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Association of neighborhood built environments with childhood obesity: Evidence from a 9-year longitudinal, nationally representative survey in the US

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A R T I C L E I N F O

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A B S T R A C T

Background: The built environment is an important contributor to childhood obesity; however, large-scale and longitudinal studies designed to examine their associations remain limited. This study aimed to examine whether walkable neighborhoods were associated with childhood obesity risk over a 9-year period.

Methods: We used data collected in the US nationally representative Early Childhood Longitudinal Study – Kindergarten (ECLS-K) Cohort, with 9440 kindergarteners followed up until their 8th grade (1998–2007). Four built environmental variables, street intersection density, residential density, fitness facility density, and recreational facility density, were calculated from national census, business, and road network datasets, and then matched with ECLS-K samples. Mixed-effect models were performed to estimate associations between built environments and child weight status.

Results: Children who experienced increased intersection density during 1998–2007 had a lower BMI in 2007 ($\beta = -0.49, p < 0.01$), especially girls ($\beta = -0.79, p < 0.01$) and suburban children ($\beta = -0.66, p < 0.05$). They also had lower obesity risk in 2007 (OR = 0.79 [95% CI = 0.66–0.94]), especially girls (OR = 0.68 [95% CI = 0.52–0.88]). Girls and boys who lived in neighborhoods with the higher (but not highest) residential density in 1998 showed lower obesity risk (OR = 0.54 [95% CI = 0.30–0.98]) and overweight risk (OR = 0.54 [95% CI = 0.30–0.95]) in 2007, respectively.

Conclusions: National data indicate that in the US greater walkability in residential neighborhoods may lead to lower child BMI and obesity risk after nine years, and the association was stronger among girls and in suburban regions. This provides useful evidence for future obesity prevention and urban planning.

1. Introduction

Effective interventions are needed to stop the growing obesity epidemic in the US and worldwide (Cai et al., 2014; Wang and Beydoun, 2007; Wang et al., 2015; Wang and Lobstein, 2006; Ng et al., 2014). The built environment, an important contributor to childhood obesity (White House Task Force, 2010), is garnering increased attention from multiple disciplines due to its easy modification relative to genetic changes (Brownson et al., 2009; Hirsch et al., 2014; Huang et al., 2015; Jia et al., 2017a). A walkable built environment can promote physical activity and improve health, such as complete sidewalks, small blocks, high street connectivity and high residential density (Roberts et al., 2015). However, the longitudinal research findings to support the link between the built environment and obesity risk remain limited and these few results are mixed (Hirsch et al., 2014; Huang et al., 2015; Crawford et al., 2010).

Some studies reported that children living in neighborhoods with less recreational open space, sidewalk completeness, residential

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density, traffic density, intersection density and land use mix were more likely to have a higher body mass index (BMI) z-score and also an increasing BMI z-score over time (Schwartz et al., 2011; Duncan et al., 2014). However, most of the existing evidence has come from cross-sectional (Rundle et al., 2007; Gordon-Larsen et al., 2006; Kowaleski-Jones and Wen, 2013; Wen and Kowaleski-Jones, 2012; Witten et al., 2008; Sarkar, 2017) or local studies (Hirsch et al., 2014; Crawford et al., 2010; Duncan et al., 2014; Berry et al., 2010; Boone-Heinonen et al., 2013; Gose et al., 2013; Timperio et al., 2010). To our knowledge, there has not been any large-scale and longitudinal study designed to examine the associations between the built environment and children's weight status, with the dynamics of built environments and children's weight status both taken into consideration. In addition, the heterogeneity associated with urbanicity and gender is another dimension that has not been fully examined and understood, as boys and girls, as well as children living in different geographical settings, may distinctively respond to the changes in built environments (Durand et al., 2011; Wang et al., 2013).

To provide longitudinal evidence on the effects of built environments on children's weight status, using longitudinal data collected from a nationally representative sample in the US, we examined: 1) temporal changes of built environments in the US between 1998 and 2007; 2) the associations between residential built environments and children's weight status in a longitudinal study design; and 3) variations in these associations across gender and urbanicity.

2. Methods

2.1. Study design and subjects

This study used the US nationally representative data in the Early Childhood Longitudinal Study–Kindergarten Cohort (ECLS-K), collected from children during kindergarten (aged 6–7) in 1998–1999 and followed up until their 8th grade (2007) (Rock and Pollack, 2002). Sponsored by several US federal government agencies, including the National Center for Education Statistics, ECLS-K data were collected to examine child development, school readiness and early school experiences. The ECLS-K cohort includes about 22,000 kindergarteners from > 1200 schools, and 9440 of them were successfully followed up throughout the 9-year study period.

Data collected in 1998–1999 (baseline data, called "the 1998 wave" in this paper) and 2007 (the last follow-up survey) were analyzed to examine the impact of residential built environments and their changes on child BMI and obesity risks. The study included only the children who lived in the contiguous US (Alaska and Hawaii excluded) and had a measured BMI and residential location (census tract, or CT) in 1998 and 2007. Our final analytical samples included 6900 children.

2.2. Key study variables

2.2.1. Outcome variables

Child weight status. Children's body weight and height were measured twice at each interview, using a digital scale (Seca, Model 840, Seca North America West, Chino, CA) recording to the nearest 0.1 kg and the Shorr stadiometer (Shorr Productions LLC, Olney, MD) recording to the nearest 0.1 cm, respectively. The two height measurements were averaged if they differed < 5.08 cm (i.e., 2 in.); the two weight measurements were averaged if they differed < 2.3 kg (i.e., 5 pounds). Otherwise, the measurement nearer to the median weight/height for that age was retained (Datar et al., 2011). The measured weight and height were used to calculate BMI (kg/m^2) for each child. Obesity was defined as sex-age-specific BMI ≥95th percentile of the 2000 CDC Growth Chart, while overweight was ≥85th percentile (Kuczmarski et al., 2000).

2.2.2. Exposure variables

To characterize neighborhood built environments where ECLS-K children lived in 1998 and 2007, three US national geographic datasets available in the most proximate years, the Census 2000 and 2010, the road network datasets in 2000 and 2007, and the Dun and Bradstreet (D&B) commercial datasets in 1998 and 2007, were used to build four geographic variables across the contiguous US in a Geographic Information Systems (GIS) environment: street intersection density, residential density, fitness facility density, and recreational facility density. All these variables were constructed at a CT level, specifically the CT in 2000, which was the finest geographic unit at which built environments have been associated with children's outdoor physical activity (PA) (Brownson et al., 2009) and also the residential location of ECLS-K children was recorded.

Street intersection density, calculated as the number of junctions of three or more street segments per hectare (10,000 m^2) in a CT (Wang et al., 2013) (a street segment is defined as a line segment between any two intersections/junctions), was used to measure street connectivity as a high street connectivity may imply a walking-friendly environment that is more likely to promote children's outdoor physical activity (PA) (Jia et al., 2017a; Duncan et al., 2014). The road network data in 2000 and 2007 were used to extract the streets and calculate the intersection density for the kindergarteners and the 8th graders, respectively.

Residential density was defined as the number of housing units per km^2 in a CT. The high residential density can be associated with more vibrant street life and child PA, because children might see others being physically active and be able to walk to the homes of other children (Jia et al., 2017a; Duncan et al., 2014; Forsyth et al., 2007). The Census 2000 included the numbers of housing units within the 2000 CTs, which were directly used for calculating the residential density for the kindergarteners. An *areal weighting interpolator* method (Jia et al., 2017b, 2017c) was used to transfer the numbers of housing units within the 2010 CTs, derived from the Census 2010, to the 2000 CTs. This method assumes that housing units are uniformly distributed within a CT. The implementation began with intersecting the 2000 and 2010 CT layers to split the 2010 CTs into intersected zones. According to the areal proportion of intersected zones, the number of housing units in each 2010 CT was apportioned to each intersected zone. The estimated numbers in all intersected zones located within each 2000 CT were then added to yield the number of housing units in 2010 for this study. The average number of housing units in 2000 and 2010 within the 2000 CT was divided by the CT area to approximately represent the residential density for the 8th grade.

Fitness facility density and recreational facility density, commonly indicating the availability of PA opportunities (Salois, 2012; Black et al., 2010), were defined as the number of physical fitness facilities (Standard Industrial Classification (SIC) code = 7991) and sports/recreational facilities (SIC code = 7997 and 7999) per km^2 in a CT, respectively. The D&B data in 1998 and 2007 were used to produce both variables that temporally matched with the kindergarteners and the 8th graders, respectively.

For more meaningful analyses and interpretation of model coefficients, samples were ranked on the basis of each built environmental variable and classified into quartiles from lowest (quartile 1) to highest values (quartile 4). If the percentage of the children living in the CTs without a given type of built environmental feature was > 25% but ≤50%, then all samples in those CTs were assigned as one category (density = 0), with the remaining samples ranked and evenly divided into two categories. If that percentage was > 50%, then all samples were divided into only two categories (density = 0 and > 0). In addition, the changes in each built environmental feature from 1998 to 2007 were calculated by subtracting the density in 1998 from the density in 2007, with each sample labelled as one of the three categories for each variable: *decreased* (negative change), *constant* (no change), and *increased* (positive change).

2.2.3. Covariates

Child-level covariates included age, sex, race/ethnicity (White, Black, Hispanic, Asian, and others), socioeconomic status (SES), parental education, and urbanicity. Children's SES was defined as four categories, based on parental report on their household annual income: ≤$30,000, $30000–50,000, $50000–75,000, and > $75,000. Parental education was determined based on the parent who had the higher education level, recoded as four categories: high school and below, vocational/tech/college, bachelor's degree, and graduate degree. Seven categories representing the urbanicity of children's residential location were grouped into urban (large and mid-size city), suburban (large and mid-size suburb), and rural regions (large and small town, and rural).

2.3. Statistical analysis

First, χ^2 tests (for categorical variables) and *t*-tests (for continuous variables) were conducted to identify significant disparities between genders in children's socio-demographic characteristics and weight status, the built environment where children had lived, and changes in the built environment over a 9-year period. McNemar's tests (for categorical variables) and paired *t*-tests (for continuous variables) were used to examine the significance of the changes in child weight status and built environments during 1998–2007.

Given the nested data structure (i.e., children within CTs), two-level mixed-effect models were performed to estimate the relationships between residential built environments, including the baseline and dynamics of the built environment in CTs, and changes in child BMI. We specified the BMI at the 8th grade as the dependent variable and the baseline and changes in built environmental features as independent variables. CT-level random intercept represented variation of the BMI among children across CTs, with the effects of individual-level variables modeled as fixed across individuals. Also, we used cluster robust logistic regression to model binary weight status variables (i.e., overweight/obesity and obesity only) at the 8th grade. We also fitted separate models to examine the potential effect modification by gender and urbanicity. All models adjusted for children's sex, race/ethnicity, baseline age, SES, parental educational level, BMI/weight status, and urbanicity.

All spatial operations and analyses were conducted in *ArcGIS* (Version 10.4.1, ESRI, Redlands, CA). All statistical analyses were performed using Stata 14 (College Station, TX) with the stratification of the survey design and the study's sampling weights taken into account.

3. Results

3.1. Sample characteristics

At baseline in 1998, the mean age of these children was 6.2 years, with boys older than girls on average ($p = 0.011$) (Table 1). The racial, parental education, and SES structures were similar between genders. The baseline weight status was similar between genders, with a mean BMI of 16.4 kg/m^2 and the prevalence of overweight/obesity and obesity being 26.2% and 11.0%, respectively. The significant increases that occurred during 1998–2007 in mean BMI (from 16.4 to 22.8, $p < 0.001$) and prevalence of overweight/obesity (from 26.2% to 35.0%, $p < 0.001$) and obesity (from 11.0% to 19.1%, $p < 0.001$) also occurred in boys and girls separately. In 2007, although a higher BMI was developed among girls than boys (23.1 vs. 22.4, $p = 0.004$), there were no gender differences in the prevalence of overweight/obesity and obesity.

These ECLS-K children's living built environments have significantly changed over nine years, including increased street connectivity, fitness facility density, and recreational facility density. No gender differences were found in any aspect of the residential built environment in both 1998 and 2007 (Table 1).

Table 1
Socio-demographic characteristics, weight status, and residential built environments and their temporal changes (from 1998 to 2007) of the US children in ECLS-K[a].

Variables	% or Mean ± SD			*p*-Value
	All (n = 6900)	Boy (n = 3440)	Girl (n = 3460)	
Socio-demographic characteristics (1998)				
Age (years)	6.2 ± 0.4	6.3 ± 0.3	6.2 ± 0.3	0.011
Race/ethnicity				0.252
White	57.9	58.0	57.7	
Black	17.8	18.5	17.2	
Hispanic	18.6	18.8	18.3	
Asian	2.9	2.2	3.6	
Others	2.8	2.5	3.2	
Parental education				0.257
≤High school	32.9	34.6	31.1	
Vocational/college	32.1	31.6	32.6	
Bachelor	19.9	19.8	20.1	
≥Graduate	15.1	14.0	16.2	
Household annual income ($)				0.647
≤30,000	34.0	34.7	33.2	
> 30,000 but ≤50,000	23.9	23.8	24.0	
> 50,000 but ≤75,000	18.7	17.8	19.7	
> 75,000	23.4	23.7	23.1	
Urbanicity				0.870
Urban	39.3	39.7	38.7	
Suburban	39.2	39.1	39.4	
Rural	21.5	21.2	21.9	
Weight status[c] in 1998 (baseline)				
BMI (kg/m^2)	16.4 ± 2.2	16.4 ± 1.9	16.3 ± 2.3	0.916
Overweight and obesity	26.2	25.2	27.2	0.297
Obesity	11.0	11.0	11.1	0.988
Weight status[c] in 2007 (last follow-up)				
BMI (kg/m^2)	22.8 ± 5.6	22.4 ± 5.0	23.1 ± 5.8	0.004
Overweight and obesity	35.0	34.9	35.1	0.894
Obesity	19.1	20.2	18.0	0.194
Built environments in 1998				
Intersection density (/ha)[d]	0.3 ± 0.3	0.3 ± 0.2	0.3 ± 0.3	0.204
Residential density (persons/ha)[d]	6.3 ± 13.8	5.9 ± 11.2	6.7 ± 15.3	0.128
Fitness facility density (/km^2)	0.1 ± 0.6	0.1 ± 0.2	0.1 ± 0.8	0.253
Recreational facility density (/km^2)	0.3 ± 0.9	0.3 ± 0.6	0.3 ± 1.2	0.089
Built environments in 2007				
Intersection density (/ha)[d]	0.3 ± 0.3	0.3 ± 0.2	0.3 ± 0.3	0.771
Residential density (persons/ha)[d]	6.0 ± 13.8	5.8 ± 11.4	6.2 ± 15.1	0.475
Fitness facility density (/km^2)	0.2 ± 0.9	0.2 ± 0.5	0.2 ± 1.1	0.378
Recreational facility density (/km^2)	0.5 ± 1.4	0.5 ± 1.1	0.5 ± 1.6	0.219
Changes in built environments from 1998 to 2007				
Intersection density				0.781
Decreased	33.6	33.2	34.0	
Constant	10.6	10.3	10.9	
Increased	55.8	56.5	55.1	
Residential density				0.101
Decreased	33.0	31.3	34.8	
Constant	–	–	–	
Increased	67.0	68.7	65.2	
Fitness facility density				0.599
Decreased	8.0	7.8	8.1	
Constant	54.9	54.0	55.9	
Increased	37.1	38.2	36.0	
Recreational facility density				0.843
Decreased	20.4	19.9	20.9	
Constant	25.2	25.2	25.1	
Increased	54.4	54.9	54.0	

[a] Sampling weights were used in the analyses.

[b] *p*-Values tested the differences in each variable between genders and were based on χ^2 tests for categorical variables or *t*-tests for continuous variables.

[c] Children were classified as overweight and obesity if their sex-age-specific body mass index (BMI) ≥ 85th and 95th percentiles of the 2000 CDC Growth Chart, respectively.

[d] Ha means hectare (i.e. 10,000 m^2).

3.2. Associations of residential built environments and child weight status

The children exposed to an increase in intersection density during 1998–2007 had a lower BMI on average in 2007 ($\beta = -0.49$, SE = 0.19, $p < 0.01$), compared to those who experienced a decrease in intersection density (Table 2). This trend was also observed in both genders, but only significant among girls ($\beta = -0.79$, SE = 0.25, $p < 0.01$), as well as in all three regions but only significant in suburban regions ($\beta = -0.66$, SE = 0.31, $p < 0.05$) (Table 2). Moreover, those children exposed to increased intersection density during 1998–2007 also had a lower obesity risk in 2007 (OR = 0.79 [95% CI = 0.66–0.94]), especially girls (OR = 0.68 [95% CI = 0.52–0.88]) (Table 3).

Girls in quartile 2 of the baseline residential density showed a lower obesity risk in 2007 (OR = 0.54 [95% CI = 0.30–0.98]), compared to their counterparts in quartile 1 (Table 3). Boys in quartile 3 of the baseline residential density also showed a lower overweight/obesity risk in 2007 (OR = 0.54 [95% CI = 0.30–0.95]), compared to boys in quartile 1 (Table 4). Despite not being significant, the baseline residential density was found to be positively and negatively associated with the overweight/obesity risk in urban and non-urban regions, respectively. The density of fitness facilities and recreational facilities was not found to be associated with children's weight status or overweight and obesity risks.

4. Discussion

This is a large-scale longitudinal study using nationally representative data in the US to investigate the impact of residential built environments on children's weight status. The significant temporal changes in residential neighborhood built environments during 1998–2007 have been observed at a national scale, which implies that the dynamics of built environments need to be taken into account in such studies, in order to accurately estimate individual exposure to the built environment in the vicinity. Four primary PA-related, also calculable in a national scope, built environmental variables were selected. Overall, we found that 1) children's exposure to increased street connectivity in residential neighborhoods over nine years was associated with a lower child BMI in 2007, especially in girls and suburban regions, as well as a lower obesity risk in 2007, especially in girls; and 2) the higher residential density in 1998 was associated with a lower obesity risk in girls after nine years, and also with a lower overweight/obesity risk in boys. The robustness of these findings was enhanced by our study design using a CT level of analysis, the finest available areal unit second only to using individual addresses.

In previous studies, the built environmental factor was found to be differently associated with child BMI (or weight status) at varied locations and scales. For example, a negative association between street connectivity and BMI (or weight status) was found in some studies,

Table 2

Associations (coefficient and standard error) of residential built environments in 1998 (at baseline) and their changes from 1998 to 2007 with child body mass index (BMI) in 2007[a].

Built environments	All (n = 6900)		Boy (n = 3440)		Girl (n = 3460)		Urban (n = 2710)		Suburban (n = 2550)		Rural (n = 1640)	
Intersection density												
1998 (/ha)[b]												
< 0.05 (ref)												
0.05–0.20	0.17	(0.44)	−0.40	(0.54)	0.69	(0.65)	−0.12	(0.86)	0.48	(0.67)	−0.11	(0.94)
0.20–0.41	0.18	(0.51)	0.40	(0.62)	−0.08	(0.76)	0.41	(0.91)	−0.21	(0.80)	−0.80	(1.42)
> 0.41	−0.19	(0.55)	−0.12	(0.66)	−0.27	(0.82)	0.39	(0.94)	−0.88	(0.86)	−2.91	(2.00)
1998–2007												
Decreased (ref)												
Constant	−0.32	(0.23)	−0.09	(0.28)	−0.54	(0.34)	−0.18	(0.29)	−0.43	(0.40)	−0.74	(0.67)
Increased	**−0.49****	(0.17)	−0.17	(0.20)	**−0.79****	(0.25)	−0.22	(0.22)	**−0.66***	(0.31)	−0.82	(0.42)
Residential density												
1998 (units/ha)[b]												
< 0.58 (ref)												
0.58–3.08	−0.29	(0.44)	0.06	(0.54)	−0.58	(0.65)	−0.03	(0.85)	−0.96	(0.67)	0.39	(0.93)
3.08–7.37	−0.10	(0.51)	−0.78	(0.62)	0.65	(0.76)	−0.61	(0.91)	−0.19	(0.81)	–	–
> 7.37	−0.19	(0.55)	−0.55	(0.67)	0.21	(0.82)	−0.85	(0.94)	−0.00	(0.88)	–	–
1998–2007												
Decreased (ref)												
Constant	–	–	–	–	–	–	–	–	–	–	–	–
Increased	0.03	(0.17)	−0.24	(0.21)	0.32	(0.26)	0.11	(0.20)	−0.38	(0.31)	0.85	(0.51)
Fitness facility density												
1998 (/km^2)												
0 (ref)												
> 0	−0.06	(0.23)	0.27	(0.27)	−0.35	(0.34)	0.03	(0.30)	−0.07	(0.39)	−0.22	(0.58)
1998–2007												
Decreased (ref)												
Constant	0.24	(0.34)	0.47	(0.40)	−0.01	(0.53)	0.07	(0.45)	−0.01	(0.61)	0.84	(0.83)
Increased	0.35	(0.34)	0.54	(0.40)	0.10	(0.53)	0.44	(0.45)	0.24	(0.60)	0.23	(0.82)
Recreational facility density												
1998 (/km^2)												
0 (ref)												
> 0–0.2	0.11	(0.20)	0.08	(0.23)	0.18	(0.30)	−0.14	(0.33)	0.32	(0.36)	−0.11	(0.39)
> 0.2	−0.04	(0.19)	0.24	(0.23)	−0.24	(0.29)	−0.09	(0.23)	−0.01	(0.34)	−0.14	(0.89)
1998–2007												
Decreased (ref)												
Constant	0.32	(0.23)	0.30	(0.28)	0.34	(0.34)	0.09	(0.30)	0.77	(0.41)	0.12	(0.57)
Increase	0.22	(0.20)	0.27	(0.25)	0.15	(0.30)	0.16	(0.27)	0.33	(0.36)	0.18	(0.50)

[a] All two-level (i.e., children and census tract) models adjusted for age, sex, race/ethnicity, socioeconomic status, parental education, and urbanicity, with only the 2nd level intercept random. Boldfaced numbers indicate statistical significance ($^{*}p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$).

[b] Ha means hectare (i.e. 10,000 m^2).

Table 3

Associations (odds ratio and 95% confidence interval) of residential built environments in 1998 (at baseline) and their changes from 1998 to 2007 with childhood obesity[a] in 2007[b].

Built environments	All (n = 6900)		Boy (n = 3440)		Girl (n = 3460)		Urban (n = 2710)		Suburban (n = 2550)		Rural (n = 1640)	
Intersection density												
1998 (/ha)[c]												
< 0.05 (ref)												
0.05–0.20	1.16	[0.76,1.76]	0.80	[0.43,1.51]	1.68	[0.94,3.01]	1.27	[0.42,3.86]	1.07	[0.61,1.85]	1.23	[0.56,2.71]
0.20–0.41	1.25	[0.76,2.06]	1.00	[0.49,2.07]	1.55	[0.75,3.23]	1.46	[0.45,4.73]	1.17	[0.54,2.51]	0.70	[0.21,2.34]
> 0.41	1.15	[0.67,1.97]	0.85	[0.40,1.81]	1.54	[0.70,3.41]	1.62	[0.49,5.37]	0.85	[0.37,1.92]	0.20	[0.04,1.03]
1998–2007												
Decreased (ref)												
Constant	0.83	[0.65,1.06]	0.90	[0.64,1.26]	0.76	[0.53,1.09]	0.89	[0.62,1.27]	0.75	[0.48,1.16]	0.90	[0.51,1.59]
Increased	**0.79****	[0.66,0.94]	0.89	[0.71,1.12]	**0.68****	[0.52,0.88]	0.86	[0.65,1.12]	0.75	[0.55,1.01]	0.70	[0.47,1.04]
Residential density												
1998 (units/ha)[c]												
< 0.58 (ref)												
0.58–3.08	0.71	[0.46,1.08]	0.92	[0.49,1.73]	**0.54***	[0.30,0.98]	0.62	[0.20,1.89]	0.73	[0.42,1.29]	0.67	[0.30,1.47]
3.08–7.37	0.65	[0.39,1.07]	0.64	[0.30,1.35]	0.70	[0.34,1.42]	0.47	[0.14,1.54]	0.78	[0.35,1.72]	–	–
> 7.37	0.63	[0.36,1.09]	0.71	[0.32,1.56]	0.56	[0.25,1.24]	0.43	[0.13,1.44]	0.87	[0.37,2.06]	–	–
1998–2007												
Decreased (ref)												
Constant	–	–	–	–	–	–	–	–	–	–	–	–
Increased	1.02	[0.85,1.23]	0.91	[0.72,1.16]	1.20	[0.91,1.59]	0.95	[0.74,1.22]	0.97	[0.68,1.38]	1.52	[0.93,2.46]
Fitness facility density												
1998 (/km^2)												
0 (ref)												
> 0	0.93	[0.71,1.22]	1.07	[0.76,1.51]	0.76	[0.49,1.17]	0.89	[0.59,1.35]	1.13	[0.71,1.80]	0.80	[0.45,1.42]
1998–2007												
Decreased (ref)												
Constant	1.13	[0.73,1.73]	1.09	[0.66,1.81]	1.17	[0.57,2.40]	1.18	[0.62,2.23]	0.99	[0.50,1.96]	1.34	[0.50,3.62]
Increased	1.10	[0.72,1.70]	1.13	[0.68,1.89]	1.06	[0.51,2.17]	1.15	[0.61,2.17]	1.07	[0.54,2.14]	1.11	[0.40,3.05]
Recreational facility density												
1998 (/km^2)												
0 (ref)												
> 0–0.2	1.00	[0.81,1.24]	1.04	[0.80,1.35]	0.95	[0.70,1.30]	0.96	[0.64,1.44]	1.06	[0.73,1.52]	0.90	[0.62,1.33]
> 0.2	1.03	[0.84,1.25]	1.18	[0.91,1.53]	0.88	[0.65,1.20]	1.12	[0.85,1.46]	0.83	[0.59,1.17]	1.77	[0.75,4.17]
1998–2007												
Decreased (ref)												
Constant	1.14	[0.88,1.48]	1.15	[0.82,1.60]	1.11	[0.76,1.62]	1.16	[0.79,1.72]	1.09	[0.72,1.65]	1.17	[0.64,2.15]
Increase	1.15	[0.91,1.46]	1.14	[0.83,1.55]	1.13	[0.81,1.58]	1.32	[0.93,1.87]	1.12	[0.77,1.62]	0.97	[0.56,1.69]

[a] Children were classified as obesity if their sex-age-specific BMI ≥ 95th percentile of the 2000 CDC Growth Chart.

[b] All two-level (i.e., children and census tract) models adjusted for age, sex, race/ethnicity, socioeconomic status, parental education, and urbanicity, with only the 2nd level intercept random. Boldfaced numbers indicate statistical significance ($^{*}p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$).

[c] Ha means hectare (i.e. 10,000 m^2).

which, however, were all conducted in one city (Hirsch et al., 2014; Crawford et al., 2010; Burdette and Whitaker, 2004; Burgoine et al., 2015; Corsino et al., 2013; Hinckson et al., 2014). Other inner-city (Christian et al., 2011; Duncan et al., 2011) and multi-county studies (Huang et al., 2015; Crider et al., 2014; Hill et al., 2012; Hoehner et al., 2013; Hosler, 2009) revealed no such associations, and even some inner-city studies found a positive association (Coombes et al., 2010). Also, a consistent relationship between residential density and child weight status was lacking, especially under a longitudinal study design (Jia et al., 2017a; Dunton et al., 2009), although some cross-sectional studies found a negative association (Duncan et al., 2014). The density of fitness and recreational facilities was justified as an important built environmental factor to be linked with children's physical activity positively and weight status negatively (Black et al., 2010; Gordon-Larsen et al., 2006), but a consistent relationship remained unclear as well (Salois, 2012). Our study advanced the obesogenic environment research by providing longitudinal evidence at a national level, which also justifies and will stimulate more future efforts on built environmental data construction and maintenance.

The effects of neighborhood built environmental factors on individual weight status may be more complex than linearity. For example, compared to the counterparts in quartile 1 of the baseline residential density, the lower risks of overweight/obesity and obesity only were only observed among the boys in quartile 3 and among the girls in quartile 2, respectively. This indicates that the association between residential density and weight status might be nonlinear, such as a U-shaped curvilinear association, where the obesity risk decreases as the residential density increases, but only down to a certain point (e.g., somewhere in quartile 2 for girls or in quartile 3 for boys), after which the obesity risk turns to increase as the residential density continues to increase. Furthermore, an effect modification by urbanicity was found in our study, where the association of the exposure to increased street connectivity with lower BMI was only found in suburban regions. This is consistent with some previous findings. For example, the negative associations of street connectivity with obesity risk were only observed in the more-, but not the most-, urbanized areas (Wang et al., 2013). Our study further confirms the varied mechanisms through which the built environment may influence individual weight status differently across urbanicity.

This study has some limitations. First, the large proportion of lost-to-follow-up children is a limitation of the data. We compared the baseline demographic characteristics of those lost-to-follow-up to the children remaining in the cohort, and found that only Asians were slightly under-represented in our sample. Although there is no evidence showing that lost-to-follow-up is not random, the findings of this study should be generalized to the entire US population with caution. In our

Table 4
Associations (odds ratio and 95% confidence interval) of residential built environments in 1998 (at baseline) and their changes from 1998 to 2007 with childhood overweight[a] in 2007[b].

Built environments	All (n = 6900)		Boy (n = 3440)		Girl (n = 3460)		Urban (n = 2710)		Suburban (n = 2550)		Rural (n = 1640)	
Intersection density												
1998 (/ha)[c]												
< 0.05 (ref)												
0.05–0.20	1.09	[0.72,1.67]	0.96	[0.59,1.55]	1.22	[0.69,2.15]	0.59	[0.22,1.58]	1.57	[0.84,2.93]	0.96	[0.52,1.74]
0.20–0.41	1.19	[0.74,1.92]	1.34	[0.76,2.35]	0.98	[0.51,1.88]	0.77	[0.28,2.15]	1.67	[0.83,3.37]	0.40	[0.16,1.02]
> 0.41	1.26	[0.76,2.09]	1.40	[0.76,2.57]	1.07	[0.53,2.15]	0.92	[0.32,2.65]	1.40	[0.67,2.93]	0.36	[0.11,1.22]
1998–2007												
Decreased (ref)												
Constant	0.92	[0.75,1.13]	0.88	[0.66,1.18]	0.99	[0.75,1.32]	1.06	[0.79,1.41]	0.84	[0.60,1.18]	0.77	[0.46,1.29]
Increased	0.88	[0.76,1.02]	0.89	[0.72,1.09]	0.87	[0.70,1.07]	0.97	[0.77,1.23]	0.80	[0.62,1.04]	0.89	[0.63,1.25]
Residential density												
1998 (units/ha)[c]												
< 0.58 (ref)												
0.58–3.08	0.86	[0.56,1.30]	1.04	[0.64,1.68]	0.71	[0.40,1.25]	1.68	[0.63,4.51]	0.63	[0.33,1.19]	0.81	[0.45,1.44]
3.08–7.37	0.72	[0.45,1.15]	**0.54***	[0.30,0.95]	1.01	[0.54,1.90]	1.12	[0.39,3.19]	0.55	[0.26,1.14]	–	–
> 7.37	0.78	[0.47,1.30]	0.65	[0.35,1.21]	0.98	[0.49,1.98]	1.18	[0.40,3.46]	0.65	[0.30,1.42]	–	–
1998–2007												
Decreased (ref)												
Constant	–	–	–	–	–	–	–	–	–	–	–	–
Increased	1.02	[0.88,1.19]	0.92	[0.75,1.14]	1.15	[0.93,1.43]	1.09	[0.89,1.35]	0.99	[0.76,1.27]	0.99	[0.65,1.51]
Fitness facility density												
1998 (/km^2)												
0 (ref)												
> 0	0.95	[0.77,1.17]	1.06	[0.81,1.38]	0.86	[0.63,1.16]	0.84	[0.60,1.17]	1.09	[0.79,1.50]	1.03	[0.65,1.65]
1998–2007												
Decreased (ref)												
Constant	1.21	[0.89,1.65]	1.14	[0.76,1.71]	1.29	[0.82,2.02]	1.15	[0.68,1.95]	1.09	[0.67,1.78]	1.60	[0.83,3.07]
Increased	1.22	[0.90,1.65]	1.16	[0.77,1.75]	1.28	[0.82,1.99]	1.22	[0.72,2.05]	1.17	[0.73,1.89]	1.43	[0.76,2.71]
Recreational facility density												
1998 (/km^2)												
0 (ref)												
> 0–0.2	1.12	[0.94,1.35]	1.09	[0.85,1.39]	1.17	[0.92,1.50]	1.06	[0.74,1.53]	1.24	[0.91,1.67]	1.02	[0.74,1.40]
> 0.2	1.07	[0.90,1.26]	1.05	[0.84,1.32]	1.09	[0.85,1.39]	1.00	[0.80,1.26]	1.04	[0.79,1.36]	1.44	[0.85,2.44]
1998–2007												
Decreased (ref)												
Constant	1.05	[0.86,1.29]	1.01	[0.75,1.34]	1.11	[0.84,1.48]	0.92	[0.67,1.27]	1.27	[0.91,1.78]	0.94	[0.60,1.47]
Increase	0.96	[0.80,1.15]	0.98	[0.75,1.27]	0.94	[0.73,1.21]	0.95	[0.71,1.26]	1.07	[0.79,1.44]	0.82	[0.55,1.22]

[a] Children were classified as overweight (including obesity) if their sex-age-specific BMI ≥ 85th percentile of the 2000 CDC Growth Chart.

[b] All two-level (i.e., children and census tract) models adjusted for age, sex, race/ethnicity, socioeconomic status, parental education, and urbanicity, with only the 2nd level intercept random. Boldfaced numbers indicate statistical significance ($^{*}p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$).

[c] Ha means hectare (i.e. 10,000 m^2).

future efforts, we will use several approaches (e.g., inverse probability weighting and other propensity score-based methods) for dealing with missing data and compare with the findings of this study. Second, possible different effects of built environments on childhood obesity could neither be examined at finer urbanicity levels (e.g., large and mid-size suburb, large and small town) due to a limited sample size, nor in exclusively rural areas due to insufficient variation and magnitude of built environmental variables (e.g., there was a trivial number of rural samples in quartile 4 of the residential density). Third, the built environments at the CT level were considered as individual routine exposures. However, the CT size varies region by region, and in some small CTs individual outdoor behaviors may also be affected by built environments in neighboring CTs. We are also aware that indicators for built environments could only reflect the potential that residents may have interaction with their surrounding environment, instead of the actual interactions they have. Individual routine activity space and actual exposure may be measured more accurately by advanced technologies, such as global positioning system-based wearable sensors and devices (Jia et al., 2019a). Fourth, only four built environmental variables were included due to lack of fine-scale national, longitudinal datasets for other important features, such as completeness of sidewalks and proximity to green space (Jia et al., 2017a), which may confound associations found in this study. Therefore, whether the associations we found is likely to be real and direct needs to be confirmed in future studies where more aspects of the neighborhood built environment are measured (e.g., by remote sensing technology (Jia et al., 2019b; Jia and Stein, 2017)). Also due to limited scope and snapshots of built environmental conditions captured (i.e., only for the contiguous US in 2000, 2007, and 2010), we did not include Hawaii and Alaska or more waves of ECLS-K data between ECLS-K baseline and last follow-up.

5. Conclusions

This study revealed the relationships between residential built environments and children's BMI and obesity risk over a 9-year follow-up period in a US nationally representative study. It suggests that greater walkability, indicated by increased street connectivity and higher residential density, is protective. This landmark study has some important public health implications, in particular, for future obesity prevention and urban planning (Karjalainen et al., 2017). More broadly speaking, it demonstrates the usefulness of combining multiple sources of spatial data, as well as the demand for using more (temporally) frequent remote sensing data in chronic disease research (Jia, 2019).

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