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Original Contribution

Changes in the Built Environment and Changes in the Amount of Walking Over Time: Longitudinal Results From the Multi-Ethnic Study of Atherosclerosis

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Lack of longitudinal research hinders causal inference on the association between the built environment and walking. In the present study, we used data from 6,027 adults in the Multi-Ethnic Study of Atherosclerosis who were 45–84 years of age at baseline to investigate the association of neighborhood built environment with trends in the amount of walking between 2000 and 2012. Walking for transportation and walking for leisure were assessed at baseline and at 3 follow-up visits (median follow-up = 9.15 years). Time-varying built environment measures (measures of population density, land use, number of destinations, bus access, and street connectivity) were created using geographic information systems. We used linear mixed models to estimate the associations between baseline levels of and a change in each built environment feature and a change in the frequency of walking. After adjustment for potential confounders, we found that higher baseline levels of population density, area zoned for retail, social destinations, walking destinations, and street connectivity were associated with greater increases in walking for transportation over time. Higher baseline levels of land zoned for residential use and distance to buses were associated with less pronounced increases (or decreases) in walking for transportation over time. Increases in the number of social destinations, the number of walking destinations, and street connectivity over time were associated with greater increases in walking for transportation. Higher baseline levels of both land zoned for retail and walking destinations were associated with greater increases in leisure walking, but no changes in built environment features were associated with leisure walking. The creation of mixed-use, dense developments may encourage adults to incorporate walking for transportation into their everyday lives.

environment design; geographic information systems; leisure activities; longitudinal/prospective studies; neighborhoods; residence characteristics; transportation; walking

Abbreviations: GIS, geographic information systems; MESA, Multi-Ethnic Study of Atherosclerosis; SD, standard deviation.

Although walking has numerous short- and long-term health benefits with regard to cardiovascular disease (1, 2), diabetes (3, 4), and cancer (4), individual-level strategies to increase walking may be less effective within environments that do not support walking (5, 6). Many reviews have summarized the growing evidence of the associations of the built environment (land use, transportation, and design) with walking (7–9) and physical activity (7, 10–12). Almost all identified the dearth of longitudinal research as a barrier to causal inference (7–14), and leveraging longitudinal data has been identified as a crucial component of the research agenda (7, 13–15).

In several studies, investigators relied on residential relocation data to investigate how changes in features of the physical environment are related to health behaviors (16–26). The results suggested that neighborhood changes were associated with walking (18, 21–25), bicycling (16), travel behavior (18–20), and physical activity level (17, 18, 24, 26). Few studies have had longitudinal assessments of the built environment, and little research has been done to investigate the associations between neighborhood change and physical activity level or other health-related outcomes (28–33). These studies used county-level data (31), census data (28), or self-reported perceptions (29, 32) to determine measures of the neighborhood environment. This is problematic, as using county-level data, census data, or self-reports may lead to misclassification of the built environment exposure (33, 35). Furthermore, the follow-up period in some studies was less than 1 year (29, 32), and the built environment changes that were investigated were small-scale design or commercial features (i.e., aesthetics, traffic volume, or gasoline prices) rather than large-scale land-use and transportation features. Additional longitudinal evidence is needed to explore the role that objectively measured environmental features play in shaping changes in walking over time.

In the present study, we used population-based data to investigate the association of walking with features of the built environment, including population density, zoned land-use patterns, access to destinations, street connectivity, and access to buses in a multi-ethnic and geographically diverse cohort of adults. We investigated changes that occurred around residents rather than relying only on residential relocation. Time-varying measures, which were created using geographic information systems (GIS), allowed us to determine which built environment elements might be most influential in affecting changes in walking patterns. We hypothesized that higher baseline levels of and subsequent increases in land-use mix, population density, number of destinations, street connectivity, and access to public transportation would be associated with increases over time in walking for transportation (hereafter referred to as transport walking). However, we hypothesized that these features would have little influence on changes over time in leisure walking, which may be influenced by aesthetic quality, green space, or other design elements.

METHODS

Study sample

Participants came from the Multi-Ethnic Study of Atherosclerosis (MESA), a study of 6,814 adults 45–84 years of age without clinical cardiovascular disease at baseline (36). Participants were recruited between July 2000 and August 2002 from 6 sites (Baltimore, Maryland; Chicago, Illinois; Forsyth County, North Carolina; Los Angeles, California; New York, New York; and St. Paul, Minnesota). After a baseline examination, participants attended 4 follow-up examinations (examination 2 was conducted between July 2002 and February 2004; examination 3, between January 2004 and September 2005; examination 4, between September 2005 and May 2007; and examination 5, between April 2010 and February 2012) (36). Neighborhoods were characterized using GIS and linked to MESA households by the MESA Neighborhood Study. All addresses were geocoded using TeleAtlas EZ-Locate web-based geocoding software (Tele Atlas North America, Inc., Lebanon, New Hampshire) and were included if the geocoding was accurate to the street (99.9%) or zip code+4 (0.1%) level. Of the MESA participants, 6,191 participated in the MESA Neighborhood Study, and 6,027 had accurately geocoded information, completed at least 2 examinations, and had complete information on walking outcomes or built environment at examinations that they attended. The study was approved by institutional review boards at each site, and all participants gave written informed consent.

Walking

An interviewer-administered questionnaire adapted from the Cross-Cultural Activity Participation Study (37–40) was used to assess physical activity level at examinations 1, 2, 3, and 5 (physical activity was not assessed at examination 4). Walking was determined to be either transport walking (i.e., walking to get to places such as to the bus, car, work, or store) or leisure walking (i.e., walking for leisure, pleasure, or social reasons, during work breaks, or with the dog). Participants were asked whether they had engaged in each type of walking during a typical week in the past month, and if so, on how many days per week and for how much time per day. These data were combined to estimate the minutes of transport and leisure walking per week over the previous month for each participant. For ease of interpretation and because violations of normality did not meaningfully affect inferences, walking was examined as a continuous variable in the original metric (41). We performed a sensitivity analysis using log-transformed walking measures and one that was restricted to participants who walked 12 hours/day or fewer; the results showed the same directional patterns and significance (data not shown).

Neighborhood built environment

On the basis of previous frameworks (42), we investigated 5 built environment domains: population density, zoned land-use patterns, access to destinations, public transportation, and street connectivity (Table 1). Elements of these domains may make it easier for people to complete daily tasks on foot, subsequently increasing transport walking and physical activity levels. Data were obtained from regional governments or commercially available business listings and processed using ArcGIS 10.1 (Esri, Redlands, California). Neighborhoods were defined by fitting Euclidean buffers around participants' addresses. Primary results are reported for Euclidean buffers with a 1-mile radius because areas of this size are thought to best capture the relationship between built environment characteristics and walking in MESA's diverse urban contexts. Euclidean buffers with radii of a half mile and 3 miles were examined in sensitivity analyses; results for all 3 buffer sizes were consistent (results for the half-mile Euclidean buffers are shown in Web Table 1, available at http://aje.oxfordjournals.org/). Population density was measured using population counts from the US Census. Land-use parcel files were obtained from local planning departments, city governments, and regional entities. Two investigators independently classified parcels into 2 mutually exclusive land-use categories (retail and residential) based on land-use codes. Areas with higher percentages of land zoned for retail use and lower percentages zoned for residential use were considered to have a higher land-use mix. Social and walking

Table 1. Built Environment Measures and Data Calculation Method by Year of Availability and Site, Multi-Ethnic Study of Atherosclerosis, 2000–2013

Domain	Measure	Description	Method of Calculation	Dates for Which Data Were Available (Site[a])
Population	Population density	Population per square mile within a 1-mile Euclidean buffer of a participant's home.	Population from the US Census at the block level divided by the land area. When a block was not fully contained within a participant's neighborhood Euclidean buffer, its population density was assumed to be uniform within each block.	2000 (all sites[a]); 2010 (all sites[a])
Zoned land use	Retail area	Percentage of the area zoned for retail in a 1-mile Euclidean buffer around a participant's home.	Land area zoned as retail divided by total land area within a 1-mile Euclidean buffer. When a parcel was not fully contained within a participant's neighborhood buffer, only the area of the parcel contained within the buffer was included.	2001 (CA, IL); 2002 (MD, NY); 2003 (NY); 2004 (NY); 2005 (CA, IL, NC); 2006 (MN; NY); 2008 (CA, MD); 2009 (MN[b]); 2010 (MN[b], NC); 2011 (NY)
	Residential area	Percentage of the area zoned for residential use in a 1-mile Euclidean buffer around a participant's home.	Land area zoned as residential divided by total land area within a 1-mile Euclidean buffer. When a parcel was not fully contained within a participant's neighborhood buffer, only the area of the parcel contained within the buffer was included.	
Destinations	Social destinations	Simple density[c] of social destinations (count per square mile) within a 1-mile Euclidean buffer around a participant's home.	Number of destinations that facilitate social interaction and promote social engagement (e.g., beauty shops and barbers, performance-based entertainment, participatory entertainment, stadiums, amusement parks and carnivals, membership sports and recreation clubs, libraries, museums, art galleries, zoos, aquariums, civil and political clubs, religious locations, and dining places) divided by the land area within a 1-mile Euclidean buffer.	2000–2010 (all sites[a])
	Walking destinations	Simple density[c] of walking destinations (count per square mile) within a 1-mile Euclidean buffer around a participant's home.	Number of common walking destinations (e.g., post offices, drug stores and pharmacies, banks, food stores, coffee shops, and restaurants) divided by the land area within a Euclidean 1-mile buffer.	
Public transportation	Distance to bus stops	Euclidean distance (in miles) between a participant's home and the nearest bus route.	Euclidean distance (in miles) was calculated between a participant's home and the closest bus line.	2001 (NC); 2005 (CA, IL, MN); 2007 (CA); 2009 (MD, MN, NC); 2010 (CA, NY); 2012 (CA)
Street connectivity	Network ratio	The proportion of a buffer created using Euclidean distance that is covered by a buffer created using network distance.	The area of a 1-mile network buffer divided by the area of a 1-mile Euclidean buffer around a participant's home. The ratio varies between 0 and 1, with 0 meaning none of the area can be reached through the road network and 1 meaning the entire area can be reached through the street network. One denotes the highest level of connectivity.	2003 (all sites[a]); 2012 (all sites[a])

Abbreviations: CA, California; IL, Illinois; MD, Maryland; MN, Minnesota; NC, North Carolina; NY, New York.

[a] Counties included in the Multi-Ethnic Study of Atherosclerosis sites were as follows: California: Ventura, Los Angeles, Orange, Riverside, and San Bernadino Counties; Illinois: Kane, DuPage, Cook, and Will Counties; Maryland: Baltimore City and Baltimore County; Minnesota: Anoka, Hennepin, Ramsey, Washington, Carver, Scott, and Dakota Counties; North Carolina, Forsyth County; New York: Queens, Kings, New York, and Bronx Counties.

[b] Washington County, Minnesota, is the only county in Minnesota for which data for 2009 are available. The remaining Minnesota counties have data for 2010.

[c] Simple and kernel densities of destinations within each Euclidean buffer were calculated, but measures were highly correlated (Pearson correlation coefficients were 0.98 for social destinations and 0.97 for walking destinations; both $P < 0.0001$), so only simple densities are shown.

destinations were identified using Standard Industrial Classification codes and data obtained from the National Establishment Time Series database (43, 44). Files containing data on bus routes were obtained from local planning departments, city governments, and regional entities. Trains and subways were excluded because of a lack of change in rail infrastructure at most sites during the study. Street calculations were performed using StreetMap and StreetMap Premium for ArcGIS (Esri). StreetMap files may be less accurate than data provided by municipalities (45), but they are uniform across cities. Addresses of MESA participants at each examination were assigned to the data collected closest to the time of examination within that site. For participants who moved outside of the study areas, we had no data on built environment measures after the move. Change in the built environment was calculated as the difference between examination and baseline measures.

Covariates

Potential confounders were identified from the literature. Information on age, sex, race/ethnicity (Hispanic, non-Hispanic white, non-Hispanic Chinese, or non-Hispanic black), and educational level (less than a high school diploma, high school diploma/general education development certificate but less than college, or college degree or higher) was obtained using an interviewer-administered questionnaire. Information on time-varying measures of income, employment status (working at least part time vs. not working at least part time, which included employed but on leave, unemployed, and retired), marital status (currently married or living with a partner vs. other, which included widowed, divorced, separated, and never married), household car ownership (no car ownership vs. any car ownership), self-rated health compared with others of the same age (better, same, or worse), and arthritis (flare-up in past 2 weeks, yes vs. no) was also collected through interviewer-administered questionnaires at each examination. Each participant selected the 1 of 14 categories that best represented his or her total combined family income, and the midpoint of the selected category in US dollars was assigned as the continuous income. Cancer diagnosis, another time-varying measure, was defined as a hospitalization due to cancer any time before the examination self-reported by patients and verified through a review of death certificates or medical records (*International Classification of Diseases, Ninth Revision* codes 140–208.92). Time-varying body mass index was calculated as measured weight (in kilograms) divided by measured height (in meters) squared. If information was missing on marital status, self-reported health, and car ownership, we used data from the examination closest to the one in question.

Statistical analyses

We used descriptive analyses to contrast participant characteristics and walking levels across examinations. We also described mean levels of the baseline built environment measures and average changes per 5 years for the full sample and by site.

We used linear mixed models to estimate the associations of changes in the built environment with changes in transport and leisure walking over follow-up. We modeled repeated walking measures on each participant as a function of baseline built environment measures, time in years since baseline (to capture the change in walking behavior over follow-up), term for the interaction between baseline built environment measures and time (potential impact of baseline built environment on changes in walking over time), change in the built environment since baseline, a term for the interaction between change in the built environment and time (to capture how changes in the built environment affect changes in waking over the follow-up), and both time-invariant (site, baseline age, sex, race/ethnicity, and educational level) and time-varying (income, employment, marital status, car ownership, cancer, arthritis, body mass index, and health status) confounders.

All models included a random intercept and random time slope for each participant to allow the baseline responses and the time slope to vary between individuals. A random intercept for neighborhood was unnecessary because there was an essentially null correlation within census tracts. Because there was high correlation and collinearity between built environment measures, each measure was modeled separately. When time-varying population density was added to all other models in the sensitivity analyses, the results remained consistent (data not shown). Participants who were older had different overall walking/time trends than did those who were younger; similarly, different overall walking/time trends were found for different racial/ethnic groups. All estimates of trends in walking were adjusted to the mean age and to the racial/ethnic composition of the sample at baseline. Coefficients from the final model were used to compare changes in walking over time for different levels of baseline built environment measures and changes in built environment. All variables were mean-centered and scaled so that a 1-unit increase was equivalent to 1 standard deviation. Analyses were conducted in 2013 using SAS, version 9.2 (SAS Institute, Inc., Cary, North Carolina).

RESULTS

Participant characteristics

Follow-up time ranged from 1.11 years (completing only examinations 1 and 2) to 11.38 years (completing all 5 examinations), with a median follow-up time of 9.15 years (interquartile range, 6.13; mean = 7.43 years; standard deviation (SD), 3.05). The number of moves ranged from 0 to 8; 69.1% of participants never moved, 20.6% moved only once, and 10.3% moved 2 or more times. We performed sensitivity analyses that were adjusted for the number of moves and the results did not meaningfully change (data not shown). Participant age at baseline ranged from 45 to 84 years, with a mean of 62.0 (SD, 10.2) years (Table 2).

Built environment characteristics

At baseline, participants' neighborhoods were relatively dense (mean population density = 15,720 (SD, 19,347) people per square mile; social destination density = 91.1 (SD, 118.9) per square mile; and walking destination density = 56.5 (SD,

Table 2. Selected Characteristics of Participants at Baseline and Follow-up Examinations, Multi-Ethnic Study of Atherosclerosis, 2000–2012

Characteristic	Baseline (*n* = 6,027)		Examination 2 (*n* = 5,901)		Examination 3 (*n* = 5,636)		Examination 5 (*n* = 4,166)	
	Mean (SD)	%	Mean (SD)	%	Mean (SD)	%	Mean (SD)	%
Time elapsed since baseline, years			1.6 (0.3)		3.2 (0.3)		9.4 (0.5)	
Age, years	62.0 (10.2)		63.6 (10.1)		65.0 (10.0)		70.0 (9.5)	
Female sex		52.6		52.6		52.9		53.5
Race/ethnicity								
Non-Hispanic white		39.1		39.2		39.6		40.4
Non-Hispanic black		27.4		27.2		27.2		26.4
Non-Hispanic Chinese		11.9		11.9		11.9		11.8
Hispanic		21.7		21.6		21.3		21.4
Educational level								
High school/GED or less		35.0		34.8		34.4		32.1
Some college		28.5		28.4		28.7		29.0
BA or above		36.5		36.8		36.9		38.9
Income, $ (in thousands)	49.9 (34.1)		49.5 (34.4)		50.3 (34.7)		53.8 (35.6)	
Currently employed		54.2		51.9		50.8		43.5
Currently married		61.5		61.5		61.8		58.8
Own at least 1 car		82.5		82.6		82.0		83.7
Diagnoses with cancer		7.9		9.7		11.2		15.2
Arthritis flare-up in past 2 weeks		12.6		11.5		13.2		19.4
Body mass index[a]	28.3 (5.4)		28.3 (5.5)		28.3 (5.5)		28.4 (5.7)	
Self-rated health compared with others								
Better		60.3		60.5		60.2		59.3
Same		34.8		34.6		34.9		35.5
Worse		5.0		4.8		4.9		5.2
Walking, minutes/week[b]								
Transportation	150.0 (375.0)		105.0 (280.0)		120.0 (285.0)		150.0 (395.0)	
Leisure	90.0 (240.0)		90.0 (225.0)		90.0 (240.0)		120.0 (300.0)	

Abbreviations: BA, bachelor of arts degree; GED, general education development degree; SD, standard deviation.
[a] Weight (kg)/height (m)^2.
[b] Values are expressed as median (interquartile range).

75.6) per square mile) (Table 3). On average, participants' neighborhoods had some mixed land-use zoning (mean percentage zoned for retail = 6.0% (SD, 4.3); mean percentage zoned for residential use = 46.5% (SD, 18.1)) and good access to public transportation (mean distance to bus = 0.28 (SD, 0.77) miles). Over time, population density, percentage of land zoned for retail, percentage of land zoned for residential use, and density of walking destinations decreased, whereas density of social engagement destinations and distance to bus increased. Baseline levels of built environment measures and changes in those measures varied across sites.

Changes in walking over time

Among participants at baseline, the median amount of time spent walking for transportation was 150.0 minutes/week (interquartile range, 375.0) and the amount spent walking for leisure was 90 minutes/week (interquartile range, 240). Using the baseline race/ethnicity distribution and mean age of the sample and after adjustment for other individual-level covariates, transport walking increased 1.97 minutes/week each year (95% confidence interval: 0.33, 3.61) and leisure walking increased 3.04 minutes/week each year

Table 3. Built Environment Features at Baseline (2000) and Mean Change Per Each 5-Year Increment, Overall and by Site, Multi-Ethnic Study of Atherosclerosis, 2000–2012

Feature	Overall		Study Site: Los Angeles, California		Chicago, Illinois		Baltimore, Maryland		St. Paul, Minnesota		Forsyth County, North Carolina		New York, New York	
	Baseline Mean (SD)	Mean Change[a] (SE)	Baseline Mean (SD)	Mean Change[a] (SE)	Baseline Mean (SD)	Mean Change[a] (SE)	Baseline Mean (SD)	Mean Change[a] (SE)	Baseline Mean (SD)	Mean Change[a] (SE)	Baseline Mean (SD)	Mean Change[a] (SE)	Baseline Mean (SD)	Mean Change[a] (SE)
Population density	15,720 (19,347)	−269.8 (23.9)	10,656 (4,721)	−303.7 (44.6)	13,929 (6,008)	−303.9 (52.4)	6,960 (4,498)	−271.1 (34.2)	4,725 (1,601)	−147.5 (16.0)	1,622 (845)	72.8 (7.5)	55,485 (13,673)	−658.2 (114.7)
% of land zoned for retail	6.0 (4.3)	−0.9 (0.0)	5.7 (2.9)	−0.1 (0.0)	7.5 (3.4)	−0.1 (0.0)	8.6 (7.2)	−4.1 (0.1)	5.2 (3.2)	−2.3 (0.1)	2.1 (2.3)	−0.1 (0.0)	6.6 (2.2)	0.5 (0.0)
% or land zoned for residential use	46.5 (18.1)	−2.5 (0.1)	48.3 (12.5)	−1.5 (0.1)	39.0 (19.3)	0.5 (0.1)	55.3 (13.2)	0.2 (0.2)	52.5 (12.4)	−6.9 (0.2)	61.0 (15.4)	−8.3 (0.2)	24.9 (5.2)	1.0 (0.1)
Social destinations	91.1 (118.9)	14.1 (0.3)	57.3 (41.6)	5.9 (0.4)	132.8 (133.9)	20.4 (1.1)	56.6 (65.3)	4.7 (0.5)	29.2 (16.2)	−0.6 (0.2)	13.0 (11.9)	2.0 (0.1)	251.4 (144.0)	48.6 (1.2)
Walking destinations	56.5 (75.6)	−0.9 (0.2)	38.6 (36.2)	−1.7 (0.3)	70.2 (73.8)	−4.6 (0.5)	26.0 (35.6)	−2.2 (0.3)	14.5 (10.0)	−0.5 (0.1)	6.2 (6.5)	0.1 (0.1)	178.6 (74.6)	3.9 (0.7)
Distance to bus, miles	0.28 (0.77)	0.15 (0.02)	0.14 (0.15)	0.84 (0.09)	0.08 (0.12)	0.18 (0.06)	0.21 (0.45)	0.08 (0.03)	0.12 (0.14)	0.04 (0.01)	1.16 (1.60)	−0.30 (0.02)	0.04 (0.05)	0.02 (0.01)
Network ratio	0.42 (0.15)	0.00 (0.00)	0.47 (0.12)	−0.01 (0.00)	0.47 (0.10)	0.00 (0.00)	0.40 (0.16)	0.00 (0.00)	0.45 (0.11)	−0.01 (0.00)	0.23 (0.12)	0.00 (0.00)	0.50 (0.09)	0.01 (0.00)

Abbreviations: SE, standard error; SD, standard deviation.

[a] Mean change was determined using a multilevel random-effects model of time in years regressed on change in each built environment measure since baseline, with random intercepts for each participant.

(95% confidence interval: 1.65, 4.42). Higher baseline age was associated with a less-pronounced increase, such that no increase (or decrease) in walking over time was observed in the oldest subjects. The mean differences in annual change per each 1-standard-deviation increase in baseline age were −3.20 minutes/week (95% confidence interval: −4.86, −1.54) for transport walking and −4.65 minutes/week (95% confidence interval: −6.04, −3.25) for leisure walking. Hispanic ethnicity was associated with a more pronounced increase in transport walking, and non-Hispanic white and Chinese participants experienced a more pronounced increase in leisure walking (data not shown).

Figure 1 and Web Table 2 show the associations of the baseline built environment measures and changes in the built environment with annual changes in transport walking after adjustment for individual-level covariates. Higher baseline levels of population density, land zoned for retail, social destinations, walking destinations, and network ratio (see Table 1 for definition) were associated with greater increases (or less pronounced decreases) in transport walking. The mean differences in annual change in transport walking per each 1-standard-deviation increase in baseline levels were 4.13, 3.23, 2.78, 4.35, and 1.76 minutes/week, respectively. In contrast, a higher percentage of land zoned for residential use and greater distance to a bus route were associated with less pronounced increases (or greater decreases) in transport walking. The mean differences in annual change in transport walking per each 1-standard-deviation increase in baseline levels were −3.39 and −2.26 minutes/week, respectively. Increases over time in percentage of land zoned for retail, number of social destinations, number of walking destinations, and network ratio were also associated with increases in transport walking (mean differences in annual change per each 1-SD increase in built environment measures: 1.73, 3.53, 3.33, and 1.81 minutes/week, respectively), although only changes in the number of social destinations, the number of walking destinations, and network ratio were significant at the level of $P = 0.05$.

Figure 2 and Web Table 2 show the associations of baseline measures of and changes in built environment characteristics with annual changes in leisure walking after adjustment for individual-level covariates. Higher baseline levels of land zoned for retail and walking destinations were associated with greater increases (or less pronounced decreases) in leisure walking; the mean differences in annual change in leisure walking per each 1-standard-deviation increase in baseline levels were 1.83 and 1.72, respectively. None of the built environment changes were associated with changes in leisure walking at the level of $P = 0.05$.

DISCUSSION

The present study is one of the first in which the associations between time-varying GIS-based built environment measures and changes in walking were examined. In this multi-ethnic and geographically diverse cohort of adults, changes in walking were influenced by both baseline levels of and changes in built environment features. We found smaller associations for street connectivity and bus access than for population density, land-use zoning, and access to

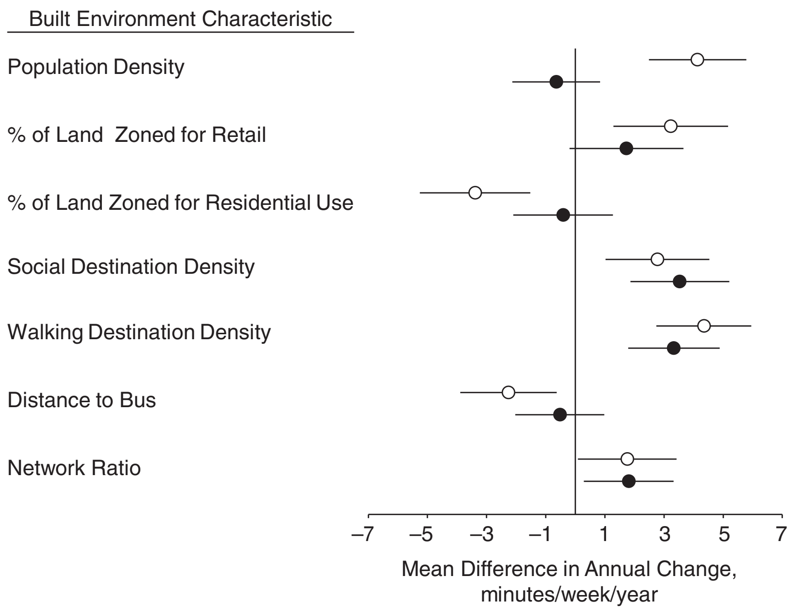

Figure 1. Associations of baseline measures of and changes in built environment characteristics with annual changes in walking for transportation, Multi-Ethnic Study of Atherosclerosis, 2000–2012. The open circles denote the mean difference in annual walking (minutes per week per year) for a 1-standard-deviation higher score for the built environment measure at baseline. The black circles denote the mean difference in annual walking (minutes per week per year) for a 1-standard-deviation increase in the change in the built environment feature over time. Estimates were from models that were controlled for baseline built environment measures, changes in built environment, time (in years), baseline age, an interaction between baseline age and time, sex, race, an interaction between race and time, educational level, income, employment, marital status, car ownership, cancer, arthritis, body mass index, self-rated health compared with others, and site.

destinations. Higher baseline levels of population density, land zoned for retail, access to destinations, access to buses, and street connectivity were associated with greater increases in the amount of walking over time. Increases in access to destinations and street connectivity were also associated with greater increases in the amount of walking over time. Built environment features had more influence on changes in transport walking than on changes in leisure walking. Higher baseline levels of access to retail and walking destinations were associated with greater increases in leisure walking over time, but built environment changes were not associated with leisure walking changes.

In contrast to cross-sectional studies, our longitudinal analyses capitalize on time-varying information to establish whether built environment features are associated with changes in walking. Our results were consistent with those from previous residential relocation research, which indicated that moving to an area with higher walkability (18, 46), a lower sprawl index (24), higher street connectivity (23), increased access to destinations (17, 19–22), and higher population density (16) was associated with increases in walking or physical activity. Our analyses add to existing work by showing these associations in a mixed sample that included a large proportion of subjects who did not move. Demonstrating that associations are also present in this population is important because analyses based on people who move may be affected by unobservable preferences related to both choice of residential location and behavior. Our finding that associations are present in a diverse sample supports the possible effectiveness of environmental interventions in the population at large.

The present analysis helps to identify the relative importance of each built environment feature with regard to walking by investigating specific changes in built environment measures rather than changes in an overall summary measure of walkability. However, given the high correlation between features, we were unable to identify the individual associations of each feature with walking independent from those of all other features. Our results suggest that a higher percentage of land zoned for retail, a higher population density, and more access to destinations were more strongly and more consistently associated with changes in walking than were street connectivity and bus access. The importance of the density of destinations that we found is consistent with results from cross-sectional research (8, 47) and previous work on the perceived environment, which showed that access to mixed services was related to higher levels of physical activity (16, 17, 21, 22, 29). Future analyses should explore which specific types of destinations encourage more walking.

Baseline levels of the built environment measures were slightly more strongly associated with changes in walking than were changes in the built environment. Initial environmental conditions may influence subsequent changes in walking over time, whereas relatively short-term changes from the initial environment may have smaller influences on these changes in walking over time. Selection bias remains a possible explanation for these baseline results. Persons who want to be active and who are likely to increase

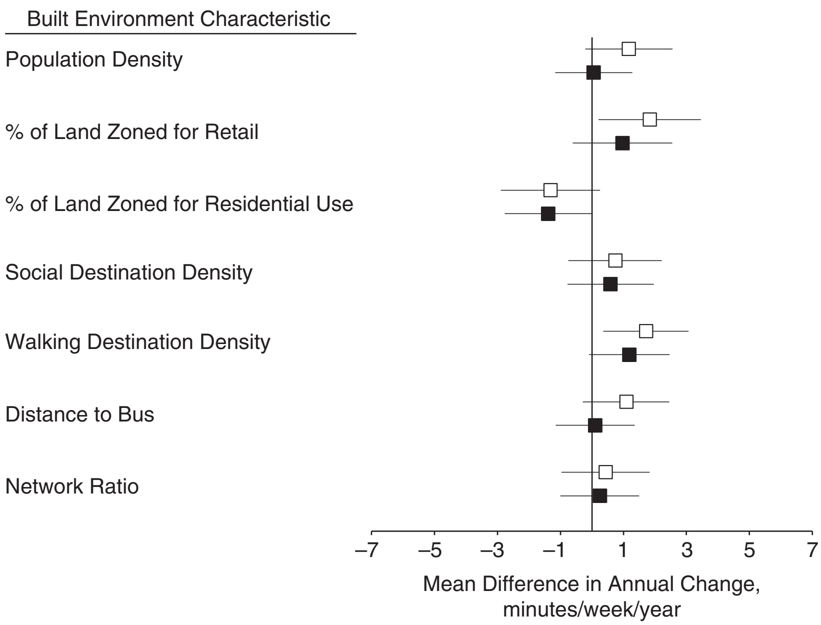

Figure 2. Associations of baseline measures of and changes in built environment characteristics with annual changes in walking for leisure, Multi-Ethnic Study of Atherosclerosis, 2000–2012. The open squares denote the mean difference in annual walking (minutes per week per year) for a 1-standard-deviation higher score for the built environment measure at baseline. The black squares denote the mean difference in annual walking (minutes per week per year) for a 1-standard-deviation increase in the change in the built environment feature over time. Estimates were from models that were controlled for baseline built environment measures, changes in built environment, time (in years), baseline age, an interaction between baseline age and time, sex, race, an interaction between race and time, educational level, income, employment, marital status, car ownership, cancer, arthritis, body mass index, self-rated health compared with others, and site.

the amount of walking that they do over time may have chosen to live in more walkable environments at the outset of this study. However, because all models controlled for the association of the baseline built environment measures with initial walking (and included a random intercept for each person), the associations between baseline levels and change in walking that we found were not confounded by higher walking levels among persons who lived in more supportive environments at baseline.

Although our baseline built environment results support the idea that built environment features may affect subsequent changes in walking behaviors, they cannot directly demonstrate that changes in the built environment are related to changes in walking. In contrast, results from our analyses investigating the associations of built environment changes with changes in walking behaviors help to establish which neighborhood modifications could improve walking levels in existing residents. Changes in the number of social destinations, the number of walking destinations, and street connectivity were associated with changes in the amount of transport walking, even after accounting for the relationship between initial levels and subsequent changes in walking. These findings highlight the importance of these built environment features for urban planning policy interventions. However, questions remain about how much or what types of changes are necessary to increase physical activity levels. Future work should attempt to identify potential thresholds or physical forms of these features that optimize health behavior changes.

The lack of associations between changes in the built environment and changes in leisure walking is consistent with previous cross-sectional research (48–52) and longitudinal research (46), as well as research on the specific built environment measures investigated. The measures used in the present study omit elements that may encourage leisure walking, such as aesthetic quality, level of street traffic, or the availability of sidewalks and walking trails. Differences in the associations of built environment features with transport and leisure walking emphasize the significance of pairing environmental measures with specific behaviors when studying associations between the environment and health behaviors (8, 53). The associations of baseline levels of land zoned for retail and access to destinations with leisure walking may reflect an interesting environment (e.g., one conducive to window shopping). Further quantitative and qualitative research should investigate this relationship.

The appropriate geographic context in which to investigate the association between the built environment and walking remains unclear. The use of Euclidean buffers centered around participants' homes is less likely to introduce spatial misclassification than is the use of arbitrarily defined geographic areas (33, 35). However, the geographic scale most relevant to walking may vary by location type, neighborhood characteristics, specific outcome, or individual characteristics (54, 55). Previous research indicated that associations may vary depending on the size and shape of the buffers (56). Sensitivity analyses in which we used half-mile and 3-mile buffers showed results that were similar but of different magnitudes. The use of residential addresses ignores the influence of other locations, such as work. Research comparing home and work built environments indicates that there are typically differing influences of each geographic location (57, 58). Euclidean buffers may represent accessible areas less accurately than street network buffers (33, 59). Novel global positioning systems methods to identify individual activity spaces may further reduce potential geographic uncertainties and misspecification of the relevant spatial context (60–62).

Limitations

Limitations of the present study include self-reported information on walking and potential residual confounding by individual-level factors or other built environment features. There was low power to examine the association between changes in the built environment and changes in walking over time within cities or to compare all built environment features simultaneously in one model. However, sensitivity analyses in which we allowed changes in walking over time to vary by site or added population density to the models showed consistent results. Effect modification by demographic characteristics was not addressed in these analyses and may yield potentially interesting and useful results.

Several limitations are inherent to the built environment data used. First, we relied on land-use and transportation information collected from various sources in different years. Second, using parcel area to determine land-use patterns penalizes vertical development (e.g., this method treats a parcel with a 4-story building the same as a parcel with a 1-story building). Third, existing land uses that are inferred from zoning information may not accurately reflect what is on the ground. Finally, Euclidean distances may not represent the distance required to travel along a street network.

Self-selection continues to potentially threaten the study's internal validity. We were unable to utilize a fixed-effects approach (63) that accounted for all person-specific characteristics because of restricted statistical efficiency that resulted from limited within-person variability in walking. Results from the present study may not be generalizable to younger samples or other cities. This sample of adults had a higher percentage of persons engaged in walking and potentially higher increases in walking than national samples (64), which could have affected their responsiveness to built environment features. Loss to follow-up may have contributed to this, although participants who attended the final examination had baseline levels of transport walking that were similar to those of persons who did not attend all examinations. Persons who attended the final examination did, however, have higher baseline levels of leisure walking than did those who did not attend all examinations. These patterns are consistent with data that suggested that walking replaces vigorous physical activity as people age (65).

Conclusion

The present study illustrates the longitudinal association between GIS-based built environment measures and changes in walking over time. Baseline measures of and changes in the built environment were associated with positive changes in the amount of transport walking. Although higher baseline levels of several built environment features were associated with increases walking for leisure over time, changes in those features were not.

Walking is the most common leisure activity among adults, and it can be an important component of physical activity (66–69). In April 2013, the United States Surgeon General announced the "Every Body Walk!" campaign (http://www.everybodywalk.org/) to promote walking as a simple and effective form of physical activity. The success of public health campaigns is likely to be influenced by whether environmental conditions, such as those identified in this research, make walking feasible. Increased collaborations between persons in the fields of public health and urban planning are necessary. As planners continue designing healthy communities, it is crucial that data support evidence-based planning practices. Creation of mixed-use, dense development may encourage adults to incorporate transport walking into their lives.

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