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Prospective associations between neighborhood features and body mass index in Montreal adolescents.

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ABSTRACT

Purpose: To investigate the association between the neighborhood built environment and trajectories of body mass index (BMI) in youth.
Methods: Data were collected in a prospective study of 1293 adolescents in Montreal. Built environment variables were obtained from public databases for road networks, land use, and the Canadian Census. Anthropometric data were collected when participants were ages 12.5, 15 and 17 years. We undertook hierarchical cluster analysis to identify contrasting neighborhood types based on features of the built environment (e.g., vegetation, population density, walkability). Associations between neighborhood type and trajectories of BMI z-score (BMIz) were estimated using multivariable linear mixed regression analyses, stratified by sex.
Results: We identified three neighborhood types: *Urban*, *Suburban*, and *Village*. In contrast to the *Urban* type, the *Suburban* type was characterized by more vegetation, few services and low population density. *Village* and *Suburban* types were similar, but the former had greater land use diversity, population density with more parks and a denser food environment. Among girls, living in *Urban* types was associated with decreasing BMIz trajectories. Living in *Village* types was associated with increasing BMIz trajectories. No associations were observed among boys.
Conclusions: Neighborhoods characterized by greater opportunities for active living appear to be less obesogenic, particularly among girls.

Introduction

The prevalence of overweight and obesity is increasing worldwide, with Canadians well above the global average[1]. In 2015, more than one in three Canadian youth (age 5–17 years) with overweight or obesity[2], with little apparent decline in the last decades despite numerous public health strategies[3,4]. Obesity is of particular concern in pediatric populations since children with obesity are at increased risk of cardiometabolic pathologies and adverse psychological and social developmental comorbidities[5–7]. Furthermore, obesity in youth tends to persist into adulthood leading to lower life expectancy[8,9].

The etiology of obesity is complex and multifactorial. Beyond behaviors and genetics, numerous environmental factors are implicated, including neighborhood features[10,11]. Modifiable neighborhood features are appealing intervention targets, in part because of their broad potential reach. However, opportunities to engage in healthful behaviors vary extensively across neighborhoods, and may partly underpin the substantial variation in the prevalence of obesity in North America[12]. Higher prevalence of obesity in children and youth are associated with neighborhood poverty[13–17], lack of neighborhood infrastructure (e.g., parks, green and recreational spaces)[18,19], and low walkability (e.g., low land-use diversity, high volumes of vehicular

Abbreviations: BMI, Body Mass Index; BMIz, Body Mass Index z-score; CMA, Census Metropolitan Area; DMTI, Digital Map Product Company; MVPA, Moderate to Vigorous Physical Activity; NDIT, Nicotine Dependence in Teens; NDVI, Normalized Difference Vegetation Index; PA, Physical Activity; SD, Standard deviation.

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traffic, low residential density)[18,20–22]. Access to supermarkets is generally negatively associated with obesity, while the reverse is observed with the density of fast-food restaurants, convenience stores, and food deserts[23–27]. Overall, few relationships between neighborhood features and obesity-related outcomes emerge consistently across studies, in part because studies differ substantially in study population, geographical location, and type of data collected[20,21,28].

Our aim was to investigate the relationship between neighborhood features and longitudinal patterns of body mass index (BMI) in adolescents. Because residential factors comprise multiple elements that are generally strongly correlated[29–31], we examined them in combination in order to identify "types" of neighborhoods in Montreal rather than examining variables in isolation.

Methods

Participants and data collection

Data were drawn from Nicotine Dependence in Teens (NDIT)[32], a prospective study that investigates the natural course and determinants of nicotine dependence. Between 1999 and 2000, grade 7 students were recruited in a purposive sample of ten secondary schools located in the Montreal Census Metropolitan Area (Montreal CMA). We used a purposive sampling approach to ensure diversity and representativity of schools with respect to language of instruction, population density, and school socio-economic status. Environmental data were drawn from a geographical information system called MEGAPHONE ® (*Montreal Epidemiological and Geographical Analysis of Population Health Outcomes and Neighborhood Effects*) which combines administrative, census and topographic data for Montreal CMA, overlapping 9 secondary schools. Among the 1293 NDIT participants at inception, we excluded 505 individuals without environmental data (n = 380 without postal code and n = 125 with non-available cartographic data), 14 without any anthropometric measures of interest, yielding a final sample of 774 participants. Complete case analysis comprised 709 participants (Figure A).

Data were collected in self-report questionnaires administered at school every three months during the ten-month school year, from grade 7 (age 12–13) to 11 (age 17–18), for a total of 20 data collection cycles during high school. Only data from the first 19 cycles, covering a period of 57 months, were used. Participants provided assent and their parents or guardians provided written informed consent at baseline.

Variables

Weight status

Height and weight were measured when students were aged 12.5, 15 and 17 years on average (cycles 1, 12 and 19, labelled Time 1, 2 and 3, respectively herein [T1, T2, T3]) by trained technicians using standardized methods[33]. Two measures of height to the nearest 0.1 cm and weight to the nearest 0.2 kg were obtained for each participant. If differences greater than 0.5 cm for height and 0.2 kg for weight were observed between the two measures, a third measure was obtained. The average of the two closest measures was recorded. To assess inter-rater reliability, we obtained repeat measures for a systematic subsample of one in 10 students. Inter-rater reliability (split-half coefficient) of 0.99 was observed for height and weight. BMI was calculated as weight (kg) divided by height squared (m^2). BMI z-scores (BMIz) were calculated using age and sex-specific reference data from Centers for Disease Control and Prevention growth tables[34]. Weight status was described using a categorical variable based on established thresholds: underweight/normal (<1.04), overweight (1.04 to 1.64), and obesity (≥ 1.64).

Neighborhood definition and environmental variables

Residential neighborhoods were defined by the 750 m road network buffer surrounding the centroid of the area corresponding to the postal code of participants' place of residence at cycle 13. The 2010 road network data were prepared by DMTI inc., a cartographic products company. Indicators of the physical, food and socio-demographic environment were generated for each neighborhood.

Physical environment

The total length of streets and roads (km), the number of intersections with at least three branches, and land use diversity were calculated using 2002 DMTI data. Land use diversity, considering up to 7 categories (e.g., leisure, residential, commercial, industrial) was represented by a continuous indicator ranging from 0 (low) to 1 (high)[35]. The normalized difference vegetation index, calculated from the 2001 DMTI data, ranges from − 1 (low) to + 1 (high) and reflects the level of vegetation abundance based on satellite images. A variable describing the number of parks (partially or completely inside the participants' neighborhood) was extracted from 2002 census agglomerations and was divided into tertiles for analysis ([0,1], 2 and >2). Since neighborhood size was standardized, number of intersections and parks are more informative than density measures.

Food environment

The number of "healthy" (e.g., hypermarkets, supermarkets, grocery stores, fruit stores) and "unhealthy" (e.g., fast-food restaurants, convenience stores) stores in the neighborhood was extracted using data from 2003 DMTI and categorized into tertiles. Absolute numbers of stores were more discriminating than ratios of what? in our study.

Socio-demographic indicators

Population density (inhab/km^2) was retrieved from the 2001 Census for each dissemination area (the smallest area for which census data are published). The percentage of single-parent families, university graduates (among those ≥20 years), and unemployed people were also retrieved for each dissemination area. Area-level poverty was defined as the percentage of residents aged ≥ 15 years living below the low-income cut-off.

Other measures

Other covariates collected at baseline (cycle 1) included sex, age, country of birth (Canada, other), single-parent family (yes, no), smoking status (ever smoked: yes, no), past month alcohol consumption (yes, no) and language(s) spoken at home (English, French, both or other). Parental education was categorized according to the highest level of education of either parent (≤ high school, vocational, ≥ university). Physical activity (PA) was defined as the number of episodes of moderate to vigorous PA (MVPA) of ≥ five minutes during the past week in which participants engaged, selected from a list of 30 activities commonly engaged in by young people in Montreal; this question was adapted from the Weekly Activity Checklist[36]. The average of the PA measures at baseline and in the following three cycles completed in one school year was used to take seasonal variations in PA into account.

Statistical analysis

Descriptive analysis

Baseline characteristics of included and excluded participants were described (frequencies for categorical variables, means (standard deviation) for normally distributed continuous variables and medians (interquartile range) otherwise).

Estimation of neighborhood type

We used cluster analysis to identify distinct neighborhood types. Guided by the literature, and after removing observations with many missing values and with little or no variation, five variables were retained for the cluster analysis: intersection number, total length of roads, population density, land-use diversity and vegetation index.

Distinct neighborhood types with high intra-class similarity and low inter-class similarity of variables were created using ascending hierarchical classification with Ward's method. An algorithm that aggregates the most similar neighborhoods based on Euclidean distances was used [37]. The procedure was repeated until all neighborhoods were aggregated into a single group. The optimal number of clusters was obtained by examining all possible combinations of clusters, distance measurements, and clustering methods using the "NbClust" package[38].

BMIz slope by neighborhood type

Slopes were estimated to describe BMIz evolution as participants aged. We examined the association between neighborhood type and BMIz evolution in multivariable mixed linear regression models stratified by sex, as sex differences in BMIz by neighborhood type are commonly reported[13,16,23,39,40]. BMIz slopes between girls and boys were statistically significantly different across the clusters (P-global interaction = 0.048). Models were adjusted for country of birth (proxy for ethnicity), highest level of parental education, and percentage of persons living below the low-income threshold in the neighborhood at baseline. The use of mixed models allowed us to retain participants with at least one BMIz measure (albeit with no missing data for all other covariates). Because only 8 % of participants were excluded due to missing data, the main analysis was performed using a case-complete approach. All estimated models used an unstructured variance-covariance matrix and included a random intercept to account for inter-participant variability and an interaction term with time. We allowed for both fixed and random slopes, retaining the least complicated if the addition of a random slope was not necessary based on fit indices. Time (in years) was defined as the interval between measurements and baseline divided by five. Thus, model parameters are interpreted for a 5-year increase/decrease in BMIz. Model adequacy was verified using a spline function, testing for the linearity of continuous variables. Residuals were normally distributed with stable variance over time. We estimated differences in mean BMIz at baseline for each pairwise contrast. We plotted BMIz slopes for each neighborhood type and estimated differences in slopes. Associations and interactions were tested by maximum likelihood ratio or Wald tests.

In sensitivity analyses, missing data on covariates were imputed using Multiple Imputation Chained Equation (n = 30). We also restricted analyses to participants with confirmed "non-residential moving" status.

All analyses were conducted with R, version 4.0.3.

Results

The sample included 774 students (367 boys and 407 girls (53 %)) (Figure A). The median years of follow-up was 4.3 (Q1-Q3 = 4.1–4.4 for boys and 4.2–4.4 for girls). Attrition from T1 to T3 was ~10 %. Approximately 9 % of boys and 6 % of girls changed address during the 5-year follow-up period (Table 1).

Participants were ages 12.5, 15 and 17 years on average at T1, T2 and T3, respectively. More than 90 % were born in Canada, and 60 % were English-speaking at home; the remainder were French (20 %), both English and French (10 %), or other (10 %). Most participants had at least one parent with a university education. Mean BMIz was higher in boys than girls. On average, it increased at T2 and decreased at T3, more markedly in boys than girls. The proportion of participants who had overweight or obesity decreased during follow-up in boys (26 %, 21 % and 18 % at T1, T2 and T3) and in girls (21 %, 18 % and 14 % at T1, T2 and T3). Boys were more physically active than girls on average (median number of MVPA episodes in the past week) = 17 (11– 26) for boys and 12 ((7– 20)for girls) (Table 1).

Cluster analyses

Three neighborhood types were identified using cluster analysis; these were labelled "*Suburban*", "*Urban*" and "*Village*" types (Table 2).

Table 1
Participant Characteristics by Sex (n = 774). NDIT Study, Montreal, Canada. 1999 2005.

	Boys		Girls	
	n (%)	Mean (SD)	n (%)	Mean (SD)
Age (years)				
Time 1	367 (100)	12.7 (0.4)	407 (100)	12.6 (0.4)
Time 2	355 (96.7)	15.2 (0.4)	393 (96.6)	15.1 (0.4)
Time 3	327 (89.1)	17.0 (0.4)	361 (88.7)	16.9 (0.3)
Language spoken at home				
English	226 (61.6)		243 (59.7)	
French	68 (18.5)		90 (22.1)	
French and English	38 (10.4)		41 (10.1)	
Other	35 (9.5)		33 (8.1)	
Single parent family, yes	23 (6.6)		43 (11.1)	
Parent education[a]				
≤ High school	44 (13.3)		74 (19.6)	
Collegial/Vocational	68 (20.5)		76 (20.1)	
≥ University	219 (66.2)		228 (60.3)	
Changed residence				
No	235 (64.0)		295 (72.5)	
Yes	32 (8.7)		24 (5.9)	
Do not know	100 (27.2)		88 (21.6)	
BMIz				
Time 1	344 (93.7)	0.31 (1.0)	380 (93.4)	0.16 (1.0)
Time 2	350 (95.4)	0.34 (0.9)	381 (93.6)	0.22 (0.8)
Time 3	322 (87.7)	0.25 (0.9)	348 (85.5)	0.13 (0.8)
Weight status, Time 1				
Normal	256 (74.4)		299 (78.7)	
Overweight	53 (15.4)		49 (12.9)	
Obesity	35 (10.2)		32 (8.4)	
Weight status, Time 2				
Normal	278 (79.4)		312 (81.9)	
Overweight	42 (12.0)		47 (12.3)	
Obesity	30 (8.6)		22 (5.8)	
Weight status, Time 3				
Normal	263 (81.7)		300 (86.2)	
Overweight	31 (9.6)		35 (10.1)	
Obesity	28 (8.7)		13 (3.7)	
Number of PA episodes[b,c]	364 (99.2)	16.5 (10.0 – 26.4)	396 (97.3)	11.5 (7.0 – 19.8)
Ever smoked, yes	80 (22.9)		96 (24.7)	
Alcohol consumption[d]**, yes**	145 (42.2)		141 (36.5)	

Abbreviation: BMIz: body mass index z-score; PA, physical activity; SD: standard deviations

[a]highest level between both parents

[b]average of the first year of monitoring moderate and vigorous physical activity episodes (collected during the first four cycles)

[c]median (interquartile range)

[d]in the month before the cycle

Compared to the other types, the *Suburban* type included neighborhoods with lower walkability, lower population density, fewer parks, fewer food sources of any kind, and more vegetation. The *Urban* type was characterized by relatively greater walkability, higher population density, more parks, more food sources, less vegetation and higher area disadvantage than non-Urban types. The *Village* type was similar to the *Suburban* type albeit with greater land use diversity, population density with more parks and a denser food environment.

The distribution of participants by Montreal neighborhood type is mapped in Fig. 1. There were 288, 271 and 229 participants in the *Suburban*, *Urban* and *Village* types, respectively. Boys were more physically active in the *Suburban* type than in other types. Mean BMIz with confidence intervals over time are illustrated across sex and neighborhood type (Fig. 2). The estimated proportion of participants with obesity or overweight was lower among boys in the *Suburban* type at T1 compared to the other two types, whereas for girls, proportions were similar across the three neighborhood types (Table 3).

Table 2
Environmental Characteristics According to Neighborhood Type (n = 788). NDIT Study, Montreal, Canada. 1999–2005.

	Suburban n = 288	Urban n = 271	Village n = 229
NDVI*, median (Q1-Q3)	0.07 (0.02 – 0.14)	-0.10 (−0.13 – −0.06)	0.02 (−0.07 – 0.06)
Land use diversity*, median (Q1-Q3)	0.13 (0.05 – 0.21)	0.37 (0.27 – 0.49)	0.39 (0.32 – 0.43)
Number of parks, n (%)			
[0; 1]	187 (64.9)	86 (31.7)	126 (55.0)
2	65 (22.6)	94 (34.7)	60 (26.2)
> 2	36 (12.5)	91 (33.6)	43 (18.8)
Total length of roads (km)*, mean (SD)	8.06 (2.8)	15.17 (2.8)	7.84 (2.5)
Number of intersections*, median (Q1-Q3)	36 (27 – 47)	67 (57 – 80)	36 (27 – 45)
Population density (inhab/km^2)*, median (Q1-Q3)	2413 (1499 – 3330)	7560 (6144 – 9680)	2651 (2014 – 3448)
Number of healthy stores†, n (%)			
0	211 (73.3)	9 (3.3)	99 (43.2)
1 or 2	57 (19.8)	21 (7.7)	93 (40.6)
> 2	20 (6.9)	241 (88.9)	37 (16.2)
Number of unhealthy stores‡, n (%)			
0	227 (78.8)	7 (2.6)	119 (52.0)
1 or 2	46 (16.0)	30 (11.1)	81 (35.4)
> 2	15 (5.2)	234 (86.3)	29 (12.7)
Persons age ≥ 15 living below the low-income cut-off (%), median (Q1-Q3)	7.6 (4.7 – 13.8)	28.9 (23.7 – 34.0)	9.8 (6.6 – 16.6)
Unemployment rate (%), median (Q1-Q3)	4.8 (3.6 – 6.1)	9.4 (7.8 – 11.5)	5.5 (4.1 – 7.2)
Persons age ≥ 20 with a university degree (%), median (Q1-Q3)	30.5 (25.6 – 39.5)	21.5 (12.2 – 30.3)	29.2 (21.8 – 35.7)
Single parent family (%), median (Q1-Q3)	10.9 (7.8 – 16.0)	21.7 (18.5 – 24.2)	13.0 (9.2 – 17.9)

Abbreviations: NDVI: normalized difference vegetation index; Q1-Q3: interquartile range; SD: standard deviations
* variables used in cluster analysis to define neighborhood type
† includes hypermarkets, supermarkets, grocery stores and fruits store
‡ includes convenience stores and fast-food restaurants

Linear mixed regression

After adjusting for parental education, country of birth, and number of persons living below the low-income cut-off, there was no difference in average BMIz across neighborhood types at T1 in boys nor in girls (Table 4).

In boys, there were no differences in BMIz slopes over time across neighborhood types ($P = 0.13$, Table 4). In girls, the average BMIz in the *Suburban* and *Village* types increased by 0.09 and 0.19 units over five years, respectively. It decreased by 0.16 units in the *Urban* type (Table 4). More precisely, the BMIz differed over time for the *Urban* type compared to the other two neighborhood types (difference with *Suburban* type β = −0.25, 95 % confidence interval (95 %CI): − 0.39, − 0.10; difference with the *Village* type β = 0.35, 95 %CI: 0.21, 0.49), but not between *Village* and *Suburban* types (β = 0.10, 95 %CI: −0.05, 0.25). The variance of the random intercept was 0.77 for boys and 0.70 for girls.

Results remained unchanged after further adjustment for smoking, alcohol consumption, number of weekly MVPA episodes, and/or age at T1, language spoken at home as well as when slopes were included either as fixed or random effects. In the interest of parsimony, we retained models with fixed slopes, indicating that the effect of time was assumed to be identical for all participants (Figures B). Results using imputed data (367 boys; 407 girls) were similar to complete-case analyses. Finally, restricting analyses to participants who did not change residence (212 boys and 280 girls) did not impact our findings substantively (Tables A).

Discussion

We compared BMIz evolution in adolescents between neighborhood types identified based on characteristics of the physical environment and population density. After adjusting for covariates, no meaningful association was observed between neighborhood type and BMIz evolution in boys. On average, girls living in an *Urban* neighborhood experienced a decrease in BMIz over time, whereas those living in a *Village* neighborhood experienced an increase in BMIz. No change in BMIz over time was observed for the *Suburban* neighborhood type.

Urban neighborhoods may be more conducive to healthier lifestyles for adolescents. The greater density of roads and more numerous intersections could permit more direct paths and greater mobility for active travel and journeys to more destinations, providing more opportunities for PA. Number and diversity of food sources could also be factors influencing health-related behaviors.

Consistent with other studies[18,41], our results suggest that living in a neighborhood that promotes walking and with multiple and diverse services available is associated with decreasing BMIz over time in girls. More walkable, more densely populated neighborhoods, or more spaces for outdoor activities tend to be favorably associated with BMI and obesity [18,30], while greater supermarket access and food deserts are adversely associated with BMI [23,25,27]. Similar to studies supporting a protective association between high population density and obesity [18,22], we observed an inverse association among girls. Greater population density correlates with more diversified land use, programs and services available to residents, all of which could promote PA[42].

In contrast to our results, higher vegetation density has been associated with decreases in BMI and the prevalence of obesity[28,29]. The vegetation index in the *Suburban* cluster appeared to reflect fields or agricultural land rather than parks and public open spaces, which are more conducive to PA. Still, comparisons across studies are not straightforward, given substantial heterogeneity in methods regarding populations studied, geographic location, and the nature and source of data.

Our data suggest that girls may be more vulnerable to environmental features and/or opportunities than boys; similar findings regarding gender have been reported previously[13]. Another study reported that moving to a lower-poverty neighborhood resulted in improvements in mental and physical health among girls but not boys, suggesting a moderating effect of gender in the relationship between neighborhood environment and obesity risk[43]. This phenomenon may reflect gender norms related to parental concerns about neighborhood safety, or to differences in community infrastructures and investments. This explanation has been proposed in a study using electronic medical records from Houston, Texas[44]. The authors reported that girls were more vulnerable to neighborhood characteristics than boys and posited that girls may be faced with greater restrictions to outdoor activities when living in disadvantaged areas due to parental perceptions of threats to personal safety[44].

Results should be interpreted with caution due to the limitations of this study. The physical environment constructs are largely data-driven and should be explored in other populations. However, this method is a well-established approach and the components that emerged have reasonable face validity. Next, attrition bias may be present; however, it is unlikely to be associated with neighborhood cluster type. Moreover, while excluded participants had slightly higher BMIz (Tables B), this difference was not clinically meaningful. Though internally robust, generalizability to other populations is unknown; additional research is needed in more diverse populations and settings while ensuring sufficient numbers for sex-specific analyses[30,31]. A potential selection bias related to families choosing neighborhoods could exist. However, children are arguably less involved in such decisions; parents may be

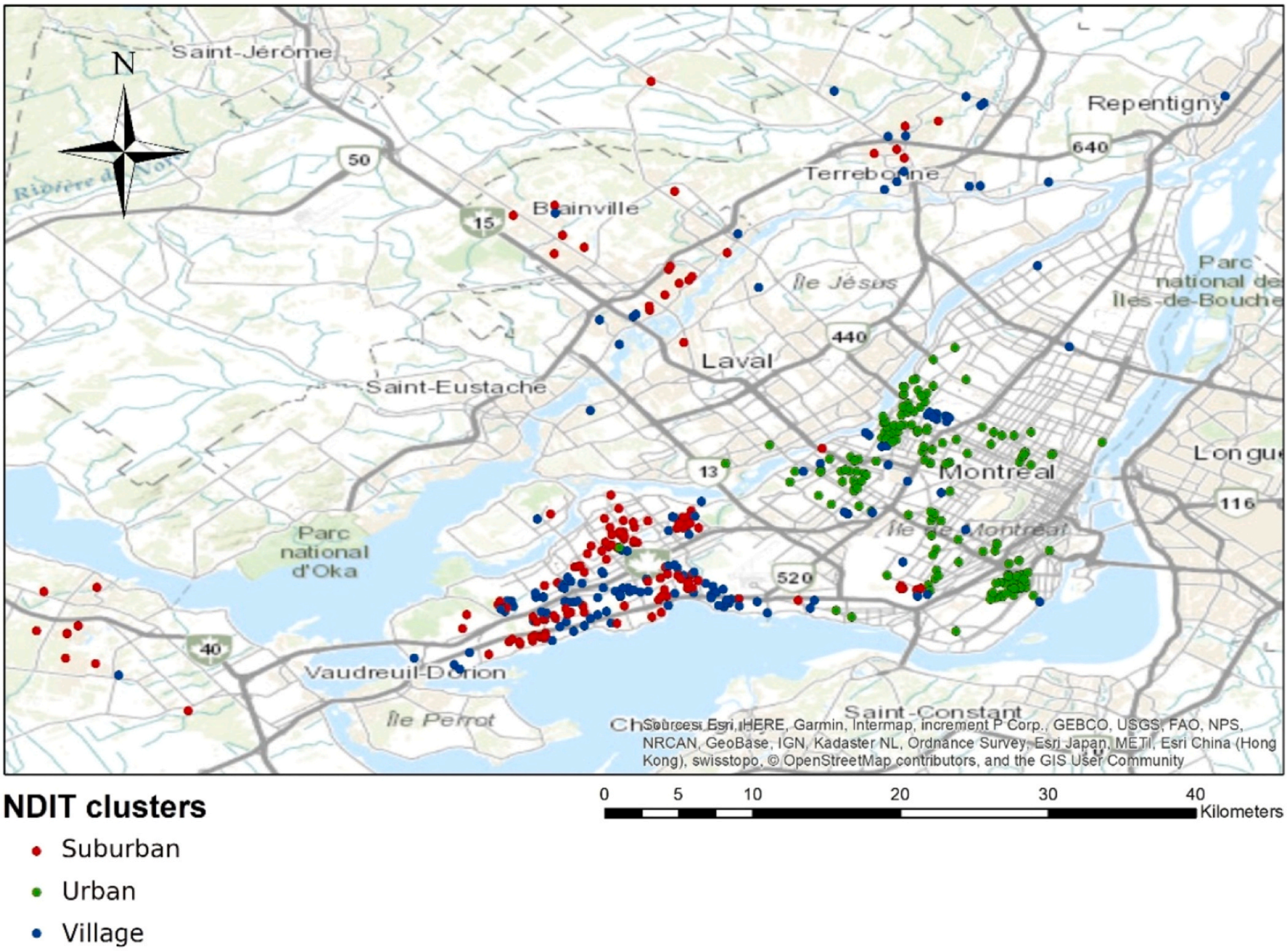

Fig. 1. Location of Participants by Neighborhood Type in Montreal, Canada.

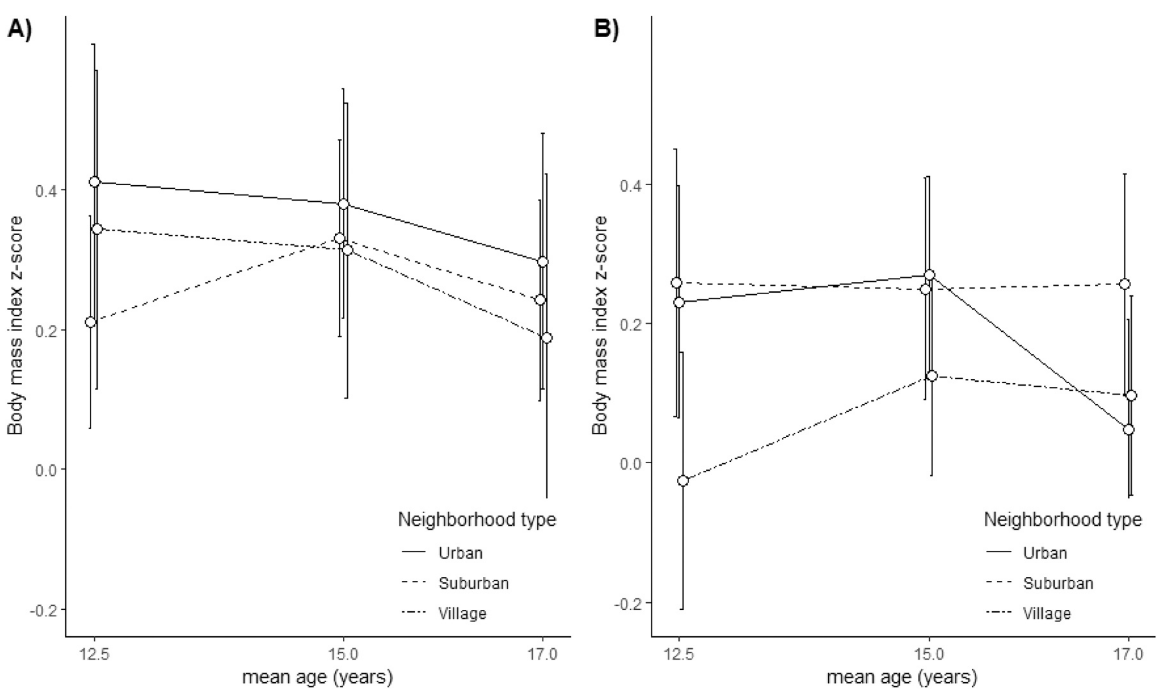

Fig. 2. Crude Z-scores of Mean Body Mass Index (with 95 % Confidence Intervals) Over Time in Boys (A) and Girls (B). NDIT Study, Montreal, Canada. 1999–2005.

Table 3
Participant Characteristics by Sex and Neighborhood Type (n = 709). NDIT Study, Montreal, Canada. 1999–2005.

	Boys			Girls		
	Suburban n = 138	Urban n = 105	Village n = 88	Suburban n = 117	Urban n = 142	Village n = 119
Age (years), mean (SD)						
Time 1	12.7 (0.4)	12.7 (0.5)	12.7 (0.4)	12.6 (0.3)	12.6 (0.4)	12.6 (0.4)
Time 2	15.1 (0.4)	15.2 (0.5)	15.2 (0.4)	15.1 (0.3)	15.1 (0.4)	15.1 (0.4)
Time 3	17.0 (0.4)	17.0 (0.4)	17.0 (0.4)	16.9 (0.3)	16.9 (0.4)	16.9 (0.3)
Language spoken at home, n (%)						
English	112 (81.2)	32 (30.5)	63 (71.6)	96 (82.1)	51 (35.9)	76 (63.9)
French	5 (3.6)	49 (46.7)	9 (10.2)	3 (2.6)	67 (47.2)	15 (12.6)
Both	17 (12.3)	8 (7.6)	8 (9.1)	14 (12.0)	7 (4.9)	19 (16.0)
Other	4 (2.9)	16 (15.2)	8 (9.1)	4 (3.4)	17 (12.0)	9 (7.6)
Single parent family, yes, n (%)	6 (4.8)	8 (7.7)	7 (8.4)	11 (9.9)	19 (14.0)	9 (8.0)
Parent education* (%)						
≤ high school	16 (11.6)	16 (15.2)	12 (13.6)	19 (16.2)	28 (19.7)	27 (22.7)
Collegial/Vocational	26 (18.8)	25 (23.8)	17 (19.3)	19 (16.2)	32 (22.5)	25 (21.0)
≥ university	96 (69.6)	64 (61.0)	59 (67.0)	79 (67.5)	82 (57.7)	67 (56.3)
Changed residence, n (%)						
No	95 (68.8)	58 (55.2)	59 (67.0)	84 (71.8)	97 (68.3)	99 (83.2)
Yes	11 (8.0)	11 (10.5)	7 (8.0)	9 (7.7)	5 (3.5)	7 (5.9)
Do not know	32 (23.2)	36 (34.3)	22 (25.0)	24 (20.5)	40 (28.2)	13 (10.9)
BMIz, mean (SD)						
Time 1	0.27 (0.9)	0.46 (1.0)	0.34 (1.1)	0.25 (1.0)	0.22 (1.0)	-0.01 (1.0)
Time 2	0.39 (0.9)	0.41 (0.9)	0.31 (1.0)	0.22 (0.8)	0.25 (0.9)	0.15 (0.8)
Time 3	0.29 (0.9)	0.31 (1.0)	0.14 (1.0)	0.26 (0.8)	0.02 (0.9)	0.12 (0.8)
Weight status, Time 1, n (%)						
Normal	102 (77.9)	69 (69.7)	56 (69.1)	86 (77.5)	105 (77.2)	88 (82.2)
Overweight	21 (16.0)	16 (16.2)	14 (17.3)	16 (14.4)	16 (11.8)	14 (13.1)
Obesity	8 (6.1)	14 (14.1)	11 (13.6)	9 (8.1)	15 (11.0)	5 (4.7)
Weight status, Time 2, n (%)						
Normal	104 (79.4)	78 (77.2)	65 (77.4)	85 (81.0)	107 (79.3)	101 (87.1)
Overweight	13 (9.9)	13 (12.9)	14 (16.7)	15 (14.3)	18 (13.3)	11 (9.5)
Obesity	14 (10.7)	10 (9.9)	5 (6.0)	5 (4.8)	10 (7.4)	4 (3.4)
Weight status, Time 3, n (%)						
Normal	102 (80.3)	70 (80.5)	63 (81.8)	82 (82.0)	105 (87.5)	95 (88.8)
Overweight	15 (11.8)	7 (8.0)	8 (10.4)	15 (15.0)	9 (7.5)	8 (7.5)
Obesity	10 (7.9)	10 (11.5)	6 (7.8)	3 (3.0)	6 (5.0)	4 (3.7)
Number of PA episodes†, median (Q1-Q3)	19.3 (12.9 – 31.0)	15.2 (8.5 – 24.0)	15.5 (9.4 – 24.1)	12.3 (7.9 – 22.8)	9.8 (5.2 – 14.8)	12.7 (8.2 – 22.1)
Already smoked, yes, n (%)	26 (20.5)	24 (23.1)	18 (21.4)	26 (23.2)	41 (29.7)	22 (19.8)
Alcohol consumption‡, yes, n (%)	53 (42.4)	43 (42.6)	34 (41.0)	45 (40.2)	52 (38.2)	33 (30.0)

Abbreviations: BMIz: body mass index z-score; PA, physical activity; Q1-Q3: interquartile range; SD: standard deviation
* highest level between both parents
† average of the first year of monitoring moderate and vigorous physical activity episodes (collected during the first 4 cycles)
‡ in the month before the cycle

Table 4
Estimated Mean Differences in Body Mass Index Z-scores (BMIz) at Baseline and Slopes by Neighborhood Type. Result of Multivariable Mixed Linear Regression. NDIT Study, Montreal, Canada. 1999–2005.

	Boys n = 331						Girls n = 378					
	Unadjusted model			Adjusted model‡			Unadjusted model			Adjusted model‡		
Neighborhoods type	$\hat{\beta}$	95 % CI	*P*	$\hat{\beta}$	95 % CI	*P*	$\hat{\beta}$	95 % CI	*P*	$\hat{\beta}$	95 % CI	*P*
Pairwise contrasts at baseline*			0.36			0.31			0.04			0.10
Urban *(Reference: Suburban)*	0.17	-0.06, 0.39		0.26	-0.09, 0.62		0.02	-0.20, 0.23		-0.03	-0.34, 0.27	
Village *(Reference: Suburban)*	0.08	-0.16, 0.32		0.02	-0.23, 0.28		-0.24	-0.47, − 0.02		-0.23	-0.47, − 0.001	
Village *(Reference: Urban)*	-0.09	-0.35, 0.17		-0.24	-0.59, 0.11		-0.26	-0.47, − 0.04		-0.20	-0.49, 0.08	
Slope†			0.23			0.13			< 0.0001			< 0.0001
Suburb	0.05	-0.04, 0.15		0.05	-0.05, 0.15		0.09	-0.01, 0.20		0.09	-0.02, 0.20	
Urban	-0.07	-0.18, 0.04		-0.11	-0.23, 0.01		-0.15	**-0.24, − 0.06**		-0.16	**-0.25, − 0.06**	
Village	-0.04	-0.17, 0.09		-0.04	-0.17, 0.09		0.19	**0.08, 0.29**		0.19	**0.09, 0.30**	

Abbreviations: 95 % CI = 95 % confidence interval, *P*: p-value
* estimated mean difference in BMIz at baseline between neighborhood types
† mean increase/decrease in BMIz for a 5-year unit
‡ adjusted for parent education, country of birth and percentage of persons aged ≥ 15 living below the low-income cut-off in the neighborhood, and number of PA episodes

selecting specific areas for a range of reasons including schools, services, and infrastructure. We were unable to apply a nested structure within schools (non-convergence of models), which would have allowed for greater specificity in the sampling strategy. However, adjusting for school did not substantially change the magnitude nor the precision of the findings. Environmental variables were collected once between 2001 and 2003 while neighborhoods were defined based on the 2010 road network buffers. However, road network (i.e., road length, number of intersections) transformations over this timeframe were minor (<4 %), and the potential bias was likely negligible. Approximately 7 % of participants moved during the follow-up, potentially leading to misclassification error of the exposure. However, this proportion is relatively low, and sensitivity analyses yielded similar results, albeit with a loss of precision. Finally, despite the fact that several covariates were considered, the presence of bias remains possible, both through unmeasured variables or residual confounding (e.g. crime, perception of safety or noise).

Our study has several strengths. First, our findings are novel given that, of the dozen longitudinal studies identified on this topic [14,15,41,43–51], only one study involved adolescents[51], despite adolescents being major targets for prevention[5,6,8]. Secondly, the use of mixed models allowed for a more sophisticated approach to baseline variations. Our use of cluster analysis was also a reasonable and pragmatic approach that closely mirrors reality by allowing for strong correlations between the environmental factors under study. Finally, NDIT is a well-established, rigorous study that includes standardized and objectively assessed measures[32], and incorporates multiple strategies to minimize loss to follow-up and potential errors (e.g., several visits for the same follow-up, maintaining personalized contacts with participants, use of validated tools).

Conclusion

Our study makes a unique contribution by using a multifactorial, realistic and longitudinal approach, and providing public health authorities with additional support for evidence-based decision-making. Our results suggest disparities in Montreal neighborhoods in terms of access to walking infrastructure and food sources, all of which may be consequential for youth obesity.

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CRediT authorship contribution statement

Jennifer O'Loughlin: Writing – review & editing, Resources, Project administration, Investigation, Data curation. **Anna Smyrnova:** Data curation. **Andraea Van Hulst:** Writing – review & editing, Methodology, Conceptualization. **Tracie Barnett:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Marie-Pierre Sylvestre:** Supervision, Formal analysis. **Clémence Cavaillès:** Writing – original draft, Methodology, Investigation, Formal analysis, Data curation.

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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Data are available upon reasonable request.

Appendix

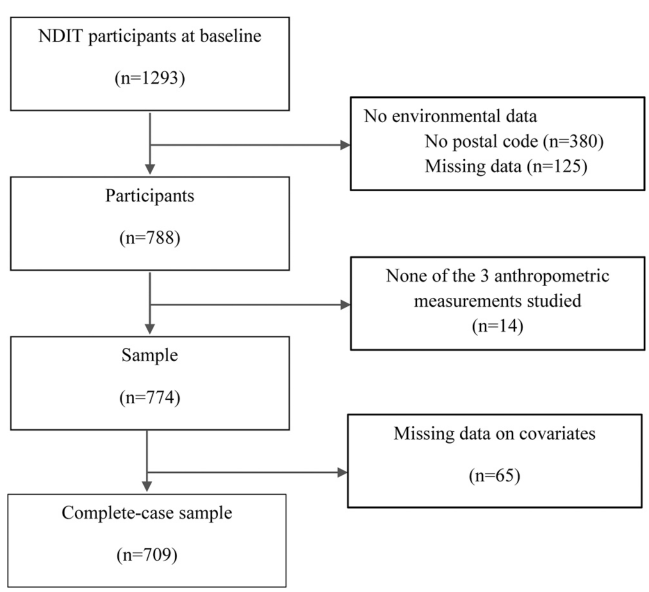

Figure A. Flow chart.

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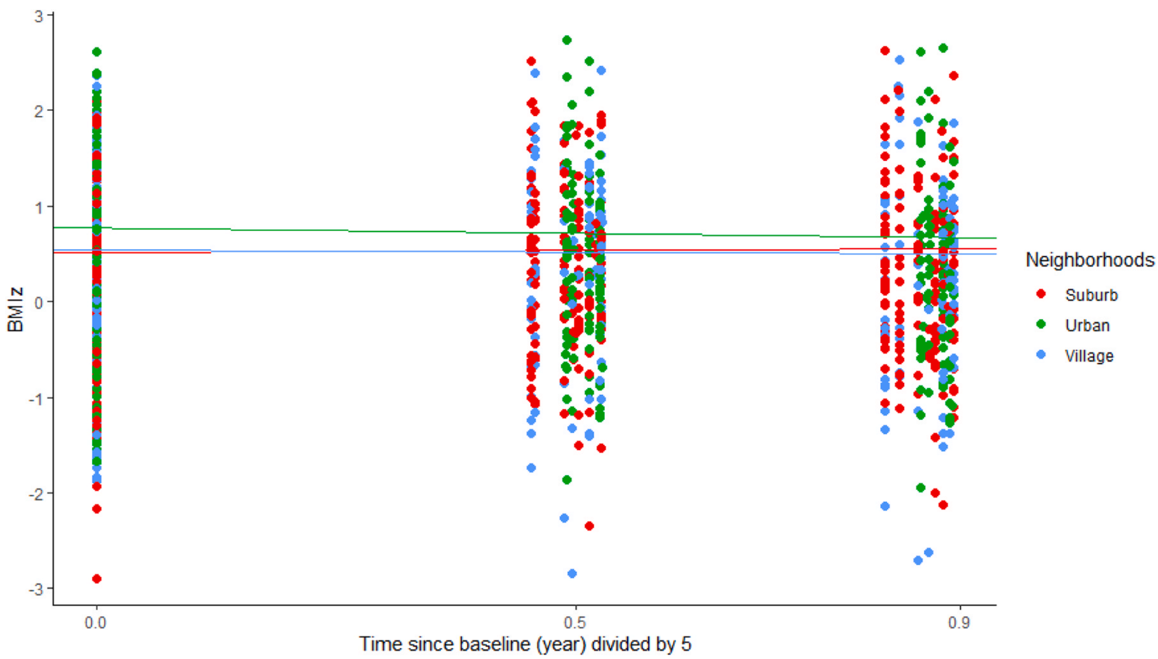

Figure B.1. Mean estimated slopes by neighborhood type in boys.

.

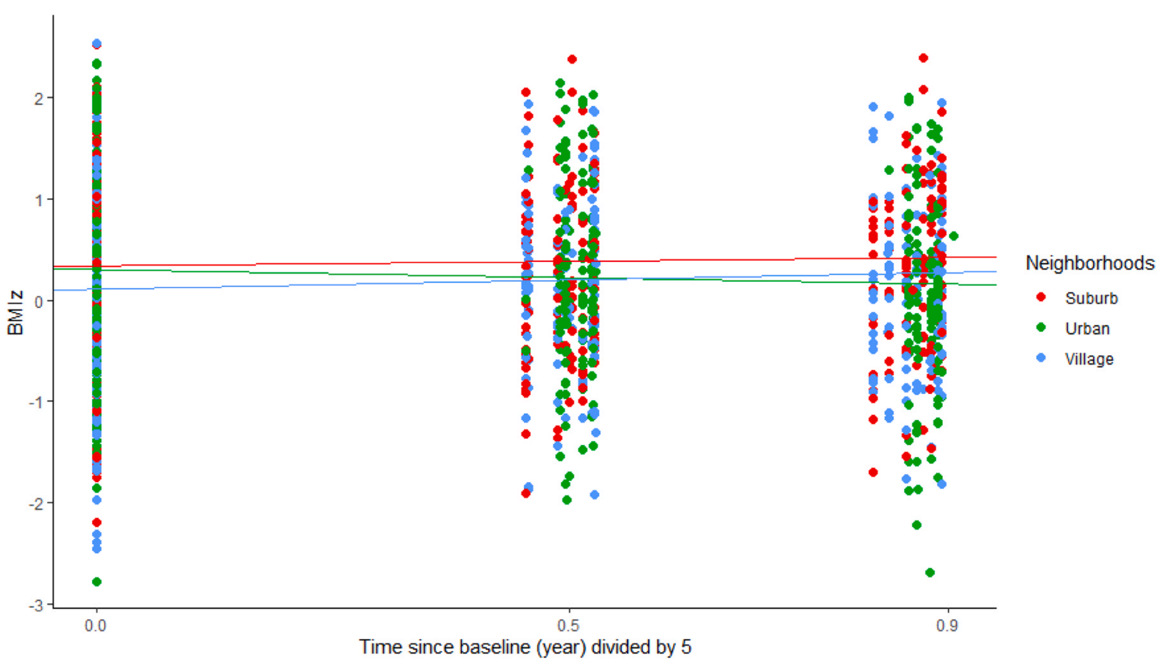

Figure B.2. Mean estimated slopes by neighborhood type in girls.

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Table A.1
Estimated Mean Differences in Body Mass Index Z-scores (BMIz) at Baseline and Slopes by Neighborhood Type. Result of Multivariable Mixed Linear Regression on Imputed Data. NDIT Study, Montreal, Canada. 1999–2005.

	Boys			Girls		
	n = 367			n = 407		
Neighborhoods type	$\hat{\beta}$	95% CI	*P*	$\hat{\beta}$	95% CI	*P*

(*continued on next page*)

Table A.1 (*continued*)

	Boys			Girls		
	n = 367			n = 407		
Pairwise contrasts at baseline[1]			0.24			0.07
Urban *(Reference: Suburban)*	0.27	-0.07, 0.60		-0.04	-0.33, 0.26	
Village *(Reference: Suburban)*	0.09	-0.16, 0.3		-0.27	-0.50, − 0.04	
Village *(Reference: Urban)*	-0.18	-0.52, 0.16		-0.23	-0.51, 0.04	
Slope[2]			0.14			0.001
Suburb	0.05	-0.04, 0.15		0.09	-0.01, 0.20	
Urban	-0.07	-0.18, 0.05		-0.15	-0.24, − 0.06	
Village	-0.04	-0.17, 0.09		0.19	0.08, 0.29	

Abbreviations: 95% CI = 95% confidence interval, *P*: p-value
Adjusted model for parent education, country of birth and percentage of persons aged ≥ 15 living below the low-income cut-off in the neighborhood on complete data
[1]: estimated mean difference in BMIz at baseline across neighborhood
[2]: mean increase/decrease in BMIz for a 5-year unit

Table A.2
Estimated Mean Differences in Body Mass Index Z-scores (BMIz) at Baseline and Slopes by Neighborhood Type. Result of Multivariable Mixed Linear Regression on Complete Cases who did not Move Residence. NDIT Study, Montreal, Canada. 1999–2005.

	Boys			Girls		
	n = 212			n = 280		
Neighborhoods type	$\hat{\beta}$	95% CI	*P*	$\hat{\beta}$	95% CI	*P*
Pairwise contrasts at baseline[1]			0.80			0.51
Urban *(Reference: Suburban)*	0.12	-0.31, 0.55		-0.02	-0.37, 0.33	
Village *(Reference: Suburban)*	-0.03	-0.34, 0.28		-0.14	-0.41, 0.12	
Village *(Reference: Urban)*	-0.14	-0.57, 0.29		-0.13	-0.45, 0.20	
Slope[2]			0.49			0.003
Suburb	0.04	-0.09, 0.16		0.12	-0.00, 0.25	
Urban	-0.08	-0.24, 0.07		-0.10	-0.21, 0.02	
Village	-0.01	-0.17, 0.14		0.17	**0.06, 0.29**	

Abbreviations: 95% CI = 95% confidence interval, *P*: p-value
Adjusted model for parent education, country of birth and percentage of persons aged ≥ 15 living below the low-income cut-off in the neighborhood on complete data
[1]: estimated mean difference in BMIz at baseline across neighborhood
[2]: mean increase/decrease in BMIz for a 5-year unit

Table B
Characteristics of Included and Excluded Participants by Sex (n = 1293). NDIT Study, Montreal, Canada. 1999–2005.

	Boys				Girls			
	Included		Excluded		Included		Excluded	
	n = 331		n = 292		n = 378		n = 292	
	n (%)	Mean (SD)	n (%)	Mean (SD)	n (%)	Mean (SD)	n (%)	Mean (SD)
Individual characteristics								
Age (years)								
Time 1	331 (100.0)	12.7 (0.4)	292 (100.0)	12.9 (0.7)	378 (100.0)	12.6 (0.4)	292 (100.0)	12.9 (0.7)
Time 2	320 (96.7)	15.2 (0.4)	153 (52,4)	15.3 (0.5)	367 (97.1)	15.1 (0.4)	147 (50.3)	15.2 (0.5)
Time 3	296 (89.4)	17.0 (0.4)	105 (36,0)	17.0 (0.4)	340 (89.9)	16.9 (0.3)	103 (35.3)	17.0 (0.4)
Language spoken at home								
English	207 (62.5)		121 (41.4)		223 (59.0)		114 (39.0)	
French	63 (19.0)		113 (38.7)		85 (22.5)		128 (43.8)	
Both	33 (10.0)		35 (12.0)		40 (10.6)		35 (12.0)	
Other	28 (8.5)		23 (7.9)		30 (7.9)		15 (5.1)	
Single parent family, yes	21 (6.7)		26 (9.4)		39 (10.9)		28 (10.2)	
Parent education[a]								
≤ high school	44 (13.3)		15 (19.0)		74 (19.6)		21 (28.0)	
Collegial/Vocational	68 (20.5)		27 (34.2)		76 (20.1)		22 (29.3)	
≥ university	219 (66.2)		37 (46.8)		228 (60.3)		32 (42.7)	
Changed residence								
No	212 (64.0)		60 (20.5)		280 (74.1)		75 (25.7)	
Yes	29 (8.8)		9 (3.1)		21 (5.6)		9 (31)	
Do not know	90 (27.2)		223 (76.4)		77 (20.4)		208 (71.2)	
BMIz								
Time 1	311 (97.2)	0.35 (1.0)	266 (91.2)	0.34 (1.1)	354 (93.7)	0.16 (1.0)	264 (90.4)	0.27 (1.0)
Time 2	316 (95.5)	0.37 (0.9)	146 (50.0)	0.23 (1.0)	356 (94.2)	0.21 (0.8)	133 (45.5)	0.42 (1.0)
Time 3	291 (87.9)	0.25 (0.9)	98 (33.6)	0.26 (1.0)	327 (86.5)	0.13 (0.8)	85 (29.1)	0.41 (0.9)
Weight status, Time 1								
Normal	227 (73.0)		190 (71.4)		279 (78.8)		201 (76.1)	
Overweight	51 (16.4)		47 (17.7)		46 (13.0)		37 (14.0)	

(*continued on next page*)

Table B (*continued*)

	Boys				Girls			
	Included		Excluded		Included		Excluded	
	n = 331		n = 292		n = 378		n = 292	
	n (%)	Mean (SD)	n (%)	Mean (SD)	n (%)	Mean (SD)	n (%)	Mean (SD)
Obesity	33 (10.6)		29 (10.9)		29 (8.2)		26 (9.8)	
Weight status, Time 2								
Normal	247 (78.2)		119 (81.5)		293 (82.3)		97 (72.9)	
Overweight	40 (12.7)		16 (11.0)		44 (12.4)		22 (16.5)	
Obesity	29 (9.2)		11 (7.5)		19 (5.3)		14 (10.5)	
Weight status, Time 3								
Normal	235 (80.8)		76 (77.6)		282 (86.2)		63 (74.1)	
Overweight	30 (10.3)		12 (12.2)		32 (9.8)		16 (18.8)	
Obesity	26 (8.9)		10 (10.2)		13 (4.0)		6 (7.1)	
Number of PA episodes[b], median (Q1-Q3)	328 (99.0)	17.0 (10.3 – 27.0)	288 (98.6)	13,6 (7.8 – 22.3)	368 (97.4)	11.5 (7.0-19.8)	287 (98.3)	11.7 (6.8 – 18.7)
Already smoked, yes	68 (21.6)		103 (37.7)		89 (24.7)		130 (47.6)	
Alcohol consumption[c], yes	130 (42.1)		143 (53.0)		130 (36.3)		128 (47.4)	
Environmental characteristics								
NDVI, median (Q1-Q3)	331 (100.0)	0.00 (−0.09 – 0.07)	86 (29.5)	0,00 (−0.04 – 0.08)		-0.02 (−0.10 – 0.07)	101 (34.6)	-0.02 (−0.07 – 0.09)
Land use diversity, median (Q1-Q3)	331 (100.0)	0.29 (0.15 – 0.40)	39 (13.3)	0.26 (0.17 – 0.36)		0.32 (0.19 - 0.42)	40 (13.7)	0.33 (0.18 – 0.44)
Number of parks								
[0; 1]	158 (47.7)		22 (56.4)		200 (52.9)		19 (47.5)	
2	100 (30.2)		8 (20.5)		101 (26.7)		10 (25.0)	
> 2	73 (22.1)		9 (23.1)		77 (20.4)		11 (27.5)	
Total length of roads (km), mean (SD)	331 (100.0)	10.3 (4.4)	87 (29.8)	8.1 (3.8)		10.6 (4.4)	101 (34.6)	7.9 (3.3)
Number of intersections, median (Q1-Q3)	331 (100.0)	44 (31.5 – 60.0)	87 (29.8)	31 (26.5 – 42.0)		48 (33.0 – 61.0)	101 (34.6)	31 (23.0 – 43.0)
Population density (inhab/km^2), median (Q1-Q3)	331 (100.0)	3038 (2100 – 6426)	87 (29.8)	1449 (357 – 2923)		3674 (2333 – 6915)	101 (34.6)	1224 (338 – 2933)
Number of healthy stores[d],								
0	133 (40.2)		51 (58.6)		156 (41.3)		46 (45.5)	
1 or 2	77 (23.3)		21 (24.1)		75 (19.8)		40 (39.6)	
> 2	121 (36.6)		15 (17.2)		147 (38.9)		15 (14.9)	
Number of unhealthy stores[e]								
0	156 (47.1)		53 (60.9)		162 (42.9)		51 (50.5)	
1 or 2	64 (19.3)		21 (24.1)		77 (20.4)		35 (34.7)	
> 2	111 (33.5)		13 (14.9)		139 (36.8)		15 (14.9)	
Persons age ≥ 15 living below the low-income cut-off (%), median (Q1-Q3)	331 (100.0)	14.5 (6.6 – 24.9)	87 (29.8)	11.0 (7.1 – 21.0)		14.7 (7.1 – 26.1)	101 (34.6)	11.7 (6.4 – 21.0)
Unemployment rate (%), median (Q1-Q3)	331 (100.0)	6.1 (4.5 – 8.8)	87 (29.8)	5.3 (4.4 – 10.4)		6.2 (4.4 – 8.8)	101 (34.6)	6.1 (4.8 – 8.5)
Persons age ≥ 20 with a university degree (%), median (Q1-Q3)	331 (100)	28.5 (20.1 – 36.9)	87 (29.8)	12.9 (9.5 – 24.7)		27.3 (19.0 – 35.2)	101 (34.6)	12.9 (8.5 – 21.9)
Single parent family (%), median (Q1-Q3)	331 (100)	15.9 (9.4 – 20.6)	87 (29.8)	14.3 (11.4 – 15.8)		15.6 (10.5 – 21.4)	101 (34.6)	14.3 (11.0 – 16.7)

Abbreviations: BMIz: body mass index z-score; NDVI: normalized difference vegetation index; Q1-Q3: interquartile range; SD: standard deviation
[a]highest level between both parents
[b]average of the first year of monitoring moderate and vigorous physical activity episodes (collected during the first 4 cycles)
[c]in the month before the cycle
[d]includes hypermarkets, supermarkets, grocery stores and fruits store
[e]includes convenience stores and fast-food restaurants

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