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Original Contribution

Neighborhood Physical Environment and Changes in Body Mass Index: Results From the Multi-Ethnic Study of Atherosclerosis

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Longitudinal associations between neighborhood characteristics and body mass index (BMI; weight (kg)/height (m)^2) were assessed from 2000 to 2011 among 5,919 participants in the Multi-Ethnic Study of Atherosclerosis. The perceived availability of healthy food and walking environment were assessed via surveys, and 1-mile (1.6-km) densities of supermarkets, fruit-and-vegetable stores, and recreational facilities were obtained through a commercial database. Econometric fixed-effects models were used to estimate the association between within-person changes in neighborhood characteristics and within-person change in BMI. In fully adjusted models, a 1-standard-deviation increase in the healthy food environment index was associated with a 0.16-kg/m^2 decrease in BMI (95% confidence interval (CI): −0.27, −0.06) among participants with obesity at baseline. A 1-standard-deviation increase in the physical activity environment index was associated with 0.13-kg/m^2 (95% CI: −0.24, −0.02) and 0.14-kg/m^2 (95% CI: −0.27, −0.01) decreases in BMI for participants who were overweight and obese at baseline, respectively. Paradoxically, increases in the physical activity index were associated with BMI increases in persons who were normal-weight at baseline. This study provides preliminary longitudinal evidence that favorable changes in neighborhood physical environments are related to BMI reductions in obese persons, who comprise a substantial proportion of the US population.

body mass index; geographic information systems; leisure activities; neighborhoods; obesity; prospective studies; residence characteristics; social environment

Abbreviations: BMI, body mass index; CI, confidence interval; GIS, geographic information systems; MESA, Multi-Ethnic Study of Atherosclerosis; NETS, National Establishment Time Series; SFV, supermarkets and fruit-and-vegetable markets.

Currently, 70% of the US population aged 20 years or more is above the recommended level of body mass index (BMI; weight (kg)/height (m)^2) (1). Individual lifestyles, such as diet and physical activity, have important influences on BMI (2). Individual behaviors are constrained by cultural, socioeconomic, and environmental contexts. Neighborhoods in which people live represent an important environment and may set boundaries for engaging in healthy lifestyles (3, 4). Experimental evidence suggests that neighborhoods influence obesity (5). Low-income women randomly assigned to receive government support for moving to lower-poverty neighborhoods showed a lower risk of obesity than controls after 12 years of follow-up (5), yet the specific mechanisms through which neighborhoods influence weight were not identified. Understanding which neighborhood characteristics are predictors of weight change could facilitate the development of interventions directed toward reducing population weight.

Cross-sectional studies investigating the links between body weight and neighborhood features have focused on food availability, the walking environment, and access to recreational facilities. Increased weight has been linked to resident perceptions of low availability of healthy food in the neighborhood (6), low density of places that sell healthy foods (7, 8), high density of places that sell unhealthy foods (9–11), or closer distances to sources of fast food (12). Higher perceived walkability (6), census-derived walkability indices

(13), and land-use mix have also been linked to lower BMI (14, 15). In addition, obesity and higher BMI have been associated with lower access to recreational facilities (16, 17). Although suggestive of an impact of neighborhood environment on BMI, results of cross-sectional studies have not always been consistent, and causal inferences cannot be drawn from them (3, 18). Additionally, researchers have interchangeably used survey-based and geographic information system (GIS)-based measures for determining neighborhood attributes, but these measures are poorly correlated and probably reflect different aspects of the neighborhood environment, requiring simultaneous assessment (19, 20). Both survey- and GIS-based neighborhood measures may be needed to capture both subjective (e.g., food affordability and accessibility) and objective (e.g., presence of healthy food stores) aspects of neighborhood environment (21, 22).

Few studies have examined the impact of changes in neighborhood environment on simultaneous changes in BMI, an approach that provides stronger evidence of causal effects (4). Two studies have linked access to convenience stores and fast-food restaurants to increases in adult BMI (23, 24), but the investigators did not consider other aspects of neighborhood that might be relevant to weight change, such as the physical activity environment. To our knowledge, no study to date has examined the associations between changes in both the healthy-food and physical-activity environments and change in adult BMI.

In the present study, we investigated whether changes in neighborhood physical environments over time are related to changes in BMI in an ethnically diverse study sample. We hypothesized that residents of neighborhoods with improvements in food availability, physical activity, and walking environment would experience decreases in BMI over time. We also hypothesized that these associations would be stronger in persons who were obese at baseline, because their weight is high to begin with and hence they may be the ones among whom weight reduction is most sensitive to environmental conditions.

METHODS

The Multi-Ethnic Study of Atherosclerosis (MESA) is a longitudinal study investigating the progression of known subclinical cardiovascular disease in 6 US urban areas (Baltimore, Maryland; Chicago, Illinois; Forsyth County, North Carolina; Los Angeles, California; New York, New York; and St. Paul, Minnesota). The study recruited 6,814 participants aged 45–84 years at baseline who were free of cardiovascular disease. Baseline assessment was conducted from 2000 to 2002, with 4 follow-up examinations occurring at approximately 1.5- to 2-year intervals (25). The study was approved by the institutional review boards of the participating institutions, and all participants provided informed consent.

Body mass index

BMI was calculated from direct measurements of weight (kg) and height (m), available from all MESA examinations.

Neighborhood characteristics

Neighborhood indicators were compiled and linked to MESA participants by investigators in the MESA Neighborhood Study, an ancillary study to MESA (26). Four measures of neighborhood food and physical activity environment were derived using community perceptions of the neighborhood environment and a business establishment database.

Community perceptions of healthy food availability and walking environment

Measures of healthy food availability and walking environment were obtained from questionnaires administered to MESA participants during examinations 2 and 3 (2002–2005) and examination 5 (2010–2011) and 2 auxiliary surveys (community surveys administered in 2004 and 2012 to random samples of other residents of MESA neighborhoods) (27). Respondents were asked to consider their "neighborhood" as the area within a 20-minute walk or 1 mile (1.6 km) from their home. Questions regarding healthy food availability (large selections of fresh fruit and vegetables and low-fat foods) and walking environment (pleasurability and ease of walking and frequency of other people walking or exercising in the neighborhood) were answered using a 5-point Likert scale. Scales derived from these questions (27, 28) have acceptable internal consistency (Cronbach's $\alpha = 0.82$ for healthy food availability and 0.65 for walking environment) (29). To increase sample size and the reliability of scale estimates, responses from the community surveys were pooled with those from the MESA respondents to obtain neighborhood aggregate measures. By averaging across individuals, we expected to reduce the influence of individual subjectivity, producing a more valid measure of the objective reality of the neighborhood (27, 30). Scales based on a 1-mile (1.6-km) buffer around residential addresses were created by taking the crude mean of the responses for all respondents living within a 1-mile buffer, excluding the index individual to avoid same-source bias. Only respondents who answered all questions within the domain were included. There were a median of 69 respondents across all of the 1-mile buffers for which estimates were generated. Time-varying address information was used to link MESA participants to time-varying survey measures, using the survey measure closest in calendar time. For all scales, higher values represent better neighborhood conditions.

GIS-based measures of supermarket/fruit-and-vegetable market density and recreational density

Data on food stores and commercially available recreational facilities for every zip code within a 5-mile (8-km) radius of MESA participant households were obtained from the National Establishment Time Series (NETS) database (Walls & Associates, Denver, Colorado) for 2000–2010 (31). Fifteen standardized industrial codes were used to identify supermarkets and fruit-and-vegetable markets (SFV). These data were enhanced by adding supermarket data from Nielsen/TDLinx (32, 33). Recreational resources were identified from 114 standardized industrial codes and included indoor conditioning (health clubs/

gyms, yoga, etc.), dance, bowling, golf, team and racquet sports, and water activities (34). Simple densities of SFV and recreational resources for 1-mile (1.6-km) buffers surrounding participant households were calculated using ArcGIS 9.3 (ESRI, Redlands, California) for each year of follow-up. Time-varying address information was used to link MESA participants to time-varying density measures for the corresponding calendar year.

Covariates

Sociodemographic data were obtained from MESA questionnaires. Time-invariant covariates were measured at baseline and included age, sex, race/ethnicity (non-Hispanic white, non-Hispanic Chinese, non-Hispanic black, Hispanic), education, and duration of residence (years) in the neighborhood. Education was ascertained from 8 categories, and a continuous measure of years of education was derived using the midpoint of the selected category. Time-varying covariates included marital status (married or living with a partner, other), total annual gross family income (US dollars), and cancer diagnosis (yes/no) (35). Family income was selected from 14 categories, and a continuous measure of income was derived using the midpoint of the selected category. Information on marital status and total annual gross family income was available for 4 out of 5 examinations. For all time-varying measures, missing information was imputed using the value from the examination closest in time.

Statistical analysis

Out of 6,191 participants who agreed to participate in the MESA Neighborhood Study, 181 were excluded due to missing data at baseline and 91 due to no follow-up data. Participants included in the analysis ($n = 5{,}919$) provided a total of 26,297 observations over a median of 9.1 years of follow-up. Descriptive statistics were calculated for all sociodemographic variables at each examination. We also estimated mean levels of BMI and neighborhood characteristics at baseline, as well as changes over time in BMI and neighborhood characteristics by sociodemographic variables using linear regression models.

To estimate the association between within-person change in exposure to neighborhood measures and within-person change in BMI, we implemented fixed-effects models. This approach capitalizes on within-person variability in exposure in estimating associations and tightly controls for time-invariant individual characteristics (36). The following covariates were included for adjustment purposes: time since baseline, income, cancer diagnosis, marital status, and interactions of age at baseline, sex, race/ethnicity, education, and duration of neighborhood residence with time.

Each neighborhood variable (SFV density, perceived healthy food availability, recreational density, and walking environment) was initially examined separately (single-variable models), adjusting for covariates. Spearman coefficients for correlations between neighborhood variables and changes in neighborhood variables over time were examined to assess collinearity. A second set of models examined the food environment domain (SFV density, perceived healthy food availability) and the physical activity domain (recreational density and walking environment) separately. To investigate the independent associations for summary measures of food and physical activity environments, we generated 2 final models: "Full models" included all 4 neighborhood variables separately, while "summary models" included these neighborhood measures summarized in a food environment score and a physical activity score, created by adding *z* scores for each variable within each domain.

Given that BMI changes could depend on excess weight status at baseline (BMI <25 (underweight and normal), BMI 25–29.9 (overweight), or BMI ≥30 (obese)), we fitted a second set of models adding terms for interaction between neighborhood characteristics and BMI category at baseline. To facilitate comparison across different measures, in regression analyses all neighborhood variables were transformed into standard deviation units. As people age, they could interact differently with their neighborhood; to assess this possibility, we tested a triple interaction involving age at baseline, time elapsed since baseline, and neighborhood characteristics. Self-selection of participants with an increasing weight trend into neighborhoods experiencing a decrease in healthy food or recreational resources was a possibility; thus, as a sensitivity analysis, we restricted our models to participants who did not move during follow-up.

RESULTS

Participant characteristics are presented in Table 1. At baseline, the mean age was 61.9 years, males represented 47% of the sample, and the majority of participants were non-Hispanic white (39.3%). Mean annual family income was $49,600 and increased slightly over time. At baseline, 61.8% of participants were married or living with a partner, mean duration of education was 13.2 years, and participants had lived in their neighborhood for an average of 19 years. Cancer diagnoses had occurred in 7.8% of participants at baseline, increasing to 16.9% by examination 5. During the study period, 24% of participants moved.

The distribution of BMIs and neighborhood characteristics at baseline, as well as 10-year changes in these characteristics, are shown in Web Table 1 (available at https://academic.oup.com/aje). Mean BMI was 28.3 at baseline, and it increased an average of 0.07 kg/m^2 (standard error, 0.03) over 10 years of follow-up. At baseline, average SFV density was 2.4 stores per square mile (0.9 stores per km^2), recreational density was 4.2 facilities per square mile (1.6 facilities per km^2), perceived healthy food availability was 3.5 units (possible range, 1–5), and mean perceived walking environment score at baseline was 3.9 units (possible range, 1–5). All neighborhood measures increased over time and were patterned by socioeconomic indicators and race/ethnicity.

At baseline, densities of SFV and recreational facilities were highly correlated (Spearman correlation (r_s) = 0.75), while for perceived healthy food availability and walking environment, correlation was moderate ($r_s = 0.52$). Within each domain, the density and perceived measures were moderately correlated (for SFV and perceived healthy food availability, $r_s = 0.54$; for

Table 1. Selected Characteristics of Participants at the Baseline and Follow-up Examinations, Multi-Ethnic Study of Atherosclerosis, 2000–2011

Variable	Examination									
	1 (n = 5,919)		2 (n = 5,773)		3 (n = 5,482)		4 (n = 5,085)		5 (n = 4,038)	
	%	Mean (SD)	%	Mean (SD)	%	Mean (SD)	%	Mean (SD)	%	Mean (SD)
Age, years		61.9 (10.1)		63.5 (10.1)		64.9 (10.0)		66.4 (9.9)		69.9 (9.4)
Male sex	47		47.2		46.9		46.6		46	
Race/ethnicity										
Non-Hispanic white	39.3		39.4		40.0		40.3		40.6	
Non-Hispanic Chinese	11.9		11.9		11.8		11.7		11.7	
Non-Hispanic black	27.4		27.4		27.3		27.1		26.7	
Hispanic	21.4		21.3		20.9		20.9		21.0	
Annual family income, dollars (per $1,000)		49.6 (34.1)		49.4 (34.4)		50.1 (34.6)		50.6 (34.6)		53.9 (35.6)
Currently married or living with a partner	61.8		61.8		62.2		62.5		59.4	
Education, years		13.2 (4.0)		13.2 (4.0)		13.3 (14.2)		13.3 (3.9)		13.5 (3.9)
Duration of residence in neighborhood at baseline, years		19.0 (14.2)		19.1 (14.2)		19.2 (14.2)		19.3 (14.0)		18.9 (13.5)
Diagnosed with cancer[a]	7.8		9.8		11.3		13.2		16.9	
Had moved since baseline	0.0		6.7		12.4		16.5		23.7	

Abbreviation: SD, standard deviation.
[a] Cancer diagnosis before or at the time of examination.

recreational density and perceived walking environment, r_s = 0.44). Correlations between changes in neighborhood characteristics over time were weaker: For SFV and recreational density, $r_s = 0.15$; for healthy food availability and walking environment, $r_s = 0.47$; for SFV and perceived healthy food availability, $r_s = 0.08$; and for recreational density and perceived walking environment, $r_s = -0.03$.

Table 2 shows associations of within-person changes in neighborhood characteristics with within-person changes in BMI after adjustment for covariates. Point estimates were in the hypothesized direction, but no statistically significant associations were observed for neighborhood variables. Associations did not change in domain models, which included SFV density and perceived healthy food availability or recreational resources and perceived walking environment. Results did not change in models considering all variables simultaneously (full model) or using standardized summary indices for healthy food and recreational environments (summary model).

Table 3 shows associations of within-person changes in neighborhood characteristics with within-person changes in BMI using fixed-effects models conditional on baseline BMI categories after adjustment for covariates. In separate analyses of each neighborhood variable (adjusted for potential time-varying confounders), increases in SFV density were associated with decreases in BMI among persons who were normal-weight at baseline and persons who were obese at baseline, but associations were not statistically significant. A 1-standard-deviation increase in perceived healthy food availability was associated with a 0.13-kg/m^2 (95% confidence interval (CI): −0.20, −0.07) decrease in BMI among participants who were obese at baseline. A 1-standard-deviation increase in recreational density was associated with a 0.32-kg/m^2 (95% CI: −0.45, −0.19) decrease in persons who were obese at baseline. However, an increase in recreational density was associated with an increase in BMI (0.16 kg/m^2, 95% CI: 0.04, 0.28) among persons with normal weight at baseline. Improvements in the perceived walking environment were associated with reductions in weight among persons who were overweight or obese, but only associations among overweight persons were statistically significant (mean differences were −0.08 kg/m^2 and −0.07 kg/m^2 for overweight and obese individuals, respectively).

Similar findings were observed in domain models, where results were simultaneously adjusted for perceived healthy food availability and SFV density and perceived walking environment and density of recreational resources. The pattern of association remained unchanged when the 4 neighborhood variables were included in the full model, except for perceived healthy food availability in overweight persons, which became statistically significant (0.07 kg/m^2, 95% CI: 0.01, 0.13). In summary measure models, a 1-standard-deviation increase in the food environment standardized index was associated with a 0.16-kg/m^2 (95% CI: −0.27, −0.06) decrease in BMI among participants with obesity at baseline; an increase in the physical activity standardized index was associated with a 0.13-kg/m^2 (95% CI: 0.02, 0.25) increase in BMI among participants with normal weight at baseline and with 0.13-kg/m^2 (95% CI: −0.24, −0.02) and 0.14-kg/m^2 (95% CI: −0.27, −0.01) decreases in BMI among participants who were overweight and obese at baseline, respectively.

The triple interaction of age at baseline, time elapsed since baseline, and neighborhood characteristics was not significant. Results from models restricted to participants who did not move during follow-up were similar to those of models including the complete sample.

Table 2. Within-Person Mean Difference in Body Mass Index[a] Associated With Within-Person Mean Differences in Neighborhood Healthy Food Environment and Neighborhood Recreational Environment[b], Multi-Ethnic Study of Atherosclerosis, 2000–2011

Neighborhood Characteristic	Model[c]											
	Single-Variable Model			Domain Models			Full Model			Summary Model		
	β[d]	95% CI	*P* Value	β[d]	95% CI	*P* Value	β[d]	95% CI	*P* Value	β[d]	95% CI	*P* Value
Density of SFV	−0.04	−0.15, 0.07	0.465	−0.04	−0.15, 0.07	0.482	−0.04	−0.15, 0.08	0.515	−0.02	−0.07, 0.04	0.601
Perceived healthy food availability	−0.02	−0.05, 0.02	0.412	−0.02	−0.05, 0.02	0.426	0.00	−0.05, 0.04	0.841			
Recreational resources	−0.01	−0.09, 0.06	0.694	−0.02	−0.09, 0.06	0.686	−0.01	−0.09, 0.06	0.741	−0.04	−0.11, 0.02	0.214
Perceived walking environment	−0.03	−0.07, 0.01	0.132	−0.03	−0.07, 0.01	0.131	−0.03	−0.08, 0.02	0.206			

Abbreviations: CI, confidence interval; SFV, supermarkets and fruit-and-vegetable markets.

[a] Weight (kg)/height (m)^2.

[b] Econometric fixed-effects models adjusted for time-varying covariates (income, marital status, and cancer diagnosis) and time-invariant covariates with time interaction (baseline age, race/ethnicity, sex, education, duration of residence (years) in neighborhood).

[c] Single-variable models introduced 1 neighborhood variable at a time; domain models included either food (SFV density, perceived healthy food availability) or physical activity (recreational resources, perceived walking environment) variables simultaneously; the full model included all 4 neighborhood variables in the same model; and the summary model included the *z* score index for the food and physical activity environments simultaneously.

[d] Neighborhood characteristics were rescaled to represent a 1-standard-deviation change (for SFV density, 3.6 stores per square mile (1.4 stores per km^2); for perceived healthy food availability, 0.6 units; for physical activity resources, 8.4 facilities per square mile (3.2 facilities per km^2); and for perceived walking environment, 0.3 units).

DISCUSSION

This study examined how contemporaneous changes in exposure to neighborhood physical environments were associated with changes in BMI over a median of 9.1 years of follow-up. In the full sample, changes in neighborhood characteristics were not associated with changes in BMI. However, there was some evidence that in persons who were obese (or in some cases overweight) at baseline, improvements in neighborhood food and physical activity environments were associated with reductions in BMI.

Improving neighborhood access to healthy food has been proposed as an intervention to improve dietary choices and reduce weight (37). The few studies that have investigated whether changes in food availability are related to changes in diet and BMI have had mixed results (23, 24, 38–40). In a previous MESA study restricted to nonobese participants at baseline, Auchincloss et al. (41) found that 1-standard-deviation higher perceived healthy food availability at baseline was associated with a 10% decrease in the 5-year obesity risk. Our study built on this finding by incorporating additional follow-up time, enriching neighborhood measures (including both survey-based and GIS measures), and using fixed-effects models that control for time-invariant person-specific characteristics. We found that increases in perceived healthy food availability were associated with decreases in BMI among participants with obesity at baseline. Associations of changes in BMI with changes in healthy food store density were in the expected direction, though not statistically significant—possibly reflecting limitations in the extent to which this measure actually captures access to healthy foods.

Few studies have evaluated how physical activity environments relate to BMI changes over time. Two longitudinal studies have shown that women moving to a neighborhood with higher housing density and better street patterns walk more (42, 43). In MESA, people living in neighborhoods that experienced an increase in street connectivity and in social and walking destinations reported an increase in walking for transportation (44). In addition, increased intensity of development (higher population and walking destinations and lower residential land use) was associated with slower increases or greater decreases in BMI (45). Only 1 longitudinal study analyzed the influence of access to recreational facilities on BMI changes: After 3 years of follow-up, women who lived within 2 km (1.25 miles) of a pool or gym at baseline experienced a 0.42-kg/m^2 decrease in BMI (46). We found that increases in recreational density were associated with decreases in BMI among persons who were obese at baseline, and improvements in the walking environment were associated with decreases in BMI, but only among overweight individuals. Paradoxically, increases in recreational density were associated with statistically significant increases in BMI among people who were normal-weight at baseline.

Heterogeneity of effects of exposures on BMI change across BMI categories is not unheard of in the dietary-change literature. In a recent fixed-effects analysis, middle-aged Swedish women with obesity at baseline experienced larger decreases in BMI when they changed to healthier diets, compared with women classified as normal or overweight at baseline, who experienced smaller decreases (47). Excess weight is produced by a positive energy imbalance caused by high energy intake or low energy expenditure (48). Thus, people with obesity at baseline should have worse diets and less physical activity than their normal-weight and overweight counterparts. It is reasonable to assume that these persons would be most affected by environmental change. However, further

Table 3. Within-Person Mean Difference in Body Mass Index[a] Associated With Within-Person Mean Differences in Neighborhood Healthy Food Environment and Neighborhood Recreational Environment, by Baseline Body Mass Index Category[b], Multi-Ethnic Study of Atherosclerosis, 2000–2011

Neighborhood Characteristic and BMI Category[d]	Model[c]											
	Single-Variable Model			Domain Models			Full Model			Summary Model		
	β[e]	95% CI	*P* Value	β[e]	95% CI	*P* Value	β[e]	95% CI	*P* Value	β[e]	95% CI	*P* Value
Density of SFV			0.354[f]			0.329[f]			0.315[f]			<0.001[f]
Normal	−0.09	−0.31, 0.13	0.421	−0.10	−0.32, 0.12	0.370	−0.14	−0.36, 0.08	0.209	0.03	−0.07, 0.14	0.534
Overweight	0.06	−0.12, 0.23	0.536	0.06	−0.12, 0.23	0.514	0.05	−0.12, 0.23	0.539	0.09	−0.01, 0.18	0.065
Obese	−0.12	−0.32, 0.07	0.210	−0.12	−0.32, 0.07	0.213	−0.10	−0.30, 0.09	0.314	−0.16	−0.27, −0.06	0.002
Perceived healthy food availability			<0.001[f]			<0.001[f]			<0.001[f]			
Normal	0.06	0.00, 0.13	0.067	0.06	0.00, 0.13	0.061	0.04	−0.03, 0.11	0.219			
Overweight	0.02	−0.03, 0.08	0.441	0.02	−0.03, 0.08	0.437	0.07	0.01, 0.13	0.032			
Obese	−0.13	−0.20, −0.07	<0.001	−0.13	−0.20, −0.07	<0.001	−0.13	−0.20, −0.06	<0.001			
Recreational resources			<0.001[f]			<0.001[f]			<0.001[f]			<0.001[f]
Normal	0.16	0.04, 0.28	0.010	0.15	0.03, 0.27	0.014	0.15	0.03, 0.28	0.013	0.13	0.02, 0.25	0.021
Overweight	0.05	−0.06, 0.17	0.365	0.05	−0.06, 0.17	0.356	0.04	−0.08, 0.15	0.517	−0.13	−0.24, −0.02	0.020
Obese	−0.32	−0.45, −0.19	<0.001	−0.32	−0.45, −0.19	<0.001	−0.30	−0.43, −0.17	<0.001	−0.14	−0.27, −0.01	0.030
Perceived walking environment			0.009[f]			0.014[f]			0.004[f]			
Normal	0.06	−0.01, 0.14	0.097	0.06	−0.02, 0.13	0.121	0.04	−0.04, 0.12	0.295			
Overweight	−0.08	−0.15, −0.02	0.014	−0.08	−0.15, −0.02	0.013	−0.13	−0.20, −0.05	0.001			
Obese	−0.07	−0.14, 0.01	0.092	−0.06	−0.13, 0.02	0.156	0.03	−0.06, 0.11	0.579			

Abbreviations: BMI, body mass index; CI, confidence interval; SFV, supermarkets and fruit-and-vegetable markets.

[a] Weight (kg)/height (m)^2.

[b] Econometric fixed-effects models adjusted for time-varying covariates (income, marital status, and cancer diagnosis) and time-invariant covariates with time interaction (baseline age, race/ethnicity, sex, education, duration of residence (years) in neighborhood). Differences across BMI categories were estimated from a term for interaction between BMI category and neighborhood exposure.

[c] Single-variable models introduced 1 neighborhood variable at a time; domain models included either food (SFV density, perceived healthy food availability) or physical activity (recreational resources, perceived walking environment) variables simultaneously; the full model included all 4 neighborhood variables in the same model; and the summary model included the *z* score index for the food and physical activity environments simultaneously.

[d] Normal-weight, BMI <25; overweight, BMI 25–29.9; obese, BMI ≥30.

[e] Neighborhood characteristics were rescaled to represent a 1-standard-deviation change (for SFV density, 3.6 stores per square mile (1.4 stores per km^2); for perceived healthy food availability, 0.6 units; for physical activity resources, 8.4 facilities per square mile (3.2 facilities per km^2); and for perceived walking environment, 0.3 units).

[f] *P* value for interaction term between neighborhood characteristics and BMI category at baseline.

analyses are required to confirm and investigate the reasons for these heterogeneous results.

Some limitations of this study must be mentioned. Baseline neighborhood measures were highly correlated. However, fixed-effect models rely on within-person variability, and within-person changes in various neighborhood exposures were only weakly or moderately correlated. Despite our having access to more detailed assessments of neighborhoods than prior work, our neighborhood measures were still limited; for example, SFV density is a crude measure of exposure compared with direct observations of store content (49, 50). Our survey measures probably included important measurement error and were interpolated based on the closest data available, limiting their time-varying nature. In particular, the walking environment scale had a low Cronbach's α and was less consistently associated with BMI than the healthy food access scale. We used the NETS data set (31) to estimate the density of healthy food stores and recreational resources; NETS is one of the most comprehensive establishment data sets and provides year-to-year information for longitudinal analyses (51). However, NETS has a fair sensitivity to detect food outlets compared with a field census (52), so we leveraged the information with Nielsen/TDLinx information on supermarkets (32, 33). Commercial data sets have been found to be limited in their ability to identify the presence of recreational venues; however, errors are considered to be random and small when counts are aggregated at an area level, biasing associations towards the null (53). Despite measurement challenges, our study was unique in the availability of time-varying survey and GIS data, which capture complementary aspects of the environment but have their own limitations.

The study of BMI changes in the elderly population is challenging, because weight tends to decrease with age due to loss of nonfat tissue (54). We included a term for interaction between baseline age and time in order to account for differences by baseline age in starting levels and trends over time. In addition, as people age they may relate to their neighborhood in a different manner, possibly leading to heterogeneity of effects. We tested this possibility by creating an interaction term involving neighborhood characteristic, baseline age, and time; this interaction was not significant. Additionally, neighborhood living experiences could be affected by disability or by living in a nursing home; data on these variables were not available, and thus we could not adjust for them.

As in any observational study, confounding by omitted or mismeasured variables remains a possibility. In a sensitivity analysis, we further adjusted for population density, and results remained unchanged. Self-selection has been a major concern in neighborhood and health studies (55, 56). We used fixed-effects models that adjusted for time-invariant factors related to neighborhood selection, but confounding by time-varying factors related to neighborhood choice and BMI trajectory remains a possibility. In sensitivity analyses, we excluded participants who moved to a new neighborhood during the study to reduce their influence. Among people who did not move, we found the same pattern of association. However, given the observational nature of our data, even our analytical approach cannot completely rule out time-varying confounding or selection/endogeneity.

In recent years, the study of neighborhoods and health has moved from a general framework to identifying the specific mechanisms through which neighborhoods influence health. Yet longitudinal evidence necessary to support policy interventions remains scant. Our study is among the first to comprehensively evaluate how changes in neighborhood environments measured using both reports and densities are related to longitudinal changes in BMI using analytical approaches that eliminate the possibility of confounding by time-invariant person-specific confounders. As such, it provides preliminary longitudinal evidence that neighborhood physical environments are related to BMI change among persons who are obese (and in some cases overweight), a substantial proportion of the US population. These neighborhood characteristics are susceptible to intervention. Although the impact on a given individual is likely to be small, environmental interventions may provide substantial health benefit by shifting the risk distribution of the entire population.

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REFERENCES

1. Flegal KM, Carroll MD, Kit BK, et al. Prevalence of obesity and trends in the distribution of body mass index among US adults, 1999–2010. *JAMA*. 2012;307(5):491–497.
2. Wadden TA, Webb VL, Moran CH, et al. Lifestyle modification for obesity: new developments in diet, physical activity, and behavior therapy. *Circulation*. 2012;125(9): 1157–1170.

3. Black JL, Macinko J. Neighborhoods and obesity. *Nutr Rev*. 2008;66(1):2–20.
4. Diez Roux AV, Mair C. Neighborhoods and health. *Ann NY Acad Sci*. 2010;1186:125–145.
5. Ludwig J, Sanbonmatsu L, Gennetian L, et al. Neighborhoods, obesity, and diabetes—a randomized social experiment. *N Engl J Med*. 2011;365(16):1509–1519.
6. Mujahid MS, Diez Roux AV, Shen M, et al. Relation between neighborhood environments and obesity in the Multi-Ethnic Study of Atherosclerosis. *Am J Epidemiol*. 2008;167(11): 1349–1357.
7. Jennings A, Welch A, Jones AP, et al. Local food outlets, weight status, and dietary intake: associations in children aged 9–10 years. *Am J Prev Med*. 2011;40(4):405–410.
8. Rundle A, Neckerman KM, Freeman L, et al. Neighborhood food environment and walkability predict obesity in New York City. *Environ Health Perspect*. 2009;117(3):442–447.
9. Bodor JN, Rice JC, Farley TA, et al. The association between obesity and urban food environments. *J Urban Health*. 2010; 87(5):771–781.
10. Galvez MP, Hong L, Choi E, et al. Childhood obesity and neighborhood food-store availability in an inner-city community. *Acad Pediatr*. 2009;9(5):339–343.
11. Inagami S, Cohen DA, Brown AF, et al. Body mass index, neighborhood fast food and restaurant concentration, and car ownership. *J Urban Health*. 2009;86(5):683–695.
12. Davis B, Carpenter C. Proximity of fast-food restaurants to schools and adolescent obesity. *Am J Public Health*. 2009; 99(3):505–510.
13. Sallis JF, Saelens BE, Frank LD, et al. Neighborhood built environment and income: examining multiple health outcomes. *Soc Sci Med*. 2009;68(7):1285–1293.
14. Lovasi GS, Neckerman KM, Quinn JW, et al. Effect of individual or neighborhood disadvantage on the association between neighborhood walkability and body mass index. *Am J Public Health*. 2009;99(2):279–284.
15. Frank LD, Andresen MA, Schmid TL. Obesity relationships with community design, physical activity, and time spent in cars. *Am J Prev Med*. 2004;27(2):87–96.
16. Kruger J, Carlson SA, Kohl HW. Fitness facilities for adults: differences in perceived access and usage. *Am J Prev Med*. 2007;32(6):500–505.
17. Mobley LR, Root ED, Finkelstein EA, et al. Environment, obesity, and cardiovascular disease risk in low-income women. *Am J Prev Med*. 2006;30(4):327–332.
18. Papas MA, Alberg AJ, Ewing R, et al. The built environment and obesity. *Epidemiol Rev*. 2007;29:129–143.
19. Bailey EJ, Malecki KC, Engelman CD, et al. Predictors of discordance between perceived and objective neighborhood data. *Ann Epidemiol*. 2014;24(3):214–221.
20. Lucan SC, Hillier A, Schechter CB, et al. Objective and self-reported factors associated with food-environment perceptions and fruit-and-vegetable consumption: a multilevel analysis. *Prev Chronic Dis*. 2014;11:E47.
21. Moore LV, Diez Roux AV, Brines S. Comparing perception-based and geographic information system (GIS)-based characterizations of the local food environment. *J Urban Health*. 2008;85(2):206–216.
22. Caspi CE, Kawachi I, Subramanian S, et al. The relationship between diet and perceived and objective access to supermarkets among low-income housing residents. *Soc Sci Med*. 2012;75(7):1254–1262.
23. Gibson DM. The neighborhood food environment and adult weight status: estimates from longitudinal data. *Am J Public Health*. 2011;101(1):71–78.
24. Block JP, Christakis NA, O'Malley AJ, et al. Proximity to food establishments and body mass index in the Framingham Heart Study offspring cohort over 30 years. *Am J Epidemiol*. 2011; 174(10):1108–1114.
25. Bild DE, Bluemke DA, Burke GL, et al. Multi-Ethnic Study of Atherosclerosis: objectives and design. *Am J Epidemiol*. 2002; 156(9):871–881.
26. Diez Roux AV, Mujahid MS, Hirsch JA, et al. The impact of neighborhoods on CV risk. *Glob Heart*. 2016;11(3): 353–363.
27. Mujahid MS, Diez Roux AV, Morenoff JD, et al. Assessing the measurement properties of neighborhood scales: from psychometrics to ecometrics. *Am J Epidemiol*. 2007;165(8): 858–867.
28. Echeverria SE, Diez-Roux AV, Link BG. Reliability of self-reported neighborhood characteristics. *J Urban Health*. 2004; 81(4):682–701.
29. Osypuk TL, Diez Roux AV, Hadley C, et al. Are immigrant enclaves healthy places to live? The Multi-Ethnic Study of Atherosclerosis. *Soc Sci Med*. 2009;69(1):110–120.
30. Raudenbush SW, Sampson RJ. Ecometrics: toward a science of assessing ecological settings, with application to the systematic social observation of neighborhoods. *Sociol Methodol*. 1999;29(1):1–41.
31. Walls & Associates. *National Establishment Time-Series (NETS) Database: 2012 Database Description*. Denver, CO: Walls & Associates; 2012. http://exceptionalgrowth.org/downloads/NETSDatabaseDescription2013.pdf. Accessed July 23, 2013.
32. Nielsen Company. *The Ultimate Source Retail Site Database—The Ultimate Source Trade Dimensions*. New York, NY: Nielsen Company; 2012.
33. Auchincloss AH, Moore KA, Moore LV, et al. Improving retrospective characterization of the food environment for a large region in the United States during a historic time period. *Health Place*. 2012;18(6):1341–1347.
34. Evenson KR, Huston SL, Wood JL, et al. Change in the prevalence of leisure activity with the number of activities recalled. *Med Sci Sports Exerc*. 2003;35(11):1882–1886.
35. Prospective Studies Collaboration; Whitlock G, Lewington S, et al. Body-mass index and cause-specific mortality in 900 000 adults: collaborative analyses of 57 prospective studies. *Lancet*. 2009;373(9669):1083–1096.
36. Allison PD. *Fixed Effects Regression Methods for Longitudinal Data Using SAS*. Cary, NC: SAS Institute, Inc.; 2005.
37. Story M, Kaphingst KM, Robinson-O'Brien R, et al. Creating healthy food and eating environments: policy and environmental approaches. *Annu Rev Public Health*. 2008;29: 253–272.
38. Cummins S, Petticrew M, Higgins C, et al. Large scale food retailing as an intervention for diet and health: quasi-experimental evaluation of a natural experiment. *J Epidemiol Community Health*. 2005;59(12):1035–1040.
39. Boone-Heinonen J, Gordon-Larsen P, Kiefe CI, et al. Fast food restaurants and food stores: longitudinal associations with diet in young to middle-aged adults: the CARDIA Study. *Arch Intern Med*. 2011;171(13):1162–1170.
40. Wrigley N, Warm D, Margetts B. Deprivation, diet, and food-retail access: findings from the Leeds 'food deserts' study. *Environ Plann A*. 2003;35(1):151–188.
41. Auchincloss AH, Mujahid MS, Shen M, et al. Neighborhood health-promoting resources and obesity risk (the Multi-Ethnic Study of Atherosclerosis). *Obesity (Silver Spring)*. 2012;21(3): 621–628.

42. Coogan PF, White LF, Adler TJ, et al. Prospective study of urban form and physical activity in the Black Women's Health Study. *Am J Epidemiol*. 2009;170(9):1105–1117.
43. Wells NM, Yang Y. Neighborhood design and walking. A quasi-experimental longitudinal study. *Am J Prev Med*. 2008; 34(4):313–319.
44. Hirsch JA, Moore KA, Clarke PJ, et al. Changes in the built environment and changes in the amount of walking over time: longitudinal results from the Multi-Ethnic Study of Atherosclerosis. *Am J Epidemiol*. 2014;180(8): 799–809.
45. Hirsch JA, Moore KA, Barrientos-Gutierrez T, et al. Built environment change and change in BMI and waist circumference: Multi-Ethnic Study of Atherosclerosis. *Obesity (Silver Spring)*. 2014;22(11):2450–2457.
46. Timperio A, Jeffery RW, Crawford D, et al. Neighbourhood physical activity environments and adiposity in children and mothers: a three-year longitudinal study. *Int J Behav Nutr Phys Act*. 2010;7:18.
47. Newby PK, Weismayer C, Akesson A, et al. Longitudinal changes in food patterns predict changes in weight and body mass index and the effects are greatest in obese women. *J Nutr*. 2006;136(10):2580–2587.
48. Chow CC, Hall KD. The dynamics of human body weight change. *PLoS Comput Biol*. 2008;4(3):e1000045.
49. Franco M, Diez-Roux AV, Nettleton JA, et al. Availability of healthy foods and dietary patterns: the Multi-Ethnic Study of Atherosclerosis. *Am J Clin Nutr*. 2009;89(3):897–904.
50. Farley TA, Rice J, Bodor JN, et al. Measuring the food environment: shelf space of fruits, vegetables, and snack foods in stores. *J Urban Health*. 2009;86(5):672–682.
51. Kaufman TK, Sheehan DM, Rundle A, et al. Measuring health-relevant businesses over 21 years: refining the National Establishment Time-Series (NETS), a dynamic longitudinal data set. *BMC Res Notes*. 2015;8:507.
52. Liese AD, Colabianchi N, Lamichhane AP, et al. Validation of 3 food outlet databases: completeness and geospatial accuracy in rural and urban food environments. *Am J Epidemiol*. 2010; 172(11):1324–1333.
53. Boone JE, Gordon-Larsen P, Stewart JD, et al. Validation of a GIS facilities database: quantification and implications of error. *Ann Epidemiol*. 2008;18(5):371–377.
54. Buffa R, Floris GU, Putzu PF, et al. Body composition variations in ageing. *Coll Antropol*. 2011;35(1):259–265.
55. Alviola PA 4th, Nayga RM Jr, Thomsen MR, et al. The effect of fast-food restaurants on childhood obesity: a school level analysis. *Econ Hum Biol*. 2014;12:110–119.
56. Drichoutis AC, Nayga RM Jr, Rouse HL, et al. Food environment and childhood obesity: the effect of dollar stores. *Health Econ Rev*. 2015;5:37.