Effects of urban green space on human cognition: A systematic search and scoping review

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Abstract

Urban green space is associated with cognitive functions, but the underlying mechanisms remain unclear due to limited research. Given the diverse forms of green space, which lead to distinct health effects, it is essential to differentiate between types of green space. In this review, we propose a novel conceptual framework categorizing three primary effects of green space on cognitive function: functional, spatial, and perceptual. We then conduct a scoping review using the Web of Science, identifying 37 relevant studies. Among them, 20 studies employ modeling to explore potential mechanisms, while 17 studies infer pathways indirectly. Most studies examine reduced air pollution and increased physical activity as mediating factors, with stronger support for air pollution reduction as a protective mediator. However, evidence on physical activities as a mediator remains mixed. Some studies suggest that merely perceiving green space enhances brain activity, and exposure to nature is linked to improved test performance. Other potential pathways, such as heat reduction and social interaction, remain underexplored. We highlight the limitations of current methods in distinguishing various forms of green space and emphasize the need for advanced methods, such as local climate zones and street view imagery, for more precise assessment.

Keywords: urban greenery, environmental exposure, cognitive development and impairment, local climate zone, street view imagery, built environment

1. Introduction

Studies have shown that urban green space can benefit people's health (Maas et al., 2006; Barboza et al., 2021; Hunter et al., 2023). With more than half of the world's population currently living in urban areas and this number expected to exceed two-thirds by 2050 (Kohlhase, 2013), it is essential to understand the mechanisms of this relationship—specifically, the pathways through which urban green space benefits health.

In the existing literature, Lachowycz and Jones (2013) developed a socio-ecological framework to understand this relationship, highlighting three key factors: the presence of a park and its environmental benefits, the pleasure and relaxation derived from viewing greenery, and the usage of green space for physical activities and interactions. Hartig et al. (2014) listed four pathways linking the natural environment to health and well-being: reduced air pollution, increased physical activity, enhanced social interactions, and reduced stress. Additional mechanisms may include noise reduction, improved immune system, urban heat island mitigation, and optimized sunlight exposure (Lee and Maheswaran, 2011). Building on existing frameworks, the effects of green space on human health can be summarized as functional, spatial, and perceptual effects. Functional effects refer to the biochemical interactions of vegetation with the atmosphere and environment, such as reducing air pollution via dry deposition and photosynthesis (Diener and Mudu, 2021), cooling urban heat via evapotranspiration and shading (Cheung et al., 2022), and mitigating noise pollution as trees and shrubs act as natural barriers (Van Renterghem et al., 2012; Dzhambov and Dimitrova, 2014). Spatial effects arise from the physical presence of green space, offering urban residents with a retreat from the built environment dominated by concrete and asphalt, which may be perceived as stressful (Grahn and Stigsdotter, 2010), while also fostering opportunities for recreation, social interaction, and engagement with nature (Sugiyama et al., 2008). Perceptual effects stem from the aesthetic and psychological benefits of green space, enhancing residents' perception of their living environment (Kothencz et al., 2017; Chang et al., 2021). Beautiful landscapes and natural settings offer enjoyment, contributing to well-being and overall satisfaction with urban life (Grahn and Stigsdotter, 2010).

All three functions are critical, but they may arise from different forms of green space. For example, an open grass area may provide space for physical activities and social interactions, but its ability to clean air will be inferior to that of an urban forest with similar coverage. There are various forms of green space. For example, Abhijith et al. (2017) examined the different air pollution abatement performances of trees, hedges, green walls, and green roofs. Beyond conventional green space, blue space is often considered a special type of "green space" due to its similar effects (Lee and Maheswaran, 2011), and both fall under the broader terms "open space" or "public space". Space, as an important component of modern cities, shapes different urban landscapes alongside buildings and infrastructure.

The categorization of urban landscapes can be complicated. There is an existing system called the *local climate zones* (Stewart and Oke, 2012) that describes the components of green space and buildings in urban areas. Green space is, in fact, an umbrella term encompassing various forms of urban landscapes (Zou and Wang, 2021). Within the framework of local climate zones, green space may include dense trees, scattered trees, bush or scrub, low plants, bare rock or paved, bare soil or sand, and water. Their combinations with mixed urban environments (compact or open, low-, mid-, or high-rise) affect the local environment in terms of air, heat, and noise, as well as people's behaviors. For example, compact high-rise urban design, which is typical in Asia, promotes walking and increases daily physical activity (Althoff et al., 2017; Sit et al., 2025). However, compact high-rise development also contributes to urban heat, which may impose health risks (Zheng et al., 2023). It is therefore inaccurate to consider all these urban landscapes as a single type of green space or to assume they provide equally important benefits to human health.

Human health is a broad concept encompassing general well-being, including both physical and mental health (Zautra et al., 2010). Of the top 10 causes of disease worldwide in 2019 (WHO, 2020), green space may affect six of them: (1) ischemic heart disease (Liu et al., 2022); (2)

stroke (Paul et al., 2020); (3) chronic obstructive pulmonary disease (Fan et al., 2020); (4) trachea, bronchus, and lung cancers (Mueller et al., 2022); (5) Alzheimer's disease and other dementia (cognitive functions) (Astell-Burt et al., 2020); and (6) diabetes mellitus (Yang et al., 2023). Focusing on cognitive functions as an example, studies have shown that increased physical activities are associated with lower risks of cognitive impairment in older adults (Dzhambov et al., 2019; Yu et al., 2018; Ruiz-Gonzalez et al., 2021), whereas exposure to higher ambient air pollution, particularly $PM_{2.5}$ and NO_2, is associated to an increased risk of dementia (Chen et al., 2017; Yuchi et al., 2020; Zhu et al., 2023). Additionally, contact with natural environments may benefit cognitive functions and mental health (Bratman et al., 2012). The three effects of urban green space on human health have all been found to provide potential cognitive benefits.

Studies have also illustrated the benefits of urban green space on cognition, either as protection against cognitive decline for adults and older adults (Klompmaker et al., 2021; Paul et al., 2020) or for cognitive development in children (Dadvand et al., 2015). Since different forms of green space vary in their functional, spatial, and perceptual effects, it is crucial to understand how urban green space affects cognitive functions rather than simply stating that "green space is good for cognition". Existing literature provides evidence of the link between green space (exposure) and cognition (outcome), as well as the link between mediators (such as air pollution and physical activity) and cognition. However, it is crucial to recognize the connection between exposure and outcome through mediators. In this scoping review, we summarize current research on green space and cognition (both development and decline) and extract key insights on the functional, spatial, and perceptual effects of green space on cognitive functions. We highlight studies that directly examined pathways and those that used multiple types of green space to infer pathways. This synthesized knowledge will be valuable for designing urban green spaces that enhance living environments.

2. Characterizing Types of Green Space

Green space is an umbrella terminology encompassing various types of spaces (Lee and Maheswaran, 2011; Panduro and Veie, 2013; Abhijith et al., 2017; Zou and Wang, 2021). These spaces can be categorized based on the volume of vegetation. Figure 1 illustrates three examples. Figure 1a shows an open grass area in Los Angeles. Such small open grass areas are common worldwide, particularly in public spaces like universities and parks, offering spaces for entertainment and relaxation (Thompson, 2002). Figure 1b depicts a large urban forest (Central Park) in New York City, and similar settings can be found in Paris (Wood of Vincennes) and other cities around the world (Hopkins, 2015). Compared to open grass, urban forests contain more biomass and are more effective in reducing air pollution (Godina et al., 2023), blocking traffic noise, and mitigating urban heat islands (Gaffin et al., 2008). However, urban forests are generally less accessible than open grass areas, as they have limited entry points, reducing opportunities for casual daily use (Ha et al., 2022). Figure 1c shows Sai Wan Pier in Hong Kong, where people gather to enjoy the sunset. Similar settings include the Santa Monica Pier and other coastal city piers (Fullerton, 2011; Pryor, 2022). Although these various forms of open space have little to no vegetation, they serve similar social and recreational functions as open grass areas or urban forests by providing spaces for gathering and scenic enjoyment (Mueller et al., 2020; Pryor, 2022). Since open space without greenery is often more accessible than urban forests and offers larger areas than small open grass patches—important for physical activities—the number of people visiting (and the associated health benefits) may be greater (Mueller et al., 2020).

Figure 1: Examples of urban green space (from left to right: open grass, urban forest, and open space without green). Photos of open grass and open space without green are from the authors. Credit (photo of the urban forest): Central Park Conservancy (https://www.centralparknyc.org).

2.1. Functional, Spatial, and Perceptual Effects of Green Space

A more detailed framework categorizes urban green space into six forms based on their ability to clean air (Abhijith et al., 2017). We adopt this framework and extend their ratings to include potential spatial and perceptual effects (Table 1). The ratings for functional effects, primarily air pollution reduction, are adapted from Abhijith et al. (2017), while the ratings for spatial effects are based on typical size, with larger areas receiving better ratings for spatial benefits. Trees generally provide good functional effects, including roadside trees, dense forests with access, and dense forests without access, but their spatial effects range from moderate to poor due to limited accessibility. Open grass has moderate functional effects for cleaning air but not for blocking noise, while offering good spatial effects for physical activities and social interaction. Green wall/roof (Abhijith et al., 2017), a specialized form of urban greening, particularly in mid- and high-rise built environments, has lower functional effects for cleaning air or absorbing heat and does not provide space. Maximizing the value of urban green space is critical, as land in cities is expensive. Therefore, understanding the mechanisms linking urban green space to human health is essential for allocating more beneficial forms of green space within the local built environment.

Table 1: Forms of urban green space and grades of their functional, spatial, and perceptual effects on health

Type	Functional	Spatial	Perceptual
Roadside trees/hedges	good	poor	depends on the landscape
Green walls/roofs	moderate	poor	
Open grass	moderate	good	
Open space without green	poor	good	
Dense forests with access	good	moderate	
Dense forests without access	good	poor	

3. Search Criteria

We searched the keywords ("green space" or "greenness") and ("Alzheimer" or "dementia" or "cognitive" or "cognition") in all full texts on the Web of Science up to December 31, 2024, yielding a collection of 1105 documents. After an initial screening, 888 articles were included, removing review articles, editorials, abstracts, and preprints. The diagram illustrating the selection process is provided in the supplementary materials. Among the 888 articles, 20 were excluded for not being in English, 468 for not being epidemiology studies or not examining associations, 232 for not addressing cognitive functions, 81 for not considering green space exposure, and 46 for not examining pathways. Some articles met multiple exclusion criteria, but we listed the first identified reason for exclusion. Although mental health (e.g., depression) is often related to cognitive studies, we excluded studies focused on mental health as it differs from cognitive outcomes. After these exclusions, 41 articles underwent further examination by reviewing their methodology, data, and results. Four additional articles were excluded because they did not examine pathways. Ultimately, 37 articles were included in this review: 20 directly examined pathways between green space and cognitive functions, while 17 examined them indirectly. A full list of included and excluded studies is provided in the supplementary materials.

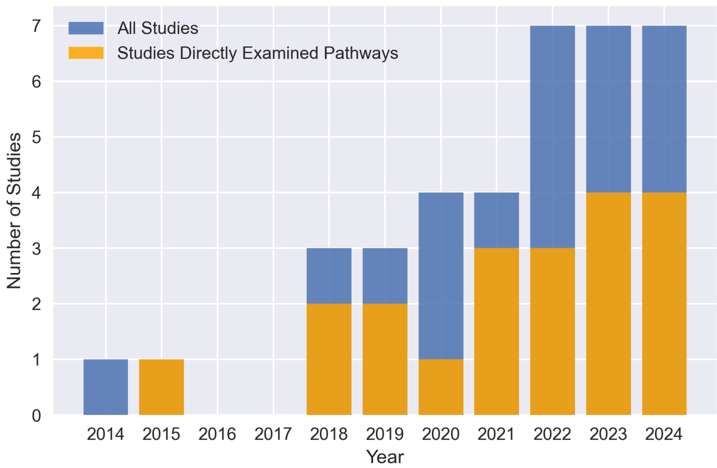


Figure 2: Number of studies each year, covering the period from January 1, 2014 to December 31, 2024. The number of studies that directly examined pathways is highlighted in orange.

The number of research articles devoted to this topic has grown over time, as shown in Figure 2. The earliest study dates back to 2014, and from 2014 to 2024 (as of September 30, 2024), the number of articles has steadily increased each year. The majority of these works directly examined the mediators or the associations between green space and cognition.

4. Results

We summarized the 20 studies that directly examined pathways based on cognitive development (school-aged children) in Table 2 and cognitive impairments (mid to older adults aged 45+)

in Table 3. One study by Wang et al. (2023) included two age groups: school-aged children and mid-life adults. Since the significant result was found in adolescents rather than mid-life adults, and the sample size of adolescents was three times larger, we categorized this article under the cognitive development group.

Table 2: Summary of 12 out of 20 selected articles directly examining the pathways between green space and cognition (cognitive development group).

Study	Sample	Age	Region	Outcome	Exposure	Model	Pathways
Almeida (2022)	3827	10	Portugal	IQ test	30-m NDVI within 800 m	Generalized mixed models, adjusted for NO_2 and physical activity (no association with NO_2)	Spatial (activity), no functional (air)
Asta (2021)	465	7	Italy	IQ test	30-m NDVI within 500 m	Generalized additive models, adjusted for NO_2 (explained 35% of the association)	Functional (air)
Binter (2022)	5403	4-5	UK, France, Spain, & Greece	Verbal and non-verbal abilities, motor function	30-m NDVI within 500 m	Multi-exposure analysis with Deletion-Substitution-Addition algorithm, adjusted for NO_2 and $PM_{2.5}$ (explained 75% of the association)	Functional (air)
Chang (2021)	44	mean 23.7	HK (lab)	Biomarker via fMRI (posterior cingulate cortex activity), behavioural tasks	Images of green urban landscape	General linear model (directly related to perceptual effects)	Perceptual
Claesen (2021)	851 schools	Students in Years 3 and 5	Australia	School scores (reading, writing, spelling, grammar & punctuation, & numeracy)	30-m NDVI within 2000 m	Generalized linear models, adjusted for traffic-related air pollution (explained 50-66% of the association)	Functional (air)
Dadvand (2015)	2593	7-10	Spain	12-month change of working memory and attention	5-m NDVI within 250 m (residential), 50 m (commuting route), and 50 m (school)	Multilevel modeling, adjusted for traffic-related air pollution (explained 20-65%)	Functional (air)
Liao (2019)	1312	2	China	Neurodevelopment of children	500-m NDVI within 300 m	Multiple linear regression models, adjusted for traffic-related air pollution $PM_{2.5}$ (explained 14-28% of the association)	Functional (air)
Mason (2022)	65	8.25±0.43	Italy	Math and attention test	Exposure to natural green space (vs. controlled group in normal classroom)	Linear mixed models, adjusted for perceived restorativeness score (explained 71% of the association)	Spatial (interaction)
Wallner (2018)	64	16-18	Austria	Attention test	Staying in green space	Stanine value comparison and t-test (higher score associated with large park)	Spatial (activity)
Wang (2023)	6220, 2623	14.4±0.5, 48±5.0	Australia	Cogstate tests	30-m NDVI within 1600 m	Mixed-effects generalized linear models, adjusted for $PM_{2.5}$ and NO_2 (no mediated percentage provided, adjustment only found in adolescents but not in mid-life adults)	Functional (air)
Binter (2024)	2725; 95	9-12	Netherlands, France	white matter microstructure outcomes including average of fractional anisotropy (FA) and mean diffusivity (MD) from imaging data	access to major parks from land use data; area surface of green space,	interquartile range linear regressions controlling for $PM_{2.5}$, NOx, BMI, etc.; road-traffic noise mediated 19% and 52% of these associations; air pollution no association	Functional (noise)
Buczylowska (2024)	689	10-13	Poland	ADHD diagnosis	percentage of grass and tree cover in 500 m and 1 km buffers from 20-m land cover data, measured from life-long residential addresses	Structural equation modeling, with mediators including social cohesion (8%), perceived green space (7%), and physical activity (6%)	Spatial (social, activity); Perceptual

4.1. Study design

The 20 selected articles can be classified into three categories. Twelve research works are classic population health studies that examined a specific population or cohort, measuring individual

Table 3: Summary of 8 of 20 selected articles directly examining the pathways between green space and cognition (cognitive impairment group).

Study	Sample	Age	Region	Outcome	Exposure	Model	Pathways
Astell-Burt (2023)	109,688	45+	Australia	dementia	Tree canopy cover from 2-m land use data within 1.6 km	Marginal structural models with mediators including physical activity, social support, and sleep duration	Spatial (activity, social)
Dzhambov (2019)	112	45-55	Bulgaria	cognitive tests (main), cortical thickness from MRI (25 samples)	30-m NDVI within 100 m	Multivariate linear regression models, adjusted for lower waist circumference (no mediated percentage provided) and NO_2 (not significant)	Spatial (activity)
Hu (2023)	375,342	57.1±8.0	UK	Cases of dementia, Alzheimer's, and vascular dementia	10-m green space within 300 or 1000 m	Cox proportional hazard regression models, adjusted for $PM_{2.5}$ and PM_{10} (explained 25-66% of the association)	Functional (air)
Yu (2018)	3240	65+	HK	Improvement in frailty status	1-m NDVI within 300 m	Ordinal logistic regression, adjusted for physical activity (explained 45% of the association)	Spatial (activity)
Yuchi (2020)	678,000	45-84	Canada	Dementia, Alzheimer's and Parkinson's disease	30-m NDVI within 100 m	Greenness mediated the association between road proximity (air pollution) and odds ratios of Alzheimer's disease	Functional (air)
Zhu (2023)	29,025	63.3±9.4	China	Cases of neurodegenerative diseases	500-m NDVI within 1000 m	Linear model and Cox proportional hazard model, adjusted for $PM_{2.5}$, PM_{10} and NO_2 (PM_{10} explained 33.9% of the association between neurodegenerative disease and NDVI)	Functional (air)
Besser (2024)	162	50+	USA	Cognitive tasks and biomarkers, including number symbol coding task, Montreal Cognitive Assessment and white matter hyperintensity volume	Perceived greenspace access and time spent in greenspaces	Multivariable linear regression models controlling for age, gender, race, ethnicity, education; examined interpersonal discrimination	Spatial (social); Perceptual
Cerin (2024)	1160	60+	Australia	mild cognitive impairment via a series of cognitive tests including Wechsler Memory Scale, Symbol Digit Modalities Test, California Verbal Learning Test, and Mini-Mental State Examination	1-km buffer along road networks, air pollution ($PM_{2.5}$, NO_2), land use data (tree cover, parks, blue space)	Generalised additive mixed models controlling with directed acyclic graphs	Functional (air); Spatial (activity)

cognitive test performance and individual green space exposure (Almeida et al., 2022; Asta et al., 2021; Astell-Burt et al., 2023; Dadvand et al., 2015; Hu et al., 2023; Yu et al., 2018; Yuchi et al., 2020; Zhu et al., 2023; Besser et al., 2024; Cerin et al., 2024; Binter et al., 2024; Buczyłowska et al., 2024). One study examined both adolescents and middle-aged adults (Wang et al., 2023). Within the classic study design, two studies focused on unique populations—infants and very young children under age 5 (Binter et al., 2022; Liao et al., 2019). In both studies, children and their mothers were paired to assess cumulative exposure to green space and air pollution prior to birth. One research work used a case-control study design in a school setting to test whether exposure to natural green space benefited math and attention test scores (Mason et al., 2022). In another case-control experiment, Wallner et al. (2018) tested whether staying in green space improved attention tests among adolescents aged 16-18. Two research works used a case-control study design in a lab environment, employing equipment to capture brain activity signals via fMRI machines (Chang et al., 2021). Two studies also obtained biomarker imaging data (Dzhambov et al., 2019; Binter et al., 2024). Additionally, there is one ecological study by Claesen et al. (2021).

4.2. Populations

Of the 20 research works, four studies focused on older adults aged 60+ (Hu et al., 2023; Yu et al., 2018; Zhu et al., 2023; Cerin et al., 2024), one on middle-aged adults (Dzhambov et al., 2019), and three on adults aged 45-85 (Astell-Burt et al., 2023; Yuchi et al., 2020; Besser et al., 2024). Three studied very young children and traced their exposure prior to birth (Binter et al., 2022; Liao et al., 2019; Binter et al., 2024). Seven studies focused on school-aged children and adolescents (Almeida et al., 2022; Asta et al., 2021; Claesen et al., 2021; Dadvand et al., 2015; Mason et al., 2022; Wallner et al., 2018). One study combined middle-aged adults and adolescents (Wang et al., 2023), and one examined young adults with an average age of 23.7 years (Chang et al., 2021).

4.3. Outcomes

The most common outcome is cognitive tests, which are often designed locally to accommodate local language and culture. The Wechsler Intelligence Scale for Children is the most popular cognitive test for children, including three dimensions of cognitive function: verbal, performance, and global (Watkins et al., 1997). Two studies in Portugal and Italy, respectively, used this cognitive test (Almeida et al., 2022; Asta et al., 2021). Other cognitive tests include the McCarthy Scales of Children's Abilities in four European countries (Binter et al., 2022), the Bayley Scales of Infant Development (BSID) (Liao et al., 2019), the Stroop Test and Neurobehavioral Evaluation System 3, or school scores (Claesen et al., 2021). Some studies used biomarkers, including human posterior cingulate (Chang et al., 2021) and cortical thickness (Dzhambov et al., 2019) via MRI machine. While most studies focused on an end-point outcome in a cross-sectional fashion, a few studies examined the change in cognitive functions over time, such as the 12-month change in working memory and attention (Dadvand et al., 2015), the d2-R test (Wallner et al., 2018), improvement in frailty status (Yu et al., 2018), and math and attention tests before and after exposure to green space (Mason et al., 2022). Studies on older populations also used the incidence of dementia, Alzheimer's, Parkinson's disease, and neurodegenerative diseases as outcome variables (Astell-Burt et al., 2023; Hu et al., 2023; Yuchi et al., 2020; Zhu et al., 2023).

Table 4: The mechanisms by which green space could affect cognition. Those marked with an asterisk (*) did not directly examine the pathways, but we may infer such a mechanism by comparison of types of green space. The studies are listed by the last name of the first author and year of publication.

		Positive protective effects	No association or inconclusive
Functional	Air	Asta (2021), Astell-Burt (2020)*, Binter (2022), Bijnens (2022)*, Cerin (2024), Claesen (2021), Crous-Bou (2020)*, Dadvand (2015), Godina (2023)*, Hu (2023), Jarvis (2022)*, John (2023)*, Liao (2019), Maes (2021)*, Subiza-Perez (2023)*, Tallis (2018)*, Wang (2023), Wu (2014)*, Yuchi (2020), Zhu (2023)*	Almeida (2022)
	Noise	Binter (2024)	Garkov (2024)*
	Heat	None	None
Spatial	Physical Activity	Astell-Burt (2023), Almeida (2022), Brown (2024)*, Buczylowska (2024), Cerin (2024), Cherrie (2019)*, Dadvand (2017)*, Dzhambov (2019), Yu (2018), Zhang (2022)*	Astell-Burt (2020)*, Maes (2021)*, Wu (2020)*
	Social Interaction	Astell-Burt (2023), Buczylowska (2024), Hu (2024)*	None
	Interaction with Nature	Mason (2022), Wallner (2018)	None
Perceptual	Perception, relaxing and landscape	Besser (2024), Bijnens (2022)*, Buczylowska (2024), Chang (2021)	None

4.4. Exposures

The measurement of exposures is limited compared to the measurement of outcomes. The majority of studies (17 out of 20) used either NDVI from satellite images for greenness or extracted urban green space from land use data. The spatial resolution of NDVI or land use data varies, from 1 m land use to 30 m to 250-500 m NDVI (Landsat and MODIS, respectively). In terms of the effective range of green space, a buffering radius of up to 1.6 km (one mile) was common, assuming it matches a walking distance of 15-20 min. Other common buffering radii included 300-500 m (15 min walking distance for older adults) or a search range from 100 to 2000 m. A few exceptions include one study based on visual images of green space (Chang et al., 2021) and two studies examining before-after exposure to nature (Mason et al., 2022; Wallner et al., 2018).

4.5. Pathways directly modeled from the 20 studies

In Table 4, we summarize and categorize the 36 reviewed papers, including those that directly and indirectly modeled the pathways, based on their mechanisms. Research works from which we could infer potential pathways are marked with an asterisk (*) and are discussed later in Section 4.6. In this section, we first review the 20 studies that directly examined the pathways.

4.5.1. Functional effects via reduced air pollution

Twelve studies analyzed the mediator of functional effects on reduced air pollution via modeling. Asta et al. (2021) presented a directed acyclic graph showing potential mechanisms, in which

NO_2 was a potential mediator between greenness and cognitive functions. Since the correlation between NDVI and NO_2 was not significant, they proposed estimating the natural direct effect, controlled direct effect, and natural indirect effect to determine NO_2's role as a mediator, which accounted for 35% of the total effects of green space. The other 65% may be attributed to other forms of air pollution (e.g., $PM_{2.5}$), physical activities, etc., but required further investigation. Binter et al. (2022) showed that $PM_{2.5}$ mediated 74% of the association between NDVI in a 300 m buffer and children's verbal abilities. Traffic-related air pollution was found to mediate 22-25% of the association between NDVI in a 300 m buffer and students' academic performance in Australia (Claesen et al., 2021). In a UK study by Dadvand et al. (2015), traffic-related air pollution explained 20-65% of the association between school greenness and 12-month progress in cognitive functions. Liao et al. (2019) examined the association between NDVI and early childhood neurodevelopment mediated by $PM_{2.5}$ and found that reduced traffic-related air pollution explained 13.6-28.0% of the association. Hu et al. (2023) used the Baron method to study the mediation effects of air pollution and found that $PM_{2.5}$ and PM_{10} generated from land use regression models might mediate air pollution reduction among 375,342 UK Biobank participants. Rodriguez-Loureiro et al. (2022) found that reduced air pollution ($PM_{2.5}$, NO_2) was directly associated with lower neurodegenerative disease mortality, but green space still played a role in reducing neurodegenerative disease risk in Belgium after controlling for air pollution. Yuchi et al. (2020) showed that greenness mediated the association between road proximity and Parkinson's disease and dementia by 0.3%-28% in a population-based study in Vancouver, Canada (N=678,000). Cerin et al. (2024) used generalized additive mixed models with directed acyclic graphs to directly estimate air pollution ($PM_{2.5}$, NO_2) as mediators.

4.5.2. Functional effects via noise reduction

With research continuing to grow, one recent study by (Binter et al., 2024) used interquartile range linear regressions to directly estimate the contributions of noise reduction as a mediator between green space exposure and cognitive outcome measured as white matter volume. The results from the Netherlands and France show that road-traffic noise mediated 19% and 52% of these associations, with no moderation effects from air pollution.

4.5.3. Spatial effects via physical activity

Five studies showed direct evidence that physical activity may mediate the association between green space and cognitive functions. Almeida et al. (2022) used the self-reported daily time in physical activity and found a positive association between physical activity and IQ test. Yu et al. (2018) showed that green space both directly and indirectly (via physical activity) affected frailty status using analysis of variance (ANOVA). Dzhambov et al. (2019) concluded that a greener neighborhood might be associated with better cognitive functions in middle-aged Bulgarians, where the association is possibly mediated by lower central adiposity. Recently, Astell-Burt et al. (2023) used marginal structural models to directly model the causal mediation effects and found that the association between urban tree canopy and dementia was mediated partially by physical activity and diabetes. Buczyłowska et al. (2024) used structural equation modeling to directly estimate the contribution of each pathway towards ADHD diagnosis, of which physical activity accounted for the third-largest contribution, being 6%.

4.5.4. *Spatial effects via social interaction or interaction with nature*

Four studies showed the benefit of interaction with nature. Mason et al. (2022) designed an experiment on two groups of students in Italy and set them in two different classroom settings: a regular indoor classroom and a green school garden. Students were randomized and switched to the other classroom setting one week later. They found that the green school garden could enhance children's attention and math performance. Although they did not identify the specific items (e.g., daylight, breeze) within nature/green space as the mediator, their result is sufficient to conclude that green space provides the spatial function for exposure to nature, increasing cognitive performance. Similarly, Wallner et al. (2018) conducted an experiment with three classroom settings (small park, large park, forest) and found higher d2-R test scores after students had stayed in green space after lunch break. The findings from Astell-Burt et al. (2023) also showed that social support partially mediated the association between urban tree canopy and dementia. Social cohesion was the mediator with the largest contribution between green space exposure and ADHD diagnosis (Buczyłowska et al., 2024).

4.5.5. *Perceptual effects*

Four studies show that the perception of urban green space is enough to benefit people's cognition. In a lab environment with 44 participating young adults, viewing images of green urban landscapes was associated with activity in brain regions for spatial processing, spatial and executive attention, and sensory encoding (Chang et al., 2021). In a well-designed study using structural equation modeling, Buczyłowska et al. (2024) showed that subjectively perceived green space was the second-largest moderator between green space exposure and ADHD diagnosis, being 7%.

4.6. *Potential pathways inferred from another 17 articles*

Table 5 lists another 17 articles that did not directly investigate the mechanisms through modeling but from which we can infer the potential pathways by comparing green space exposure. This comparison can be drawn from the variation among different types of green space exposure, the comparison between green space and blue space or non-photosynthetic vegetation, or inferred through a co-modeling method (where the third variable is not used as a mediator). Even seasonal comparisons can indirectly suggest such pathways due to the reduced or nonexistent air pollution mitigation effects of trees in winter. From these indirect approaches, we may infer the potential mediators from the results of an additional 17 articles. These research works are also listed in Table 4 with an asterisk (*). We list them here in Table 5.

4.6.1. *Functional effects*

By distinguishing the types of green space, we may infer some potential pathways. In an Australian study by Astell-Burt and Feng (2020), land cover data were used as a measure of exposure, and more tree canopy within a 1.6 km radius showed protective effects on self-rated memory, but such an association was not seen between open grass and memory. As a result, the benefit of green space is likely due to effects that tree canopy can provide but open grass cannot, such as reducing air pollution. Similarly, John et al. (2023) concluded that areas with over 30% tree cover showed positive impacts on healthy aging, but the same benefits were not seen from grass cover, thus supporting the functional pathways. A British study drew a similar conclusion

Table 5: Summary of 17 articles from which we can infer potential pathways via which green space affects cognition, by comparing different types of green space. They are marked with an asterisk (*) and listed by first author and year of publication.

Study	N	Pathways	Inference	Category
Ahmed (2022)*	936	Spatial (activity)	Proximity to non-photosynthetic vegetation is associated with children's school scores, but residential green space is not	non-green space
Wu (2020)*	4955	Spatial (activity)	Proximity to public parks is associated with lower odds of dementia, but greenness is not	non-green space
Subiza-Perez (2023)*	1,738	Functional (air)	Blue space did not show positive impacts but green space (tree cover) showed positive impacts	green space comparison
Astell-Burt (2020)*	45,644	Functional (air)	Exposure to tree canopy is associated with better memory, but open grass is not	green space comparison
Bijnens (2022)*	596	Functional (air)	Green space higher than 3 m is associated with faster reaction time, but low green is not	green space comparison
Godina (2023)*	2141	Functional (air)	No association between overall greenness and mild cognitive impairment (MCI); forest greenness associated with lower odds of MCI; green space diversity associated with lower hazard of incident dementia	green space comparison
Jarvis (2022)*	27,539	Functional (air)	Stronger positive association for residential exposure to tree cover relative to grass cover (beta coefficient: 0.26±0.11 vs. 0.12±0.10)	green space comparison
Maes (2021)*	3568	Functional (air)	Higher exposure to woodland, not grassland, is associated with higher cognitive score	green space comparison
Tallis (2018)*	495 schools	Functional (air)	Urban trees associated with higher elementary school test scores, but not rural trees	green space comparison
John (2023)*	22,715	Functional (air)	Areas with over 30% tree cover show positive impacts on healthy ageing, but the same benefits were not seen from grass cover	green space comparison
Hu (2024)*	422,649	Spatial (interaction)	Domestic gardens have protective effects (better than other green space), a spatial effect for social interaction	green space comparison
Cherrie (2019)*	281	Spatial (activity)	Park availability is associated with better cognitive aging with low traffic density, but not with high traffic density	co-modeling but not mediators
Crous-Bou (2020)*	2743	Functional (air)	Greenness not associated with greater cortical thickness after adjusting for air pollution	co-modeling but not mediators
Zhang (2022)*	16,337	Spatial (activity)	Lower precipitation is associated with slower cognitive decline, precipitation limits usage of green space, and thus physical activity is a pathway	co-modeling but not mediators
Brown (2024)*	230,738	Spatial (activity)	Older adults living in high greenness neighborhoods had lower odds of AD incidence, walkability decreased the odds via co-modeling	co-modeling but not mediators
Garkov (2024)*	12,159	Spatial (noise)	no evidence of an association between $PM_{2.5}$ exposure and cognitive performance in children in England, nor between noise and cognitive performance	co-modeling but not mediators
Wu (2014)*	905 schools	Functional (air)	Positive association between greenness in Spring and Summer and academic performance, but negative association between greenness in Autumn and and academic performance	seasonal comparison

on adolescents' cognition and mental health, finding that woodland—but not grassland and blue space—was associated with higher cognitive development scores (Maes et al., 2021). Godina et al. (2023) found that forest green space (rather than other types of green space) was associated with a lower risk of mild cognitive impairment, which could be due to the strong photosynthesis of forests leading to air pollution reduction. Jarvis et al. (2022) investigated the impacts of early-life green space exposure on childhood development in Vancouver, Canada, and found that tree cover had a stronger association with childhood development than grass cover. Tallis et al. (2018) found that only urban trees, rather than rural trees, were associated with higher elementary school test scores in California, which they argued was due to the higher air pollution and thus greater air pollution reduction by trees in urban school settings. Their findings were also supported by the null association between NDVI/agricultural areas and test scores.

Non-photosynthetic vegetation and photosynthetic vegetation's seasonal effects provide another way to infer potential pathways. An early ecological study by Wu et al. (2014) showed a positive association between the greenness of schools in March (Spring) and July (Summer) and academic performance but a negative association with the greenness of schools in October (Autumn) in Massachusetts after adjusting for socioeconomic factors. The authors claimed this might be due to the inaccurate coarse-resolution NDVI from MODIS (250–500 m resolution). Another possible explanation may be that the photosynthesis process by plants is strong in Spring and Summer but weak in Autumn, leading to differences in the functional (biochemical) effects of greenness on cognitive development. However, more investigation is needed to confirm one or both assumptions. Ahmed et al. (2022) found an association between exposure to non-photosynthetic vegetation and poor academic performance; since non-photosynthetic vegetation does not provide an air pollution reduction function, it may be viewed as indirect evidence of green space's functional effects. Another way to compare green space and non-green space exposure is through blue space (Subiza-Pérez et al., 2023).

An interesting study by Bijnens et al. (2022) is also worth mentioning. They treated air pollution as a confounding variable instead of a mediator and found that the height of green space was associated with better attention in children. Although they did not report the coefficient of air pollution, from their study, we can infer the functional effects via reduced air pollution. One study (Dadvand et al., 2017) showed a null association between tree cover and better attention among children but a positive association between general residential greenness and better attention. In other words, open grass is better than tree cover. We may infer that air pollution is not the primary mediator between green space and cognitive development. Crous-Bou et al. (2020) showed that green space was not associated with Alzheimer's dementia after controlling for air pollution, from which we may infer that air pollution is the pathway between green space and cognition.

Three studies discussed air pollution but did not mention whether it was related to green space (Crous-Bou et al., 2020; Falcón et al., 2021; Yuchi et al., 2020). They examined multiple exposures, including air pollutants and green space individually, but did not analyze the pathways. From their results, we can only infer that, in addition to air pollution, other mechanisms contribute to the association between green space and cognition.

4.6.2. *Spatial effects*

Spatial effects can be indirectly inferred from various types of green space. Cherrie et al. (2019) showed that park availability in adolescence with low traffic accidents was associated with better cognitive aging in later life, but the association was not significant with high traffic accidents. High traffic accidents (and possibly high traffic volumes) may reduce adolescents' usage of parks, thereby limiting their physical activity. Almeida et al. (2022) found a positive association between students' IQ tests and urban green space but not with greenness. Greenness is related to vegetation's photosynthetic function, which is associated with air pollution reduction; the fact that greenness is not a positive factor but exposure to urban green space is suggests that the "space" function likely plays a major role. Zhang et al. (2022) analyzed the association between green space exposure (with physical activity, air pollution) and cognitive test scores from the China Health and Retirement Longitudinal Study. Significant associations were found between higher test scores and lower precipitation as well as higher physical activity. Since precipitation impacts green space accessibility, the authors were confident that physical activity was at least one pathway through which green space affects cognitive functions. Similarly, Hu et al. (2024) showed that domestic gardens, compared to other green spaces, provided better protective effects, and Brown et al. (2024) showed that walkability decreased the odds of AD incidence in co-modeling.

Similarly, the opposite association may be inferred from three studies: a positive association was found between memory and tree canopy but not open grass (Astell-Burt and Feng, 2020), between adolescents' cognition and woodland but not grassland (Maes et al., 2021), and between dementia and living close to daily amenities but not local green space (Wu et al., 2020).

4.6.3. *Perceptual effects*

Similarly, the study by Bijnens et al. (2022) showed that even after controlling for air pollution, greater surrounding green space, such as trees, remained associated with better attention in children, whereas low green space was not. From this result, we may infer that, in addition to functional effects, trees also provide perceptual benefits that enhance cognitive function. A recent study found that while engaging in sports activities in both green outdoor environments and urban indoor environments improves short-term memory, better cognitive function was observed in the green exercise group (Baena-Extremera et al., 2024). The authors suggest that the perception of greenness may preferentially stimulate the right frontal areas and call for further research to explore the underlying mechanisms.

5. Discussion

5.1. *Summary of findings*

Despite a large number of studies examining the association between green space and cognitive functions, only a very few have investigated potential pathways and mediators. Of these, most used a framework to examine a single mediator, with air pollution reduction and physical activity being the most common. A comprehensive understanding of the modification effects across functional, spatial, and perceptual pathways is still lacking. In addition, the first study to directly examine noise as a potential mediator was only recently published in 2024 (Binter et al., 2024), despite its established association with cognitive functions (Jafari et al., 2019). Yet, recent studies have introduced more comprehensive frameworks, particularly those using structural equation modeling to estimate the contributions of one or more mediators (Buczyłowska et al., 2024). Our review thus focuses on directly modeling modification effects between green space and cognitive functions.

Indirect inference through green space comparisons also provides valuable insights. By analyzing different types of green space, 17 additional studies have contributed to our understanding of potential pathways. However, a comprehensive characterization of land use data remains a significant gap. Implementing globally consistent land use modeling approaches, such as the local climate zone framework, could enhance consistency and improve our understanding of how diverse landscapes contribute to cognitive development and decline.

5.2. Lack of mechanism studies focusing on older adults

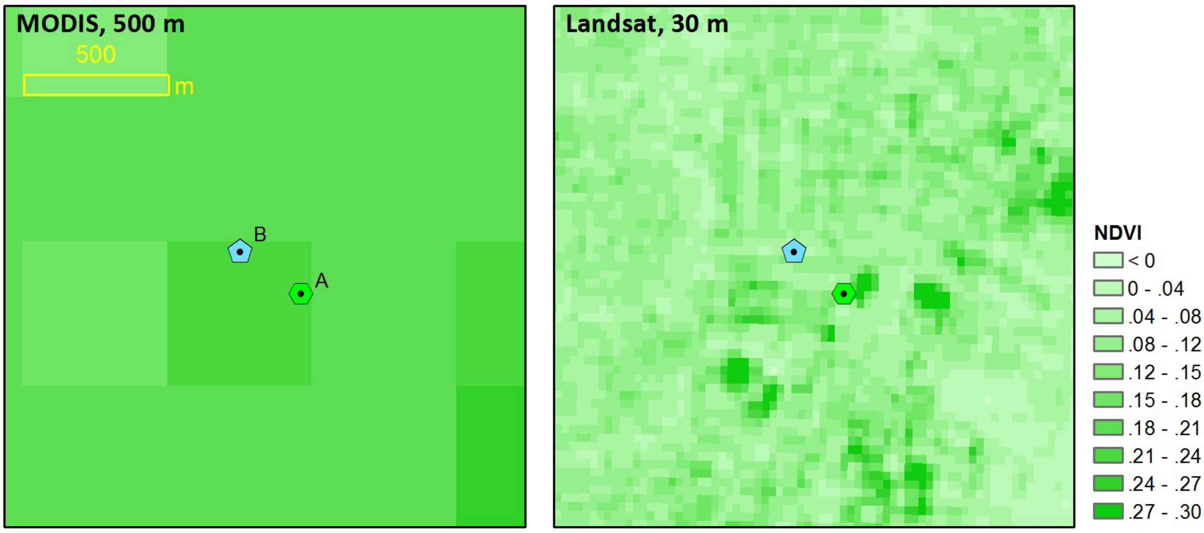
While reading the full text of the candidate articles, we observed that the number of studies on older adults and children/adolescents was relatively similar. However, among the 20 articles that directly examined underlying mechanisms, only three of them focused on older adults aged 60 and older. This imbalance has its reasons: (1) case-control studies involving school-aged children provide a natural experimental framework that has drawn researchers' interest, and (2) assessing cumulative lifetime exposure to green space and other environmental factors solely based on the current residential address of older adults is challenging. However, since cognitive impairment diseases such as dementia and Alzheimer's predominantly affect older adults, understanding how cognitive decline unfolds across the life course is crucial. Investigating older populations' lifetime exposure to green space, air pollution, and physical activity through modeling will help achieve this goal. While compiling a comprehensive cohort or dataset would be costly, large lifetime datasets, such as the UK Biobank, could provide valuable insights by enabling near-lifetime exposure assessments.

5.3. Limited methods for measuring green space

Land cover data and NDVI were the only two measures of green space used in studies conducted outside of a lab setting. The spatial resolution ranged from 500 m for MODIS to 30 m for Landsat, 10 m for Sentinel, and 1 m for IKONOS or high-resolution land cover data. Surprisingly, seven studies used MODIS data despite the widespread availability of higher-resolution land cover datasets and Landsat imagery worldwide (de Keijzer et al., 2018; Jin et al., 2021; Liao et al., 2019; Markevych et al., 2019; Wu et al., 2014; Xu et al., 2019; Zhu et al., 2020). At this scale, only very large areas of green space can be captured, while many roadside trees remain undetected in NDVI values. In some studies (de Keijzer et al., 2018; Markevych et al., 2019; Jin et al., 2021; Liao et al., 2019; Zhu et al., 2020), the buffer zone was barely one or two pixels wide. These rough, imprecise measurements of green space may explain why some studies report null or inconclusive associations between green space and cognitive function (Markevych et al., 2019; Jin et al., 2021).

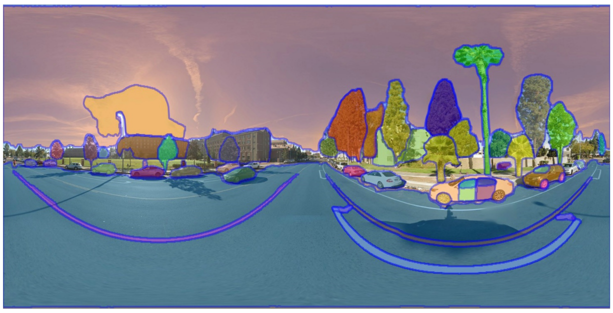
Surprisingly, despite the growing trend in health studies of shifting from satellite-derived overhead NDVI to street-view greenness using panoramic images (as illustrated in Figure 3)(Larkin and Hystad, 2019; Kang et al., 2020; Xiao et al., 2021), no study has yet adopted this new measure of green space. Horizontal-view assessments of greenness often provide more precise measurements. Figure 3 compares NDVI values at 500 m (MODIS) and 30 m (Landsat) resolutions alongside street-view images at locations A (Hexagon) and B (Pentagon). In the coarse-resolution

NDVI, both locations share the same value, making it impossible to distinguish differences in exposure. In the high-resolution NDVI, a more accurate measure emerges, revealing that location A has higher NDVI exposure. Using street-view imagery combined with semantic segmentation techniques such as Segment Anything(Kirillov et al., 2023), we estimate that location A has 20% green space exposure, while no greenery is visible at location B. Street-view imagery thus provides a more precise assessment of green space exposure, particularly in complex urban environments.



(a)

(b)



(c)

Figure 3: Comparisons of using 500 m satellite data (MODIS), 30 m satellite data (Landsat), and street view imagery to measure green space exposure. (a) Overhead MODIS NDVI at 500 m resolution and Landsat NDVI at 30 m resolution. Hexagon A is an area with high green space exposure, and Pentagon B is an area with low green space exposure. (b) Street view of Pentagon B, with semantic segmentation result showing low green space exposure. (c) Street view of Hexagon A, with semantic segmentation result showing relatively high green space exposure. The street view image segmentation results were generated using the Segment Anything model hosted by Meta AI (Meta AI, 2024)

5.3.1. Effective range of green space: size of buffer zones

The size of buffer zones used to measure green space exposure varied across the reviewed studies, ranging from 100 to 2,000 m. The two most common buffer sizes—500 and 1,000 m—were largely chosen for convenience. A few studies justified the usage of 1,500 or 1,600 m (one mile) buffer zones because this range is teh walking distance within 15 minutes (Astell-Burt et al., 2023; Wang et al., 2023), corresponding to the concept of 15-minute cities (Bruno et al., 2024). The effective range of green space depends on the underlying mechanisms. If functional effects dominate, green space needs to be close enough to alter biochemical components of the atmosphere; this range is likely small and within 1 km. If spatial effects dominate, the 15-minute city framework becomes relevant, suggesting an effective range of 1.5–2 km. Despite these considerations, existing studies often relied on pre-set values, limiting our understanding of the true effective range.

5.4. Distinguishing varying forms of urban green space

Most studies did not distinguish between different forms of green space, as they relied on NDVI at 30 m or even 500 m resolution. However, distinguishing various forms of urban green space can be achieved in at least three ways.

5.4.1. High-resolution land use land cover data

First, one approach is to utilize existing well-maintained high-resolution land use data, such as the ib1000 dataset with 1 m spatial resolution in Hong Kong (Wang et al., 2021), the Geovision Product with 2 m resolution in Australia (Astell-Burt and Feng, 2019), or the Urban Atlas Land Use dataset with 5 m resolution in Europe (Kolcsár et al., 2021). Beyond regional land cover data, global land use and land cover datasets with resolutions better than 10 m offer various green vegetation categories, including the Esri 2020 Land Cover product (10 m resolution), the ESA WorldCover product (10 m resolution), and the OSM Land Cover dataset (10 m resolution) (Venter et al., 2022). All these products provide a more accurate estimation of green space forms compared to NDVI at 500 m resolution.

5.4.2. Finer-grained classification using local climate zones

Second, scene classification can be used for fine-grained classification of green space, e.g., the local climate zone classification system (Figure 4). Instead of relying solely on spectral information (greenness), which performs poorly in distinguishing high trees from low bushes, scene classification schemes provide a more detailed categorization of green space by analyzing global image features, such as tree canopy shading. As shown in Figure 4, natural environments can be categorized into seven classes: dense trees, scattered trees, bush or scrub, low plants, bare rock or paved, bare soil or sand, and water. Their combination with low- and high-rise built environments likely influences air pollution reduction and physical activity. For example, cities and populated regions tend to have higher air pollution (Zhang et al., 2020), while high-rise built environments, often accompanied by public transportation, generally promote more walking (Althoff et al., 2017). Leveraging data from this comprehensive framework enables a more precise characterization of different forms of green space within the built environment, thereby improving our understanding of the relationship between green space and cognition.

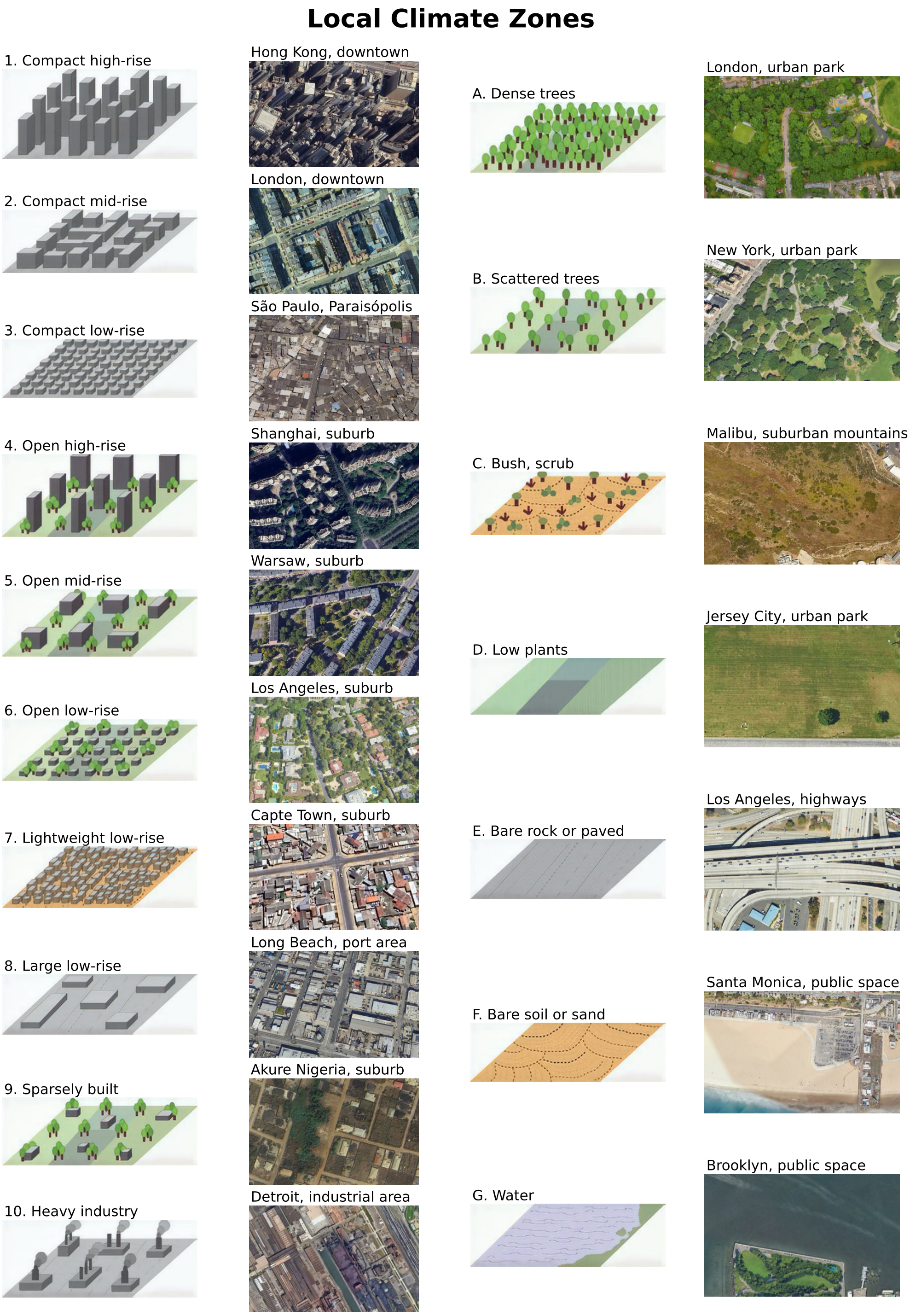


Figure 4: Urban landscape categorization using the local climate zone system. The conceptual models representing local climate zones are based on Stewart and Oke (2012), and the satellite images are from Google Earth with the highlighted cities selected by the authors.

5.4.3. Street view imagery

Third, the use of street view imagery. As mentioned, instead of overhead NDVI, horizontal-view (eye-level) measures of green space provide a more accurate representation of urban forests and open grass areas. Eye-level imagery also better reflects people's daily perception of green space (Larkin and Hystad, 2019; Kang et al., 2020; Xiao et al., 2021).

5.5. Mechanisms from green space to cognitive functions

There are ten articles directly investigating air pollution as a potential mediator in their modeling, one article demonstrated that green space is a mediator of urban heat on hospitalization and deaths related to Alzheimer's disease, and three articles provided direct evidence that simply perceiving green space is enough to bring benefits to the brain. However, some studies suggest a null association between physical activity, air pollution, and noise. More research is needed to explore these mechanisms, particularly with improved categorization of green space.

5.5.1. Limited studies on social interaction

No study has analyzed the potential effects of social interactions on cognitive functions. The reason may be due to the difficulty of capturing social interactions compared to physical properties. However, there may be some viable proxies. In an Irish study (Dempsey et al., 2018), a U-shaped relationship was found between surrounding green space and obesity: both low and high levels of green space were associated with a higher probability of obesity. Although the authors did not provide a clear explanation, one possible theory is that people living in areas with abundant green space tend to reside in remote locations with low population density, where social interaction is limited. If green spaces were categorized based on their surrounding population density—a potential proxy for social interaction—studies on this topic could become feasible.

6. Conclusions and future directions

This scoping review identified 37 studies from the Web of Science examining the association between green space and cognitive function. Among these, 20 studies directly investigated the pathways via modeling, while 17 studies provided indirect evidence by comparing different types of green space. While findings support all three pathways, the functional effect of reducing air pollution is the most commonly studied, followed by the spatial effect of promoting physical activity. Regarding perceptual effects, three case-control studies provided supporting evidence. However, no studies have explored other potential pathways, including heat and social interaction.

A key limitation identified in most studies is the coarse measurement of green space. We highlighted MODIS, Landsat, and street view imagery as three levels of green space measurement, emphasizing the need for more accurate green space measurement for cognition studies. Future studies should refine their definition of green space and adopt appropriate measurement techniques to better understand the functional, spatial, and perceptual pathways linking green space to cognitive function. Incorporating local climate zones as a systematic framework can help differentiate green space types, which is essential for elucidating the underlying mechanisms.

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