health problems; for some of these, very few publications were identified, and many of the studies included have provided insufficient evidence to draw conclusions. Among the included studies, there was a general lack of mechanistic studies that explored pathways, which also hinders drawing clear conclusions. Finally, the marked heterogeneity in the methods used for assessing exposure to greenness further hindered comparisons between studies and we deemed that the data available were not suitable for a meta-analysis. Among the included studies NDVI was the most widely used tool to measure greenness. NDVI can be measured very easily, and this means that cohort studies created for other purposes can assess the effect of greenery exposure afterward. Nonetheless, this measure does not differentiate between vegetation types and, hence, poses important methodological limitations.

4.2. Recommendations for future studies

Although most of the studies included in our review report benefits associated with exposure to greenness, it is essential to confirm these results with further research based on studies using more rigorous methods. The evidence obtained could then be used to guide specific interventions capable of strengthening children's neuropsychological development and mental health. For this reason, there is a need to develop study designs that allow us to accurately assess which characteristics of greenness have an impact on each outcome and identify the mechanisms underlying these benefits.

With this goal, future observational studies should have a longitudinal design that would allow us to infer causality in the relationships observed. Studies should also make an effort to explore pathways linking greenness exposure to mental health and neuropsychological outcomes by employing mediator analysis. Mechanistic studies would enable understanding the real effect exposure to greenness has, by determining how the different mediators interact with each outcome. Similarly, they should assess exposure in specific areas, dividing areas into different non-overlapping zones, to understand how each interacts independently with the outcome, taking into account patterns in individuals' spatio-temporal movements. They should also combine both objective and subjective measures to assess exposure to greenness to paint a more detailed and balanced picture of their exposure. Subjective measures are of great interest since the perception of parents and children themselves of a given green space may influence the way they use it (Putra et al., 2021a; Aggio et al., 2015; Cleary et al., 2019; Fongar et al., 2019; Bringolf-Isler et al., 2019; Schüle et al., 2018; Abbasi et al., 2020). On the other hand, objective measurement techniques should be used to quantify greenness and accessibility to green spaces, as well as to differentiate between types of vegetation and green spaces (e.g., parks, playgrounds, forests, etc.) within a specific area. This would enable researchers to determine what types of greenness have the most influence on children's mental health and neuropsychological development, and would also improve the understanding of the underlying pathways. Further research should also adopt valid tools for assessing the outcomes and provide results adjusted for potential confounders, especially socioeconomic status. Finally, emphasis should be placed on analyzing the influence of exposure to greenness differentiating between children living in urban, semi-urban and rural areas to improve our understanding of why urban dwellers seem to benefit most.

5. Conclusion

The current evidence is promising given that the majority of studies have indicated that exposure to greenness has benefits for both the neuropsychological development and the mental health of children. Nonetheless, the heterogeneity in the methods used to assess exposure and the diversity of domains within each main outcome make it difficult to draw clear conclusions. Moreover, we have found limited evidence supporting causal relationships, half of the studies included having a cross-sectional design. In the future, studies should be conducted that are longitudinal to confirm causality between exposure to greenness and the outcomes studied and use measures that would allow us to identify what characteristics of greenness have the most impact on children's mental health and neuropsychological development and which pathways are involved in the benefits observed. Although the evidence is limited and heterogeneous, most of the associations found remained after adjustments, and therefore, these findings warrant the attention of policymakers, healthcare workers and urban planners.

Credit author statement

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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.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envres.2021.112599.

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