



HAL
open science

Does urban environment at birth and adolescence affect cardiometabolic morbidity in adolescents? Results from the PARIS birth cohort study

Léa Lefebvre, Emmanuel Marion, Frédérique Prédali, Malika Viola, Thierry Feuillet, Céline Roda, Isabelle Momas

► To cite this version:

Léa Lefebvre, Emmanuel Marion, Frédérique Prédali, Malika Viola, Thierry Feuillet, et al.. Does urban environment at birth and adolescence affect cardiometabolic morbidity in adolescents? Results from the PARIS birth cohort study. *Health & Place*, 2026, 98, pp.103622. <10.1016/j.healthplace.2026.103622>. <hal-05573052>

HAL Id: hal-05573052

<https://hal.science/hal-05573052v1>

Submitted on 30 Mar 2026

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons CC BY 4.0 - Attribution - International License



Does urban environment at birth and adolescence affect cardiometabolic morbidity in adolescents? Results from the PARIS birth cohort study

Léa Lefebvre^{a,b}, Emmanuel Marion^c, Frédérique Prédali^c, Malika Viola^a, Thierry Feuillet^{d,e}, Céline Roda^{a,f,*}, Isabelle Momas^{a,f,1}

^a Université Paris Cité, IRD U261, INSERM U1344, UMR MERIT, HERA Team, Paris, France

^b ADEME – Agence de la transition écologique, Angers, France

^c L'Institut Paris Region, Paris, France

^d Université de Caen Normandie, UMR 6266, IDEES CNRS, Caen, France

^e Université Sorbonne Paris Nord and Université Paris Cité, INSERM, INRAe, CNAM, UMR 1153-CRESS, EREN Team, Bobigny, France

^f Faculté de Pharmacie, Paris, France

ARTICLE INFO

Keywords:

Urban environment
Cohort
Adolescents
Overweight
Traffic related air pollution
Walkability
Green spaces

ABSTRACT

This study aims to examine the association between urban environment characteristics at birth and at adolescence and cardiometabolic health in adolescents from the PARIS birth cohort.

Body mass index z-scores (BMIZ) trajectories from birth to adolescence, weight status and two cardiometabolic profiles at adolescence were determined. Traffic-related air pollution (TRAP) exposure was estimated by a nitrogen oxides air dispersion model. The French Deprivation Index, walkability percentage, and the use of green spaces were considered. Built environment typologies were identified by a cluster analysis. Associations were assessed using multivariable (multinomial) logistic regression models and potential modifier effects were examined.

Among 617 adolescents who participated in the health checkup, around one in ten were living with overweight/obesity. Five BMIZ trajectories were identified. After adjustment, walkability and the use of green spaces at adolescence were negatively associated with overweight/obesity. Early TRAP exposure showed a positive association with overweight/obesity and with each BMIZ trajectory compared to the low stable trajectory, with a higher level of association observed for the two ascending trajectories. TRAP exposure, parental overweight, use of green spaces, and sedentary behavior modified the associations between the urban environment and overweight.

These findings show the beneficial effects of neighborhood walkability and using green spaces on overweight/obesity in adolescents. They also demonstrate that early TRAP exposure increases the risk of overweight. These results highlight the necessity of effective urban planning to contribute to a healthy environment.

1. Introduction

Cardiometabolic health is characterized by the interaction and combination of cardiovascular morbidity and metabolism. Metabolic syndrome (MetS) is the co-occurrence of several known cardiometabolic risk factors, including insulin resistance, obesity, atherogenic dyslipidemia, and hypertension (Huang, 2009). In adults, MetS doubles the risk of developing cardiovascular disease and increases the risk of type 2 diabetes fivefold over a period of five to ten years (Alberti et al., 2009). An international literature review estimates that MetS affects 3.3% of

the pediatric population, 11.9% of children living with overweight, and 29.2% of children living with obesity (Friend et al., 2013).

Since 1998, the World Health Organization (WHO) has considered the global epidemic of overweight and obesity in children to be one of the most serious public health challenges worldwide. In 2020, WHO estimated that 39 million children under the age of 5 and 150 million children aged 5 to 19 were living with overweight or obesity. These figures are projected to reach 40 million and 254 million, respectively, by 2030 (WHO (World Health Organization), 2021). In France, the prevalence of overweight and obesity is estimated at 17% and 4%,

* Corresponding author. 4 Avenue de l'Observatoire, 75006, Paris, France.

E-mail address: celine.roda@u-paris.fr (C. Roda).

¹ equal contribution.

respectively, among 6- to 17-year-olds (Verdot et al., 2017). Childhood and adolescence are critical periods for the development of overweight. Indeed, 80% of adolescents with obesity will remain obese in adulthood (Simmonds et al., 2016). Several factors—genetic, behavioral, and environmental—can influence weight gain during childhood (Campbell, 2016; Gupta et al., 2012).

More than 55% of the world's population lives in urban areas, a proportion that is expected to reach 68% by 2050 according to WHO (WHO (World Health Organization), 2024). Consequently, emerging literature is investigating the link between the urban environment and cardiometabolic morbidity during childhood. The urban environment is generally assessed through built environment characteristics: walkability (Frank et al., 2010) and features such as road intersection density or land use mix, as well as green spaces. The hypotheses underlying this link involve changes in health-related behaviors and lifestyles in response to changes in the built environment, such as physical activity or sedentary behavior. Beyond these changes, built environment influences exposure to traffic-related air pollution (TRAP), which has also been linked to adverse cardiometabolic outcomes (Rajagopalan et al., 2024). Therefore, it is essential to simultaneously study both the built environment and TRAP.

A number of studies have recently investigated the associations between walkability and BMI or percentage of body fat among children and/or adolescents, finding either negative associations (Neshteruk et al., 2023; Barnett et al., 2022; Puttaswamy et al., 2023; Gallotta et al., 2022) or no association (Kowalski et al., 2023; Wayas et al., 2023; Molina et al., 2021). The results concerning green spaces are more ambiguous, with some studies showing a beneficial effect of their presence (do et al., 2023; Morgan et al., 2017), while others show a detrimental effect (Neshteruk et al., 2023; Lozano et al., 2024) or no effect at all (Poulain et al., 2020; Reis et al., 2020; Zhou et al., 2020). To our knowledge, only one study has considered the frequency of green space use but it focused solely on physical activity (Bozkurt, 2021). Increased levels of air pollution have been reported to be harmful in relation to overweight in children (de Bont et al., 2020; de Bont et al., 2021a; de Bont et al., 2021b; Wilding et al., 2020). Few studies have described the urban environment in a combined manner using clusters (Barnett et al., 2022; de Bont et al., 2021b; Warembourg et al., 2021; de Albuquerque et al., 2023a; de Albuquerque et al., 2023b; Filgueiras et al., 2024; Pereira et al., 2019), allowing the identification of exposure typologies, and most are cross-sectional studies.

Thus, our aim is to assess the association between the urban environment (walkability, green spaces, TRAP) and adolescent cardiometabolic morbidity in the PARIS (Pollution and Asthma Risk: an Infant Study) birth cohort and to study potential modifying effects.

Understanding how these factors influence cardiometabolic health outcomes in adolescents is crucial for developing targeted public health interventions and urban planning strategies to promote healthier lifestyles and reduce the burden of cardiometabolic diseases.

2. Methods

2.1. PARIS birth cohort

The PARIS birth cohort involved 3840 healthy full-term babies born between 2003 and 2006 in five Paris maternity hospitals. Follow-up was based on regular questionnaires and health checkups (Clarisse et al., 2007). A total of 2117 adolescents are still followed (Fig. A1). The French Ethics Committees approved the PARIS study (permission nos. 031153, 051289, ID-RCB, 2009-A00824-53, and 2009-12-04 MS2), and parents and adolescents gave written informed consent. This study deals with adolescents who participated in the health checkup at 15–16 years.

2.2. Cardiometabolic outcomes

Height and weight were collected from medical records: at birth, 1,

3, 6, 9, and 12 months, at 2, 3, 4, 5, 6, 8–9, 13, and at 15–16 years, and measured in health check-ups at 18 months, 8–9, and 15–16 years. Body mass was assessed during checkups using a Tanita MC-780MA segmental analyzer (Tanita Corp., Tokyo, Japan). Height was measured to the nearest 0.1 cm using a Kern® MSF 200N mechanical height rod (Kern & Sohn GmbH, Balingen, Germany). Body mass index z-scores (BMIz) were estimated according to sex and age with reference to WHO 2006 (ages 0–5) and 2007 (ages 5–19) growth standards (WHO Multicentre Growth Reference Study Group, 2006). At 15–16 years, adolescence were classified as underweight (< -2 standard deviation (SD)), normal ($\geq -2SD$, $< 1SD$), overweight ($\geq 1SD$, $< 2SD$), or obese ($\geq 2SD$).

BMIz longitudinal trajectories (Lefebvre et al., 2025) were identified for adolescents with available data for z-score calculation (height, weight, and age at measurement) at specific time periods: birth, 18 months, 3 or 4 years, 5 or 6 years, 8–9 or 13 years, and 15–16 years using group-based trajectory modeling (GBTM) using Stata plug-in *Traj*. Five trajectories were obtained: “Low stable BMI” (10.0%), “Continuous increase BMI” (23.3%), “Continuous decrease BMI” (27.2%), “Early increase and slight decrease BMI” (29.5%), and “Early high stable BMI” (10.0%) (Fig. A2).

Additionally, other anthropometric and biological parameters—such as body composition, blood pressure, heart rate, and blood samples—were collected during the adolescent checkup.

Body composition was measured by multifrequency bioelectrical impedance analysis using a Tanita MC-780MA segmental analyzer (Tanita Corp., Tokyo, Japan) and was assessed by the percentage or mass in kilograms (kg) of fat, muscle, and lean mass. Waist and hip circumferences were determined to the nearest 0.1 cm. Heart rate, systolic blood pressure (SBP) and diastolic blood pressure (DBP) levels were recorded with an Omron HEM-RML31 cuff blood pressure monitor (Omron Healthcare Co. Ltd, Kyoto, Japan), and the average of three measurements was calculated. Triglycerides (grams per liter (g/L)), blood glucose (g/L), total cholesterol (g/L), and high-density lipoprotein (HDL) (g/L) concentrations were determined by an enzymatic method (GPO-PAP, hexokinase, CHOD-PAP, and a mixture of polyanions and detergents, respectively) using a Roche Cobas® 6000 (c501) analyzer. Low-density lipoprotein (LDL) cholesterol levels (g/L) were calculated using the Friedewald formula. Based on these anthropometric and biological data, cardiometabolic profiles were previously identified using *k*-means algorithm, an unsupervised cluster analysis, revealing 356 adolescents in the “healthy” profile (67.2%) and 174 in the “at cardiometabolic risk” profile (32.8%) (Lefebvre et al., 2023).

2.3. Assessment of urban environment

The residential addresses at birth and at age 15–16 were geocoded. When reliability was insufficient, the geographical coordinates were corrected manually. The selected indicators are based on a large amount of detailed, locally collected data and best reflect the characteristics of the study area.

The French Deprivation Index (FDep) (Rey et al., 2009) was calculated at the IRIS (*îlots regroupés pour l'information statistique*, the smallest administrative unit in France for the dissemination of census data) level using 2009 and 2019 aggregated data from the National Institute of Statistics and Economic Studies (Insee) on: unemployment rate, proportion of workers in the economically active population aged 15–64 years, proportion of high-school graduates in the non-student population over 15 years old, and median household income. The FDep was derived from the first principal component (43.2% and 42.5% of the explained variance in 2009 and 2019, respectively) of a principal component analysis of these four aggregated variables. Each child was assigned FDep2009 and FDep2019 based on their IRIS residence at birth and at age 15–16.

The population densities of the IRIS at birth and adolescence were determined from the number of inhabitants per square kilometer, using 2006 and 2019 census data from Insee.

The walkability index was developed by *L'Institut Paris Region* using information on public spaces, schools, healthcare and administrative facilities, cultural and recreational facilities, physical activity equipment, businesses, public transport stations, rail and road networks, urban heat islands, and land use (Prédali and Marion, 2022) (detailed method available in the supplementary material). Each data point was weighted based on its impact on walkability (positive or negative), the supposed frequency of use, and the size of the road networks, within 200×200 m squares, to produce the “static grade.” The weighted sum of each square accessible within a 15-min walk taking account of the topography was determined and was called the “dynamic grade.” The total grade was the sum of the “static” and “dynamic” grades. For each child, the assigned walkability index corresponds to the “dynamic” grade of the square in which they lived. The relevance of the index was evaluated through field surveys conducted by *L'Institut Paris Region*.

Using land use data from *L'Institut Paris Region* for 2003 and 2021, the percentage of green spaces (woods or forests, forest clearings or logging areas, poplar plantations, open areas with shrub or herbaceous vegetation, parks or gardens and, grassed areas with or without shrubs) within a 300-m radius around the home (Annerstedt et al., 2016) at birth and during adolescence was calculated. At 15–16 years old, adolescents reported the presence of a green space (municipal park, forest ...) freely accessible within a 15-min walk from their home and whether they used this green space.

TRAP exposure was assessed by the ExTra index to estimate ambient air concentrations of nitrogen oxides (NO_x) (Sacré et al., 1995; Reungoat et al., 2003) in front of both residential and day-care addresses during the first year of life and at residential addresses for the year before the health checkup at 15–16 years. The ExTra index integrates a regional component corresponding to background levels measured by the PARIS air quality monitoring network (AIRPARIF) and a local component modeled using an air pollution dispersion model, adapted from the Danish operational street pollution model (Hertel and Berkowicz, 1989), taking into account traffic conditions, topography, and meteorology. The ExTra index is expressed in $\mu\text{g}/\text{m}^3 \text{NO}_2$ equivalent.

2.4. Covariates

At the maternity hospital, data were collected on the baby's sex, weight, and height; the parents' geographical origin, socioeconomic status (SES), and level of education; the residence places (accounting for moving throughout life); the number of siblings; the delivery mode; and the mother's age. Parents' SES was categorized based on the lowest occupation of both parents (high or medium/low). High category refers to high-level white-collar workers, medium to craftsmen, shopkeepers, intermediate-level white-collar workers and low to unemployed, students, blue-collar workers, low-level white-collar workers. The mother's age was dichotomized according to the median age of the study population. The mother's active smoking during pregnancy and breastfeeding between 0 and 3 months was documented. Parents' weight status according to their BMI was categorized as “living with underweight/normal weight” ($\text{BMI} \leq 25 \text{ kg}/\text{m}^2$) and “living with overweight/obesity” ($>25 \text{ kg}/\text{m}^2$).

Each child's adiposity rebound age was determined as the age at which their BMI began to rise again after reaching its lowest point. Early adiposity rebound was defined as ≤ 4.5 years (Kroke et al., 2006).

The occurrence of a stressful event within the family (e.g., death, job loss, divorce, and illness) between 0 and 2 years of age was documented. At 15–16 years, adolescents provided information about any stress or anxiety they had experienced in their relationship with their parents.

The types, frequency and number of hours per week of extracurricular sport activities that participants practiced at 15–16 years were documented. Using metabolic equivalent of task (MET) values for each activity, the intensity of each physical activity was then determined, and the number of hours spent in moderate to vigorous physical activity (MVPA) (≥ 3 METs) was calculated. Sedentary lifestyle was analyzed by

daily screen time, and adolescents were grouped into those who spent “less than 3 h a day” and those who spent “at least 3 h a day” in front of screens.

2.5. Statistical analyses

Statistical analyses were performed using Stata® (version SE 17, Stata Corporation, TX, USA) and R (version 4.2.1, R Development Core Team, 2010) softwares.

We assessed the normality of quantitative variables using the Shapiro-Wilk test and Henry's graphical method. The baseline characteristics of participating and non-participating adolescents were compared using the chi-squared/Fisher's exact test or the Student's *t*-test.

A hybrid hierarchical *k*-means clustering approach (using the *hkmeans* R package) was employed to identify built environment clusters at birth and adolescence, based on deprivation index, walkability, population density, and percentage of green spaces. Initially, hierarchical cluster analysis was conducted using Ward's method. The hierarchical tree was then divided into *k* clusters, and the centers of these clusters were used to perform an unsupervised *k*-means (Hartigan and Wong, 1979) cluster analysis. Two to six groups were tested and the optimal number of clusters was selected based on 30 statistical indices using the *NbClust* R package. The relevance of groups was also considered.

Associations between the urban environment, assessed by separate parameters and clusters, and cardiometabolic morbidity were investigated using multivariable logistic and multinomial regression models. The models were adjusted according to the main risk factors recognized in the literature and identified by a directed acyclic graph (DAG). Results were expressed as adjusted odds ratios (aORs) with 95% confidence intervals (95% CI). Associations were regarded as significant when the *p*-value was less than 0.05.

The potential modifier effects of multiple variables were explored by testing multiplicative interaction terms using a significance level of 0.10.

3. Results

This study is based on the 617 adolescents who participated in the 15–16 year olds' checkup. Parents of participating adolescents had higher SES and post-secondary education rates compared with non-participants, but there was no difference in their geographical origin and place of residence. Participating adolescents had older mothers and were more likely to have been breastfed between 0 and 3 months, but no differences were found regarding their sex and weight at birth nor their exposure to tobacco smoke (Table 1).

At 15–16 years old, 7.6% of the adolescents were living with overweight and 2.3% with obesity.

Comparisons between the urban environment at birth and adolescence are shown in Table 2. The mean exposure to TRAP halved between the first year of life and the year before the 15–16 year olds' health checkup. Walkability and population density near the homes of adolescents were, on average, lower than at birth, whereas the mean deprivation index was higher. The distribution of green spaces at birth and adolescence did not differ.

Four built environment clusters were identified at birth, and five at adolescence (Fig. 1). Among the study population at birth, cluster A grouped children living in neighborhoods with the highest population density; cluster B was characterized by the lowest population density and walkability; cluster C was defined by the lowest deprivation index and highest walkability; and cluster D had the highest percentage of green spaces near children's homes. In adolescence, cluster 1 included adolescents living in neighborhoods with the highest population density; cluster 2 was the closest to the population mean; cluster 3 featured the highest deprivation index and low walkability; cluster 4 had the lowest levels of deprivation and the highest walkability; and cluster 5

Table 1

Baseline characteristics of adolescents from the PARIS birth cohort still being followed up at 15–16 years of age who participated, or did not participate, in the health checkup (N = 2117).

| Baseline characteristics | Participants (N = 617) | Non-participants (N = 1500) | p-value |
|---|---------------------------|--------------------------------|---------|
| Male sex, n (%) | 312 (50.6) | 771 (51.4) | 0.7 |
| Weight at birth, kg (mean ± SD) | 3.4 (0.4) | 3.4 (0.4) | 0.3 |
| Height at birth, cm (mean ± SD) | 50.3 (1.9) | 50.1 (1.8) | 0.035 |
| Breastfeeding between 0 and 3 months, n (%) | 207 (33.8) | 385 (26.7) | 0.001 |
| Place of residence at birth | | | 0.8 |
| Paris city, n (%) | 387 (62.7) | 933 (62.2) | |
| Paris suburbs, n (%) | 230 (37.3) | 567 (37.8) | |
| Low/middle socioeconomic status of parents at birth | | | 0.011 |
| Yes, n (%) | 186 (30.2) | 539 (35.9) | |
| No, n (%) | 431 (69.8) | 961 (64.1) | |
| Parents' level of education ^a | | | 0.009 |
| Primary, n (%) | 1 (0.1) | 11 (0.7) | |
| Secondary, n (%) | 38 (6.2) | 144 (9.6) | |
| Post-secondary, n (%) | 578 (93.7) | 1345 (89.7) | |
| Geographical origin of parents | | | 0.2 |
| Both parents born in France, n (%) | 458 (74.2) | 1070 (71.3) | |
| At least one parent born outside France, n (%) | 159 (25.8) | 430 (28.7) | |
| Mother's age at birth, years (mean ± SD) | 33.2 (3.9) | 32.7 (4.0) | 0.008 |
| Mother actively smoking during pregnancy, n (%) | 55 (8.9) | 145 (9.7) | 0.6 |
| Smokers at home at birth, n (%) | 112 (18.4) | 299 (20.2) | 0.4 |

SD: standard deviation.

p-value from chi-squared/Fisher's exact test or Student's t-test.

^a highest among parents.

was defined by the highest percentage of green spaces near adolescents' homes and low levels of population density and walkability.

The associations between urban environment characteristics and cardiometabolic health are shown in Table 3 and Table A1. Early TRAP exposure was positively associated with overweight and BMIz trajectories compared to the “low stable” trajectory, with stronger associations for the two ascending trajectories (aOR (95% CI) = 1.84 (1.10–3.10) and 2.05 (1.17–3.61) for the “continuous increase” and “early high stable” BMI trajectories, respectively). TRAP exposure in the year before the health checkup, parental overweight, use of green spaces, and sedentary behavior were found to be modifiers of the associations with overweight (Fig. 2). A negative association was observed between an increase in walkability index (interquartile range (IQR): 1994.7) and overweight at adolescence, mainly in adolescents with less sedentary behavior (aOR (95% CI) = 0.16 (0.04–0.55)). The use of green

Table 2

Comparison of the urban environment at birth and adolescence in adolescents from the PARIS birth cohort.

| | N | Mean (SD) | Min; Max | Median (IQR) | p33; p66 | p-value |
|---|-----|---------------------|-----------------|---------------------|--------------------|---------|
| NO _x 0–1 year (µg/m ³ NO ₂ eq.) | 614 | 79.7 (22.1) | 42.1; 248.0 | 74.7 (20.1) | 69.6; 82.6 | <0.001 |
| NO _x 14–15 years (µg/m ³ NO ₂ eq.) | 591 | 39.3 (9.0) | 19.8; 68.8 | 38.0 (13.0) | 34.9; 42.5 | |
| FDep at birth | 617 | 1.7 (1.2) | –2.7; 5.5 | 1.8 (1.5) | 1.4; 2.3 | <0.001 |
| FDep at adolescence | 617 | –1.7 (1.4) | –6.5; 2.8 | –1.9 (1.8) | –2.5; 1.3 | |
| Walkability at birth | 617 | 3184.6 (1706.1) | 422.6; 10,404 | 2947.6 (1994.7) | 2248.2; 3601.9 | <0.001 |
| Walkability at adolescence | 617 | 2685.9 (1701.2) | 85.0; 9571.0 | 2258.1 (2256.6) | 1565.8; 3161.5 | |
| % green spaces at birth | 617 | 8.0 (7.1) | 0; 60.3 | 6.2 (7.0) | 4.4; 8.4 | 0.4 |
| % green spaces at adolescence | 617 | 8.3 (7.9) | 0; 52.0 | 6.1 (7.6) | 4.2; 8.9 | |
| Population density at birth (nb/km ²) | 617 | 29,929.6 (16,078.0) | 578.9; 70,071.6 | 29,379.1 (26,857.7) | 20,888.9; 38,107.9 | <0.001 |
| Population density at adolescence (nb/km ²) | 617 | 24,003.8 (16,209.6) | 37.0; 76,039.0 | 20,159.7 (26,933.3) | 13,054.8; 32,765.2 | |

Eq.: equivalent; FDep: French Deprivation Index; IQR: interquartile range; Max: maximum; Min: minimum; Nb: number; NO_x: nitrogen oxides; NO₂: nitrogen dioxide; p: percentile; SD: standard deviation.

p-value from paired t-test.

spaces was also negatively associated with overweight at adolescence, especially in adolescents without parental overweight (aOR (95% CI) = 0.05 (0.00–0.55)), and those who were exposed to high levels of TRAP in the year before the health checkup (aOR (95% CI) = 0.09 (0.02–0.43)). TRAP exposure in the year before the health checkup was positively associated with overweight only among adolescents who did not use green spaces near their home (aOR (95% CI) = 4.03 (1.19–13.67)). No association was found with the cardiometabolic profiles.

Built environment clusters at birth were not associated with cardiometabolic health in adolescence nor with BMIz trajectories (Table 4 and Table A2). In adolescence, cluster 3, characterized by higher levels of deprivation and low walkability, tended to be positively associated with overweight at adolescence (aOR (95% CI) = 2.72 (0.90–8.21)).

4. Discussion

4.1. Key results

This study shows that the urban environment at adolescence, evaluated using parameters (walkability, deprivation index, percentage and use of green spaces, and TRAP exposure) and typologies, impacts overweight in adolescence and BMIz trajectories. Walkability and the use of green spaces were associated with a reduction in the risk of overweight, especially in subgroups. However, no association was observed with cardiometabolic profiles in adolescents. The urban environment at birth was not associated with overweight or BMI trajectories, nor with cardiometabolic profiles. Conversely, early exposure to TRAP increased the risk of overweight and ascending BMI trajectories at adolescence.

4.2. Urban environment at birth and adolescence

This study shows the evolution of the urban environment in the neighborhoods of our sample population from birth to adolescence. The average exposure levels to the urban environment (deprivation index, walkability, population density and TRAP exposure) varied from birth to adolescence. One explanation is that 20% of families moved outside the Paris metropolitan area to peripheral areas, which are characterized by lower population density and walkability. The significant decrease in TRAP exposure is the result of several measures (more stringent emission standards for new vehicles, traffic reduction, and reduction in diesel use). The decreased deprivation index could be explained by families moving to areas with a higher SES.

4.3. Associations between the urban environment and cardiometabolic morbidity in adolescence

Early TRAP exposure was associated with the risk of overweight in

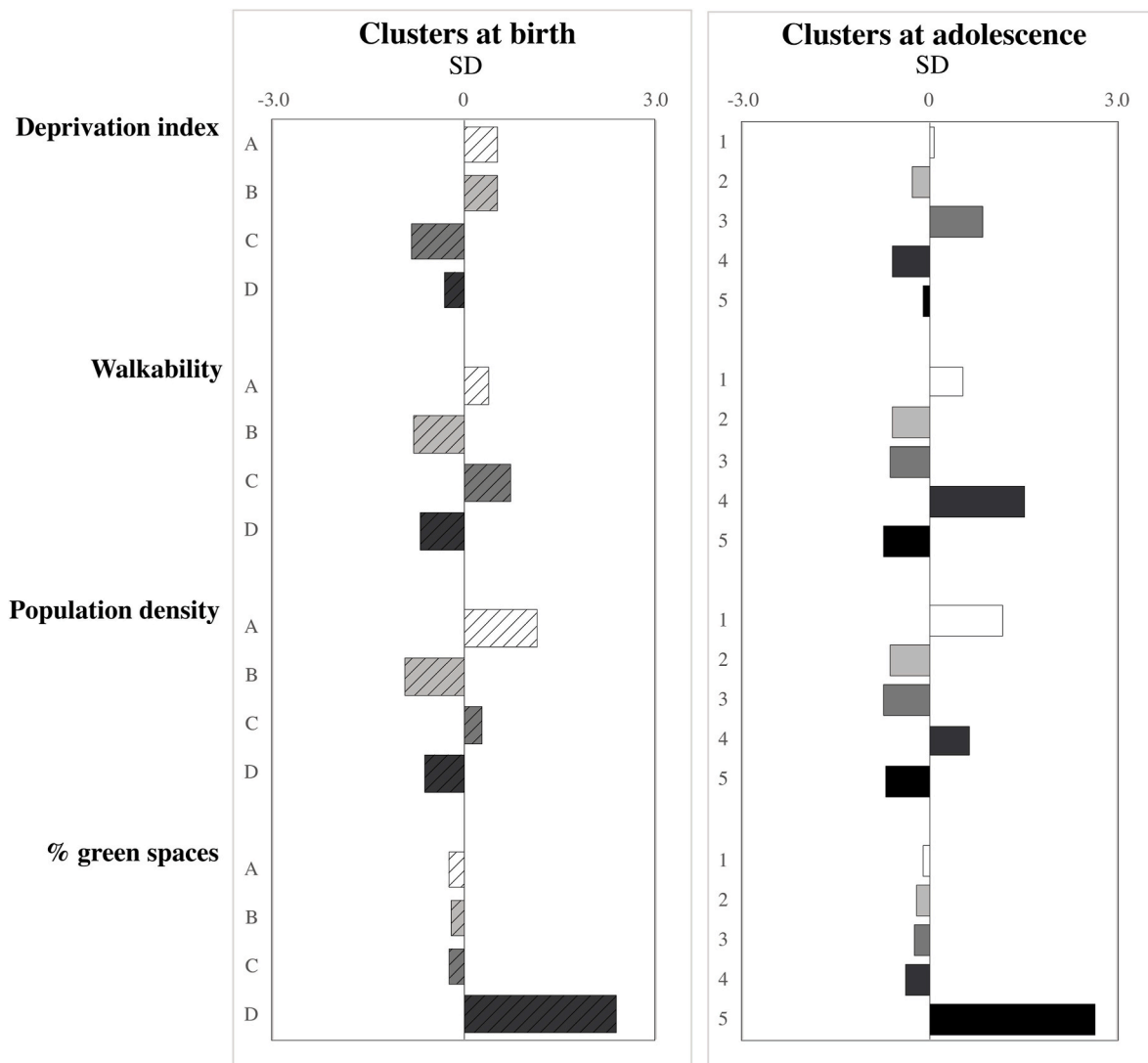


Fig. 1. Description of the built environment clusters at birth and at adolescence obtained from hierarchical *k*-means clustering of the PARIS birth cohort. The bars represent the standard deviation of the mean of the entire population in each cluster for the built environment characteristics used in the analysis. SD: Standard deviation.

adolescence, which is consistent with the literature (de Bont et al., 2020; de Bont et al., 2021a; Wilding et al., 2020; Bloemsma et al., 2019). A recent meta-analysis aiming to determine the association between air pollutants and the weight status of children and adolescents shows that the pooled OR (95 % CI) of overweight/obesity was 1.12 (1.05, 1.19) per 10 $\mu\text{g}/\text{m}^3$ increment in NO_x exposure (Zheng et al., 2024). Similar associations were also observed with BMI trajectories. Early TRAP exposure increased the risk of belonging to any trajectory compared to the “low stable BMI” trajectory, with stronger estimates for the two ascending trajectories that increase over the child’s life. The mechanisms underlying this association is not completely understood. Potential TRAP mechanisms include changes in basal metabolism that induce inflammation, oxidative stress, and hormone disruption (Bolton et al., 2012; Wei et al., 2016). Additionally, TRAP may increase brain inflammation, including microglial activation and anxiety leading to higher caloric intake (Sun et al., 2009).

Our study clearly documents the impact of the urban environment on overweight at adolescence. Increased walkability in adolescents’ neighborhoods reduces the risk of overweight. The literature on associations between walkability and weight status in the pediatric population is unclear (Yang et al., 2021), with some studies finding associations (Neshteruk et al., 2023; Puttaswamy et al., 2023; Gallotta

et al., 2022; Stowe et al., 2019; HaGani et al., 2019; Spence et al., 2008) and others not (Kowalski et al., 2023; Molina-et al., 2021; Zhou et al., 2020; Amram et al., 2020). A longitudinal study of 2838 children with obesity at recruitment showed that high walkability was negatively associated with persistent obesity during the follow-up (Neshteruk et al., 2023). The effect of the built environment was confirmed by the cluster analysis. Cluster 3, characterized by one of the lowest walkability scores and the highest deprivation index in adolescence among the study population, was positively associated with overweight. Among the few studies that have examined the built environment using clusters, a cross-sectional study of 485 children aged 8 to 10 found similar results (Barnett et al., 2022). In that study, five clusters were identified, and the cluster with low walkability and safety was associated with higher BMI. Children’s behaviors related to weight status, such as physical activity, sedentary behavior, and diet, could be influenced by walkability (Yang et al., 2021). In our study, the walkability index was associated with lower overweight risk only in adolescents who were less sedentary suggesting greater use of their urban environment.

The use of green spaces, rarely considered in the literature, is another parameter for evaluating how adolescents interact with their urban environment. Many studies have looked at the density, presence, or distance of green spaces from residences without considering if children

Table 3
Associations between urban environment characteristics and cardiometabolic health in adolescents from the PARIS birth cohort.

| | Overweight (ref. No) | | | | BMI trajectories (ref. Low stable BMI) | | | | Cardiometabolic risk profile (ref. Healthy profile) | | | | | | | | | |
|------------------------------------|-------------------------|-----------|-------------------------|------|--|-------|-----------------------|-----------|---|------|-----------|-------|------|-----------|-------|------|-----------|-------|
| | Continuous increase BMI | | Continuous decrease BMI | | Early increase and slight decrease BMI | | Early high stable BMI | | aOR | | 95% CI | | p | | | | | |
| | aOR | 95% CI | p | aOR | 95% CI | p | aOR | 95% CI | p | aOR | 95% CI | p | aOR | 95% CI | p | | | |
| At birth | | | | | | | | | | | | | | | | | | |
| Walkability (+IQR) | 1.29 | 0.75–2.20 | 0.361 | 1.20 | 0.72–1.99 | 0.490 | 1.02 | 0.62–1.68 | 0.926 | 1.00 | 0.58–1.57 | 0.861 | 0.70 | 0.37–1.34 | 0.282 | 1.07 | 0.74–1.54 | 0.713 |
| Deprivation index (+quintile) | 1.00 | 0.73–1.35 | 0.978 | 1.09 | 0.84–1.43 | 0.514 | 1.03 | 0.80–1.34 | 0.808 | 1.01 | 0.78–1.30 | 0.950 | 0.96 | 0.69–1.33 | 0.806 | 1.02 | 0.82–1.25 | 0.882 |
| % green spaces (+tertile) | 1.15 | 0.72–1.84 | 0.554 | 1.29 | 0.81–2.05 | 0.276 | 1.10 | 0.71–1.73 | 0.665 | 1.12 | 0.72–1.74 | 0.623 | 1.41 | 0.80–2.49 | 0.236 | 1.05 | 0.77–1.45 | 0.746 |
| NO _x 0–1 year (+IQR) | 1.50 | 1.12–2.01 | 0.006 | 1.84 | 1.10–3.10 | 0.021 | 1.69 | 1.01–2.82 | 0.044 | 1.73 | 1.04–2.87 | 0.036 | 2.05 | 1.17–3.61 | 0.012 | 1.03 | 0.81–1.32 | 0.786 |
| At adolescence | | | | | | | | | | | | | | | | | | |
| Walkability (+IQR) | 0.40 | 0.19–0.83 | 0.014 | | | | | | | | | | | | | 0.93 | 0.59–1.49 | 0.776 |
| Deprivation index (+quintile) | 0.96 | 0.71–1.30 | 0.805 | | | | | | | | | | | | | 0.99 | 0.81–1.21 | 0.912 |
| % green spaces (+tertile) | 0.98 | 0.61–1.57 | 0.934 | | | | | | | | | | | | | 1.00 | 0.72–1.38 | 0.992 |
| Use of green spaces (vs. no) | 0.43 | 0.21–0.85 | 0.016 | | | | | | | | | | | | | 0.69 | 0.43–1.10 | 0.121 |
| NO _x 14–15 years (+IQR) | 1.40 | 0.76–2.57 | 0.285 | | | | | | | | | | | | | 0.89 | 0.58–1.37 | 0.587 |

aOR: adjusted odds ratio; BMI: body mass index; CI: confidence interval; IQR: interquartile range; NO_x: nitrogen oxides; *p*: *p*-value.
 IQR: walkability at birth: 2256.6; walkability at adolescence: 1994.7; NO_x 0–1 year: 20.1 µg/m³ NO₂ equivalent; NO_x 14–15 years: 13.0 µg/m³ NO₂ equivalent.
 Adjusted for sex, socioeconomic status (SES), parental overweight, early BMI rebound age, mother actively smoking during pregnancy, stressful events during ages 0–2, parent–child relationship stress, time spent in front of screens, extracurricular moderate to vigorous physical activity, moving house during life.
 Urban environment characteristics at adolescence not included in the multivariate analysis of BMI trajectories.

use these spaces. Bozkurt et al. showed that children attending green spaces for regular physical activity had a lower risk of overweight (Bozkurt, 2021). In our study, the use of green spaces appeared protective only in adolescents with non-overweight parents. Two Spanish studies have shown that the association between the urban environment and cardiometabolic risk was mediated by the mother's BMI (de Albuquerque et al., 2023a; Filgueiras et al., 2024). The influence of parental weight status may be stronger than the beneficial effect of spending time in green spaces. Additionally, behaviors related to overweight, such as a child's diet or physical activity, can be influenced by the parents due to the ability they have to control and guide such practices.

TRAP exposure the year before the health checkup was positively associated with overweight only among adolescents who did not use green spaces near their home; no association was found among adolescents who frequented green spaces. A Chinese study reported a similar interaction: a 10 µg/m³ increase in nitrogen dioxide (NO₂) exposure was associated with a 65% increase in the risk of overweight and obesity in children and adolescents, with an adjusted Hazard Ratio (aHR) of 1.65 (95% CI: 1.62–1.68) in the low-level group of greenness and an aHR of 1.22 (95% CI: 1.20–1.24) in the high-level group of greenness (Chen et al., 2022). Exposure to green spaces thus appears to reduce the effect of TRAP exposure on overweight within the pediatric population. Urban vegetation contributes to reducing certain air pollutants by absorbing gaseous pollutants such as NO_x, ozone, volatile organic compounds (VOCs), and carbon dioxide (CO₂), and by trapping suspended particles (Janhäll, 2015).

The percentage of green spaces within a 300-m radius around the home was not linked to overweight in adolescents. However, the percentage of green space was positively associated with the “early increase and slight decrease BMI” trajectory. The association between green spaces and overweight shows heterogeneous results in the literature with studies finding positive (Neshteruk et al., 2023), negative (Molina-et al., 2021; Daniels et al., 2021) or no association (de Bont et al., 2020; Melo et al., 2021). The types of green spaces included in these studies vary, for example, in terms of whether or not they have sports facilities, which may influence physical-activity-related behaviors and could explain the ambiguous results.

The urban environment did not impact cardiometabolic profiles in our study population. The profiles were based on individuals with generally good cardiometabolic health and a lower prevalence of overweight than that observed in the general 6- to 17-year-old French population, where 17% live with overweight (Verdot et al., 2017). The cardiometabolic risk profiles was subclinical. This may explain why no association was found with urban environment. Previous studies using pediatric-specific cardiometabolic risk scores have also not found significant association (Bloemsma et al., 2019; Nevill et al., 2021; Dengel et al., 2009).

4.4. Strengths and limitations

This study analyzes a well-characterized cohort through prospectively and regularly collected data. The cardiometabolic health of adolescents is well described due to anthropometric measurements and biological data collected during adolescence, as well as BMI trajectories identified from birth to adolescence. The urban environment was assessed at two exposure windows using both separate parameters and clusters obtained by unsupervised methods. To our knowledge, evaluation at two temporal windows has never been carried out before. An evaluation of the built environment of the pediatric population using a cluster approach is rarely found in the literature. This method allows to assess environmental characteristics in a unified manner. Indeed, this is more the spatial layout of these features that impact on behaviors than an isolated characteristic. Moreover, the use of green spaces was also considered, which has only been examined once before in previous pediatric studies. Residential walkability was explored in detail through several parameters, while also considering walkability in the

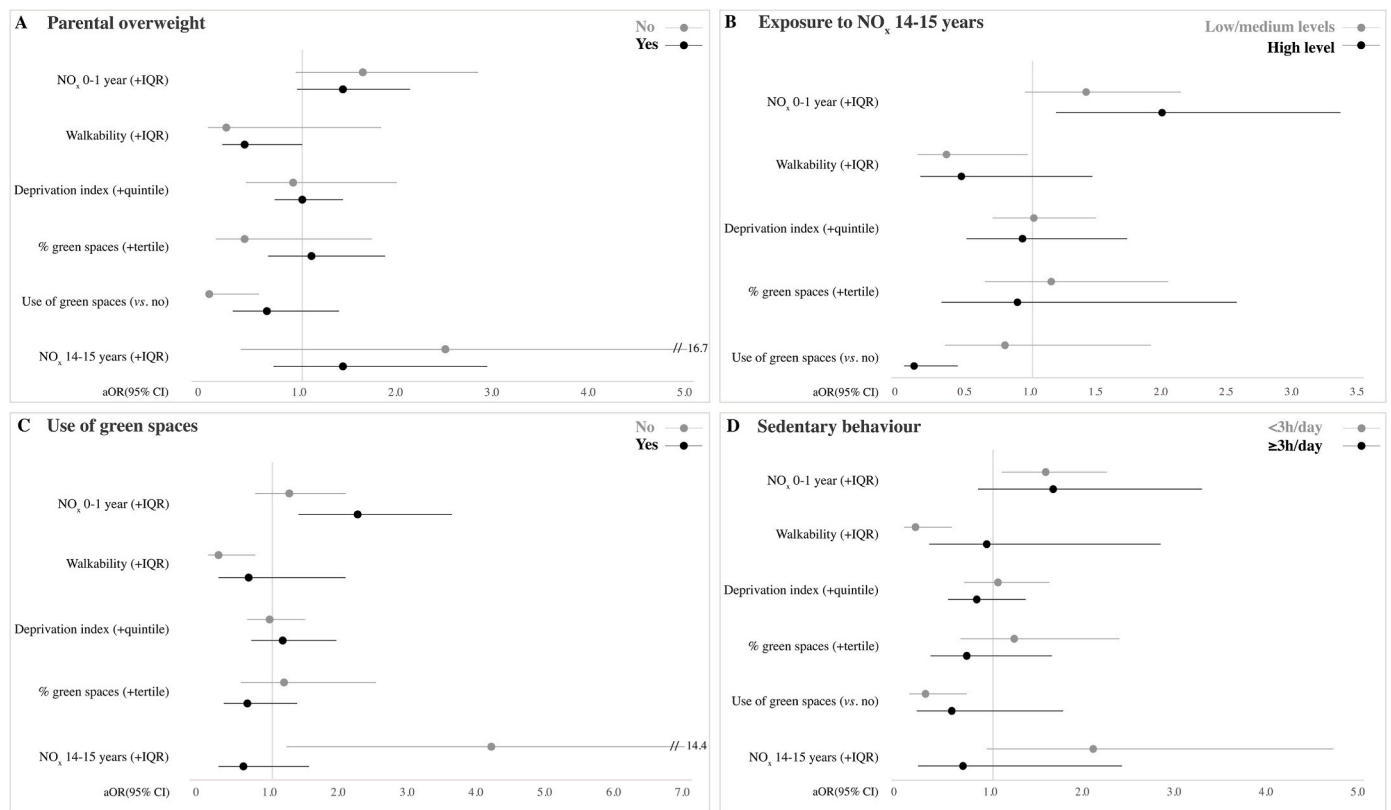


Fig. 2. Adjusted odds ratios of the association between urban environment characteristics and overweight at 15–16 years old, according to parental overweight (A), exposure to NO_x the year before the health checkup (B), the use of green spaces (C), and sedentary behavior (D). Adjusted for sex, socioeconomic status (SES), parental overweight, early BMI rebound age, mother actively smoking during pregnancy, stressful events during ages 0–2, parent–child relationship stress, time spent in front of screens, moderate to vigorous physical activity, moving house during life. aOR: adjusted odds ratio; BMI: body mass index; CI: confidence interval; IQR: interquartile range; NO_x: nitrogen oxides. IQR: Walkability at birth: 2256.6; walkability at adolescence: 1994.7; NO_x 0–1 year: 20.1 µg/m³ NO₂ equivalent; NO_x 14–15 years: 13.0 µg/m³ NO₂ equivalent. NO_x high levels at 14–15 years: ≥42.5 µg/m³ NO₂ equivalent. //: cropped confidence interval.

surrounding areas. However, since data were not available at birth, the walkability index was estimated using data from 2022. This is the first time this index has been used in an epidemiological study, and its relevance should be confirmed by further research. Additionally, the spatial units used in our analysis are not the same. The urban environment near schools was not considered, which is another limitation of our study. The residential environment of our population is homogeneous, which does not allow for highly contrasted urban environment typologies. Another limitation is the small sample size due to the attrition rate caused by participants moving outside the study area, which introduces selection bias and might limit the generalizability of the results.

5. Conclusion

The findings from this study show the beneficial effects of a high-walkability neighborhood and using green spaces on overweight and obesity in adolescents. They also demonstrate that early TRAP exposure increases the risk of overweight in adolescence. This work confirms that cardiometabolic morbidity is multifactorial, involving risk factors interacting with each other. This study provides valuable insights that can guide public health policies and advocate for the promotion of a health-supportive environment through urban planning approaches. These include enhancing walkability, increasing accessibility to urban greening, and reducing road traffic and consequently traffic-related air pollution.

Consent to participate

Parents and adolescents gave written informed consent.

Glossary

IRIS: the smallest geographic administrative unit used in France by the national institute of statistics and economic studies (Insee)

Adiposity rebound age: age at which BMI starts to rise after reaching its lowest point.

Ethics approval

The French Ethics Committees approved the PARIS study (permission nos. 031153, 051289, ID-RCB, 2009-A00824-53, and 2009-12-04 MS2). The procedures used in this study adhere to the tenets of the Declaration of Helsinki.

Ethics approval

The French Ethics Committees approved the PARIS study (permission nos. 031153, 051289, ID-RCB, 2009-A00824-53, and 2009-12-04 MS2). The procedures used in this study adhere to the tenets of the Declaration of Helsinki.

Table 4
Associations between built environment clusters, use of green spaces, exposure to TRAP and cardiometabolic health in adolescents from the PARIS birth cohort.

| | Overweight (ref. No) | | | | BMI trajectories (ref. Low stable BMI) | | | | Cardiometabolic risk profile (ref. Healthy profile) | | | | | | | | | |
|------------------------------------|-------------------------|-----------|-------------------------|------|--|-------|-----------------------|------------|---|------|-------------------------|-------|--|------------|-----------------------|------|-----------|-------|
| | Continuous increase BMI | | Continuous decrease BMI | | Early increase and slight decrease BMI | | Early high stable BMI | | Continuous increase BMI | | Continuous decrease BMI | | Early increase and slight decrease BMI | | Early high stable BMI | | | |
| | aOR | 95% CI | p | aOR | 95% CI | p | aOR | 95% CI | p | aOR | 95% CI | p | aOR | 95% CI | p | aOR | 95% CI | p |
| At birth | | | | | | | | | | | | | | | | | | |
| Cluster B (ref. A) | 0.56 | 0.19–1.68 | 0.300 | 0.40 | 0.13–1.17 | 0.095 | 0.46 | 0.16–1.34 | 0.157 | 0.79 | 0.27–2.32 | 0.663 | 0.57 | 0.15–2.08 | 0.393 | 0.88 | 0.41–1.89 | 0.751 |
| Cluster C (ref. A) | 0.58 | 0.24–1.38 | 0.217 | 0.79 | 0.27–2.32 | 0.673 | 0.74 | 0.26–2.14 | 0.584 | 1.22 | 0.41–3.58 | 0.718 | 0.65 | 0.18–2.39 | 0.517 | 0.62 | 0.34–1.12 | 0.114 |
| Cluster D (ref. A) | 0.86 | 0.22–3.31 | 0.828 | 1.62 | 0.26–9.92 | 0.603 | 1.81 | 0.30–10.68 | 0.514 | 2.97 | 0.50–17.52 | 0.230 | 4.74 | 0.67–33.44 | 0.118 | 0.88 | 0.33–2.34 | 0.804 |
| NO _x 0–1 year (+IQR) | 1.51 | 1.12–2.02 | 0.006 | 1.65 | 1.01–2.67 | 0.044 | 1.51 | 0.93–2.43 | 0.093 | 1.58 | 0.98–2.54 | 0.060 | 1.79 | 1.05–3.06 | 0.033 | 1.02 | 0.79–1.30 | 0.894 |
| At adolescence | | | | | | | | | | | | | | | | | | |
| Cluster 2 (ref. 1) | 2.16 | 0.78–5.96 | 0.139 | | | | | | | | | | | | | 0.83 | 0.41–1.68 | 0.609 |
| Cluster 3 (ref. 1) | 2.72 | 0.90–8.21 | 0.076 | | | | | | | | | | | | | 1.06 | 0.48–2.33 | 0.894 |
| Cluster 4 (ref. 1) | 1.01 | 0.31–3.33 | 0.987 | | | | | | | | | | | | | 1.09 | 0.51–2.29 | 0.830 |
| Cluster 5 (ref. 1) | 1.35 | 0.22–8.34 | 0.749 | | | | | | | | | | | | | 1.27 | 0.41–3.91 | 0.677 |
| Use of green spaces (vs. no) | 0.44 | 0.21–0.91 | 0.028 | | | | | | | | | | | | | 0.69 | 0.43–1.12 | 0.133 |
| NO _x 14–15 years (+IQR) | 1.11 | 0.63–1.96 | 0.723 | | | | | | | | | | | | | 0.87 | 0.56–1.33 | 0.515 |

aOR: adjusted odds ratio; BMI: body mass index; CI: confidence interval; IQR: interquartile range; NO_x: nitrogen oxides; p: p-value.

IQR: NO_x 0–1 year: 20.1 µg/m³; NO_x 14–15 years: 13.0 µg/m³.

Adjusted for sex, socioeconomic status (SES), parental overweight, early BMI rebound age, mother actively smoking during pregnancy, stressful events during ages 0–2, parent–child relationship stress, time spent in front of screens, extracurricular moderate to vigorous physical activity, moving house during life.

Urban environment characteristics at adolescence not included in the multivariate analysis of BMI trajectories.

Funding sources

This work was supported by the Paris Municipal Department of Social Action, Childhood, and Health (DASES) and the French National Research Agency (ANR) [16-CE36-0007-01]. Léa Lefebvre benefited from a PhD grant funded by the French Agency for Ecological Transition (ADEME) and Université Paris Cité.

CRedit authorship contribution statement

Léa Lefebvre: Formal analysis, Methodology, Visualization, Writing – original draft, Writing – review & editing. **Emmanuel Marion:** Formal analysis, Resources, Writing – review & editing. **Frédérique Prédali:** Formal analysis, Resources, Writing – review & editing. **Malika Viola:** Resources, Writing – review & editing. **Thierry Feuillet:** Writing – review & editing. **Céline Roda:** Conceptualization, Methodology, Supervision, Writing – review & editing. **Isabelle Momas:** Conceptualization, Funding acquisition, Methodology, Supervision, Writing – review & editing.

Declaration of conflicts of interest

The authors have no relevant financial or non-financial interests to disclose.

Acknowledgements

We are grateful to all the children and parents of the PARIS birth cohort who participated in this study. We wish to thank the cohort administrative staff (Chimène Himely, Dominique Viguier, Marianne Bijou) for their involvement in the follow-up of the PARIS cohort. We also thank the administrative staff members (Dr Simone Fiorentino, Dr Nathalie Catajar, Dorothee Hérisson) and medical teams (Dr Karima Hamrene, Dr Thomas Grunemwald and all nurses) from the Paris Health Insurance Center who conducted the health checkups for the PARIS adolescents, and the Réaumur Medical Biology Laboratory for conducting the biological analyses (Dr Karim Didouche, Dr Dorothee Lecocq, Mélanie Chiandotto).

ABBREVIATIONS

| | |
|-----------------|---|
| aHR | adjusted hazard ratio |
| aOR | adjusted odd ratio |
| BMI | body mass index |
| BMIz | body mass index z-score |
| CI | confidence interval |
| DAG | directed acyclic graph |
| FDep | French deprivation index |
| Insee | National institute of statistics and economic studies |
| IQR | interquartile range |
| IRIS | îlots regroupés pour l'information statistique |
| MET | metabolic equivalent of task |
| MetS | metabolic syndrome |
| MVPA | moderate to vigorous physical activity |
| NO ₂ | nitrogen dioxide |
| NO _x | nitrogen oxides |
| p | p-value |
| PARIS | Pollution and Asthma Risk: an Infant Study |
| SES | socioeconomic status |
| TRAP | traffic-related air pollution |
| WHO | World Health Organization |

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.healthplace.2026.103622>.

Data availability

Data will be made available on request.

References

- Alberti, K.G. m. m., Eckel, R.H., Grundy, S.M., et al., 2009. Harmonizing the metabolic syndrome. *Circulation* 120 (16), 1640–1645. <https://doi.org/10.1161/CIRCULATIONAHA.109.192644>.
- Amram, O., Amiri, S., Lutz, R.B., Crowley, A., Monsivais, P., 2020. The association between obesity, socio-economic status, and neighborhood environment: a multi-level analysis of Spokane public schools. *J. Community Health* 45 (1), 41–47. <https://doi.org/10.1007/s10900-019-00714-w>.
- Annerstedt van den Bosch, M., Mudu, P., Uscila, V., et al., 2016. Development of an urban green space indicator and the public health rationale. *Scand. J. Publ. Health* 44 (2), 159–167. <https://doi.org/10.1177/1403494815615444>.
- Barnett, T.A., Ghenadenik, A.E., Van Hulst, A., et al., 2022. Neighborhood built environment typologies and adiposity in children and adolescents. *Int. J. Obes.* 46 (3), 588–596. <https://doi.org/10.1038/s41366-021-01010-1>.
- Bloemsmas, L.D., Gehring, U., Klompmaker, J.O., et al., 2019. Green space, air pollution, traffic noise and cardiometabolic health in adolescents: the PIAMA birth cohort. *Environ. Int.* 131, 104991. <https://doi.org/10.1016/j.envint.2019.104991>.
- Bolton, J.L., Smith, S.H., Huff, N.C., et al., 2012. Prenatal air pollution exposure induces neuroinflammation and predisposes offspring to weight gain in adulthood in a sex-specific manner. *FASEB J.* 26 (11), 4743–4754. <https://doi.org/10.1096/fj.12-210989>.
- Bozkurt, M., 2021. Metropolitan children's physical fitness: the relationship between overweight and obesity prevalence, socioeconomic status, urban green space access, and physical activity. *Urban For. Urban Green.* 64, 127272. <https://doi.org/10.1016/j.ufug.2021.127272>.
- Campbell, M.K., 2016. Biological, environmental, and social influences on childhood obesity. *Pediatr. Res.* 79 (1), 205–211. <https://doi.org/10.1038/pr.2015.208>.
- Chen, L., Gao, D., Ma, T., et al., 2022. Could greenness modify the effects of physical activity and air pollutants on overweight and obesity among children and adolescents? *Sci. Total Environ.* 832, 155117. <https://doi.org/10.1016/j.scitotenv.2022.155117>.
- Clarisse, B., Nikasinovic, L., Poinard, R., Just, J., Momas, I., 2007. The Paris prospective birth cohort study: which design and who participates? *Eur. J. Epidemiol.* 22 (3), 203–210. <https://doi.org/10.1007/s10654-007-9109-2>.
- Daniels, K., Le-Scherban, F., Auchincloss, A.H., et al., 2021. Longitudinal associations of neighborhood environment features with pediatric body mass index. *Health Place* 71, 102656. <https://doi.org/10.1016/j.healthplace.2021.102656>.
- de Albuquerque, F.M., Pessoa, M.C., Filgueiras, M.D.S., et al., 2023a. Neighborhood obesogenic environment and cardiometabolic risk in Brazilian children: the mediation role of the mother's body mass index. *Am. J. Hum. Biol.* 35 (3), e23835. <https://doi.org/10.1002/ajhb.23835>.
- de Albuquerque, F.M., Pessoa, M.C., Filgueiras, M.D.S., et al., 2023b. Obesogenic environment around schools is associated with atherogenic risk in Brazilian children. *Am. J. Hum. Biol.* 35 (4), e23844. <https://doi.org/10.1002/ajhb.23844>.
- de Bont, J., Diaz, Y., de Castro, M., et al., 2021a. Ambient air pollution and the development of overweight and obesity in children: a large longitudinal study. *Int. J. Obes.* 45 (5), 1124–1132. <https://doi.org/10.1038/s41366-021-00783-9>.
- de Bont, J., Hughes, R., Tilling, K., et al., 2020. Early life exposure to air pollution, green spaces and built environment, and body mass index growth trajectories during the first 5 years of life: a large longitudinal study. *Environ Pollut* 266, 115266. <https://doi.org/10.1016/j.envpol.2020.115266>.
- de Bont, J., Márquez, S., Fernández-Barrés, S., et al., 2021b. Urban environment and obesity and weight-related behaviours in primary school children. *Environ. Int.* 155, 106700. <https://doi.org/10.1016/j.envint.2021.106700>.
- Dengel, D.R., Hearst, M.O., Harmon, J.H., Forsyth, A., Lytle, L.A., 2009. Does the built environment relate to the metabolic syndrome in adolescents? *Health Place* 15 (4), 946. <https://doi.org/10.1016/j.healthplace.2009.03.001>.
- do Carmo, AS do, Mendes, L.L., Cardoso, L. de O., Caiiffa, W.T., Santos, L.C.D., 2023. The influence of neighborhood safety and built environment on childhood obesity: isolated and combined effect of contextual factors. *Cad. Saude Publica* 39 (8), e00104822. <https://doi.org/10.1590/0102-311XEN104822>.
- Filgueiras, M.D.S., Pessoa, M.C., Bressan, J., et al., 2024. Obesogenic neighborhood environment is associated with body fat and low-grade inflammation in Brazilian children: could the mother's BMI be a mediating factor? *Public Health Nutr.* 27 (1), e14. <https://doi.org/10.1017/S1368980023002628>.
- Frank, L.D., Sallis, J.F., Saelens, B.E., et al., 2010. The development of a walkability index: application to the neighborhood quality of life study. *Br. J. Sports Med.* 44 (13), 924–933. <https://doi.org/10.1136/bjsm.2009.058701>.
- Friend, A., Craig, L., Turner, S., 2013. The prevalence of metabolic syndrome in children: a systematic review of the literature. *Metab. Syndr. Relat. Disord.* 11 (2), 71–80. <https://doi.org/10.1089/met.2012.0122>.
- Gallotta, M.C., Zimatore, G., Falconi, L., et al., 2022. Influence of geographical area and living setting on children's weight status, motor coordination, and physical activity. *Front. Pediatr.* 9, 794284. <https://doi.org/10.3389/fped.2021.794284>.
- Gupta, N., Goel, K., Shah, P., Misra, A., 2012. Childhood obesity in developing countries: epidemiology, determinants, and prevention. *Endocr. Rev.* 33 (1), 48–70. <https://doi.org/10.1210/er.2010-0028>.
- HaGani, N., Moran, M.R., Caspi, O., Plaut, P., Endevelt, R., Baron-Epel, O., 2019. The relationships between adolescents' obesity and the built environment: are they city dependent? *Int. J. Environ. Res. Publ. Health* 16 (9), 1579. <https://doi.org/10.3390/ijerph16091579>.
- Hartigan, J.A., Wong, M.A., 1979. Algorithm AS 136: a K-Means clustering algorithm. *J. R. Stat. Soc. Ser. C Appl. Stat.* 28 (1), 100–108. <https://doi.org/10.2307/2346830>.
- Hertel, O., Berkowicz, R., 1989. Modelling pollution from traffic in a street canyon. Evaluation of data and model development. National Environmental Research Institute 4–53. <https://doi.org/10.13140/RG.2.1.2251.6326>. Published online.
- Huang, P.L., 2009. A comprehensive definition for metabolic syndrome. *Dis. Model. Mech.* 2 (5–6), 231–237. <https://doi.org/10.1242/dmm.001180>.
- Janhäll, S., 2015. Review on urban vegetation and particle air pollution – deposition and dispersion. *Atmos. Environ.* 105, 130–137. <https://doi.org/10.1016/j.atmosenv.2015.01.052>.
- Kowalski, K., Auerbach, J., Martenies, S.E., et al., 2023. Neighborhood walkability, historical redlining, and childhood obesity in Denver, Colorado. *J. Urban Health* 100 (1), 103–117. <https://doi.org/10.1007/s11524-022-00703-w>.
- Kroke, A., Hahn, S., Buyken, A.E., Liese, A.D., 2006. A comparative evaluation of two different approaches to estimating age at adiposity rebound. *Int. J. Obes.* 30 (2), 261–266. <https://doi.org/10.1038/sj.ijo.0803143>.
- Lefebvre, L., Grunemwald, T., Hamrene, K., Roda, C., Momas, I., 2023. Unsupervised identification of cardiometabolic profiles among adolescents: findings from the PARIS birth cohort study. *Eur. J. Pediatr.* <https://doi.org/10.1007/s00431-023-05311-7>. Published online.
- Lefebvre, L., Nur, R., Grunemwald, T., Hamrene, K., Roda, C., Momas, I., 2025. Body mass index trajectories from birth to adolescence and associated factors in the PARIS cohort. *Acta Paediatr.* <https://doi.org/10.1111/apa.17570>. Published online.
- Lozano, P.M., Bobb, J.F., Kapos, F.P., et al., 2024. Residential density is associated with BMI trajectories in children and adolescents: findings from the moving to health study. *AJPM Focus* 3 (3), 100225. <https://doi.org/10.1016/j.focus.2024.100225>.
- Melo, J., Ribeiro, A.I., Aznar, S., Pizarro, A., Santos, M.P., 2021. Urban green spaces, greenness exposure and species richness in residential environments and relations with physical activity and BMI in Portuguese adolescents. *Int. J. Environ. Res. Publ. Health* 18 (12), 6588. <https://doi.org/10.3390/ijerph18126588>.
- Molina-García, J., Menescardi, C., Estevan, I., Queralt, A., 2021. Associations between park and playground availability and proximity and children's physical activity and body mass index: the BEACH study. *Int. J. Environ. Res. Publ. Health* 19 (1), 250. <https://doi.org/10.3390/ijerph19010250>.
- Morgan, Hughey S., Kaczynski, A.T., Child, S., Moore, J.B., Porter, D., Hibbert, J., 2017. Green and lean: is neighborhood park and playground availability associated with youth obesity? Variations by gender, socioeconomic status, and race/ethnicity. *Prev. Med.* 95, S101–S108. <https://doi.org/10.1016/j.ypmed.2016.11.024>.
- Neshteruk, C.D., Chandrashekar, S., Armstrong, S.C., Skinner, A.C., Delarosa, J., D'Agostino, E.M., 2023. The longitudinal association between neighbourhood and cardiovascular risk factors among youth receiving obesity treatment. *Pediatr. Obes* 18 (12), e13080. <https://doi.org/10.1111/ijpo.13080>.
- Nevill, A.M., Reuter, C.P., Brand, C., et al., 2021. Choose where you live carefully: built environment differences in children's cardiorespiratory fitness and cardiometabolic risk. *Sports (Basel)* 9 (2), 31. <https://doi.org/10.3390/sports9020031>.
- Pereira, M., Nogueira, H., Padez, C., 2019. The role of urban design in childhood obesity: a case study in Lisbon, Portugal. *Am. J. Hum. Biol.* 31 (3), e23220. <https://doi.org/10.1002/ajhb.23220>.
- Poulain, T., Sobek, C., Ludwig, J., et al., 2020. Associations of green spaces and streets in the living environment with outdoor activity, media use, overweight/obesity and emotional wellbeing in children and adolescents. *Int. J. Environ. Res. Publ. Health* 17 (17), 6321. <https://doi.org/10.3390/ijerph17176321>.
- Prédali, F., Marion, E., 2022. Les territoires de la marche en Île-de-France. L'Institut Paris Region. <https://www.institutparisregion.fr/nos-travaux/publications/les-territoires-de-la-marche-en-ile-de-france/>. (Accessed 17 June 2024).
- Puttaswamy, D., Ghosh, S., Kuriyan, R., 2023. Neighborhood walkability index and its association with indices of childhood obesity in Bengaluru, Karnataka. *Indian Pediatr.* 60 (1), 113–118.
- Rajagopalan, S., Brook, R.D., Salerno, P.R.V.O., et al., 2024. Air pollution exposure and cardiometabolic risk. *Lancet Diabetes Endocrinol.* 12 (3), 196–208. [https://doi.org/10.1016/S2213-8587\(23\)00361-3](https://doi.org/10.1016/S2213-8587(23)00361-3).
- Reis, W.P., Ghamsary, M., Galustian, C., et al., 2020. Childhood obesity: is the built environment more important than the food environment? *Clin. Med. Insights Pediatr.* 14, 1179556520932123. <https://doi.org/10.1177/1179556520932123>.
- Reungoat, P., Chiron, M., Gauvin, S., Le Moullec, Y., Momas, I., 2003. Assessment of exposure to traffic pollution using the ExTra index: study of validation. *Environ. Res.* 93 (1), 67–78. [https://doi.org/10.1016/S0013-9351\(03\)00018-5](https://doi.org/10.1016/S0013-9351(03)00018-5).
- Rey, G., Jougl, E., Fouillet, A., Hémon, D., 2009. Ecological association between a deprivation index and mortality in France over the period 1997 – 2001: variations with spatial scale, degree of urbanicity, age, gender and cause of death. *BMC Public Health* 9 (1), 33. <https://doi.org/10.1186/1471-2458-9-33>.
- Sacré, C., Chiron, M., Flori, J.P., 1995. Elaboration d'un indice d'exposition à la pollution atmosphérique d'origine automobile à l'usage des études épidémiologiques. *Sci. Total Environ.* 169 (1), 63–69. [https://doi.org/10.1016/0048-9697\(95\)04633-C](https://doi.org/10.1016/0048-9697(95)04633-C).
- Simmonds, M., Llewellyn, A., Owen, C.G., Woolacott, N., 2016. Predicting adult obesity from childhood obesity: a systematic review and meta-analysis. *Obes. Rev.* 17 (2), 95–107. <https://doi.org/10.1111/obr.12334>.
- Spence, J.C., Cutumisu, N., Edwards, J., Evans, J., 2008. Influence of neighbourhood design and access to facilities on overweight among preschool children. *Int. J. Pediatr. Obes.* 3 (2), 109–116. <https://doi.org/10.1080/17477160701875007>.
- Stowe, E.W., Hughey, S.M., Hallum, S.H., Kaczynski, A.T., 2019. Associations between walkability and youth obesity: differences by urbanicity. *Child. Obes.* 15 (8), 555–559. <https://doi.org/10.1089/chi.2019.0063>.

- Sun, Q., Yue, P., Deituliis, J.A., et al., 2009. Ambient air pollution exaggerates adipose inflammation and insulin resistance in a mouse model of diet-induced obesity. *Circulation* 119 (4), 538–546. <https://doi.org/10.1161/CIRCULATIONAHA.108.799015>.
- Verdot, C., Torres, M., Salanave, B., Deschamps, V., 2017. *Corpulence Des Enfants Et Des Adultes En France Métropolitaine En 2015. Résultats De L'Étude Esteban Et Évolution Depuis 2006*, pp. 234–241, 13.
- Warembourg, C., Nieuwenhuijsen, M., Ballester, F., et al., 2021. Urban environment during early-life and blood pressure in young children. *Environ. Int.* 146, 106174. <https://doi.org/10.1016/j.envint.2020.106174>.
- Wayas, F.A., Smith, J.A., Lambert, E.V., et al., 2023. Association of perceived neighbourhood walkability with self-reported physical activity and body mass index in South African adolescents. *Int. J. Environ. Res. Publ. Health* 20 (3), 2449. <https://doi.org/10.3390/ijerph20032449>.
- Wei, Y., Zhang, J., Jim, Li, Z., et al., 2016. Chronic exposure to air pollution particles increases the risk of obesity and metabolic syndrome: findings from a natural experiment in Beijing. *FASEB J.* 30 (6), 2115–2122. <https://doi.org/10.1096/fj.201500142>.
- WHO Multicentre Growth Reference Study Group, 2006. Assessment of differences in linear growth among populations in the WHO Multicentre growth reference study. *Acta Paediatr. Suppl.* 450, 56–65. <https://doi.org/10.1111/j.1651-2227.2006.tb02376.x>.
- WHO (World Health Organization), 2021. WHO Discussion Paper: Draft Recommendations for the Prevention and Management of Obesity over the Life Course, Including Potential Targets. Published online.
- WHO (World Health Organization). Santé urbaine. <https://www.who.int/fr/health-topics/urban-health>. (Accessed 17 June 2024).
- Wilding, S., Ziauddeen, N., Smith, D., Roderick, P., Chase, D., Alwan, N.A., 2020. Are environmental area characteristics at birth associated with overweight and obesity in school-aged children? Findings from the SLOPE (studying Lifecourse Obesity PrEdictors) population-based cohort in the south of England. *BMC Med.* 18, 43. <https://doi.org/10.1186/s12916-020-01513-0>.
- Yang, S., Chen, X., Wang, L., et al., 2021. Walkability indices and childhood obesity: a review of epidemiologic evidence. *Obes. Rev.* 22 (Suppl. 1), e13096. <https://doi.org/10.1111/obr.13096>.
- Zheng, J., Zhang, H., Shi, J., et al., 2024. Association of air pollution exposure with overweight or obesity in children and adolescents: a systematic review and meta-analysis. *Sci. Total Environ.* 910, 168589. <https://doi.org/10.1016/j.scitotenv.2023.168589>.
- Zhou, Y., Buck, C., Maier, W., von Lengerke, T., Walter, U., Dreier, M., 2020. Built environment and childhood weight status: a multi-level study using population-based data in the city of Hannover, Germany. *Int. J. Environ. Res. Publ. Health* 17 (8), 2694. <https://doi.org/10.3390/ijerph17082694>.