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Is there an association between eye-level greenness and childhood hypertension using street view? Findings from the Seven Northeastern Cities study in China

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A R T I C L E I N F O

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A B S T R A C T

There is a lack of evidence regarding associations of eye-level greenness exposure with blood pressure among children. We aimed to investigate the associations between different types of eye-level greenness and pediatric blood pressure in China. From 2012 to 2013, we recruited 9354 children aged between 5 and 17 years in northeast China. Eye-level of greenness was assessed with Street View Greenness (SVG), derived from Tencent Street View images surrounding participants' schools, utilizing a deep machine learning model. Hypertension was defined as blood pressure above the 95th percentile based on the fourth report's guidelines for children and adolescents. Generalized linear mixed-effects regression models were conducted to estimate adjusted odds ratio (aOR) and estimates of childhood hypertension and pediatric blood pressure per interquartile range (IQR) increase of SVG. Mediation analyses including air pollution and exercise time were also performed. We found the significant association of SVG-total with decreased odds of hypertension in Chinese children (aOR = 0.83, 95% CI: 0.75,0.91), especially with the decrease of SBP ($\beta = -0.76$, 95%CI: 1.09,-0.43). Interestingly, per IQR increase in SVG-tree 800m for trees was associated with lower adjusted odds of pediatric hypertension (aOR = 0.84; 95%CI: 0.76, 0.92), also with the decrease of systolic blood pressure. Mediation analyses showed that hypertension was significantly mitigated by lower levels of air pollutants, including $PM_{2.5}$, PM_{10}, SO_2 and NO_2. Results of this study suggested that eye-level greenness, especially trees, were associated with lower prevalence of hypertension in children, with air pollution exhibiting mediating effects. These findings emphasized the importance of incorporating more greenness, especially trees in both urban planning and public health interventions.

1. Introduction

Pediatric hypertension has emerged as a global public health issue. Data from the American Heart Association indicated that the global prevalence of elevated blood pressure in the pediatric population was approximately up to 13%–18% with rapid increasing trend (Falkner

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et al., 2023). The age-standardized prevalence of hypertension among children in China was witnessed a significant increase, rising from 7% in 1991 to 13% in 2015 (Wang et al., 2023). Pediatric hypertension not only affects children's physical and mental health, increasing the overall economic burden of society (Wójcik et al., 2023; Mancia et al., 2023), but also may track into adulthood and possibly associates with premature cardiovascular disease, chronic renal failure and damage to nervous system (de Simone et al., 2022; Robinson et al., 2024). Thus, it's imperative to explore the controllable factors associated with pediatric hypertension to take effective measures to mitigate the escalating disease burden.

Rapid urbanization has led to alterations to the urban environment, including the availability of greenspace (Nguyen et al., 2021). Emerging studies suggest that access to greenspace might be associated with childhood blood pressure via mitigating air pollution and environmental decibel levels, enhancing physical activity, and improving social cohesion (Nieuwenhuijsen, 2018; Yang et al., 2021). To date, a total of ten epidemiological studies have investigated the associations between greenness and hypertension of children, yielding inconsistent findings (Table S1). (Dzhambov et al., 2022; Dengel et al., 2009; Abbasi et al., 2020; Luo et al., 2022; Xiao et al., 2020; Warembourg et al., 2019; Chen et al., 2022; Markevych et al., 2014; Bloemsma et al., 2019; Bao et al., 2024) For instance, studies have demonstrated that higher values of the Normalized Difference Vegetation Index (NDVI) and the Soil-Adjusted Vegetation Index (SAVI) are associated with lower blood pressure and reduced odds of hypertension among Chinese children (Luo et al., 2022; Xiao et al., 2020). However, two other studies have showed that residential proximity to greenness and percent land use of park have no associations with reduced BP levels in school-age children from Iran or the United States (Dengel et al., 2009; Abbasi et al., 2020). The causation of inconsistent results may be pertinent to the variations in study design, methodologies for measuring greenness exposure, the potential temporal or seasonal variations in exposure and the characteristics of the participants.

At present, NDVI is the predominant metric indicator to assess exposure levels of greenspace (Zhao et al., 2022). However, NDVI is based on birds-eye overhead views of greenness, potentially failing to accurately reflect the ground-level perception of vegetation. Furthermore, NDVI cannot differentiate between various types of vegetation, such as trees and grass (Yu et al., 2021a). The inconsistencies in previous findings may be attributed to the limitations of NDVI. Recently, the street view greenness (SVG) has been introduced as an enhanced measure of greenness exposure, covering some of the limitations of NDVI. SVG refers to evaluating the level of greenness at street level by incorporating semantic segmentation of street view images (Berger et al., 2019; Kristensen et al., 2001; Yao et al., 2014). SVG offers the capability to evaluate accurately human horizontal exposure of greenness, which reflects the greenspace experienced when people walk, ride or drive, and assess the health effects of specific components (e.g., trees, grass) (Song et al., 2018; Larkin et al., 2019). The critical aspect of eye-level greenness lies in its ability to offer immediate and sustained exposure to natural elements, optimizing both visual and psychological benefits for human health (Dzhambov et al., 2018). Recent studies utilizing street view greenness have reported novel insights into associations between eye-level greenness and health impacts, such as lung function, stroke and cardiovascular diseases (Yu et al., 2021a, 2021b; Wang et al., 2022a).

Nevertheless, the associations between eye-level greenness and pediatric hypertension remain unexplored. Consequently, our current investigation was intended to identify the associations between exposure to eye-level greenness and childhood hypertension with SVG to enable a comprehensive and objective evaluation of greenness. We hypothesized that more trees and grass would be associated with lower odds of pediatric hypertension.

Table 1
Characteristics of the participants (n = 9354).

Characteristics	Total (n = 9354)	Hypertension (n = 1289)	Non-hypertension (n = 8065)	*P* Value
Age [years, (mean ± SD)]	10.8 ± 2.6	11.8 ± 2.5	10.8 ± 2.6	**<0.001**
Sex				
Girls (%)	4583 (49.0)	630 (48.9)	3953 (49.0)	0.950
Boys (%)	4771 (51.0)	659 (51.1)	4112 (51.0)	
BMI [kg/m2, (mean ± SD)]	19.5 ± 4.3	21.7 ± 5.2	19.2 ± 4.1	**<0.001**
Parents' education				
≥high school(%)	5759 (61.6)	760 (59.0)	4999 (62.0)	**0.041**
< high school(%)	3595 (38.4)	529 (41.0)	3066 (38.0)	
Exercise time [h/wk, (mean ± SD)]	7.6 ± 7.7	7.7 ± 8.6	7.6 ± 7.6	0.580
Low birth weight (%)	348 (3.7)	64 (5.0)	284 (3.5)	**0.013**
Premature (%)	494 (5.3)	94(7.3)	400(5.0)	**<0.001**
Family income in RMB				
≤30,000(%)	5473 (58.5)	781(60.6)	4692(58.2)	0.667
>30,000(%)	3881 (41.5)	508(39.4)	3373(41.8)	
Passive tobacco smoke exposure (%)	4473 (48.0)	639 (55.8)	3834 (47.3)	**0.002**
House coal utilization (%)	888 (9.5)	151 (11.7)	737 (9.1)	**<0.001**
Renovation (%)	3365 (36.0)	549 (42.6)	2816 (34.9)	**<0.001**
Family history of hypertension (%)	3599 (38.5)	558 (43.3)	3041 (37.7)	**<0.001**
SBP [mmHg; (mean ± SD)]	111.0 ± 14.1	129.1 ± 11.5	108.1 ± 12.1	**<0.001**
DBP [mmHg; (mean ± SD)]	64.5 ± 9.8	75.6 ± 11.2	62.7 ± 8.3	**<0.001**
SVG-total 800m [mean ± SD]	0.092 ± 0.030	0.087 ± 0.031	0.093 ± 0.030	**<0.001**
SVG-tree 800m [mean ± SD]	0.089 ± 0.031	0.084 ± 0.032	0.089 ± 0.031	**<0.001**
SVG-grass 800m [mean ± SD]	0.003 ± 0.003	0.002 ± 0.003	0.003 ± 0.003	0.146

Abbreviations: SD, standard deviation; BMI indicates body mass index; RMB, Chinese Yuan; SBP, systolic blood pressure; DBP, diastolic blood pressure; SVG-total 800m, street view greenness of total view with 800 m buffer; SVG-tree 800m, street view greenness of tree with 800 m buffer; SVG-grass 800m, street view greenness of grass with 800 m buffer.
30,000 Yuan is approximately equal to US $4065.67 or €3256.15.

2. Methods

2.1. Participants

We utilized data from the Seven Northeastern Cities (SNEC) study, which was a large population-based cross-sectional study conducted in Liaoning province in Northeastern China, focusing on the associations between children's exposure to environmental elements and their health outcomes. The details regarding the study have been documented in previous reports (Dong et al., 2014). In brief, between April 2012 and June 2013, 24 urban districts were randomly selected in seven cities of Liaoning Province, including 5 districts in Shenyang, 4 districts each in Dalian and Fushun, 3 districts each in Anshan, Benxi, and Dandong, and 2 districts in Liaoyang, respectively. This study employed a stratified sampling methodology. Within the scope of each selected district, a random selection process was undertaken to choose one or two primary schools and one or two secondary schools, culminating in a total of 28 primary schools and 34 secondary schools. Subsequently, within the selected schools, a random selection of one or two classes from each grade level was conducted. All children from the selected classes were enrolled in the study. The study sample was composed of 10,428 children from these 62 schools. Among them, 9567 children submitted the study questionnaires, yielding a response rate of 91.7%. Subsequently, 213 children who had lived in the study districts for less than two years were excluded, and our analyses took in 9354 children aged 5–17 as the final sample (Fig. S1).

The study protocol adhered to the World Medical Association Declaration of Helsinki-Ethical Principles for Medical Research Involving Human Subjects and was approved by the Human Studies Committee of Sun Yat-sen University. Prior to initiating data collection, written informed consent was obtained from the parents or legal guardians of all participants.

2.2. Blood pressure measurements

Blood Pressure (BP) was measured by research staff who were thoroughly trained in accordance with the guidelines established by the American Academy of Pediatrics (The fourth report on the, 2004). Children were instructed to refrain from consuming alcohol, tea, coffee, cigarettes, or exercising for 30 min prior to the BP measurement. After a 5-min rest in a quiet, temperature-controlled room, each child's blood pressure was measured on the right arm while seated, using a standardized mercury sphygmomanometer. BP was measured every 2 min for three times. Hypertension among the children and adolescents was defined as systolic blood pressure (SBP) or diastolic blood pressure (DBP) that reached or exceeded the 95th percentile for their sex, age, and height, in accordance with the guidelines outlined in The Fourth Report on the Diagnosis, Evaluation, and Treatment of High Blood Pressure in Children and Adolescents (The fourth report on the, 2004).

2.3. Street view greenness exposure measurements

Exposure to eye-level greenness was measured by street view greenness (SVG). We assessed the average SVG for each school, within 800m, 1000m and 1500m buffers of the school centroids (Yu et al., 2021a). A minimum distance of 100m between two sample points was set to reduce computing time and ensure accurate representation of green coverage. The flow chart of eye-level greenness measurement has been reported in our previous studies (Xiao et al., 2020; Yu et al., 2021a, 2021b; Wang et al., 2022a). Briefly, we used OpenStreetMap (https://www.openstreetmap.org) for selecting sample points along the road network of the selected schools within circle buffers, and we utilized Tencent Maps (https://map.qq.com) for capturing detailed and accurate street view images in China that approximate the eye-level horizontal perspective of the selected sample points. The majority of the street view data was obtained during the summer, when vegetation was at its greenest, covering the years from 2012 to 2013. We selected images in the four primary compass points (0°, 90°, 180°, and 270°) to achieve panoramic views with resolutions of 480 by 320 pixels. An average of 5108 ± 2482 images per school (a total of 500,560 images) were collected, which were used to develop an exposure metric that reflected the greenness of the view plane. For semantic segmentation of the street view images, we utilized a deep learning method, the Full Convolutional Network (FCN-8s) (Yao et al., 2019). The procedure entailed the utilization of annotated images and their semantic segmentation from the ADE20K collection to train the FCN-8 model (Tucker, 1979). Subsequently, the street view images of the research locations were inputted into the trained model to generate segmented images. The code for this process can be available for reference at https://www.urbancomp.net/archives/semantic-segmentation-software-for-visual-images-based-on-fcn. In this study, the accuracy of training data and testing data were 82.5% and 81.3% for the overall eye-level greenness, 88.7% and 85.2% for the tree, 86.5% and 83.8% for grass. The greenness was quantified using the street view greenness (SVG), where higher SVG values indicated greater green coverage. SVG was defined as the proportion of the aggregate pixel count representing greenness to the total pixels count in images captured at the four primary compass points. Specifically, for trees, SVG-tree was the ratio of pixels attributed to tree elements against the total pixel count of the images. Similarly, for grass, SVG-grass was the proportion of the pixels representing grass relative to the total number of pixels in the images.

2.4. Covariates and potential mediators

The questionnaire used in this study was adapted from the international standard questionnaire ATS (American Thoracic Society), with modifications made to align with the specific national conditions in China (The fourth report on the, 2004). Individual information such as socio-demographic and lifestyle information were gathered via parental completion of the study questionnaire. Socio-demographic information (Abbasi et al., 2020; Wang et al., 2022b) contained sex (boy/girl), age (years), highest parental education (<high school/≥high school) and annual family income in RMB (≤30,000 Yuan/>30,000 Yuan); lifestyle indicators (Dzhambov et al., 2022) included exercise time (hours per week), passive tobacco smoke exposure (yes/no), house coal utilization (yes/no) and renovation within three years (yes/no). Variables of reproductive/medical history (Yang et al., 2021) included family history of hypertension (yes/no), low birth weight (defined as less than 2500 g at birth) and premature birth (gestational age under 37 weeks). The Body Mass Index (BMI) was calculated as measured body weight divided by height squared (kg/m^2), following a protocol standardized by the World Health Organization (WHO). According to the Centers for Disease Control and Prevention (CDC) guidelines, children were classified as overweight and obesity if their BMI exceeded the age- and sex-specific 85th percentile and the 95th percentile, respectively (Dong et al., 2015). As the potential mediators, we evaluated the daily average concentrations of particulate matter (PM) with aerodynamic diameters ≤ 1 μm (PM_1), ≤2.5 μm ($PM_{2.5}$) and ≤10 μm (PM_{10}), with a spatial resolution of 1.0 km × 1.0 km, and daily mean concentrations of nitrogen dioxide (NO_2) and sulfur dioxide (SO_2), with a resolution of 10 km × 10 km. These were achieved using a random forest model that integrated Moderate Resolution Imaging Spectroradiometer aerosol optical depth data, land use, and meteorology data (Chen et al., 2018; Zhan et al., 2018).

2.5. Statistical analysis

Mean values and standard deviations (SD) were utilized to represent continuous variables, while categorical variables were quantified by computing their relative frequencies. We conducted t-tests on continuous variables and chi-square analyses on categorical variables to assess the differences in characteristics between individuals with and without hypertension. For hypertension, we applied GLMMs with logistic regression using 'glmer' in 'lme4' to associate SVG with hypertension. For pediatric blood pressure, LMERs with 'lmer' were used. Both were considered the hierarchical structure of the data with city as a random effect. Adjusted mixed effects models were implemented, adjusted for age, sex, parental education, annual family income, passive tobacco smoke exposure, house coal utilization and renovation (Luo et al., 2022; Bao et al., 2024; Ali et al., 2021). Stratified and interaction analyses were performed by age (≤12 vs. > 12 years), sex, BMI (normal vs. overweight/obesity), annual family income (≤30,000 vs. > 30,000 yuan per year), passive tobacco smoke exposure, parental education levels and house coal utilization as modifiers to identify the sensitive subgroups. Mediation analyses following the Baron-Kenny's approach were conducted to examine whether air pollutants and exercise time could mediate the effects of greenness on pediatric blood pressure and hypertension (Wang et al., 2022a). These results were generated by bootstrapping with 1000 simulations, employing the mediate function from the R package 'mediation'. In our population in China's high-density settings, a systematic review highlights the effectiveness of 500–999m buffers in predicting physical health. Therefore we selected the 800m buffer as our primary analysis range, and considered various buffer sizes and thus included 1000m and 1500m buffers for sensitivity analyses to ensure the robustness of our findings (Browning et al., 2017). To further verify the robustness of our findings, sensitivity analyses were also conducted by excluding participants with low birth weight, premature birth or family history of hypertension.

All statistical analyses were performed using R version 4.3.2, and two-tailed p-value of less than 0.05 was considered statistically significant.

3. Results

3.1. Baseline characteristics of participants

The characteristics of the recruited children in the present study were summarized in Table 1, stratified by their blood pressure (BP) status. The average age of the participants, who were recruited from the age of 5–17 years old, was 10.8 years, with a standard deviation of 2.6 years, and 51.0% (4771/9354) of boys. The average SBP and DBP were 111.0 ± 14.1 mmHg and 64.5 ± 9.8 mmHg, respectively, with a childhood hypertension prevalence of 13.8%. Children with hypertension exhibited a higher likelihood of being older, fatter, born premature or with lower birth weight, having parents with lower educational levels, being born to a cigarette smoker, utilizing house coal, having undergone house renovations within the past three years, or having family history of hypertension compared to those without hypertension ($P < 0.05$). Meanwhile, Children with hypertension exposed to less level of street view greenness and higher level of air pollutants ($P < 0.05$) (Table S2).

3.2. Associations of SVG with pediatric hypertension and BP

We observed beneficial associations between SVG (per IQR increase) and pediatric hypertension and blood pressure (Fig. 1). Higher SVG-total 800m were associated with markedly reduced odds of hypertension (aOR = 0.83, 95%CI: 0.75, 0.91). It was obvious that the majority of SVG's association was attributed to the presence of trees. Exposure to SVG-tree 800m exhibited an opposite association with hypertension (aOR = 0.84, 95%CI: 0.76, 0.92) as well. We found the similar beneficial associations between SVG with SBP. Per IQR increase in SVG-total 800m and SVG-tree 800m were associated with 0.76 mmHg (95% CI: −1.09, −0.43) and 0.81 mmHg (95% CI: −1.15, −0.47) decrease in SBP in adjusted models, respectively. There were no associations of grass exposure with children's BP in the present study.

3.3. Potential modifications and mediations

In stratified analyses, similar associations were presented at all subgroups, while interaction effects were not observed significantly (Table 2 & Table S3-5). The findings of mediation analyses were presented in Table 3 and Table S6-8. We found that 8.95%, 12.50%, 6.99%,

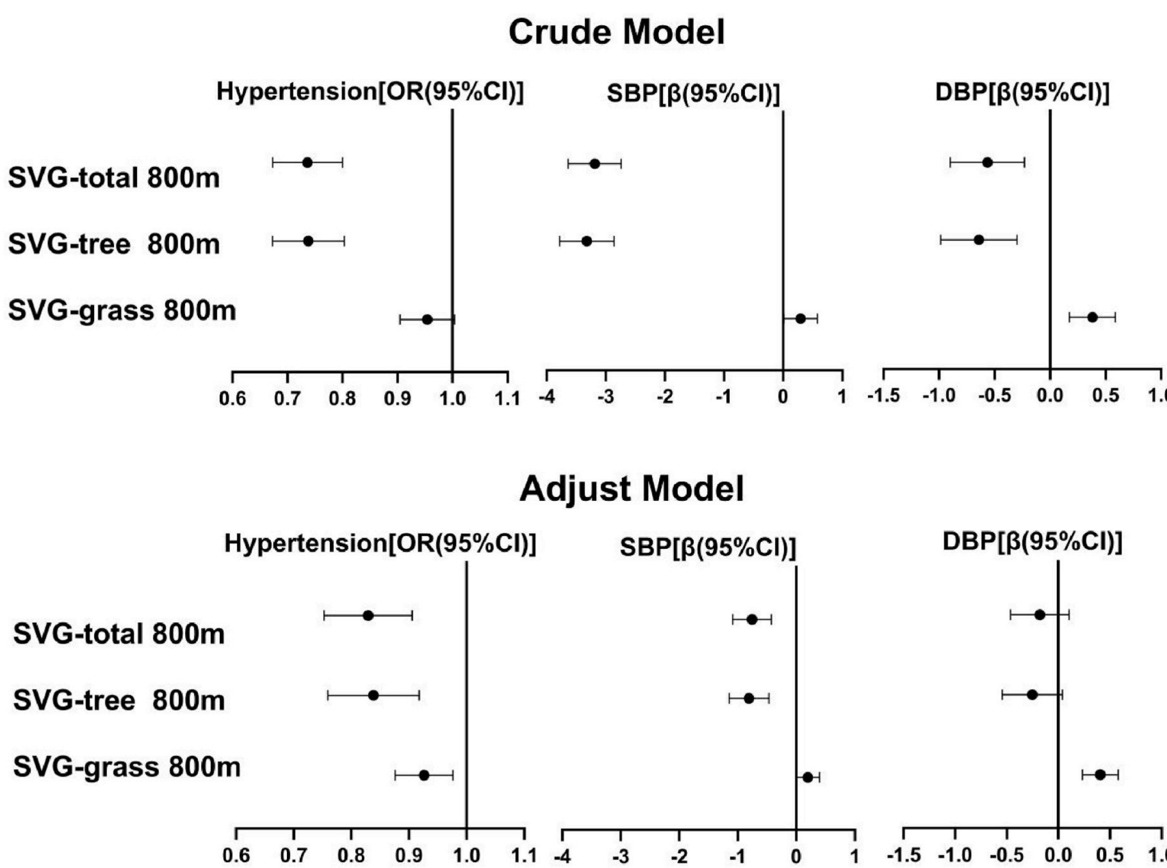

Fig. 1. Associations of per IQR increase of SVG with pediatric hypertension and BP.
Abbreviations: IQR, interquartile range; SVG-total 800m, street view greenness of total view with 800 m buffer; SVG-tree 800m, street view greenness of tree with 800 m buffer; SVG-grass 800m, street view greenness of grass with 800 m buffer; SBP, systolic blood pressure; DBP, diastolic blood pressure; OR, odds ratio; CI, confidence interval.
Adjusted for age, sex, BMI, family income, parental education, house coal utilization, passive tobacco smoke exposure and renovation.
Random entry selection: city.

Table 2
The aOR and 95% CI for the associations of SVG (per IQR increase) with hypertension, stratified by demographic factors (n = 9354).

	SVG-total 800m	SVG-tree 800m	SVG-grass 800m
Age			
≤12 years	0.84(0.73, 0.97)	0.85(0.74, 0.98)	0.91(0.84, 0.99)
>12 years	0.85(0.75, 0.96)	0.84(0.73, 0.96)	1.06(0.97, 1.15)
P for group difference	0.931	0.857	**0.013**
Sex			
Boys	0.84(0.74, 0.96)	0.85(0.74, 0.97)	0.97(0.90, 1.05)
Girls	0.81(0.71, 0.92)	0.82(0.72, 0.94)	0.87(0.81, 0.95)
P for group difference	0.628	0.778	0.064
BMI			
Normal	0.78(0.69, 0.88)	0.79(0.69, 0.89)	0.89(0.83, 0.96)
Overweight/obesity	0.90(0.78, 1.05)	0.90(0.78, 1.05)	0.99(0.91, 1.08)
P for group difference	0.112	0.159	0.065
Family income in RMB			
≤30,000	0.80(0.70, 0.90)	0.81(0.71, 0.92)	0.93(0.86, 0.99)
>30,000	0.86(0.75, 0.99)	0.87(0.75, 1.00)	0.93(0.85, 1.01)
P for group difference	0.402	0.474	0.938
passive tobacco smoke exposure			
No	0.81(0.71, 0.92)	0.82(0.72, 0.94)	0.89(0.82, 0.96)
Yes	0.84(0.74, 0.96)	0.84(0.74, 0.97)	0.96(0.89, 1.04)
P for group difference	0.720	0.797	0.145
House coal utilization			
No	0.81(0.74, 0.90)	0.82(0.74, 0.91)	0.93(0.88, 0.98)
Yes	1.00(0.73, 1.38)	1.02(0.73, 1.42)	0.91(0.74, 1.12)
P for group difference	0.223	0.234	0.850
Parent education			
≥high school	0.96(0.90, 1.03)	0.82(0.73, 0.92)	0.82(0.73, 0.92)
< high school	0.84(0.72, 0.98)	0.86(0.74, 1.01)	0.86(0.79, 0.95)
P for group difference	0.790	0.614	0.057

Abbreviations: IQR, interquartile range; BMI indicates body mass index; RMB, Chinese Yuan; SVG-total 800m, street view greenness of total view with 800 m buffer; SVG-tree 800m, street view greenness of tree with 800 m buffer; SVG-grass 800m, street view greenness of grass with 800 m buffer; aOR, adjusted odds ratio; CI, confidence interval.
Adjusted for age, sex, BMI, family income, parental education, house coal utilization, passive tobacco smoke exposure and renovation.
Random entry selection: city.
30,000 Yuan is approximately equal to US $4065.67 or €3256.15.

Table 3
The role of air pollutants in mediating associations between SVG and the prevalence of childhood hypertension (n = 9354).

	SVG-total 800m	SVG-tree 800m	SVG-grass 800m
PM_1	−0.38% (−11.26%, 7.84%)	−3.86% (−22.19%, 4.77%)	52.53% (14.61%, 480.93%)
$PM_{2.5}$	**8.95% (2.40%, 29.38%)**	5.06% (−1.74%, 22.79%)	61.70% (−216.24%, 508.23%)
PM_{10}	**12.50% (5.39%, 47.33%)**	**9.91% (3.81%, 50.25%)**	44.13% (−127.60%, 440.38%)
SO_2	**6.99% (2.22%, 30.42%)**	**9.86% (3.92%, 40.10%)**	−41.63% (−325.08%, 84.14%)
NO_2	**17.40% (2.33%, 97.43%)**	**19.11% (2.24%, 114.14%)**	−15.58% (−88.03%, 77.67%)

Abbreviations: SVG-total 800m, street view greenness of total view with 800 m buffer; SVG-tree 800m, street view greenness of tree with 800 m buffer; SVG-grass 800m, street view greenness of grass with 800 m buffer; PM_1, particle with aerodynamic diameter ≤1 μm; $PM_{2.5}$, particle with aerodynamic diameter ≤2.5 μm; PM_{10}, particle with aerodynamic diameter ≤10 μm; SO_2, sulfur dioxide; NO_2, nitrogen dioxide.
Coefficients are proportion mediated with 95% confidence intervals.
Adjusted for age, sex, BMI, family income, parental education, house coal utilization, passive tobacco smoke exposure and renovation.

and 17.40% of the effects on SVG-total 800m with the prevalence of childhood hypertension were mediated by reduced levels of ambient $PM_{2.5}$, PM_{10}, SO_2 and NO_2 ($P < 0.05$). In terms of the types of greenness, we observed the mediating effects of PM_{10}, NO_2, and SO_2 exclusively in the context of trees (Table 3). Additionally, no notable intermediary influence of exercise time was detected in the associations of SVG with hypertension (Table S9).

To evaluate the reliability of our outcomes, we carried out various sensitivity analyses. SVG measured in larger buffer size (1000m or 1500m) presented consistent conclusions (TableS10-11). Similar results were obtained when we excluded children with premature, low birth weight and family history of hypertension (Table S12-14).

4. Discussion

Our findings indicated that greater exposure to eye-level greenness, particularly trees, was associated with lower BP levels and decreased odds of pediatric hypertension. Exposure to ambient pollutants may partially mediate these associations. Up to date, this is the first study globally to explore the associations between eye-view level tree exposure and children BP.

To our knowledge, ten investigations have conducted the associations between greenness and hypertension and BP among children, but results were inconsistent (Table S1). Two cohort studies from Europe reported no associations between NDVI and BP levels in children (Warembourg et al., 2019; Bloemsma et al., 2019). Similarly, the cross-sectional studies conducted in Iran with 12,340 children aged 7–18 have failed to find a statistically significant link between residential proximity to greenspace with systolic hypertension, diastolic hypertension and hypertension (aOR = 1.03, 95%CI:0.76, 1.39; aOR = 0.96, 95%CI:0.80, 1.16; aOR = 0.98, 95%CI:0.82,1.16) (Abbasi et al., 2020). Conversely, other studies have reported significant associations between greenness and pediatric hypertension. For example, a cohort study based on 164,853 children aged 6–8 years reported that per IQR increase in NDVI within 100 m of home, school or home-school buffer was significantly associated with a reduction of 0.018–0.037 in blood pressure z-scores, as well as a 2.7%–7.6% lower risk of hypertension in southern China (Bao et al., 2024). Another cohort study, including 588, 004 children aged 7–18, found that 0.1-unit increase in NDVI was significantly associated with 25% reduction in the risk of hypertension (HR = 0.75, 95% CI: 0.74, 0.76) in Beijing and Zhongshan city, China (Chen et al., 2022). Similarly, a cross-sectional survey conducted in Austrian and Italian found that per IQR increase in NDVI with 500-m home buffer was associated with a reduction of 0.69 mmHg in SBP (95% CI: 1.32, −0.05) among 1251 schoolchildren aged 8–12 years (Dzhambov et al., 2022). Most of the above studies were performed with NDVI as the indicator of bird's-eye overhead view of greenness. Consistently, our findings indicated the beneficial associations of greenness and children BP with SVG as the indicator of eye-level exposure. The inconsistency in associations between greenness and pediatric hypertension could be attributed to various factors, including variations in the assessment of greenness exposure, categories of greenness, and basic characteristics of the participants. What's more, we found that eye-level greenness, particularly within the 800m buffer, was the most significant associate with hypertension rather than 1000m and 1500m buffers. The 800m buffer likely offers the reference ranges for our study's context in China, considering the high-density urban settings (Browning et al., 2017). The varied buffer approach allows for a nuanced understanding of how green spaces influence health and sets a foundation for future research to determine the optimal buffer size across different urban environments.

To date, only two epidemiological studies have explored the associations between exposure to trees and blood pressure. A cohort study encompassing 15,105 adults from Brazil indicated, a rise of 10,000 trees was associated with a lower odds ratio for hypertension 0.929 (95% CI: 0.878, 0.984) (Moreira et al., 2020). Similarly, one percent increment in tree canopy was linked with reduced odds of hypertension (OR = 0.993, 95% CI: 0.989, 0.997) in a study involving 46,786 participants aged over 45 from the Sax Institute's and Up Study in Australia (Astell et al., 2020). However, no study has reported the associations between tree exposure and pediatric hypertension. In the current study, exposure to the eye-level SVG-tree was found to be negatively associated with childhood hypertension, which presented novel evidence to the beneficial effects of trees on children health. These findings underscored the importance of incorporating trees more extensively into urban planning efforts aimed at constructing a child-friendly and health-promoting environment.

The mechanisms of hypertension associated with greenness exposure have remained insufficiently understood. The density and type of greenery visible in street views can vary, which could correlate with different health outcomes (Reid et al., 2018; Labib et al., 2021). Trees might provide a shelter, while grass could be associated with open spaces and opportunities for physical activity, and trees may play more of a role in providing shade, reducing noise pollution, or improving psychological restoration (Paudel et al., 2023; Reid et al., 2017). A study comparing the health benefits of trees and grass in New York City found that higher tree density was associated with higher likelihood of reporting "very good" or "excellent" health, but grass density was not associated with self-reported health (Reid et al., 2017). Previous studies have indicated that air pollutants might partially elucidate the relationships between greenness and hypertension in children (Chen et al., 2022). Greenness acts as a barrier against pollution sources, effectively removing certain particles and gaseous pollutants, such as $PM_{2.5}$, PM_{10}, NO_2 and SO_2, which may be protective against hypertension in children (Chen et al., 2016, 2018; Zhan et al., 2018; Qiu et al., 2018). A model, formulated by adjusting the land cover database using GIS techniques and field surveys, has predicted that raising tree cover to 21% would result in a 7% decrease in primary PM_{10} concentrations (McDonald et al., 2007). What's more, an experimental campaign in a traffic hotspot demonstrated that tree cover could reduce $PM_{2.5}$ and PM_{10} concentrations by as much as 50% (Gómez-Moreno et al., 2019). Moreira et al.'s study(Moreira et al., 2020) indicates that proximity to green spaces can reduce the impact of air pollutants, noise, and wind, all of which are associated with hypertension. Trees remove vehicle air pollutants through dry deposition, reducing household exposure and potentially lowering the risk of cardiovascular diseases, including hypertension. Our findings also indicated that air pollutants, specifically $PM_{2.5,}$ PM_{10}, NO_2, and SO_2, partly mediated the relationship between eye-level greenness, particularly in trees, and childhood hypertension. Moreover, urban trees help to mitigate the urban heat island effect, reducing health risks associated with high temperatures, including hypertension. This may make outdoor activities (such as walking and socializing) more comfortable, potentially increasing physical activity and helping to reduce the risk of hypertension (Moreira et al., 2020). Finally, Moreira (Moreira et al., 2020)and Astell-Burt's (Astell et al., 2020) study finds that the presence of tree canopy may be crucial for cognitive restoration and stress recovery by providing natural soundscapes, birds, and other forms of biodiversity, which may indirectly reduce hypertension risk. Future research needs to further explore these potential mechanisms, which may act alone or together to explain the relationship between tree exposure and reduced hypertension risk.

5. Strengths and limitations

Based on a pediatric population study, we applied cutting-edge semantic segmentation methods to evaluate the exposure of street view greenness and measured blood pressure using standardized protocols. Exposure to greenness was assessed with SVG, which obtains more realistic eye level of greenness by utilizing approximately 5000 images for each research location from Tencent street view and can differentiate the types of greenness. Furthermore, several sensitivity analyses robustly confirmed the reliability of these outcomes. Nevertheless, our study has inherent limitations, warranting careful interpretation of the findings. Firstly, as a cross-sectional study, causal relationships cannot be inferred. Secondly, our designated street view dataset was rooted in a buffer around school points instead of individual addresses, which may result in misclassification errors in the assessment of exposure. According to the policy of school admission in China, children spend most of the daytime at school which is near their residence, which may minimize the bias. To some extent, this can compensate for this deficiency. Thirdly, the street view data was collected during the summer and therefore may not accurately reflect the seasonal variations in greenness. However, the selection of the summer season for evaluating street greenery is predicated on the fact that summer represents the acme of vegetation growth in northern urban China, thereby affording a distinct contrast in exposure levels across the disparate study regions. Finally, since children in more polluted areas are likely exposed to different urban environments with less green cover, it is challenging to completely disentangle the impact of greenness from that of reduced pollution. This limitation could affect the robustness of the association found between greenness and pediatric hypertension.

6. Conclusion

In conclusion, our results indicate a potential association between increased eye-level greenness, especially trees, and reduced childhood hypertension. Air pollutants could potentially act as mediators in the observed associations. These findings offer novel evidence regarding the beneficial associations of greenness, especially trees, on children health. This information may assist policy makers in implementing protective measures for children during urban planning to create a children health-friendly environment.

CRediT authorship contribution statement

Huang-Min Yang: Writing – original draft, Visualization, Formal analysis. **Jing-Yao Wang:** Writing – review & editing, Validation, Software, Conceptualization. **Cheng Li:** Validation, Software, Conceptualization. **Ya-Qin Zhang:** Writing – review & editing, Supervision. **Ruoyu Wang:** Writing – review & editing. **Qi Yang:** Investigation, Data curation. **Yao Yao:** Writing – review & editing. **Zilong Wang:** Writing – review & editing. **Shu-Li Xu:** Writing – review & editing. **He-Hai Huang:** Writing – review & editing. **Qian-Sheng Hu:** Writing – review & editing. **Ru-Qing Liu:** Writing – review & editing, Visualization, Validation, Supervision. **Guang-Hui Dong:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Funding acquisition, Conceptualization.

Ethics approval

The Human Studies Committee of Sun Yat-sen University approved the study protocols (Approve number: L2018019).

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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.

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Data availability

The authors do not have permission to share data.

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