CHANGE IN THE BUILT ENVIRONMENT AND ITS ASSOCIATION WITH CHANGE IN WALKING AND OBESITY IN MIDDLE AGE AND OLDER ADULTS

by

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“The best time to plant a tree was 20 years ago.
The second best time is now.”

Dedication

This dissertation is dedicated to Drs. George Baldo and Amy Hillier. You played a crucial role in encouraging me to start scientific research and you continue to inspire me to pursue work that makes a difference in the world.

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List of Abbreviations

ACS	American Community Survey
ANOVA	Analysis of Variance
AOR	Adjusted Odds Ratio
BMI	Body Mass Index
CA	California (usually Los Angeles, CA)
CDC	Centers for Disease Control and Prevention
CI	95% Confidence Interval
Cnt	County
Cty	City
D & B	Dun and Bradstreet
GED	General Equivalency Diploma
GIS	Geographic Information Systems
HH	Spatial clusters of census tracts with high surrounded by census tracts of high
HS	High School
ICD	International Classification of Diseases
IL	Illinois (usually Chicago, IL)
IQR	Inter-Quartile Range
JHS	Jackson Heart Study
MD	Maryland (usually Baltimore, MD)
MESA	Multi-Ethnic Study of Atherosclerosis
MHHI	Median Household Income
MN	Minnesota (usually St. Paul, MN)
MS	Mississippi (usually Jackson, MS)
NC	North Carolina (usually Forsyth County or Winston-Salem, NY)
NETS	National Establishment Time Series
NHW	Non-Hispanic White
NIH	National Institute of Health
NY	New York (usually New York City, NY)
OR	Odds Ratio
SD	Standard Deviation
SES	Socioeconomic Status
SIC	Standard Industrial Classification
US	United States
WC	Waist Circumference

Abstract

The built environment, a subset of the physical environment that includes land-use patterns, transportation, and design, has been shown to influence walking and obesity. However, the majority of evidence is cross-sectional, providing little insight into the potential impact of changes in the built environment on changes in walking and obesity.

This dissertation uses longitudinal data from the Multi-ethnic Study of Atherosclerosis (MESA), to examine whether a) people who move to better built environments start walking more and lose more weight, b) people who have better built environments experience more positive trajectories in walking and weight, and c) people experiencing changes in the built environment around them experience changes in walking and obesity.

The first analysis found that participants who moved to a location with a higher walkability increased transport walking, had higher odds of meeting “Every Body Walk!” national campaign goals through transport walking, and had a reduction in Body Mass Index (BMI). The second analysis found that, among the entire cohort, a more supportive initial built environment and more positive changes in several specific built environment measures were associated with greater increases in transport walking over time. Similarly, the third analysis found that changes in the density of development towards a more walkable environment was associated with less pronounced increases or decreases in BMI and waist circumference over time. Together, these three findings indicate that changes in the built environment may be a viable option for increasing physical activity and decreasing obesity at the population level. A final analysis found that changes in the built environment are disproportionately spatially clustered in advantaged neighborhoods suggesting that urban planning policies should focus on equity in urban planning to ensure that changes do not have the unintended consequence of increased health disparities.

Collectively, this dissertation clarifies the mechanism linking built environments with health and encourages collaborative work across sectors to design and build healthy communities for all populations.

Chapter 1 Background and Introduction

Rationale

While literature in both the urban planning and health fields continues to draw connections between urban form and health behaviors, little is known about the ways in which the built environment changes and the implications of those changes for health. A majority of studies are cross-sectional in nature and fail to capture either the change in health behaviors or the change in the built environment over time. Identifying inequalities in how the built environment changes or how it affects health may highlight possible areas of intervention to reduce health disparities.

In order to better understand the mechanisms through which the built environment influences health, this research will examine how change in the built environment can influence changes in walking and health outcomes. In addition, this research will examine neighborhood characteristics associated with change in the built environment in order to understand how modifications to the environment are patterned. This will lead to more comprehensive knowledge of the ways in which the built environment may initiate or perpetuate health disparities. Ultimately, a more complete picture of this complex relationship will help facilitate interventions aimed at reducing health disparities through environmental inequalities.

Specific Aims

Specific Aim 1:

To assess the effect of moving to a different built environment on changes in walking and obesity among MESA participants.

Hypotheses:

Individuals who move to communities with better built environments (higher walkability post-move) will a) increase walking compared to pre-move walking levels and b) decrease Body Mass Index (BMI) compared to pre-move BMI more than those who move to communities with the same or worse built environments (lower walkability post-move).

Specific Aim 2:

To investigate the effect of change in the built environment on changes in walking among both moving and non-moving MESA participants.

Hypotheses:

Individuals experiencing positive changes in the built environment (increased land-use mix, increased density of destinations, increased street connectivity or increased aesthetics) will have greater increases in walking or less pronounced declines in walking over time than those who don't have positive built environment changes.

Specific Aim 3:

To investigate the effect of change in the built environment on changes in obesity among both moving and non-moving MESA participants.

Hypotheses:

Individuals experiencing positive changes in the built environment (increased land-use mix, increased density of destinations, increased street connectivity or increased aesthetics) will have greater decreases or less pronounced increases in waist circumference and BMI compared to those who don't have positive built environment changes.

Specific Aim 4:

To identify whether changes in the built environment are patterned by a) initial neighborhood sociodemographic characteristics and b) changes in neighborhood sociodemographic characteristics, over a 10 year period (2000-2011) in a sample of neighborhoods from 7 different cities.

Hypotheses:

1) The amount of change in the built environment will vary based on the scale and range of the measures. Aspects of the built environment that are smaller in scale

(density of destinations) will be more dynamic than those at larger scale or involving infrastructure (land-use mix, train networks, street connectivity).

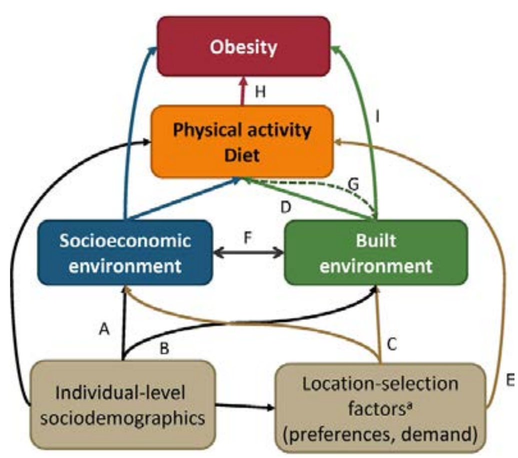
2) The amount of change will be spatially clustered within cities such that neighborhoods experiencing high levels of change are near other neighborhoods experiencing high change and neighborhoods experiencing low levels of change are near other neighborhoods experiencing low levels of change.
3) Positive change in the built environment will be patterned along socioeconomic lines:
    a. Communities with more economic, educational, and social resources or a higher percentage non-Hispanic white will disproportionately have positive changes (i.e. increased density of destinations). Communities with fewer economic, educational, and social resources will remain more constant and/or have smaller levels of positive change in the built environment.
    b. Communities in spatial clusters of positive change will have more economic, educational, and social resources or a higher percentage non-Hispanic white than communities not in spatial clusters of positive change.

Background

In the United States and elsewhere, researchers have turned to the built environment in search of explanations for decreased physical activity and possible strategies for increasing healthy behavior. As a subset of the physical environment that consists of three components, 1) land-use patterns, 2) the transportation system, and 3) design, the built environment sits at the crux of urban planning and public health.[1] Although urban planners have been exploring this topic since the 1970's, most of the literature from this field has remained practice driven and provides a normative theory of the links between urban design and behavior.[2] Concurrently, during this same period, public health practitioners fixed their attention on individual behaviors and their role in health outcomes. Starting in the 1990's the focus of public health shifted beyond individual behavior to include the role that environmental influences, specifically the built environment, play in health behavior.

Numerous reviews have documented consistent associations of multiple attributes of the built environment, especially neighborhood walkability (defined by residential density, proximity of shops and services, and street connectivity) with active transport and recreational physical activity.[1, 3-8] However, almost all research has used cross-sectional data that does not utilize longitudinal built environment indicators or longitudinal outcomes. These cross-sectional studies leave questions about how the built environment changes, the ways in which built environments may be linked to neighborhood social factors, reverse causation, and the ability to convey causal relationships as opposed to only correlation. Cross-sectional neighborhood environment studies are particularly problematic because neighborhoods and individuals evolve over time. As illustrated by Boone-Heinonen and Gordon-Larsen (figure 1-1) individuals may move into new environments according to financial or social constraints and residential preferences (pathways A and B).[9] Likewise, physical activity and food resources are placed in areas with the greatest demand (pathways F and G). Since cross-sectional literature is unable to take into account these dynamic interactions, it may misestimate the influence of neighborhood features on health behaviors. Longitudinal data would help enhance our understanding of the ways that the built environment may shape health behavior and would clarify some questions of temporality or residential selection.

Figure 1-1 Conceptual model of relationships among neighborhood environment features and individual-level characteristics, behaviors, and obesity. Location-selection factors may be difficult or impossible to measure. From Boone-Heinonen (2012)



Current longitudinal data on physical activity,[10-15] walking,[10, 11, 16-19] or other transportation[10, 20-22] and mobility[23] outcomes have been limited. Several recent studies rely on changes in residential relocation to investigate how changes in various features of the physical environment are related to health behaviors.[10-13, 16-18, 20-22, 24] Limited research has used the building of new infrastructure[25] or the passing of new policies[26] to investigate the impact of change in the built environment on behaviors. Limited research has investigated associations between longitudinally measured neighborhood change and health-related outcomes.[14, 15, 19, 23, 27] Many of these longitudinal studies, particularly those utilizing residential relocation, are limited to small geographic scales[9, 11, 15-17, 19-21] and may not be generalizable. Additionally, measures of the neighborhood environment may be limited to county-level data,[14] census-data,[23] or self-reported perceptions of the environment.[15, 19] Furthermore, the follow-up period for some was shorter than one year,[15, 19] and the specific policy of built environment changes investigated were limited to changes in design or commercial features, such as aesthetics, traffic or gasoline prices, rather than large-scale land-use and transportation changes. Additional longitudinal evidence is needed to explore the role of objectively-measured, environmental features in shaping walking trajectories.

Existing longitudinal data on obesity has been equally limited. Several studies examine obesity trajectories based on the initial characteristics of a neighborhood environment,[28-33] some rely on residential relocation,[11, 30, 34-36] and my literature search revealed only one that examined longitudinal changes in the environment with changes in obesity.[37] Two of these are exclusively in children[28, 35] who may be influenced by different environmental features in different ways than adults. Several are in small geographic regions[28, 29, 31-33, 37] or in non-United States contexts.[29, 33] Beyond these generalizability issues, only a few used measured anthropometric characteristics.[28, 31-33, 37] Most interestingly, despite fairly consistent cross-sectional literature, most of these longitudinal analyses did not show a relationship between the environment and obesity trajectories.[11, 29, 32, 34, 35, 37] Additional longitudinal evidence is needed to examine changes in the environment with obesity trajectories and to explore inconsistencies between the cross-sectional and longitudinal literatures.

Longitudinal Analysis of the Built Environment

Factors Restricting Longitudinal Research

In general, three main factors have restricted the use of longitudinal data in built environment research with individual walking and health behavior: 1) a lack of geographic information systems (GIS) data, 2) a lack of suitable cohort studies and 3) the age of this field of research.

It is standard to derive "objective" or observed built environment measures from GIS, in which data availability varies by location, type, and detail. No main source of built environment GIS data exists in the United States, limiting the ability to track change in the built environment with change in physical activity. Furthermore, most government agencies do not maintain consistent records of historic built environment GIS files, limiting the longitudinal nature of the data. In addition, few cohort studies exist that 1) have enough geographic variability to investigate the built environment, 2) have surveys on neighborhood-level data, and 3) allow participant's addresses to be located on a map ("geocoded"). Finally, interest in the built environment has only really surged over the past two decades or less. As a young field, cross-sectional data has been more easily attainable and is necessary for building evidence to support the high time and monetary cost of a cohort study.

Residential Relocation to Observe Built Environment Change

As stated prior, investigating neighborhoods as they experience changes would be most useful to understand the effects of interventions on the physical environment. Unfortunately, very few studies have longitudinal assessments of the built environment and only a few studies have examined associations between neighborhood change and health-related outcomes.[19, 23, 27] One alternative is to take advantage of changes in residential environments occurring as part of residential relocation in order to investigate how change in the built environment affects changes in health behaviors and outcomes.[38] In this way, moving creates a natural experiment in which individuals' behaviors can be compared pre- and post-move. Several recent papers capitalize on residential relocation to investigate numerous elements of the physical environment and health behaviors.[10-12, 16-18, 20-22, 34, 36] Of these, six were performed within two studies,[12, 16, 17, 20-22] most were confined to limited geographic areas,[10, 12, 16-18, 20-22] several were limited to single gender[11, 18] or single race,[11] and only a few differentiated between different types of walking.[10, 17] This may be a main factor driving previous inconsistencies in the literature, as different types of build environment features are thought to influence different types of walking (i.e. distance to destinations influencing transport walking, green space influencing leisure walking). Additionally, while results suggest an association with walking,[10, 11, 16-18] bicycling,[20] travel behavior[10, 21, 22] and overall physical activity,[10-12] studies of the effects of sprawl on BMI found mixed results.[34, 36] There is a need for additional longitudinal studies that utilize residential relocation to examine the associations between the built environment, walking, and BMI within the United States.

Longitudinal Analysis in MESA

By using the Multi-Ethnic Study of Atherosclerosis (MESA), I am able to perform longitudinal built environment analyses not previously feasible. GIS data collection in an earlier phase of MESA (2004) combined with a second collection (2011) has resulted in GIS data spanning 2000 through 2011 that can be paired with corresponding geocoded participant addresses. As a six-city study, MESA has the unique position to explore built environment effects across the United States, rather than simply within a city or county. MESA has previously been used to show cross-sectional built environment relationships,[39] but has not been utilized for longitudinal research in this area. Thus, this research will fill an important gap by investigating longitudinal relationships not previously viable using existing data.

MESA also has repeated measures of detailed walking and obesity metrics. Walking was self-reported in exams 1-3 and 5, including information on total walking, walking for transport (e.g., walking to get to places such as to the bus, car, work, or store) and for leisure (e.g., walking for leisure, pleasure, social reasons, during work breaks, and with the dog). This allows me to examine walking trajectories over time while considering the different influence of change in the built environment on different types of walking behavior. For obesity, MESA measured waist circumference in addition to BMI, which may give a more accurate reflection of fat mass and distribution in a middle- and older-age cohort.[40]

Neighborhood Socioeconomic Status and Change in the Built Environment

While a number of scientific, political, and popular movements have started to support change in the built environment,[1] no literature exists that quantifies the amount and type of changes that are occurring in the built environment over time. Even less is known about whether changes are occurring equally across neighborhoods, to reduce health disparities, or unequally across neighborhoods, deepening health disparities.

Some evidence suggests that low-income areas are disadvantaged in features such as aesthetics, traffic safety infrastructure, and crime safety.[41] Research in Austin, TX found that although low-income and Hispanic neighborhoods were ranked more highly on observed characteristics associated with walkability than high income, mostly non-Hispanic white neighborhoods, they had worse aesthetics, higher vehicular crash rates and higher crime rates.[42] A paper on master plans for non-automotive transportation found that locations with plans in place have similar demographic profile to the overall United States for median age, household income, high school education, and income inequality.[43] However, the degree of racial diversity among communities with master plans was slightly lower than the United States average.

If neighborhoods with higher socioeconomic status, or with lower percentages of minorities are more likely to experience positive built environment changes, this may further or deepen health disparities. Thus, it is important to identify which neighborhood factors may influence plans to, or actually changes in, the built environment. This research will allow us to better understand change in the built environment at the neighborhood level. By investigating neighborhood socio-demographic predictors of change, this research will answer important unanswered questions about the role of the built environment in reducing, maintaining, or even worsening health disparities.

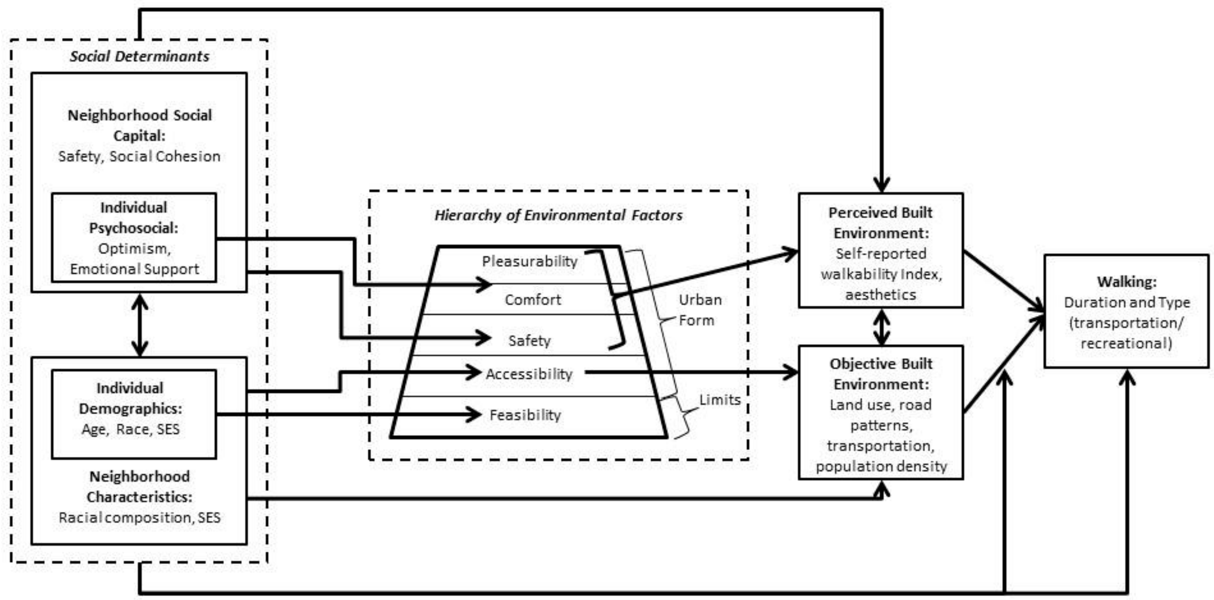
Conceptual Framework

Few conceptual frameworks encompass the complex web of connections between the social environment, built environment, individual socioeconomic status, and neighborhood socioeconomic levels.[44-49] Consistent across these frameworks is the

[1] To name a few: Transportation for America http://t4america.org/; National Complete Streets Coalition, http://www.completestreets.org/; Smart Growth America, http://www.smartgrowthamerica.org/; Robert Wood Johnson Active Living Research, http://www.activelivingresearch.org/; Bikes Belong Coalition http://www.bikesbelong.org/; WalkScore http://www.walkscore.com/

existence of a multi-level process that includes both micro and macro built environment features combined with individual and neighborhood demographics to determine physical activity outcomes.

For my project I will use a combined model of the Schulz and Northridge model[44] and the Alfonzo model of hierarchy of environmental needs.[48] My conceptual framework is shown below (larger version in Appendix A).



My research aims to incorporate social determinants of health at both the neighborhood and individual levels. As seen in the left side of my framework, I have broken the social determinants into two spheres, one representing demographic characteristics and one the social environment. These two entities are associated with each other as shown by the double arrow linking the two parts. Neighborhood level and individual level variables are separated to indicate the separate influence of each of these levels.

In the center of the diagram is the hierarchy of environmental factors salient to walking as defined by Alfonzo. This pyramid sits on a foundation of “feasibility”, a measure of personal limits. This includes mobility, time, or responsibilities and is shown in my model as a composite of individual demographic factors. Accessibility is a term that is poorly articulated between the disciplines of urban planning and public health. In my theoretical model, it represents the possibilities for activities, such as shopping, available to the residents of a neighborhood. The spatial distribution of activities as determined by land development patterns is complemented by the attributes of the transportation system that links these activities.[50] In the public health realm, many of the observed physical characteristics of the built environment play into accessibility. As previously discussed, research has indicated that the neighborhood demographics of an area may influence accessibility to resources. Neighborhoods income, education, or social power may create more or less favorable environments and differences in built environment change. If it is feasible for an individual to walk and there is accessibility due to land-use patterns, a lack of safety may still prevent that individual from walking. Finally, the top two elements, comfort and pleasurability, are structures of the walking experience. Comfort includes urban design characteristics that affect the relationship between pedestrians and motorized traffic while pleasurability refers more to the liveliness, architectural scale, and aesthetic appeal of a location. Neighborhood and individual social factors influence the more subjective aspects of the built environment including safety, comfort, and pleasurability.

Finally, these five levels in the hierarchy can be mapped onto perceived and observed or "objective" built environments. The perception of some elements of the built environment may depend on personal preference, residential history, or demographics. For example, how comfortable, safe, and pleasurable an environment is to a person may be closely linked to the residential environment an individual was raised in or spent a majority of their life in. Other elements, can be measured "objectively" and represent what may physically be present. These two aspects of the built environment are correlated and intrinsically linked as shown by the double arrow connecting them. For example, GIS may measure a high density of walking destinations, but an individual may report that it is difficult to walk to destinations, perhaps due to safety or to their frame of reference. The social determinants of health may be acting by influencing the perception of the built environment, modifying the effect of the built environment on walking, or walking levels. Thus, my conceptual framework suggests that the modification of the effect of the built environment on walking by social factors is through the hierarchy of environmental factors described by Alfonzo.

Chapter 2 Aim 1: Change in Walking and Body Mass Index Following Residential Relocation

Aim 1 will examine the influence of moving to a more walkable location on changes in transport walking and BMI. My isolating individuals who move, we are better able to examine the potential impact of large environmental changes on behavior and health outcomes. This aim also uses a composite, open-access measure of walkability (Walk Score®) that could easily be used by researchers, public health departments, community organizations, and others who may not have access to the GIS technology or skills to create each built environment measure.

Background

A recent report by the National Academy of Sciences showed that Americans live shorter lives and have consistently worse health than people in other high-income countries.[51] A high burden of obesity, diabetes, and cardiovascular disease was identified as contributing to the United States health disadvantages.[51] The report encouraged researchers and policymakers to identify the environmental factors that might be contributing to a high prevalence of these conditions in the United States, including the extent to which environmental conditions common in many communities shape the behavioral antecedents of cardiovascular disease.

Although international comparisons on levels of physical activity across countries are often inconclusive because of measurement differences,[52-54] the United States differs starkly from many other high-income countries in the extent to which residents engage in active travel, such as through walking or bicycling. For example, the overall bicycle share of work trips is currently 3 times higher in Canada than in the United States,[55] and the percentage of total trips by bicycle and foot are lower in the United States than in Ireland, France, Great Britain, Norway, Denmark, Finland, Germany, Sweden, Spain, Netherlands, and Switzerland.[56] Research indicates that walking is the most common leisure activity performed by adults and can be an important component of physical activity.[57-60] Consistent with this evidence, 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 campaigns to promote walking is likely to be strongly influenced by whether environmental conditions make walking feasible and safe.[45, 61, 62] In 2 international studies across 11 countries, fewer American participants reported having many shops within walking distance or transit stops within 10–15 minutes of their home than their international peers.[62, 63] A comparison of global cities between 1980 and 1990 also revealed that cities in the United States have accelerated dramatically in their dependence on the automobile, with little improvements in transit use,[64] and that per capita automobile use and average gasoline consumption in the United States are 2 times higher than those in Australian cities, 4 times higher than those in European cities, and 10 times higher than those in Asian cities.[64, 65] Additional disparities within the United States exist, with rates of walking and bicycling differing across various cities and states[56]; counties with high poverty and low education are less likely to implement local pedestrian- and bicycle-related projects using federal transportation funding.[66]

Although several reviews indicate that measures of neighborhood walkability (such as self-reported walkability, accessibility to destinations, and street connectivity) are cross-sectionally associated with walking,[7, 38, 67] physical activity,[38, 68-70] and body mass index (BMI),[68, 71, 72] these studies cannot be used to draw policy-relevant causal inferences partly because of the impossibility of determining the temporal relation between neighborhood walkability and walking behavior.[7, 38, 67-72] Studies that examine how changes in environmental conditions are related to changes in behaviors are therefore needed.

A major challenge in estimating the causal effects of environments on health is accounting for the possibility that persons with predispositions to certain behaviors choose to live in certain types of neighborhoods.[6, 21, 73-76] Randomized studies of environmental interventions (such as increasing walkability) are logistically challenging and unlikely to be feasible on a large scale. Hence, reliance on rigorous use of observational data is necessary. Very few cohort studies have longitudinal assessments of changes in the environment to allow investigations of associations between neighborhood change and health-related outcomes.[19, 23, 27] Because built environments often change slowly, the impact can be practically examined by investigating changes occurring as part of residential relocation.[10-12, 16-18, 20-22, 34, 36, 38, 77] Although longitudinal studies do not completely overcome the effect of self-selection on the associations observed,[38] they have the potential to improve causal evidence, especially if they investigate the impact of changes in neighborhood conditions on changes in health.

We used data from a population-based and multiethnic longitudinal study conducted in 6 diverse areas of the United States to investigate whether changes in environmental features associated with residential relocation were linked to simultaneous changes in walking for transport or for leisure in adults. The presence of such a relationship would provide strong support for consideration of land-use, development, and transportation policies as levers to increase physical activity in the United States. More generally, it would lend greater credence to the notion that at least some of the United States health disadvantages could be the unintended consequence of a range of policy and development decisions that engineered physically active lifestyles, such as walking, out of the lives of some American adults.

Methods

Our sample consisted of participants from the Multi-Ethnic Study of Atherosclerosis (MESA), a study of 6814 United States adults ages 45–84 years without clinical cardiovascular disease at baseline.[78] Participants were recruited between 2000 and 2002 from 6 study 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 additional follow-up examinations. Of 4592 participants who completed both examination 3 (January 2004–September 2005) and examination 5 (April 2010–February 2012), 934 moved between both examinations and were eligible for these analyses. Of these, 233 were excluded because of missing data in at least 1 examination or because they did not give consent to participate in the Neighborhood Ancillary Study, leaving 701 participants for analyses. The study was approved by institutional review boards at each site, and all participants gave written informed consent.

Exposure Measure

The extent to which the environment around a person's residence was conducive to walking was assessed using the Walk Score.[79] The Walk Score has been associated with both subjective and objective measures of walkability,[80-84] as well as with walking in cross-sectional analyses.[85-88] The Walk Score algorithm produces scores from 0 to 100 (higher scores indicating better walkability), based on distance to various categories of amenities (e.g., restaurants, shopping, schools, parks, and entertainment) weighted based on importance to walkability and summed. Scores are then adjusted for street network characteristics, such that areas with low intersection density and high block length receive lower scores.[89] The Street Smart Walk Score used in these analyses utilizes network distances by following the streets to amenities and allows for multiple amenities within each category to better capture depth of choice.[89] Because historical measures were not available, Walk Score measures created in May 2012 were linked to participants' street addresses between 2004 and 2012.

Outcome Measures

An interviewer-administered questionnaire adapted from the Cross-Cultural Activity Participation Study[90, 91] was used to assess physical activity. The questionnaire was developed using extensive qualitative research[92] and has acceptable test-retest reliability and validity among a sample of women.[93] Two types of walking were assessed: walking for transport (e.g., walking to get to places such as to the bus, car, work, or store) and for leisure (e.g., walking for leisure, pleasure, social reasons, during work breaks, and with the dog). For each type of walking, participants were asked whether they engaged in that activity during a typical week in the past month, how many days per week, and how many minutes per day they did that activity. Each type of walking was examined as a continuous variable and dichotomized using the cutoff of meeting "Every Body Walk!" campaign goals (≥ 150 min/week of walking).

BMI was calculated as measured weight in kilograms divided by measured height in meters squared. Categorical analyses were done using the World Health Organization classification system[54] of normal BMI (< 25 kg/m2), grade 1 overweight (25–29.9 kg/m2), grade 2 overweight (30–39.9 kg/m2), and grade 3 overweight (≥ 40 kg/m2).

Covariates

We obtained information on age, race/ethnicity, education, income, and working status by interviewer-administered questionnaire. Race/ethnicity was classified as Hispanic, non-Hispanic White, non-Hispanic Chinese, and non-Hispanic Black. Participants selected their education from 8 categories that were collapsed into 3 categories: less than high school, high school diploma or general equivalency diploma but less than college, and college degree or higher. Participants selected combined family income from 14 categories, and continuous income in U.S. dollars was assigned as the midpoint of the selected category. Working status was categorized from 10 categories of current occupations as working at least part-time or not (including employed on leave, unemployed, and retired). Current marital status was self-reported and then dichotomized as “currently married or living with a partner” or “other” (including widowed, divorced, separated, and never married).

Participants were asked to rate their health compared with others their age as better, same, or worse. Arthritis was measured as having an arthritis flare-up in the past 2 weeks. Cancer diagnosis was determined as having a hospitalization because of cancer based on *International Classification of Diseases-Version 9* code or self-reported cancer at any time before the examination. Seasons were classified as winter (January–March), spring (April–June), summer (July–September), and fall (October–December).

Statistical Analyses

Descriptive analyses contrasted movers and non-movers and compared selected characteristics across tertiles of change in Walk Score. Chi-square tests, t-tests, or analysis of variance (ANOVA) were used to test for statistically significant differences ($P<.05$) across categories, as appropriate.

We used fixed-effects models[94] to estimate associations of within-person change in Walk Score with within-person changes in walking or BMI. This approach capitalized on within-person variability in exposure to estimate associations.[94] These models were adjusted only for time-varying covariates (age, income, working status, marital status, self-reported health, arthritis, cancer diagnosis, and season) because fixed-effects models tightly controlled for time-invariant characteristics. Additional models further adjusted for the other 2 time-varying outcomes (e.g., models for BMI were further adjusted for changes in leisure and transport walking). Naïve and multilevel marginal models were explored in sensitivity analyses; results were consistent and are not presented. All analyses were conducted in 2013 using SAS 9.2 (Cary, North Carolina).

Results

The time between the 2 MESA examinations (examinations 3 and 5) ranged from 5.1 to 7.7 years, with a mean of 6.3 years (SD 0.4 years). Participants' age at the first time point ranged from 48 to 87 years, with an overall mean of 61.8 years (SD 9.3 years) (Table 2-1). Over half (52.4%) of the participants were women. Participants' initial Walk Score ranged from 0 to 100 with a mean of 57.7 (SD 30.6), and they moved to areas with changes ranging from 99 points lower to 93 points higher, with an mean of change of -7.7 (SD 31.5) between both examinations.

Compared with the nonmoving individuals excluded from these analyses, movers were more likely to be Non-Hispanic Chinese or Hispanic, currently working, have a lower initial income, and be less likely to be currently married ($P< .05$). No significant differences between movers and non-movers were found for education, self-reported health, arthritis in the past 2 weeks, initial and change in levels of walking or BMI, or initial Walk Score (data not shown).

Table 2-2 shows selected characteristics of participants according to tertiles of the change in Walk Score experienced as a result of residential relocation. Participants in tertile 1 had a mean decrease in Walk Score of 41.1 points (SD 21.1), tertile 2 had a mean decrease of 5 points (SD 5.4), and tertile 3 had a mean increase of 22.8 points (SD 20.3). Individuals who had the most negative change in walkability were slightly younger, had a higher initial income, were more likely to be currently working at examination 3 or start working between examinations 3 and 5, had lower initial levels of leisure walking, and had much higher initial Walk Scores.

A more positive change in walkability score between examinations 3 and 5 was associated with greater increases in transport walking and with decreases in BMI. Similar patterns were observed when change in the walkability index was categorized into quartiles rather than tertiles.

Moving to a location with a 10-point higher Walk Score increased transport walking levels by 17.51 min/week (95% confidence interval [CI]=5.96, 29.06), and increased odds of meeting “Every Body Walk!” goals through transport walking by 11% (adjusted odds ratio [AOR]=1.11; 95% CI=1.02, 1.21) (Table 2-3). The association between walkability and amount of transport walking was slightly attenuated or did not change at all when adjusted for change in BMI and leisure walking. In contrast, a change in Walk Score was not associated with changes in leisure walking.

Moving to an area with a 10-point higher Walk Score was associated with 0.06 kg/m^2 lower BMI (95% CI= -0.11, -0.00), even after accounting for changes in transport walking (-0.06, CI -0.12, -0.01). This is equivalent to 0.36 lbs less for an average woman (164.1 cm average height) and 0.42 lbs less for an average man (178.2 cm average height). No association was seen between change in Walk Score and categories of BMI.

Discussion

Moving to an area with higher walkability was associated with an increase in transport walking and a decrease in BMI in this multicity and multiethnic sample. There was no association between changes in walkability and changes in leisure walking. Associations persisted after controlling for observed time-varying covariates and all observed and unobserved time-invariant covariates.

The association between change in walkability and change in transport walking extended previous research that showed that living in a more highly walkable neighborhood helped individuals to maintain or increase walking levels over time.[24, 95-97] In sensitivity analyses, there were no statistically significant differences in the effect of change in walkability on change in walking by length of time in the new residence (data not shown). This might indicate that the effect of moving to more walkable neighborhoods did not diminish or increase over time. The increase in transport walking after moving to a more supportive environment was concordant with previous research in other countries[16] and select United States cities.[10, 12, 18, 22] By using data from a multiethnic and multicity sample, this research provided evidence that environmental modifications might be an important strategy for increasing walking across a broader United States context.

The lack of associations between change in walkability and change in leisure walking was consistent with previous cross-sectional research[88] and with the methods used to create the walkability index. Walk Score primarily measured access to destinations, which influenced whether errands or other transportation could occur on foot, but might not capture other elements of the built environment that encourage leisure-time walking, such as aesthetic quality, street traffic, or availability of walking trails. Differences in the associations of walkability with transport and leisure walking highlight the importance of matching environmental measures to specific behaviors when studying associations between health behaviors and the environment.[98]

The finding that moving to a more walkable neighborhood was associated with declines in BMI illustrated the potential of environmental interventions to influence health outcomes and cardiovascular risk. Previous research on neighborhood walkability and weight trajectories showed the importance of the environmental context in maintaining a healthy weight,[30, 31, 95, 99, 100] but longitudinal evidence linking changes in the environment to changes in weight and BMI was inconsistent.[29, 34, 36] Conflicting results might be because of different definitions of neighborhoods or the types of measures the built environment used. Previous studies examined radii around homes,[34] city-designated neighborhoods,[29] or counties,[36] all of which might not capture the neighborhood environment in the same way as the Walk Score. Additionally, self-reported evaluations of walkability[29] or land cover data,[29, 34, 36] might represent different aspects of the environment than the street distances to specific destinations used in the Walk Score. In our analyses, the effects of change in walkability on change in BMI was not reduced after controlling for change in transport and leisure walking, suggesting that the BMI effect was not mediated through effects on walking. Moving to more walkable areas might also be associated with greater bicycling or transit use that could help to explain the weight loss. It was also possible that more walkable locations increased options for healthier food, and that dietary changes were also associated with moving to more walkable areas. Measurement error in walking might also have affected our results.

Recent research examined the roles of lifestyle and preferences in the selection of neighborhoods.[27, 73, 75, 76, 101] Evidence suggested that walkability was an important consideration when individuals selected residential locations,[73, 102-104] that support for more walkable neighborhoods was increasing nationwide,[105] and that preference for easily walkable neighborhoods might be associated with BMI.[27] We had no information on reasons for moving or preferences in our sample. Previous studies that accounted for residential preferences or predispositions toward active transport found limited attenuation of results.[16, 20] To the extent that preferences and predispositions are stable person-level traits, we accounted for them by using fixed-effects models that accounted for all stable person-level attributes. Additional longitudinal evidence is needed that illustrates whether walking behavior responds to changes in neighborhood walkability for individuals who do not move.

Study Limitations

Self-reported measures of walking might not be as accurate as those assessed objectively using pedometers or accelerometers. However, because our analyses investigated change in walking within participants, stable overestimates and underestimates of walking by a given person were accounted for. Our study was limited to a middle-age and older adult population of movers and might not be generalizable to younger individuals or those who remained in the same residential location. The use of Walk Score from 2012 for both pre- and post-move residential locations relied on the assumption that Walk Scores for locations remained stable over time. This assumption might have introduced measurement errors and resulted in attenuations of the association between changes in Walk Score and changes in the outcomes. We could not control or examine the effect by study site because of small sample sizes. In our analyses, the persons who experienced the greatest reductions in Walk Score as a result of the move were also those with the highest starting levels. It was plausible that the effect of a given change was modified by the starting level. However, the limited sample size precluded us from investigating this important question. Limited sample size also prevented us from investigating whether a minimum change in the environment was necessary for an effect on walking behavior (i.e., whether a threshold effect was present). In addition, although we controlled for several time- varying covariates and our models tightly controlled for time- invariant person characteristics, residual confounding by other time- varying factors could not be ruled out.

Conclusion

This study provided longitudinal evidence that transport walking and BMI shifted favorably in response to changes in the walkability of the residential neighborhood.

Individuals who moved to an area with higher walkability walked more for transport and weighed less than before their move. These findings illustrated the potential for local infrastructure to support health-enhancing behaviors and highlight the potential effects of non-health policies, including urban planning, transportation policy, and economic development policy, on health-related outcomes.[106] Although changes in walking and BMI are relatively small and may not have clinical significance at the individual level but changes across an entire population have the potential to shift the overall distribution of chronic disease burden for that population. Contrasts between different neighborhood environments within the United States gave insight into the factors that might be limiting American health in comparison with other countries. Increasing effort to work collaboratively across disciplines must be pursued to facilitate changes in the neighborhood environment, which could improve the health of United States communities.

NOTE:

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Tables

Table 2-1 Selected Characteristics of Participants Included in the Analyses (n=701), Multi-Ethnic Study of Atherosclerosis (MESA) in Baseline (examination 3, January 2004– September 2005) and Follow-Up (examination 5, April 2010–February 2012)

Characteristics	Baseline Mean (SD) or %	Follow-Up Mean (SD) or %
Age, y	61.8 (9.3)	68.1 (9.3)
Female	52.4	——[a]
Race/ethnicity (%)		
Non-Hispanic White	36.5	——[a]
Non-Hispanic Chinese	17.1	——[a]
Non-Hispanic Black	23.7	——[a]
Hispanic	22.7	——[a]
Education (%)		
Completed HS/GED or less	30.4	——[a]
Some college, technical/associates	27.8	——[a]
College or higher	41.8	——[a]
Income, in thousands	50.4 (35.0)	49.7 (35.6)
Currently married (%)	58.9	54.1
Currently working (%)	61.2	47.2
Health compared with others (%)		
Better	58.6	58.9
Same	37.0	35.1
Worse	4.4	6.0
Arthritis in the past 2 wk (%)	12.4	17.3
Cancer diagnosis (%)	9.3	14.6
Transport walking, mean (min/week)	237.1 (358.3)	306.5 (436.4)
Enough to meet "Every Body Walk!" goals[b] (%)	43.1	50.6
Leisure walking, mean (min/week)	181.4 (298.3)	238.4 (367.4)
Enough to meet "Every Body Walk!" goals[b] (%)	36.5	45.4
BMI, kg/m^2	28.2 (5.5)	28.4 (5.6)
Normal[c] (%)	31.1	29.2
Grade 1 overweight (25–29.9 kg/m^2)[c] (%)	36.5	37.7
Grade 2 overweight (30–39.9 kg/m^2)[c] (%)	29.4	30.0
Grade 3 overweight (≥40.0 kg/m^2)[c] (%)	3.0	3.1
Walk Score	57.7 (30.6)	50.0 (31.5)

Note. BMI=body mass index; GED=general equivalency diploma; Walk Score=Street Smart Walk Score from Front Seat Management, LLC.
[a]These are time-invariant variables, percentages are the same between the 2 examinations.
[b]Meeting "Every Body Walk!" goals defined by ≥150 min/week.
[c]BMI categorized using World Health Organization categories.

Table 2-2 Selected Characteristics of Participants Included in the Analyses by Tertile of Change in Walkability, Multi-Ethnic Study of Atherosclerosis (MESA) in Baseline (examination 3, January 2004– September 2005) and Follow-Up (examination 5, April 2010–February 2012)

Characteristics	Change in Walk Score			
	Tertile 1[a] (n=236)	Tertile 2 (n=227)	Tertile 3 (n=238	
	Mean (SD) or %	Mean (SD) or %	Mean (SD) or %	P[b]
Age, y	60.7 (9.4)	62.2 (9.1)	62.5 (9.4)	.10
Female	55.1	51.1	50.8	.59
Race/ethnicity				
Non-Hispanic White	39.0	35.7	34.9	
Non-Hispanic Chinese	17.4	15.4	18.5	
Non-Hispanic Black	24.6	22.5	24.0	
Hispanic	19.1	26.4	22.7	.64
Education				
Completed HS/GED or less	25.4	34.4	31.5	
Some college, technical/associates	28.4	27.3	27.7	
College or higher	46.2	38.3	40.8	.28
Initial levels (exam 3):				
Income (in thousands)	54.9 (35.7)	47.8 (34.4)	48.2 (34.6)	.05
Currently married	62.7	57.3	56.7	.34
Currently working	68.2	55.1	60.1	.01
Health compared with others				
Better	58.5	58.2	59.2	
Same	36.4	35.7	38.7	
Worse	5.1	6.2	2.1	.25
Arthritis in the past 2 wk	13.1	13.2	10.9	.69
Cancer diagnosis	8.9	10.6	8.4	.72
Transport walking (mean min/week)	249.1 (372.2)	246.6 (374.1)	216.1 (328.2)	.16
Median, interquartile range	120.0 (280.0)	120.0 (280.0)	105.0 (210.0)	
Enough to meet "Every Body Walk!" goals[c]	45.8	44.1	39.5	.36
Leisure walking (mean min/week)	158.8 (273.6)	186.0 (293.9)	199.4 (324.6)	.08
Median, interquartile range	60.0 (210.0)	120.0 (225.0)	97.5 (240.0)	
Enough to meet "Every Body Walk!" goals[c]	29.7	40.1	39.9	.03
BMI (kg/m^2)	28.3 (5.6)	28.0 (5.4)	28.3 (5.6)	.77
Normal[d]	31.4	33.9	28.2	
Grade 1 Overweight (25-29.9)[d]	36.0	35.2	38.2	
Grade 2 Overweight (30-39.9)[d]	28.4	28.2	31.5	
Grade 3 Overweight (≥40.0)[d]	4.2	2.6	2.1	.69
Walk Score	69.8 (21.7)	62.8 (31.6)	40.7 (30.0)	<.001
Change (between baseline and follow up)				
Time between exams	6.4 (0.4)	6.3 (0.4)	6.3 (0.3)	.01
Change in income, in thousands	-1.1 (23.9)	1.2 (26.4)	-1.9 (23.0)	.38
Currently married				
No longer married[e]	7.2	11.5	12.2	
New marriage[e]	3.8	6.6	5.9	.18
Currently working				
Stopped working[e]	19.9	11.9	20.2	
Started working[e]	4.7	3.5	2.1	.04
Health Compared with others[f]				
Declining health	22.6	25.4	24.2	
Increased health	27.1	27.0	31.5	.86
Arthritis in the past 2 wk				
No longer have flare-up	6.8	7.5	5.9	
New flare-up	11.9	12.3	10.5	.91
New cancer diagnosis	4.2	5.3	6.3	.60
Change in transport walking, mean (min/wk)	-9.3 (460.9)	128.5 (533.3)	91.2 (462.2)	.007
Median, interquartile range	-30.0 (257.5)	0.0 (305.0)	30.0 (285.0)	
Change in leisure walking mean (min/week)	37.4 (361.5)	87.9 (420.9)	46.8 (417.7)	.36
Median, interquartile range	7.5 (210.0)	0.0 (240.0)	0.0 (180.0)	
Change in BMI (kg/m^2)	0.5 (2.2)	0.2 (1.9)	-0.1 (2.6)	.01
Change in Walk Score	-41.1 (21.1)	-5.0 (5.4)	22.8 (20.3)	——[g]

Note. BMI=body mass index; GED=general equivalency diploma; Walk Score=Street Smart Walk Score.
[a]Tertile 1 defined as Walk Score change ≤ -16; tertile 2 defined as Walk Score change >−16, and ≤1; tertile 3 defined as Walk Score change >-1.
[b]P value from χ^2 or Fisher's exact test for categorical variables and appropriate analysis of variance or Kruskal-Wallis for continuous variables across tertiles of change in Walk Score.
[c]Meeting "Every Body Walk!" goals defined by ≥150 min/week
[d]BMI, World Health Organization Categories
[e]Percentage for change in marriage and working status are over the entire sample
[f]Declining health measured as reporting a lower category of health compared with others at follow-up than baseline (going from "better" to "same" or "worse" or going from "same" to "worse"); increasing health measured as reporting a higher category of health compared with others at follow-up than baseline (going from "worse" to "same" or "better" or going from "same" to "better")
[g]Did not compare across tertiles, as this were used to determine tertile.

Table 2-3 Within-Person Change in Transportation Walking, Leisure Walking, and Body Mass Index Associated With an Increase in Walkability (measured as a 10-unit increase in Walk Score), Movers of the Multi-Ethnic Study of Atherosclerosis (MESA) Between 2004 and 2012

Variable	Unadjusted		Adjusted[a]		Further Adjusted[b]	
	Change (95% CI)	*P*	Change (95% CI)	*P*	Change (95% CI)	*P*
Transport walking						
Mean change in minutes	17.31 (5.84, 28.78)	.003	17.51 (5.96, 29.06)	.003	16.04 (5.13, 26.96)	.004
Odds ratio of meeting "Every Body Walk!" goals	1.11 (1.02, 1.20)	.01	1.11 (1.02, 1.21)	.01	1.11 (1.02, 1.21)	.01
Leisure walking						
Mean change in minutes	6.12 (-3.34, 15.57)	.20	6.51 (-3.03, 16.05)	.18	1.26 (-7.85, 10.36)	.79
Odds ratio of meeting "Every Body Walk!" goals	0.94 (0.88, 1.02)	.14	0.95 (0.88, 1.03)	.20	0.94 (0.87, 1.02)	.12
BMI						
Mean change in BMI	-0.06 (-0.11, -0.00)	.03	-0.06 (-0.11, -0.00)	.04	-0.06 (-0.12, -0.01)	.02
Odds ratio of becoming a higher BMI category	1.00 (0.97, 1.03)	.90	1.00 (0.97, 1.02)	.85	1.00 (0.97, 1.02)	.79

Note. BMI=body mass index; CI=confidence intervals.

[a]Adjusted for time-varying age, income, season, working status, current marriage status, health compared with others, arthritis in the past 2 weeks, and cancer diagnosis.

[b]Additionally adjusted for the other 2 time-varying outcomes shown in the table (e.g., the model using BMI as an outcome is additionally adjusted for transportation and leisure walking).

Chapter 3 Aim 2: Association Between Changes in the Built Environment and Walking Trajectories

While aim 1 showed that moving to a more walkable location was associated with more transport walking and lower BMI, this may not be helpful for identifying the potential effect of interventions to change the built environment around individuals in a community. Additionally, by using a composite measure of walkability it is difficulty to isolate which features of the built environment may be most impactful. Therefore, this chapter, aim 2, investigates the influence of changes in specific built environment measures on changes in transport and leisure walking across the entire MESA sample.

Background

While walking may have numerous short- and long-term health benefits relevant to cardiovascular disease,[107, 108] diabetes,[109, 110] and cancer,[110] strategies for increasing walking aimed at individuals may be less effective within an unsupportive environment.[45, 61] Growing evidence demonstrates the associations between health behaviors and the built environment, composed of land-use, transportation, and design. Although many reviews summarize the associations of the built environment with walking[7, 38, 67] and physical activity,[38, 68-70] almost all identify the dearth of longitudinal research as a barrier to causal inference[7, 38, 67-72] and leveraging longitudinal data has been identified as a crucial component of the research agenda.[38, 71, 72, 111]

Several recent studies rely on changes in residential relocation to investigate how changes in various features of the physical environment are related to health behaviors.[10-13, 16-18, 20-22, 24] Results suggest associations of changes in the physical environment with walking,[10, 11, 16-18] bicycling,[20] travel behavior,[10, 21, 22] and overall physical activity.[10-13] Limited research has used the building of new infrastructure[25] or the passing of new policies[26] to investigate the impact of change in the built environment on behaviors. These studies are limited to small geographic scales and may not be generalizable. Few studies have longitudinal assessments of the built environment and only limited research has investigated associations between neighborhood change and health-related outcomes.[14, 15, 19, 23, 27] While several of these studies focus on physical activity,[14, 15] mobility,[23] or walking,[19] measures of the neighborhood environment are limited to county-level data,[14] census-data,[23] or self-reported perceptions of the environment.[15, 19] Furthermore, the follow-up period for some was shorter than one year,[15, 19] and the specific policy of built environment changes investigated were limited to changes in design or commercial features, such as aesthetics, traffic or gasoline prices, rather than large-scale land-use and transportation changes. Additional longitudinal evidence is needed to explore the role of objectively-measured, environmental features in shaping walking trajectories.

This study uses unique, population-based data to investigate the association of walking with the built environment, including population density, land-use patterns, access to destinations, street characteristics, and access to buses, in a multi-ethnic and geographically diverse cohort of adults. This study investigates the influence of changes occurring around residents, rather than relying only on residential relocation to examine the association of change. Time-varying measures, created using Geographic Information Systems (GIS), allow the identification of which elements of the built environment may be most influential for affecting changes in walking.

Methods

The sample included participants from the Multi-Ethnic Study of Atherosclerosis (MESA), a study of 6,814 United States adults aged 45-84 years without clinical cardiovascular disease at baseline.[78] Participants were recruited between July 2000-August 2002 from six study sites (Baltimore, MD; Chicago, IL; Forsyth County, NC; Los Angeles, CA; New York, NY; and St. Paul, MN). After a baseline examination, participants attended four additional follow-up examinations occurring at approximately 1.5-2 year intervals (Exam 2, July 2002-February 2004; Exam 3, January 2004-September 2005; Exam 4, September 2005- May 2007; Exam 5, April 2010-February 2012).[78] Neighborhoods were characterized using GIS and linked to MESA households by the Neighborhood Ancillary Study. All addresses were geocoded using TeleAtlas EZ-Locate web-based geocoding software,[112] and addresses were included if geocoding accuracy was at the street or zipcode+4 level. Of the 6,814 participants recruited in

MESA, 6,191 participated in the Neighborhood Study, 6,027 were accurately geocoded, completed at least one subsequent exam, and were not missing information on walking outcomes, or built environment for the exams they attended. The study was approved by Institutional Review Boards at each site and all participants gave written informed consent.

Exposure Measures

Based on previous frameworks[2] we investigated five built environment domains: population density, land-use patterns, access to destinations, public transportation, and street patterns (Table 3-1). Data were obtained from regional governments and commercially available business listings and processed using ESRI ArcGIS 10.1 (Redlands, CA). Neighborhoods were defined as a buffer around participants' addresses. Primary results are reported for 1-mile buffers as they may represent the most salient environment across MESA's diverse urban contexts. Half- and 3-mile buffers were examined in sensitivity analyses; results were consistent and are not presented. In order to isolate and identify specific features of the built environment for interventions, each built environment characteristic was left separate, rather than placed into a factor score. Population density was measured using population counts from the United States Census. Land-use parcel files were obtained from local planning departments, city governments, and regional entities. Two investigators independently classified parcels into two mutually-exclusive categories (retail and residential) based on the land-use codes provided. Disagreements were adjudicated by an additional investigator. Higher percent retail and lower percent residential was considered indicative of more land-use mix. Measures of access to destinations were created using data obtained from the National Establishment Time Series (NETS) database from Walls and Associates for the years 2000-2010.[113] This includes time-series data on establishments derived from Dun and Bradstreet (D&B) archival establishment data. Social and walking destinations were identified using Standard Industrial Classification (SIC) codes.[114] Bus network files were obtained from local planning departments, city governments, and regional entities. Trains and subways were excluded due to a lack of change in rail infrastructure at most sites during the study time period. Street calculations were performed using Street Map 03 and from StreetMap Premium 2012 (ESRI, Redlands, CA). While StreetMap files may be less accurate than data provided by municipalities,[115] they are a uniform data source across cities. Each MESA participant's home address at each exam was assigned to the nearest time point of collected data within a site (Appendix B). Participant who moved outside of the study areas do not have built environment data post-move. Change in the built environment was calculated as the difference between an exam and baseline.

Outcome Measures

An interviewer-administered questionnaire adapted from the Cross-Cultural Activity Participation Study[90-93] was used to assess physical activity at Exams 1, 2, 3, and 5. Physical activity questionnaires were not administered during Exam 4. Walking was assessed as transport walking (e.g., walking to get to places such as to the bus, car, work, or store) and leisure walking (e.g., walking for leisure, pleasure, social reasons, during work breaks, and with the dog). For each type of walking, participants were asked whether they engaged in that activity during a typical week in the past month, how many days/week, and time per day. 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.[116]

Covariates

Potential confounders were identified from the literature. Information on age, gender, race/ethnicity, and education was obtained by interviewer-administered questionnaire. Race/ethnicity was classified as Hispanic, non-Hispanic white, non-Hispanic Chinese, and non-Hispanic black. Participants selected their education from 8 categories which were collapsed into 3 categories: less than high school, high school diploma/GED but less than college, and college degree or higher. Time-varying income, employment status, marital status, car ownership, self-rated health and arthritis were also collected through interviewer-administered questionnaires at each exam. Participants selected total combined family income from 14 categories and continuous income in U.S. dollars was assigned as the midpoint of the selected category. Employment status was categorized as working at least part-time or not (including employed on leave, unemployed, and retired). Current marital status was dichotomized as "currently married or living with a partner" or "other" (including widowed, divorced, separated, and never married). Car ownership for each participant's household was dichotomized as no car ownership (zero cars) or any car ownership (1 car or ≥2 cars). Participants rated their health compared to others their age as better, same, or worse. Arthritis was measured as having an arthritis flare-up in the past two weeks. Time-varying cancer diagnosis was defined as having a hospitalization due to cancer based on ICD-9 code or self-reported cancer at any time before the exam. Time-varying body mass index (BMI) was calculated as measured weight in kilograms divided by measured height in meters squared. Missing information on marriage, self-reported health, and car ownership were filled in using the closest available time-point.

Statistical Analyses

Descriptive analyses contrasted participant characteristics and walking across four exams. We also described mean levels of the built environment at baseline as well as average changes per five years for the full sample and by site.

We used linear mixed models to estimate associations of changes in the built environment with changes in transport and leisure walking over follow-up. We ran sensitivity analyses with log-transformed walking, results showed the same directional patterns and significance (not presented). We modeled repeated walking measures on each participant as a function of: built environment at baseline, time in years since baseline (to capture the overall change in walking over follow-up), an interaction between baseline built environment and time (impact of baseline built environment on changes in walking over time), change in the built environment since baseline, an 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 confounders including time-invariant (site, baseline age, gender, race/ethnicity, education), and time-varying (income, employment, marriage status, car ownership, cancer, arthritis, BMI, and health status) characteristics.

All models included a random intercept and a random time slope for each participant, to allow the baseline responses as well as the time slope to vary between individuals. A random intercept for neighborhood was not necessary due to essentially null correlation within census tract. Due to high correlation and collinearity between several of the built environment measures, built environment predictors were each modeled separately. Since change in some built environment features may be a product of changes in population, time-varying population density was added to each of the other models in sensitivity analyses; results remained consistent and are not presented. Baseline covariates were tested for interactions with time to allow for different trajectories. Only baseline age and race/ethnicity had statistically significant differences in walking trajectories and these time interactions were included in final models. Sensitivity analyses were also run allowing walking trajectories to vary by site but results remained consistent and are not presented. Coefficients from the final model were used to compare the walking trajectories over time for different levels of baseline built environment and changes in built environment. To allow for comparison across built environment measures, all variables were mean-centered and scaled so a one unit increase was equivalent to one standard deviation (SD). All analyses were conducted in 2013 using SAS 9.2 (Cary, NC).

Results

Participant Characteristics

Follow-up time for participants ranged from 1.11 years (completing only exams 1 and 2) to 11.38 years (completing through exam 5) with a mean follow-up time of 7.43 years (SD 3.05 years; median 9.15, Inter Quartile Range (IQR) 6.13). The number of moves ranged from 0 to 8, with 69.1% never moving, 20.6% moving once, and 10.3% moving ≥ 2 times. Participant age at baseline ranged from 45 to 84, with a mean of 62.0 years (SD 10.2) (Table 3-2). Median walking at baseline was 150.0 (IQR 375.0) minutes/week for transport and 90 (IQR 240) minutes/week for leisure. Median transport walking levels decreased slightly at exams 2 and 3 but returned to initial levels at exam 5, median leisure walking increased at exam 5.

Built Environment Characteristics

At baseline, 1-mile radii around participants' homes were relatively dense (mean (SD): population density 15,720 people per square mile (19,347); social destinations 91.1 per square mile, (118.9); walking destinations 56.5 per square mile, (75.6)) (Table 3-3). On average, participants had some mixed land-use around their homes (mean percent (SD): retail 6.0% (4.3); residential 46.5% (18.1)) and good access to public transportation (mean distance to bus 0.28 miles, SD 0.77). Population density, percent retail, percent residential, and density of walking destinations generally decreased over time. Density of social engagement destinations and distance to bus increased over time. Baseline levels and changes in the built environment varied across sites, with NY and IL having the highest population density and percent retail and NC and MN participants having the lowest density and percent retail. Participants in NY and IL also lived closer to a bus than participants in the other sites. Participants in NC had the highest percent residential and the lowest network ratios of all sites. However, NC was the only site in which population density increased over time.

Walking Trajectories

At the mean baseline age and the race/ethnicity distribution of the sample, and after adjustment for other individual-level covariates, transport walking increased 1.97 minutes/week each year (95% Confidence Interval (CI): 0.33, 3.61) and leisure walking increased 3.04 minutes/week each year (CI: 1.65, 4.42). However patterns varied by baseline age and race/ethnicity. Higher age at baseline was associated with a less pronounced increase such that at the highest ages no increase over time (or even a decrease over time) in walking was observed (mean differences in annual change per SD increase in baseline age: -3.20 minutes/week (CI: -4.86, -1.54) and -4.65 minutes/week (CI -6.04, -3.25) for transport and leisure walking, respectively). 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). For this reason all estimates of trends over time in walking are adjusted to the mean age and the race/ethnic composition of the sample at baseline.

Figure 3-1 (Table 3-4) shows associations of the baseline built environment and changes in the built environment with annual changes in transport walking, after adjustment for individual-level covariates. Overall, higher levels of baseline population density, percent retail, social destinations, walking destinations, and network ratio were associated with greater increases (or less pronounced decreases) in transport walking over time (mean differences in annual change per SD increase in baseline level: 4.13, 3.23, 2.78, 4.35, and 1.76 minutes/week, respectively). In contrast, higher percent residential and greater distance to a bus were associated with less pronounced increases (or greater decreases) in transport walking over time (mean differences in annual change per SD increase in baseline level: -3.39 and -2.26 minutes/week, respectively). Increases over time in percent retail, social destinations, walking destinations, and network ratio were also associated with increases over time in transport walking (mean differences in annual change per SD increase in built environment change: 1.73, 3.53, 3.33, and 1.81 minutes/week, respectively) although only changes in social destinations, walking destinations, and network ratio were significant at the 0.05 level.

Figure 3-2 shows associations of baseline built environment measures and changes in built environment over time with annual changes in leisure walking, after adjustment for individual-level covariates. Overall, higher levels of baseline percent retail and walking destinations were associated with greater increases (or less pronounced decreases) in leisure walking over time (mean differences in annual change per SD increase in baseline level: 1.83 and 1.72, respectively). None of the built environment changes were associated with changes in leisure walking at the 0.05 level.

Discussion

This is one of the first studies to use time-varying GIS-based measures to examine associations of the built environment (and changes in the built environment) with changes in walking over time in a diverse United States sample. In this multi-ethnic and geographically diverse cohort of adults changes over time in walking were influenced by baseline levels and changes over time in built environment features. Higher initial levels of population density, percent retail, access to destinations, access to buses, and street characteristics were associated with positive trajectories of transport walking. Greater increases in access to destinations and increases in street connectivity were also associated with more positive transport walking trajectories. Trajectories of walking for leisure increased with higher baseline access to retail and walking destinations, but were not associated with built environment changes. We found smaller associations for street characteristics and bus access than for population density, zoning, and access to destinations. Built environment features also had more influence on transport than leisure walking trajectories.

In contrast to cross-sectional studies, longitudinal analyses allow us to establish whether a built environment feature or a change in a built environment feature is associated with change in walking over time. By capitalizing on time-varying information, we were able to investigate how changes to the neighborhood environment may affect changes in behavior. Our results were consistent with previous residential relocation research indicating that moving to an area with higher walkability,[10, 117] lower sprawl index[11], higher street connectivity[18], increased access to destinations[12, 16, 17, 21, 22] and higher population density[20] was associated with increases in walking, overall physical activity, and travel behavior. Our analyses add to existing work by showing that change in the built environment is also associated with changes in walking in a mixed sample including a large proportion of non-movers. Demonstrating that associations are also present in non-movers is important because analyses based only on movers may be affected by unobservable preferences related to both choice of residential location and behavior. Additionally, different abilities to act on these residential preferences (e.g. by socioeconomic status) may make studies relying on residential relocation inaccurate for the broader population.

This analysis investigates the association of specific changes in the built environment, rather than the impact of changes in overall summary measures of neighborhood walkability. This is helpful in identifying the relative importance of each built environment feature. However, given the high correlation between features we were unable to identify the independent association of each feature. Results suggest that higher percent retail, population density, and access to destinations were comparatively stronger and more consistently associated with changes in walking than street characteristics and bus access. This is consistent with cross-sectional research[7, 74] and highlights the greater importance of walking destinations over street or transportation networks. The strong associations with density of destinations was also consistent with previous work on the perceived environment, showing the importance of convenience and access to mixed services to walking,[16, 17, 19] cycling,[20] and overall physical activity.[12] Future analyses should explore whether specific types of destinations encourage more walking than others.

Associations between baseline levels of the built environment and changes in walker were slightly stronger than those between changes in the built environment and walking. Initial environmental conditions may establish walking trajectories, while changes from the initial environment may have smaller influences on walking trajectories. Since all models controlled for the association of the baseline built environment with initial walking (and included a random intercept for each person), the associations with change are not confounded by higher walking levels among those living in more supportive environments at baseline. Changes in social destinations, walking destinations, and street connectivity were still associated with changes in transport walking, even after accounting for the impact of initial levels on walking trajectories. This highlights the importance of these features for urban planning policies intended to improve walking levels through built environment interventions.

The lack of associations between change in the built environment and change in leisure walking is consistent with previous cross-sectional research,[88, 118-121] longitudinal research,[117] and the specific built environment measures investigated. The measures used may not capture other elements that encourage leisure walking, such as aesthetic quality, street traffic, or availability of sidewalks and walking trails. Differences in the associations with transport and leisure walking emphasize the significance of pairing environmental measures with specific behaviors when studying associations between health behaviors and the environment.[7, 98]

Study Limitations

Limitations of this study include the use of self-reported walking (either interviewer- or self-administered) and potential residual confounding by individual-level factors and other built environment features. There was low power to examine the association of change in the built environment with walking trajectories within cities or to compare all built environment features simultaneously in one model. However, sensitivity analysis allowing walking trajectories to vary by site or adding population density to models showed consistent results.

Several limitations are inherent to the built environment data we used. First, we relied on land-use and transportation information collected from various sources at various years. Second, using parcel area for land-use patterns penalizes vertical development (e.g. this method treats a parcel with a four-story building the same way as a parcel with a one-story building). Third, the use of zoning to infer existing land-uses may not accurately reflect what is on the ground. Finally, although sensitivity analyses with

½-mile and 3-mile buffers showed similar results, the use of 1-mile buffers may have led to misspecification of the relevant geographic area in some cities.

Self-selection continues to be a potential threat to internal validity. We were unable to utilize a fixed effects approach[94] due to limited within-person variability in walking which restricted statistical efficiency. This method would have generated within-person estimates while controlling for residual confounding by both measured and unmeasured time invariant characteristics (including preferences) although time varying confounding can still occur. Results from this study may not be generalizable to younger samples or other cities. This sample of adults had a higher percentage engaged in walking than national samples,[122] which could have affected their responsiveness to built environment features. However, this pattern is consistent with some evidence proposing walking as a replacement for more strenuous physical activity as people age.[123]

Conclusion

This study illustrates the longitudinal association between GIS-based built environment measures and walking trajectories. Increases in baseline levels and changes in the built environment were associated with positive changes in transportation walking. While participants with higher levels of several baseline built environment features experienced higher increases in leisure walking over time, those with increases in built environment features over the study did not have significantly different leisure walking trajectories.

Walking is the most common leisure activity performed by adults and can be an important component of physical activity.[57-60] 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 to encourage walking is likely to be influenced by whether environmental conditions, such as those identified in this research, make walking feasible. Increased collaborations between public health and urban planning are crucial in order to design environments to promote walking. As planners continue to work with communities, governments, and public health practitioners to design healthy communities, it is crucial that data support evidence-based planning practices. Built environment modifications to create mixed-use, dense development may encourage middle-aged and older adults to incorporate transport walking into their daily lives.

Tables & Figures

Table 3-1 Built Environment Measures with Calculation Method and Years of Data Available by Multi-Ethnic Study of Atherosclerosis (MESA) Site. MESA Neighborhood Data from 2000-2013.

Domain	Measure	Description	Method of Calculation	Data Available By MESA Site[a]
Population	Population Density	Population per square mile within a 1-mile buffer of a participant's home.	Population from the U.S. Census at the block level divided by the land area. When a block was not fully contained within a participant's neighborhood buffer, its population density was assumed to be uniform within each block.	2000 (all sites[a]); 2010 (all sites[a])
Land-Use	% Retail	% of area zoned for retail in a 1-mile buffer around a participant's	Land area zoned as retail divided by total land area within a 1-mile 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	% of area zoned for residential in a 1-mile buffer around a participant's	Land area zoned as residential divided by total land area within a 1-mile 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 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 location, and dining places) divided by the land area within a 1-mile buffer.	2000-2010 (all sites[a], each year)
	Walking Destinations	Simple density[c] of walking destinations (count per square mile) within a 1-mile 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 1-mile buffer.	
Public Transportation	Distance to Bus	Euclidean distance (in miles) between participants' addresses and the nearest bus route.	Euclidean distance (in miles) was calculated between participants' addresses and the closest bus line.	2001 (NC); 2005 (CA, IL, MN); 2007 (CA); 2009 (MD, MN, NC); 2010 (CA, NY); 2012 (CA)
Street Pattern	Network Ratio	The proportion of the Euclidean buffer covered by a network buffer.	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, denoting highest connectivity	2003 (all sites[a]); 2012 (all sites[a])

[a]Counties included in the MESA Study Sites: Los Angeles, CA (Ventura, Los Angeles, Orange, Riverside, San Bernadino); Chicago, IL (Kane, DuPage, Cook, Will); Baltimore, MD (Baltimore City, Baltimore County); St. Paul, MN (Anoka, Hennepin, Ramsey, Washington, Carver, Scott, Dakota); Forsyth, NC (Forsyth); New York, NY (Queens, Kings, New York, Bronx).
[b]Washington County, MN is the only MN county with data for 2009. The remaining MN counties have data for 2010
[c]Simple and kernel densities of destinations within each buffer were calculated, but measures were highly correlated (Pearson correlation coefficients 0.98 for social destinations and 0.97 for walking destinations, both $P < 0.0001$) so only simple densities are shown.

Table 3-2 Selected Characteristics of Participants at Baseline and Follow-up Exams. Multi-Ethnic Study of Atherosclerosis, 2000-2012

	Baseline	Exam 2	Exam 3	Exam 5
Sample (n)	6027	5901	5636	4166
Time elapsed since baseline (mean, SD)	----	1.6 (0.3)	3.2 (0.3)	9.4 (0.5)
Age (mean, SD)	62.0 (10.2)	63.6 (10.1)	65.0 (10.0)	70.0 (9.5)
Gender				
Female (%)	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%
Education (%)				
HS/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 mean, SD)	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 one 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 two weeks (%)	12.6%	11.5%	13.2%	19.4%
Body Mass Index (Mean, SD)	28.3 (5.4)	28.3 (5.5)	28.3 (5.5)	28.4 (5.7)
Health Compared to 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 (median minutes/week, IQR)				
Transportation Walking	150.0 (375.0)	105.0 (280.0)	120.0 (285.0)	150.0 (395.0)
Leisure Walking	90.0 (240.0)	90.0 (225.0)	90.0 (240.0)	120.0 (300.0)

Abbreviations: Bachelor of Arts (BA); High School or General Education Development (HS/GED); Inter-Quartile Range (IQR); Standard Deviation (SD)

Table 3-3 Built environment features at baseline (2000) and mean change per five years* overall and by site. Multi-ethnic Study of Atherosclerosis, 2000-2012

	Overall		CA		IL		MD		MN		NC		NY	
	Baseline Mean (SD)	Mean Change* (SE)	Baseline Mean (SD)	Mean Change* (SE)	Baseline Mean (SD)	Mean Change* (SE)	Baseline Mean (SD)	Mean Change* (SE)	Baseline Mean (SD)	Mean Change* (SE)	Baseline Mean (SD)	Mean Change* (SE)	Baseline Mean (SD)	Mean Change* (SE)
Population Density	15720 (19347)	-269.8 (23.9)	10656 (4721)	-303.7 (44.6)	13929 (6008)	-303.9 (52.4)	6960 (4498)	-271.1 (34.2)	4725 (1601)	-147.5 (16.0)	1622 (845)	72.8 (7.5)	55485 (13673)	-658.2 (114.7)
% 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)
% Residential	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 (mi)	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: Los Angeles, California (CA); Chicago, Illinois (IL); Baltimore, Maryland (MD); St. Paul, Minnesota (MN); Forsyth County, North Carolina (NC); New York, New York (NY); Standard Error (SE); Standard Deviation (SD)

*Mean change was obtained through multi-level random effect models of time, in years, regressed on change in each built environment measure since baseline, with random intercepts for each participant.

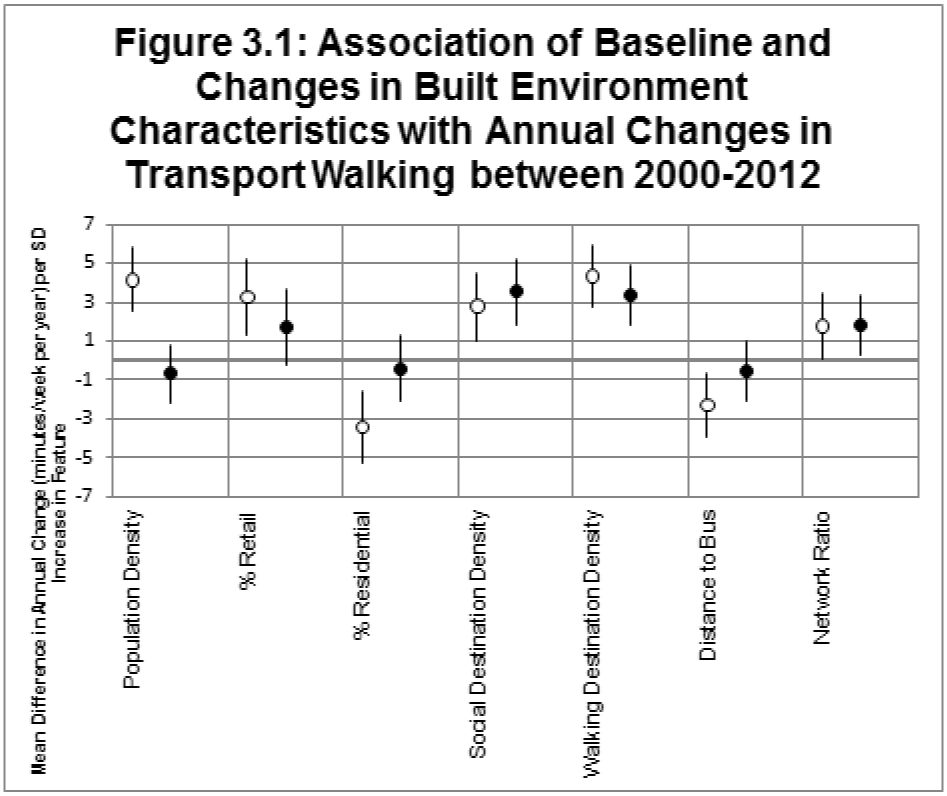
Table 3-4 Associations of Built Environment Features with Annual Changes in Transport and Leisure Walking between 2000-2012 in the Multi-Ethnic Study of Atherosclerosis.

	Transport Walking			Leisure Walking		
	Estimate[a]	95% CI	*P*-value	Estimate[a]	95% CI	*P*-value
Population Density						
Mean difference in annual change per SD increase at baseline	**4.13**	**2.49, 5.78**	**<.0001**	1.17	-0.21, 2.56	0.0977
Mean difference in annual change per SD increase in change since baseline	-0.64	-2.13, 0.84	0.3942	0.05	-1.17, 1.28	0.9326
% Retail						
Mean difference in annual change per SD increase at baseline	**3.23**	**1.29, 5.17**	**0.0011**	**1.83**	**0.21, 3.46**	**0.0271**
Mean difference in annual change per SD increase in change since baseline	1.73	-0.20, 3.66	0.0785	0.97	-0.61, 2.55	0.2279
% Residential						
Mean difference in annual change per SD increase at baseline	**-3.39**	**-5.26, -1.52**	**0.0004**	-1.32	-2.89, 0.26	0.1009
Mean difference in annual change per SD increase in change since baseline	-0.41	-2.10, 1.27	0.6304	-1.39	-2.77, 0.00	0.0503
Social Destinations						
Mean difference in annual change per SD increase at baseline	**2.78**	**1.02, 4.53**	**0.002**	0.74	-0.75, 2.22	0.3302
Mean difference in annual change per SD increase in change since baseline	**3.53**	**1.86, 5.21**	**<.0001**	0.59	-0.78, 1.97	0.3986
Walking Destinations						
Mean difference in annual change per SD increase at baseline	**4.35**	**2.74, 5.95**	**<.0001**	**1.72**	**0.36, 3.07**	**0.0129**
Mean difference in annual change per SD increase in change since baseline	**3.33**	**1.79, 4.88**	**<.0001**	1.19	-0.09, 2.47	0.0683
Distance to Bus						
Mean difference in annual change per SD increase at baseline	**-2.26**	**-3.89, -0.63**	**0.0067**	1.09	-0.29, 2.46	0.1208
Mean difference in annual change per SD increase in change since baseline	-0.52	-2.03, 0.98	0.4961	0.10	-1.15, 1.36	0.8703
Network Ratio						
Mean difference in annual change per SD increase at baseline	**1.76**	**0.09, 3.42**	**0.0387**	0.43	-0.97, 1.83	0.5485
Mean difference in annual change per SD increase in change since baseline	**1.81**	**0.29, 3.32**	**0.0193**	0.25	-1.00, 1.50	0.6931

Abbreviations: Standard Deviations (SD)

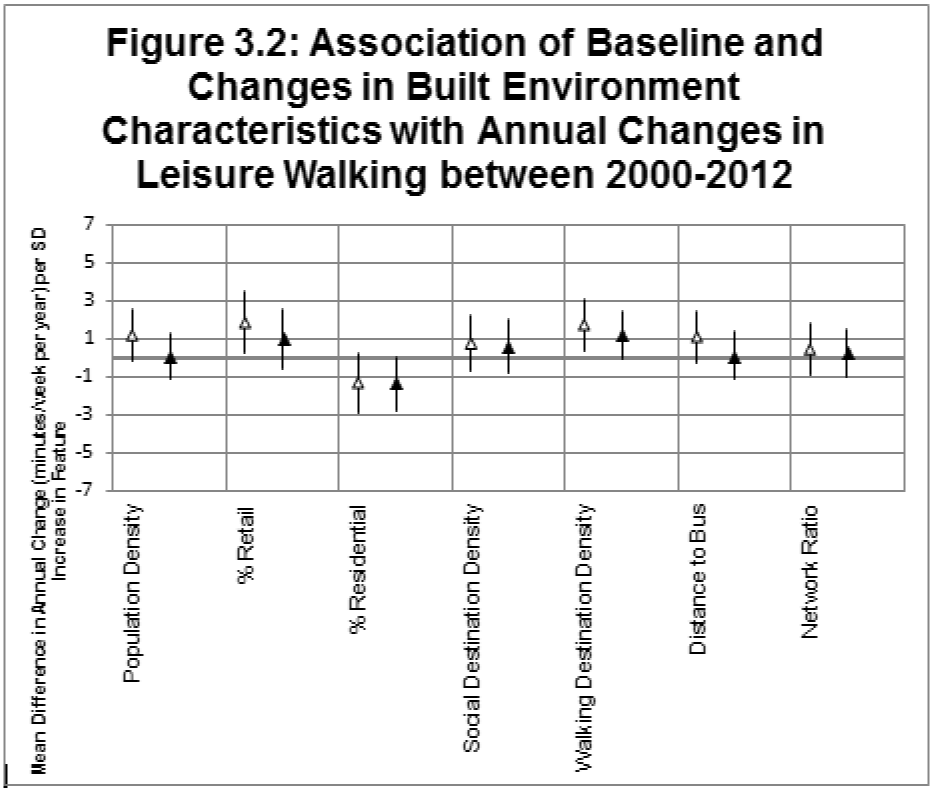
[a]Controls for: baseline built environment, change in built environment, time (in years), baseline age, baseline age*time, gender, race, race*time, education, income, employment, married, car own (yes/no), cancer, arthritis, BMI, health compared to others and site

Figure 3-1 Association of Baseline and Changes in Built Environment Characteristics with Annual Changes in Transport Walking between 2000 and 2012 in the Multi-Ethnic Study of Atherosclerosis (MESA).



White represents the mean difference in annual change in walking (minutes/week per year) per SD increase in built environment at baseline; black represents the mean difference in annual change in walking (minutes/week per year) per SD increase in change in built environment feature over time. Estimates from models controlling for: baseline built environment, change in built environment, time (in years), baseline age, an interaction between baseline age and time, gender, race, an interaction between race and time, education, income, employment, married, car ownership (yes/no), cancer, arthritis, BMI, health compared to others and site.

Figure 3-2 Association of Baseline and Changes in Built Environment Characteristics with Annual Changes in Leisure Walking between 2000 and 2012 in the Multi-Ethnic Study of Atherosclerosis (MESA).



White represents the mean difference in annual change in walking (minutes/week per year) per SD increase in built environment at baseline; black represents the mean difference in annual change in walking (minutes/week per year) per SD increase in change in built environment feature over time. Estimates from models controlling for: baseline built environment, change in built environment, time (in years), baseline age, an interaction between baseline age and time, gender, race, an interaction between race and time, education, income, employment, married, car ownership (yes/no), cancer, arthritis, BMI, health compared to others and site.

Chapter 4 Aim 3 Association of Changes in the Built Environment with Changes in Body Mass Index and Waist Circumference

After seeing an association in aim 2 between changes in built environment features and changes in transport walking, the next step was to examine whether these changes are also associated with measures of health outcomes related to physical activity (e.g. obesity) in the sample of both movers and non-movers. Therefore, this chapter, aim 3, investigates the influence of changes in the built environment on changes in BMI and WC across the entire MESA sample.

Background

Across the world obesity remains a prominent public health problem.[124] Despite recent leveling of obesity trends in the United States,[125] 35.7% of all adults aged 20 years or older are still classified as obese (body mass index (BMI)≥30 kg/m2) and an additional 33.1% are overweight (BMI 25-29.9 kg/m2).[125] Numerous studies show links between excess weight and several chronic comorbidities, most notably cardiovascular disease, diabetes, and cancers.[126] A report by the National Academy of Sciences showed that a high burden of obesity, diabetes, and cardiovascular disease may contribute to stark health disparities between the United States and other developed countries. Furthermore, a recent review concluded that obesity is estimated to account for between 0.7% and 2.8% of a country's total healthcare expenditures[127] and other research predicts that in the United States combined medical costs associated with treatment of obesity-related diseases will increase by an estimated $48-66 billion/year.[128]

While individual lifestyle changes are necessary for the prevention and reduction of overweight and obesity, policies that change the neighborhood setting may help to create supportive environments that encourage healthy behaviors.[61, 129, 130] In particular, the built environment, comprised of land-use patterns, the transportation system, and design, may encourage physical activity through transportation on foot or by bicycle.[131] In two international studies, fewer American participants reported having many shops within walking distance or transit stops within 10-15 minutes of their home than their peers in 10 other countries.[62, 63] Additionally the built environment has been shown to influence time spent driving[132] and a comparison of global cities revealed that cities in the United States have accelerated their dependence on the automobile, with little improvements in transit use.[64] A higher percentage of travel time spent driving has been implicated in higher body weight through an increase in sedentary activities and a reduction in physical and vigorous activities.[133] As a modifiable component of United States communities, the built environment may hold promise for influencing transportation-related physical activity levels and decreasing obesity at the population level.

A majority of evidence linking the built environment to physical activity and obesity remains cross-sectional.[1, 3-9, 41, 68, 71, 134, 135] Establishing causation from these studies is problematic as it is impossible to determine whether the built environment encourages health behaviors or whether those with certain health behaviors select residences with certain built environments. Several longitudinal studies have begun to show connections between the built environment and travel behavior,[21, 22] walking,[10, 11, 16-19, 24, 95-97, 117] bicycling,[20] and overall physical activity.[10-12, 136] However, longitudinal studies connecting the built environment with obesity remain limited.[11, 28-37, 95, 99, 137] Furthermore, findings from longitudinal studies have been mixed, with many failing to detect associations.[11, 29, 31, 32, 34, 35, 37, 137] Numerous methodological challenges may impact the conclusions and generalizability of the longitudinal studies that exist. Several examine obesity trajectories in relation to the initial characteristics of a neighborhood environment, giving little insight into the potential impact of changes in the environment on changing body weight.[28-33, 95, 99, 137] Some rely on residential relocation to examine changes,[11, 30, 34-36] and our search revealed only one study that examined associations of longitudinal changes in the environment with changes in obesity.[37] Despite disagreement on an appropriate metric of obesity,[40, 138-140] few used measured anthropometric characteristics[28, 31-33, 37, 99, 137] or measures of obesity other than BMI.[31, 137] Beyond these methodology issues, two of these studies are exclusively in children,[28, 35] who may be influenced by different environmental features in different ways than adults, while many were limited to non-Hispanic White populations.[11, 29, 31, 37] Finally, several are in small geographic regions[28, 29, 31-33, 37] or in non-United States contexts.[29, 33, 95, 99] Additional longitudinal evidence is needed to examine the relation of changes in the environment with obesity trajectories and to explore inconsistencies between the cross-sectional and longitudinal literatures.

This study aims to build on existing literature by examining the longitudinal association between the built environment and obesity. To address previous methodological gaps, it uses derived, individual-level built environment measures from Geographic Information Systems (GIS) and anthropometric measurements of body mass index (BMI) and waist circumference (WC) in a geographically and racial/ethnically diverse group of middle-age and older adults. By investigating whether change in obesity outcomes are related to changes in the built environment, this proposal will help clarify the causal relationships that may exist, giving further insight into the potential impact of urban planning changes on the health of Americans.

Methods

The sample included participants from the Multi-Ethnic Study of Atherosclerosis (MESA), a study of 6,814 United States adults aged 45-84 years without clinical cardiovascular disease at baseline.[78] Participants were recruited between July 2000-August 2002 from six study sites (Baltimore, MD; Chicago, IL; Forsyth County, NC; Los Angeles, CA; New York, NY; and St. Paul, MN). After a baseline examination, participants attended four additional follow-up examinations occurring at approximately 1.5-2 year intervals (Exam 2, July 2002-February 2004; Exam 3, January 2004-September 2005; Exam 4, September 2005- May 2007; Exam 5, April 2010-February 2012).[78] Neighborhoods were characterized using GIS and linked to MESA households by the Neighborhood Ancillary Study. All addresses were geocoded using TeleAtlas EZ-Locate web-based geocoding software,[112] and addresses were included if geocoding accuracy was at the street or zipcode+4 level. Of the 6,814 participants recruited in MESA, 6,191 participated in the Neighborhood Study, 6,027 were accurately geocoded, completed at least one subsequent exam, and were not missing information on obesity outcomes, or built environment for the exams they attended. Of these, 521 were missing information on covariates (most missing information on total calories consumed), leaving a final sample size of 5506. The study was approved by Institutional Review Boards at each site and all participants gave written informed consent.

Outcome Measures

Time-varying BMI (kg/m2) was calculated from weight measured to the nearest 0.45 kg, and height was measured to the nearest 0.1 cm. Time-varying WC (cm) was measured at the umbilicus to the nearest 1 cm.

Exposure Measures

Based on previous frameworks[2] we investigated six built environment measures across five built environment domains: population density, land-use patterns (zoned retail and residential), access to destinations, public transportation, and street patterns (Table 4-1). Data were obtained from regional governments and commercially available business listings and processed using ESRI ArcGIS 10.1 (Redlands, CA). Neighborhoods were defined as a buffer around participants' addresses. Primary results are reported for 1-mile buffers as they may represent the most salient environment across MESA's diverse urban contexts. Sensitivity analyses were run with ½-mile buffers; results were similar and are not presented. When data was not available for a given year, it was interpolated using a linear estimate between the two nearest measurements (Appendix B for data availability). Participant who moved outside of the study areas do not have built environment data post-move.

As built environment metrics may be interrelated and highly collinear, principle components analysis was used to identify and compute composite scores across all participants and all exams for the factors underlying these built environment components. Composite scores were created for each factor, based on the weighted sum of the standardized items which had their primary loadings on each factor. Changes in each built environment factors for descriptive analyses and multilevel models were calculated as the difference between a follow-up exam and baseline.

Covariates

Information on age, gender, race/ethnicity, and education was obtained by interviewer-administered questionnaire. Race/ethnicity was classified as Hispanic, non-Hispanic white, non-Hispanic Chinese, and non-Hispanic black. Participants selected their education from 8 categories which were collapsed into 3 categories: less than high school, high school diploma/GED but less than college, and college degree or higher. Time-varying income, employment status, marital status, car ownership, and self-rated health were also collected through interviewer-administered questionnaires at each exam. Participants selected total combined family income from 14 categories and continuous income in U.S. dollars was assigned as the midpoint of the selected category. Employment status was categorized as working at least part-time or not (including employed on leave, unemployed, and retired). Current marital status was dichotomized as "currently married or living with a partner" or "other" (including widowed, divorced, separated, and never married). Car ownership for each participant's household was dichotomized as no car ownership (zero cars) or any car ownership (1 car or ≥2 cars). Participants rated their health compared to others their age as better, same, or worse. Time-varying cancer diagnosis was defined as having a hospitalization due to cancer based on ICD-9 code or self-reported cancer at any time before the exam. Missing information on income, marriage, self-reported health, and car ownership were filled in using the closest available time-point. To account for changes that may be due to moving, an indicator of whether participants moved between the previous and current exam was created.

It is hypothesized that walking for transportation, nutrition, smoking and alcohol consumption are some of the mechanisms through which changes in the built environment may influence changes in obesity.[44, 45] Therefore, walking, nutrition, smoking, and alcohol were examined as mediators in this analysis. An interviewer-administered questionnaire adapted from the Cross-Cultural Activity Participation Study[90-93] was used to assess physical activity at Exams 1, 2, 3, and 5. Physical activity questionnaires were not administered during Exam 4, so data was interpolated using the nearest physical activity data. Transport walking minutes per week was assessed as walking to get to places such as to the bus, car, work, or store. Participants were asked whether they engaged in transport walking during a typical week in the past month, how many days/week, and time per day. Total dietary calories (kilocalories per day) were estimated at baseline from the MESA food frequency questionnaire, which was modified from the Insulin Resistance Atherosclerosis study in which comparable validity was observed for non-Hispanic white, African American, and Hispanic individuals.[78] Alcohol use (yes/no) and current smoking status (never, former, or current) were assessed at each exam based on self-report. Missing information on walking, smoking, and alcohol consumption were filled in using the closest available time-point.

Statistical Analyses

Descriptive analyses contrasted participant characteristics across the five exams. Correlation between the three built environment factors was relatively low (Pearson correlation coefficients all less than 0.40 with $P < 0.0001$, so all models are mutually adjusted. Fixed-effects models[94] were used to estimate associations between the within-person change in all three built environment factors concurrently with simultaneous within person changes in BMI or WC. This approach capitalizes on within-person variability in exposure to estimate associations.[94] These models were only adjusted for time-varying covariates (income, working status, marital status, car ownership, self-reported health, cancer diagnosis, moving indicator), since fixed effects models tightly control for time-invariant person characteristics. Baseline covariates were tested for interactions with time to allow for different trajectories. Baseline age and race/ethnicity had statistically significant differences in obesity trajectories and for this reason all estimates of trends over time in BMI and WC are adjusted to the mean age and the race/ethnic composition of the sample at baseline.

To examine mediation, time-varying transport walking, smoking and alcohol consumption was added to a final model to assess mediation of the built environment factors on obesity. Since food consumption patterns were only available at baseline, an interaction between baseline total calories consumed and time was included to evaluate mediation by dietary patterns. In sensitivity analyses, we used linear mixed models to estimate associations of changes in the built environment with changes in obesity over follow-up. All models included a random intercept and a random time slope for each participant, to allow the baseline responses as well as the time slope to vary between individuals. Results were consistent and are not presented.

To allow for comparison across built environment factors, all variables were mean-centered and scaled so a one unit increase was equivalent to one standard deviation (SD). All analyses were conducted in 2013 using SAS 9.2 (Cary, NC).

Results

Participant Characteristics

Follow-up time for participants ranged from 1.11 years (completing only exams 1 and 2) to 11.38 years (completing through exam 5) with a mean follow-up time of 7.75 years (SD 2.62 years; median 9.14, Inter Quartile Range (IQR) 4.56). The number of moves ranged from 0 to 8, with 70.97% never moving, 19.78% moving once, and 9.25% moving ≥ 2 times. Between 6.69% and 11.44% moved between the previous exam and the current one (Table 4-2). Participant age at baseline ranged from 44 to 84, with a mean of 62.03 years (SD 10.2). Over time, the sample became slightly more female, non-Hispanic white, with a higher socioeconomic status (higher percent with college education or above and higher income). Smoking and alcohol use declined in the sample and both BMI and WC increased over time.

Built Environment Characteristics

The six built environment measures loaded onto three factors (Table 4-1). Initial eigen values indicated that the first three factors explained 37%, 19%, and 15% of the variance respectively. Solutions for two and three factors were each examined using varimax rotations of the factor loading matrix. The three factor solution, which explained 81% of the variance, was preferred because of: (a) the 'leveling off' of eigen values on the scree plot after three factors; and (b) the difficulty of interpreting the loading of public transportation. Three measures (density of walking destinations, population density, and percent residential) primarily loaded onto the first factor, representing "density of development." Two measures (street connectivity and percent retail) primarily loaded onto the second factor, representing "downtown retail districts." Only distance to bus loaded onto the third factor, representing "public transportation." Throughout follow-up, density of development generally increased, downtown retail districts decreased and public transportation fluctuated, but ultimately increased.

BMI and WC Trajectories

At the mean baseline age and the race/ethnicity distribution of the sample, and after adjustment for other individual-level covariates, BMI increased a mean of 0.04 kg/m^2 per 10 years (95% Confidence Interval (CI): -0.02, 0.10) and WC increased a mean of 1.60 cm per 10 years (CI: 1.38, 1.82). However patterns varied by baseline age and race/ethnicity. Higher age at baseline was associated with a less pronounced increase such that at the highest ages no increase over time (or a decrease over time) in BMI and WC was observed (mean differences in annual change per SD increase in baseline age: -0.61 kg/m^2 (CI: -0.67, -0.55) and -1.69 cm (CI: -1.89, -1.47) for BMI and WC, respectively. Hispanic ethnicity was associated with a decrease in WC and non-Hispanic black and Chinese participants experienced a decrease in BMI over time (data not shown).

Adjusting for time-varying confounders and all measured and unmeasured time-invariant confounders, increases over time in density of development was associated with decreases in BMI and WC (Table 4-3). A SD increase in density of development was associated with a mean BMI decrease of 0.15 kg/m^2 (CI: -0.26, -0.05) and a mean WC decrease of 0.46 (CI: -0.83, -0.09) even after control for the other built environment factors. These changes in BMI are equivalent to 0.89 lbs less for an average woman (164.1 cm average height) and 1.05 lbs less for an average man (178.2 cm average height). Changes in downtown retail districts and public transportation were not associated with changes in BMI or WC at the 0.05 level in models including all built environment features. While change in smoking status and alcohol consumption were associated with changes in BMI and WC, they did not change the strength or significance of the association between change in built environment factors and change in BMI or WC. Time-varying self-reported transport walking and baseline total calories were not associated with changes in BMI or WC and also did not change the strength or significance of the association between change in built environment factors and change in BMI or WC.

Discussion

This study found evidence of a longitudinal association between change in the built environment and change in measured obesity in a multi-ethnic and multi-city sample. Increases in the density of development (density of walking destination, population density, lower percent residential) were associated with decreases in BMI and WC. However, changes in downtown retail districts (higher percent retail, higher street connectivity) and public transportation (distance to bus) were not associated with changes in BMI or WC. Associations persisted after controlling for potential mediators.

By showing an association between change in the built environment and change in BMI and WC this study illustrate a potentially key piece in a complex and inconsistent literature surrounding longitudinal built environment change and change in obesity. The association we found between increases in density of development and decreases in BMI and WC is consistent with cross sectional[30, 31, 95, 99, 100] and longitudinal[28, 30, 33, 36, 95, 99] evidence showing the importance of the environmental context in maintaining a healthy weight. However, other work has failed to find these associations.[11, 28-37, 95, 99, 137] The results isolating density of development as influencing obesity but not downtown retail districts or public transportation may help to explain a lack of consistency in previous evidence. Of the studies that failed to confirm cross-sectional associations,[11, 29, 31, 32, 34, 35, 37, 137] several used composite indices of land-use mix, street characteristics, public transit stations, and design elements that may be washing out associations from particular features of the built environment, such as density.[31, 37] Other analyses were restricted to single elements of the built environment, such as street characteristics,[32] that had no association with changes in obesity in our results. Similarly, some analyses used measures of the built environment at the county level, potentially at a scale that is not relevant to the lives and disease processes of participants.[11, 35]

In our analyses, further adjustment for mediators (transport walking, total calories, smoking, alcohol use) did not change the strength or significance of the association between change in built environment factors and change in BMI or WC. While this may indicate that changes in density are acting through separate pathways to influence obesity, the intermediate role of walking, dietary habits, smoking, and alcohol use cannot be dismissed based on these analyses. Measurement error in self-reported walking and dietary information could provide incomplete adjustment. However, since our analyses utilized change in time-varying walking within participants, stable over- and under-estimates of walking by a given person may be accounted for. Additionally, dietary information was only available at baseline. While it is unlikely total calories consumed changed dramatically within person, changes in BMI or WC may be due to changes in food intake from altered access to destinations. Smoking and alcohol use may be associated with changes in access to destinations that sell or serve these products, or could represent coping mechanisms for dealing with additional stress of living in a dense area with potentially more crime. However, adjustment for these factors did not change the associations we found between density of development and BMI and WC.

Study Limitations

This study may be limited by potential residual confounding by time-varying individual-level factors or other built environment features. In particular, equal density of development may be attained in different ways and the form of development was not measured or accounted for in these analyses. Several additional limitations are inherent to the built environment data we used. First, we relied on land-use and transportation information collected from various sources at various years. Second, using parcel area for land-use patterns penalizes vertical development (e.g. this method treats a parcel with a four-story building the same way as a parcel with a one-story building). Third, the use of zoning to infer existing land-uses may not accurately reflect what is on the ground. Finally, although sensitivity analyses with ½-mile buffers showed similar results, the use of 1-mile buffers may have led to misspecification of the relevant geographic area in some cities. While this study used a multi-ethnic and geographically diverse sample, results may not be generalizable to younger populations or individuals in other cities or countries. Additionally, loss to follow-up may create a more select sample and lead to bias if patterned by built environment or obesity.

Conclusion

This study illustrates the longitudinal association between change in the built environment, particularly increased density, and decreases in measures of obesity (BMI and WC). However, walking, nutrition, smoking and alcohol use may not be the mechanisms through which increased density decreases BMI and WC. Altering the neighborhood built environment context may be an important point of intervention for obesity. While mean changes in obesity may appear small, the changes in the environment have the potential to influence a broad population, shifting the overall distribution of obesity and decreasing chronic disease burden. These results help to clarify some of the potential causes of inconsistency in previous research, by identifying which elements are and are not associated with changes in obesity. Future research should continue to isolate and identify which specific features of the built environment, at what scale, influence which individuals. Continued collaboration between public health and urban planning is essential for clarifying the complex connection between the environments we build and the health of our populations.

Tables & Figures

Table 4-1 Built Environment Measures with Calculation Method and Years of Data Available by Multi-Ethnic Study of Atherosclerosis (MESA) Site. MESA Neighborhood Data from 2000-2013.

Domain	Measure	Description	Data Source	Data Available By MESA Site[a]	Factor Loadings		
					Factor 1: Density of Development	Factor 2: Downtown Retail Districts	Factor 3: Public Transportation
Population[c]	Population Density	Population per square mile within a 1-mile buffer of a participant's home.	U.S. Census	All sites[a] (2000, 2010)	0.87		
Land-Use[c]	% Retail	% of area zoned for retail in a 1-mile buffer around a participant's home.	Local planning departments, city governments, and regional entities	CA (2001, 2005, 2008); IL (2001, 2005); MD (2002, 2008); MN (2006, 2009[b], 2010[b]); NY (2002, 2003, 2004, 2006, 2011); NC (2005, 2010)		0.85	
	% Residential	% of area zoned for residential in a 1-mile buffer around a participant's home.			-0.83		
Destinations	Walking Destinations	Simple density[d] of walking destinations (count per square mile) within a 1-mile buffer around a participant's home.	Derived from Standard Industrial Classification (SIC) codes[114] in the National Establishment Time Series (NETS) database from Walls and Associates[113]	All sites[a] (2000-2010, each year)	0.88		
Public Transportation	Distance to Bus	Euclidean distance (in miles) between participants' addresses and the nearest bus route.	Local planning departments, city governments, and regional entities	CA (2005, 2007, 2010, 2012); IL (2005); MD (2009); MN (2005, 2009); NC (2001, 2009); NY (2010)			0.99
Street Pattern[c]	Network Ratio	The proportion of the 1-mile Euclidean buffer covered by a 1-mile network buffer.	StreetMap 03 and from StreetMap Premium 2012 (ESRI, Redlands, CA)[e]	All sites[a] (2003, 2012)		0.80	

[a]Counties included in the MESA Study Sites: Los Angeles, CA (Ventura, Los Angeles, Orange, Riverside, San Bernadino); Chicago, IL (Kane, DuPage, Cook, Will); Baltimore, MD (Baltimore City, Baltimore County); St. Paul, MN (Anoka, Hennepin, Ramsey, Washington, Carver, Scott, Dakota); Forsyth, NC (Forsyth); New York, NY (Queens, Kings, New York, Bronx).
[b]Washington County, MN is the only MN county with data for 2009. The remaining MN counties have data for 2010
[c]Linearly interpolated between time-points.
[d]Simple and kernel densities of destinations within each buffer were calculated, but measures were highly correlated (Pearson correlation coefficients 0.97 for walking destinations, $P < 0.0001$) so only simple density is shown.
[e]While StreetMap files may be less accurate than data provided by municipalities,[112] they are a uniform data source across cities.

Table 4-2 Selected Characteristics of Participants at Baseline and Follow-up Exams. Multi-Ethnic Study of Atherosclerosis, 2000-2012

	Baseline	Exam 2	Exam 3	Exam 4	Exam 5
	Mean (SD) or Percent	Mean (SD) or Percent	Mean (SD) or Percent	Mean (SD) or Percent	Mean (SD) or Percent
Sample (n)	5506	5395	5143	4825	3785
Time elapsed since baseline	----	1.63 (0.31)	3.19 (0.31)	4.82 (0.33)	9.43 (0.47)
Age	62.03 (10.19)	63.70 (10.10)	65.05 (10.03)	66.55 (9.94)	70.00 (9.48)
Gender (%)[a]					
Female	52.72	52.62	52.97	53.16	53.63
Race/Ethnicity (%)[a]					
Non-Hispanic White	40.19	40.37	40.79	41.04	41.53
Non-Hispanic Black	25.64	25.45	25.41	25.18	24.52
Non-Hispanic Chinese	12.73	12.79	12.81	12.62	12.76
Hispanic	21.43	21.39	20.98	21.16	21.19
Education (%)[a]					
HS/GED or less	34.57	34.37	33.9	33.74	31.6
Some College	27.92	27.92	28.16	27.88	28.19
BA or above	37.51	37.71	37.94	38.38	40.21
Income (in thousands)	49.93 (34.26)	49.68 (34.58)	50.14 (34.70)	50.76 (34.79)	53.76 (35.63)
Currently Employed (%)	53.87	51.49	50.46	48.08	43.36
Currently Married (%)	62.26	62.04	62.45	62.82	59.45
Own at least one car (%)	83.18	83.24	82.56	82.8	85.31
Diagnoses with Cancer (%)	7.99	9.73	11.3	13.1	15.19
Moved between previous and current exam (%)	----	7.27	8.05	6.69	11.44
Total Walking (min/week)	296.19 (416.47)	251.45 (367.24)	247.87 (366.62)	250.82 (369.18)	303.46 (416.54)
Total Calories Consumed[a]	1527.22 (791.73)	1525.91 (790.83)	1525.36 (788.31)	1525.16 (789.14)	1533.19 (795.38)
Smoking Status (%)					
Never	51.00	47.30	46.41	45.80	45.87
Former	36.94	42.13	43.53	45.06	46.82
Current	12.06	10.57	10.05	9.14	7.32
Currently using Alcohol (%)	56.48	51.21	49.39	45.06	43.43
Health Compared to others					
Better	60.37	60.63	60.3	58.32	59.84
Same	34.67	34.55	34.77	36.79	35.11
Worse	4.96	4.82	4.94	4.89	5.05
Obesity					
Body Mass Index (kg/m^2)	28.17 (5.33)	28.22 (5.39)	28.16 (5.45)	28.25 (5.52)	28.29 (5.62)
Waist Circumference (cm)	97.69 (14.14)	97.53 (14.36)	98.02 (14.36)	98.62 (14.59)	98.87 (14.66)
Change in Built Environment[b]					
Factor 1	----	0.09 (0.34)	0.16 (0.51)	0.30 (0.63)	0.33 (0.94)
Factor 2	----	-0.11 (0.47)	-0.23 (0.71)	-0.34 (0.90)	-0.55 (1.37)
Factor 3	----	0.04 (0.83)	0.06 (0.99)	0.01 (0.89)	0.11 (1.62)

Abbreviations: Bachelor of Arts (BA); High School or General Education Development (HS/GED); Standard Deviation (SD)

[a]Gender, race, education, and total calories consumed only measured at baseline. Changes across exams reflect changes in the composition of the cohort not changes in these characteristics at the individual level.

[b]Change in built environment factors since baseline. Created by subtracting factor score at exam 1 from factor scores at exams 2-5.

Table 4-3 Estimated Mean Change in Body Mass Index and Waist Circumference Associated with a Standard Deviation Increase in Built Environment Factors. Multi-Ethnic Study of Atherosclerosis, 2000-2012 (n=5506)

	Body Mass Index (BMI)		Waist Circumference (WC)	
	Model 1[a] Estimate (CL)	Model 2[a] Estimate (CL)	Model 1[a] Estimate (CL)	Model 2[a] Estimate (CL)
Factor 1: Density of Development (SD increase)	**-0.15 (-0.26, -0.05)**	**-0.16 (-0.26, -0.05)**	**-0.46 (-0.83, -0.09)**	**-0.47 (-0.84, -0.10)**
Factor 2: Downtown Retail Districts (SD increase)	0.02 (-0.03, 0.07)	0.02 (-0.02, 0.07)	0.12 (-0.05, 0.29)	0.12 (-0.05, 0.29)
Factor 3: Public Transportation (SD increase)	0.01 (-0.01, 0.03)	0.01 (-0.01, 0.03)	0.02 (-0.06, 0.10)	0.03 (-0.05, 0.11)

[a]All fixed effects models include time-varying working status, current marital status, car ownership, cancer diagnosis, self-rated health compared to others, income and an indicator of moving between the previous and current exam. Also include a time trend and interactions of time trends with selected covariates (baseline age and race/ethnicity) allowing time trends to vary by these characteristics. Model 2 also includes potential mediators: time varying transport walking minutes/week, time varying smoking status, time varying alcohol consumption status, and an interaction allowing time trends to vary by baseline calorie consumption.

Chapter 5 Aim 4: A descriptive analysis of Change in the Built Environment in Seven United States Cities

Aims 1, 2, and 3 found associations between changes in the built environment (specifically density and destinations) and changes in transport walking and obesity. This may represent a potential area of intervention to influence population-level physical activity and health outcomes. However, which neighborhoods are experiencing these changes? Are advantaged neighborhoods more likely to have positive changes? Are places with positive changes more likely to have also had increases in socioeconomic status? This final research chapter, aim 4, strives to identify whether sociodemographic characteristics are associated with changes in the built environment and discusses the potential implications of this patterning for neighborhood health disparities.

Background

Since the mid-1990s there has been an increasing interest in modifying the built environment to support healthier lifestyles. A number of scientific, political, and popular movements have emerged that support change in the built environment, including the National Complete Streets Coalition (http://www.completestreets.org/, founded in 2005), Smart Growth America (http://www.smartgrowthamerica.org/, founded in 2003), Transportation for America (http://t4america.org/, founded in 2008), Robert Wood Johnson Active Living Research (http://www.activelivingresearch.org/, founded between 1999-2000[141, 142]), and Bikes Belong Coalition (http://www.bikesbelong.org/, 1999). However, there is still very little information on how built environments are actually changing or on the factors that are associated with or drive these changes.

As a subset of the physical environment that consists of three components, 1) land-use patterns, 2) the transportation system, and 3) design, the built environment sits at the crux of urban planning and public health.[143] Numerous reviews have documented associations of multiple attributes of the built environment, especially neighborhood walkability (defined by residential density, proximity of shops and services, and street connectivity) with active transport and recreational physical activity.[8, 143-148] Change in built environment features, such as street networks and transportation systems, requires large-scale infrastructure changes that may occur over numerous decades. However, other features, such as density of destinations and land-use codes, may be more dynamic or amenable to change and may already reflect recent efforts by communities to increase walkability. Understanding how change occurs and the factors associated with change is important because these changes may have implications for physical activity behaviors that are in turn linked to many health outcomes.

Theoretical models have explored the ways in which neighborhood sociodemographic characteristics may influence behavior through unequal distribution of physical environment characteristics.[149] Some evidence suggests that low-income and minority neighborhoods have worse aesthetics or safety,[41, 150-152] and fewer opportunities for physical activity.[153-156] Little is known about whether changes in the built environment are equalizing conditions across neighborhoods or simply magnifying existing inequalities. While one study showed that locations with master plans for non-motorized transportation have similar socioeconomic characteristics as the overall United States, it also found that the degree of racial diversity among communities with plans was lower than the United States average.[157] Lack of a plan may lead to a lower likelihood of positive changes in the built environment to encourage walking and cycling. If neighborhoods with higher socioeconomic status, or with lower percentages of minorities are more likely to experience positive built environment changes, this may increase health disparities, because the benefits associated with positive change in the built environment would be experienced largely by people who already enjoy health advantages.

We described changes in land-use codes and destinations between 2000 and 2010 in a sample of neighborhoods from seven United States cities. We also described the neighborhood socio-demographic characteristics of locations that change and investigated whether four neighborhood characteristics (percent over 65, percent Non-Hispanic White, median household income, and percent without a vehicle) predict changes in the built environment.

Methods

Sample

The sample consists of 8383 census tracts from seven United States areas: Los Angeles, CA (n=3325); Chicago, IL (n=1798); Baltimore, MD (n=399); St. Paul, MN (n=685); Hinds County, MS (n=63); Forsyth County, NC (n=75); and New York, NY (n=2038). The areas were selected for study because detailed longitudinal built environment data was available as part of longitudinal studies of neighborhoods and health (The Multi-Ethnic Study of Atherosclerosis Neighborhood Study and Jackson Heart Study). Study boundaries were drawn based on land-use data availability by county (table 5-1 and figure 5-1 for study areas). Census tract boundaries are delineated to capture a set number of people, so they can vary greatly in size by population density, resulting in different number of tracts by study area. Although census tracts geographies are intended to remain stable over time, physical changes in street patterns or large population growth or decline occasionally requires that they be redrawn; this study uses census tract geographies from 2000 to maintain uniform boundaries across time. Census tracts were excluded if they were missing information on built environment or sociodemographic variables (n=164).

Built Environment Measures

Neighborhoods were characterized during the Multi-Ethnic Study of Atherosclerosis (MESA) and Jackson Heart Study (JHS) Neighborhood ancillary studies. As part of these studies, information on neighborhood environments was obtained from regional governments and national commercially available business listings. This data was then linked to 2000 census tracts using Geographic Information Systems (GIS). The following built environment measures were investigated in these analyses: percent of land-use parcels classified as retail, percent of land-use parcels classified as residential, count of number of destinations for social engagement, count of number of walking destinations, and count of number of recreational facilities.

Land-use parcel files were obtained through various sources at each study area including local planning departments, city governments, and regional entities (such as the Southern California Area Governance, SCAG, in Los Angeles, CA and Metro GIS in St.

Paul, MN). Attempts were made to obtain land-use files for years 2000 and 2010. When these years were not available, data was assigned by taking information from the nearest time point of collected data provided by a study area. Two investigators independently classified parcels into two mutually exclusive categories (retail and residential), based on the land-use codes provided for each study area. Three additional investigators verified the classification and resolved disagreements. ArcGIS 10.1 was used to calculate the percent of each census tract that is zoned for retail and residential.

Measures of access to different destinations was created using data obtained from the National Establishment Time Series (NETS) database from Walls and Associates[113] for the years 2000-2010. This data includes time-series data on establishments derived from Dun and Bradstreet (D&B) archival establishment data. Three broad categories of destinations were created: destinations for social engagement, walking destinations, and recreational environment. Social and walking destinations were derived from lists used in a previous study.[158] For social engagement destinations, 430 Standard Industrial Classification (SIC) codes were selected to represent locations that facilitate social interaction and promote social engagement, including 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 location, and dining places. 137 SIC codes were used to indicate common walking destinations, including post offices, drug stores and pharmacies, banks, food stores, coffee shops, and restaurants. For recreational environments, 114 SIC codes were selected to represent a variety of different indoor physical activity establishments such as indoor conditioning, dance, bowling, golf, team and racquet sports, and water activities derived from lists used in previous studies.[156, 159] Raw counts of destinations per census tract were calculated using ArcGIS 10.1 and area-adjusted densities were calculated by dividing raw counts by census tract land area in hectares.

Neighborhood Socio-demographics

Data for each census tract was collected from Census 2000 and American Community Survey (ACS) five-year estimates for 2005-2009. Socio-demographic variables were selected *a priori* from available census measures to reflect age structure, racial/ethnic composition, socioeconomic status and current walkability the neighborhoods. The age composition of neighborhoods may influence built environments. For example, neighborhoods with a large proportion of older residents may develop certain built environment characteristics as a result of the needs and demands of residents. Percent over 65 years of age was used to represent age structure. White and high socioeconomic status neighborhoods are often advantaged with respect to neighborhood features[41, 150-156] and may have additional economic and political power to create positive changes in the built environment.[44] Percent non-Hispanic white and inflation-adjusted median household income were used to reflect racial/ethnic composition and socioeconomic status. Although education levels, employment, poverty, and home ownership may also be associated with changes in the built environment, these were highly correlated with census tract median household income and could not be included simultaneously in analyses. Percent of total occupied housing units with no vehicle was used as a potential proxy for neighborhoods that are already more walkable, as car ownership may reflect locations that have more individuals using alternate transportation. Neighborhoods with fewer car owners may be more likely to advocate for positive changes in the built environment. Alternatively, percent of total occupied housing units with no vehicle may represent neighborhoods with numerous individuals who cannot afford a car and may have less resources to devote to advocacy and positive change.

Population counts for census tracts were measured using population data from the 2000 and 2010 United States Census blocks. This was done so as to maintain the most accurate population count in 2010 for the 2000 census boundaries. When a 2010 block was not fully contained within a 2000 census tract, its population density was assumed to be uniform within each block and was assigned in direct proportion to the area of the block contained within the census tract.

Statistical Analyses

Descriptive statistics were calculated for all neighborhood built environment and sociodemographic variables in 2000, overall and by study area. Changes in neighborhood built environment and sociodemographic variables for each tract were calculated by subtracting 2000 data from 2010 values.

Area-adjusted change in the built environment was mapped and spatial patterns were assessed within each study area using a first-order, row-standardized, rook contiguity definition of neighborhoods. Global Moran's I was used to measure overall clustering of change and Local Moran's I was used to identify statistically significant clusters of high increases surrounded by high increases (HH). Sociodemographic characteristics were compared between HH clusters and tracts that were not in these HH clusters (including tracts in low-low, high-low, and low-high clusters) using Analysis of Variance (ANOVA) or Kruskal-Wallis as appropriate.

Linear models accounting for population in 2000, land area in hectares, and study area were used to estimate the association between baseline levels of each sociodemographic variable in 2000 and change in built environment characteristics between 2000 and 2010. Fixed effects models[94] were used to estimate associations of within-census tract change in each sociodemographic variables with within-census tract changes in the built environment. This approach capitalizes on within-tract variability in exposure to estimate associations.[94] These models were adjusted only for change in population because fixed effects models tightly control for time-invariant characteristics (land area and study area). The association between change in a sociodemographic characteristic and change in the built environment was modified by the starting level of that sociodemographic characteristic. Interaction terms between the starting level and change in each sociodemographic characteristic allowed the association to vary by starting level. For ease of interpretation across neighborhood characteristics, all results are shown for an interquartile range (IQR) increase. Given the observed interactions of within tract change with baseline levels results from the fixed effects models are reported for the 25th and 75th percentiles of the sociodemographic characteristic at baseline. Mutually adjusted models included all four sociodemographic characteristics together.

Results

The size of census tracts varied greatly by study area, ranging from a median of 17.65 hectares in NY to 410.51 hectares in MS (Table 5-2). Over all study areas, census tracts had an average of 19.20 destinations for social engagement, 12.23 walking destinations, and 1.26 physical activity facilities in 2000. The mean percent of census tract area dedicated to residential uses across all study sites was 47.18%, with a low of

34.48% in MS to a high of 57.49% in NC. Retail uses were less common: mean 6.35% ranging from 2.36% (NC) to 8.49% (IL). Tracts had an average of 4340 people. The mean percent of census tract residents over 65 was 11.10%; on average the mean percent of non-Hispanic white residents was 45.29% and a mean of 22.66% tract households had no vehicle. MD and NC had higher percent over 65 than other study areas. MS and NY had the lowest percent non-Hispanic white, while MN had the highest. NY had the highest percent of households without vehicles. Median household income had a mean of $47,870 with MS having the lowest median household income and MN having the highest.

The number of all destinations increased between 2000 and 2010 (Table 5-2). Destinations for social engagement increased the most: the mean increase was 10.46 locations per tract. Census tracts had a mean increase of 1.58 walking destinations and 0.92 physical activity facilities. Changes in land-use were of very small magnitude so predictors of change in land-uses were not investigated. Percent retail decreased a mean of 0.35%, and percent residential decreased a mean of 0.30%. In all areas except NY and IL, the area zoned for residential uses decreased over time although the magnitude of the reduction differed by site from a reduction of -12.89% in NC to -0.28% in MD. Between 2000 and 2010, census tracts gained an average of 247.37 people. Mean percent over 65 increased by 0.35%, while mean percent non-Hispanic white decreased 2.92% and mean percent without a vehicle decreased 2.50%. MS experienced the highest decrease in percent non-Hispanic white (-7.69%) while NC remained fairly stable (increase of 0.02%). Median household income across all tracts, adjusted for inflation, increased by a mean of $3,300. CA, MD and NY experienced the largest increases, $4,170, $3,790 and $5,500 respective, while IL and MN experienced much smaller increases ($720 and $80, respectively). Tracts in MS and NC experienced mean median household income decreases of $2,230 and $1,640, respectively.

Positive and highly significant Global Moran's I (ranging from 0.02 to 0.62) indicated that changes were more spatially clustered within a study area than would be expected if underlying spatial processes were random (results not shown). Local Moran's I identified clusters of tracts with high changes in destinations (i.e. individual tracts with high increases in destinations bordered by other tracts with high increases, when compared to the other tracts in that study area). A total of 444 census tracts were in clusters of high increases in destinations for social engagement, 261 were in clusters of high change in walking destinations, and 372 were in high clusters of change in physical activity facilities (Table 5-3). Census tracts that experienced the highest increases in destinations between 2000 and 2010 and were surrounded by neighbors experiencing higher increases (HH), generally had higher percentage non-Hispanic whites and higher percentage of housing units without vehicles than other tracts in 2000 and experienced increases in percent non-Hispanic white (as opposed to decreases), greater increases in median household income, and larger decreases in percent of households without a vehicle than other tracts between 2000 and 2010. Percent over 65 was not generally different between clusters of high change and other tracts, with the exception that tracts in clusters of high increases in walking destinations and physical activity facilities had lower percentages over 65 in 2000 than tracts in other cluster types.

Census tract sociodemographic characteristics in 2000 were associated with changes over time in the built environment (Table 5-4, Figure 5-2). Adjusting for all other sociodemographic factors, city, land area and changes in population, tracts in 2000 with a higher percentage non-Hispanic white, median household income, and percent of households without vehicles experienced greater increases in destinations for social engagement (mean differences in 10-year change for IQR differences of percent non-Hispanic white in 2000: 5.22 (95% Confidence Interval (CI) 4.25, 6.18), median household income: 3.68 (CI 3.15, 4.10), and percent with no vehicle: 6.22 (CI 5.54, 6.90)). Tracts in 2000 with a higher percentage over 65, non-Hispanic white, and percent of households without vehicles experienced greater decreases in walking destinations (mean differences in 10-year change for IQR differences of percent over 65 in 2000: -0.18 (CI -0.30, -0.07), median household income: -0.56 (CI -0.88, -0.24), and percent with no vehicle: -0.30 (CI -0.53, -0.08)). Tracts in 2000 with a higher percentage non-Hispanic white, median household income, and percent of households without vehicles experienced greater increases in physical activity facilities (mean differences in 10-year change for IQR differences of percent non-Hispanic white in 2000: 0.97 (CI 0.85, 1.10), median household income: 0.31 (CI 0.24, 0.38), and percent with no vehicle: 0.54 (CI 0.45, 0.63)). However, tracts in 2000 with a higher percentage over 65 experienced decreases in physical activity facilities (mean difference in 10-year change for IQR difference in percent over 65 in 2000: -0.10 (CI -0.14, -0.05).

Additionally, within-tract changes in sociodemographic characteristics over 2000-2010, adjusting for change in population, were associated with within-tract changes in the built environment from 2000-2010 (Table 5-5, Figures 5-3 through 5-5). The association between changes in sociodemographic characteristics and changes in the built environment were modified by starting levels of each sociodemographic characteristic. Within-tract IQR increases in median household income between 2000 and 2010 were associated with within-tract increases in social destinations (1.32 (CI 0.92, 1.72) at the 25th percentile of baseline median household income, and 1.13 (CI 0.81, 1.45) at the 75th percentile of baseline median household income). Similarly, within-tract IQR increases in percent of households without a vehicle between 2000 and 2010 were associated with within-tract increases in social destinations (1.18 (CI 0.72, 1.64) at the 25th percentile of baseline percent with no vehicle, and 0.76 (CI 0.48, 1.04) at the 75th percentile of baseline percent with no vehicle). However, within-tract increases in percent over 65 and percent non-Hispanic white between 2000 and 2010 were associated with increases among tracts that started with higher initial levels in 2000, not among tracts that started at lower initial levels in 2000. Within tract increases in percent over 65, non-Hispanic white, and percent with no vehicle between 2000 and 2010 were associated with within-tract increases in walking destinations (mean increase between 2000 and 2010 for an IQR increase between 2000 and 2010 in percent over 65: 0.28 (CI 0.14, 0.42) for 25th baseline percentile, 0.23 (CI 0.12, 0.35) for 75th percentile; percent non-Hispanic white: 0.30 (CI 0.12, 0.48) for 25th baseline percentile, 0.23 (CI 0.09, 0.38) for 75th percentile; percent with no vehicle: 0.23 (CI 0.09, 0.38) for 25th baseline percentile, 0.10 (CI 0.01, 0.19) for 75th percentile). Within tract increases in median household income and percent with no vehicle between 2000 and 2010 were associated with within-tract increases in physical activity facilities (mean increase between 2000 and 2010 for an IQR increase between 2000 and 2010 in median household income: 0.08 (CI 0.03, 0.13) for 25th baseline percentile, 0.11 (CI 0.07, 0.15) for 75th percentile; percent with no vehicle: 0.09 (CI 0.03, 0.15) for 25th baseline percentile, 0.09 (CI 0.06, 0.13) for 75th percentile). Increases in percent non-Hispanic white was associated with within-tract increases in physical activity facilities only at lower initial percentages of non-Hispanic whites (mean increase between 2000 and 2010 for an IQR increase between 2000 and 2010 in percent non-Hispanic white: 0.21 (CI 0.14, 0.28) for 25th baseline percentile). Similarly, increases in percent over 65 was associated with within-tract increases in physical activity facilities only at higher initial percentages over 65 (mean increase between 2000 and 2010 for an IQR increase between 2000 and 2010 in percent over 65: 0.05 (CI 0.00, 0.09) for 75th baseline percentile).

Discussion

The number of destinations for social engagement, walking, and physical activity all increased between 2000 and 2010 in a geographically diverse sample of cities across the United States. Increases also occurred in land-use categories, although they were minimal in magnitude. Changes in the built environment are spatially clustered. Clusters experiencing greater change had higher percent non-Hispanic white residents, higher incomes and more housing units without vehicles at baseline. They also tended to show greater increase in non-Hispanic white residents and income over time. Higher initial levels and changes in percent over 65, percent non-Hispanic White, median household income, and percent with no vehicle were positively associated with increases in destinations between 2000 and 2010.

This study is among the first studies to examine changes in access to destinations and land-uses the United States. As more effort is placed on influencing the walkability of neighborhoods, it is crucial that efforts are taken to benchmark and track whether and where changes are occurring. Changes for destinations were much larger than changes in land-uses. This is likely due to the more dynamic nature of many popular destinations, such as commercial businesses. While land-use codes are amenable to change, these changes include numerous stakeholders and may require longer periods of time than ten years. This could also be due to differences in data collection as land-use files came from municipalities and may have a different level of accuracy than destination data. Differences across study areas may be due to differing levels of engagement to change the built environment, although external factors, such as economic development, could also be driving change. The economic downturn of 2008 may have influenced economic conditions in the study areas. Sensitivity analyses examining change in the destinations for all years show a dip in 2009 but recover in 2010. Similarly, population growth could contribute to changes in land-use in the study areas.

The patterning of change by racial composition, socioeconomic status and vehicle ownership may contribute to deepening environmental disparities. Census tracts experiencing highly positive change were more likely to have a high percentage non-Hispanic white, had higher median household incomes, and higher percentage of housing units without vehicles in 2000. Cross-sectional evidence shows that white, high-income neighborhoods are already advantaged with regards to physical activity facilities,[153-156, 160] parks,[153, 154] and aesthetics[41, 151, 152]. If these neighborhoods experience additional increases in destinations or favorable land-use changes, disparities in health behaviors that are associated with the built environment will worsen rather than improve. In addition, census tracts in high clusters of change experienced high increases in percent non-Hispanic white and median household income between 2000 and 2010. However, we do not know whether sociodemographic change preceded neighborhood changes or whether alternate processes, such as gentrification, are occurring after neighborhood resources increase. Finally, in general, census tracts that started at higher initial levels of each sociodemographic characteristic experienced slightly stronger associations between increases in sociodemographic characteristics and increases in destinations. This may illustrate the additional leverage potential of neighborhoods with higher resources at baseline. Efforts to improve the built environment should work to identify resource-scarce neighborhoods and to involve low-income and communities of color to work towards a more even distribution of resources.

As the American population ages, the environment may play an important role in maintaining independence, mobility, and the overall ability of older adults to age in place.[161] These analyses showed that clusters of high levels of improvement in walking destinations have a lower percent over 65 than other types of clusters. Additionally, tracts with a higher percent over 65 in 2000 were associated with decreases in walking destinations, physical activity facilities, and percent retail. This may restrict access for many older adults who remain in these neighborhoods. However, increases in percent over 65 were associated with increases in all built environment measures. This is consistent with qualitative research on relocation motives among older adults[162] and neighborhood design's role in active aging.[161, 163] Close destinations may be important for combining walking into daily activities and for decreasing social isolation for older adults.[161, 164] Age-friendly urban design will become critical for older people to successfully age in place and it is encouraging to see that locations with higher increases in percent over 65 are having higher increases in destinations. However, attention should be paid to locations with higher initial percent over 65 to ensure that older adults who wish to age in place have the appropriate supports to stay in their current residential location.

Study Limitations

Census tracts may not accurately reflect neighborhood boundaries. Additionally, differences in the residence rules, such as who counts in a household, and reference periods (particularly for income) could have impacted comparability between ACS 5-year estimates and Census 2000. However, the United States Census Bureau "recommend users compare derived measures such as percent" as was done in this study.[165] These analyses were limited by the GIS data obtained from the various study areas. Land-use files for each study area came from different years and the extrapolation to 2000 and 2010 may miss some changes that occur. However, as different regional and municipalities collect and revise land-use files sporadically, this data is a representation of the land-use codes on file. Additionally, some study area's land-use classification systems are more detailed than others. However, categorization was done to harmonize codes to the most broad land-use codes. One drawback of using parcel area is that it penalizes vertical development (e.g. treats a parcel with a multi-story building the same as a parcel with a one-story building). Ultimately, changes in the built environment may take longer than ten years or may occur in small-scale design features that are difficult to measure across multiple study areas, such as crosswalks, bicycle lanes, and sidewalks.

Conclusions

Positive changes are occurring in the built environment to improve the walkability of these seven study areas across the United States. However, due to the unequal distribution of changes across neighborhood sociodemographic characteristics, efforts to improve the built environment should focus on disadvantaged neighborhoods in order to reduce environmental and health disparities. Differences in the association across neighborhoods of varying initial sociodemographic characteristics may illuminate the additional influence potential of neighborhoods with higher resources. Additionally, differences seen in racial and age composition, independent of socioeconomic advantage, indicate areas of concern to track for potential environment justice and health equity issues.

Tables & Figures

Table 5-1 Counties included for each study area.

Site	County Names
CA	Ventura, Los Angeles, Orange, Riverside, and San Bernadino
IL	Kane, DuPage, Cook, and Will
MD	Baltimore City and Baltimore County
MN	Anoka, Hennepin, Ramsey, Washington, Carver, Scott, and Dakota
MS	Hinds
NC	Forsyth
NY	Queens, Kings, New York, and Bronx

Table 5-2 Mean built environment and sociodemographic characteristics at baseline (2000) and mean change between 2000 and 2010 for the full sample and by study area

	Overall	CA	IL	MD	MN	MS	NC	NY
N	8383	3325	1798	399	685	63	75	2038
	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)
Land Area (hectares) (median (IQR)	115.62 (260.90)	156.55 (242.37)	142.86 (329.92)	140.55 (205.39)	339.66 (534.60)	410.51 (832.49)	870.62 (1911.96)	17.65 (7.86)
Baseline (2000)								
Destinations								
Social Engagement (count)	19.20 (20.70)	21.54 (22.43)	18.41 (16.90)	18.81 (19.44)	16.55 (14.65)	26.27 (18.10)	26.85 (14.74)	16.55 (22.44)
Walking (count)	12.23 (14.68)	13.46 (14.92)	10.88 (12.43)	10.81 (14.12)	9.21 (11.70)	12.97 (11.78)	13.31 (11.65)	12.64 (16.91)
Physical Activity Facilities (count)	1.26 (1.89)	1.49 (2.04)	1.32 (1.84)	1.08 (1.46)	1.56 (1.65)	0.95 (1.21)	1.76 (1.76)	0.74 (1.71)
Land-Uses								
Percent Retail	6.35 (7.13)	5.22 (5.84)	8.49 (8.19)	8.22 (10.71)	5.20 (6.79)	2.48 (2.88)	2.36 (2.75)	6.59 (6.87)
Percent Residential	47.18 (21.12)	43.22 (19.69)	54.77 (23.84)	54.83 (25.06)	48.99 (23.03)	34.48 (15.51)	57.49 (17.75)	44.87 (16.67)
Sociodemographics								
Total Population (1000 people)	4.34 (2.34)	4.88 (2.19)	4.45 (2.68)	3.51 (1.60)	3.85 (1.50)	3.98 (1.92)	4.08 (1.65)	3.70 (2.42)
Percent over 65	11.10 (6.76)	10.48 (7.33)	10.95 (6.02)	14.38 (6.92)	9.97 (6.36)	11.39 (4.75)	13.29 (5.15)	11.91 (6.30)
Percent non-Hispanic white	45.29 (33.53)	40.33 (28.94)	51.36 (35.19)	53.87 (36.97)	81.52 (20.31)	33.74 (31.90)	62.32 (31.49)	33.90 (31.98)
Median Household Income (1000 USD)	47.87 (23.32)	49.85 (24.22)	51.63 (25.05)	42.29 (20.58)	55.81 (19.98)	32.87 (15.75)	42.23 (17.70)	40.41 (19.53)
Percent without a vehicle	22.66 (23.41)	10.71 (10.63)	17.56 (16.88)	23.53 (21.02)	9.09 (10.50)	12.45 (10.54)	11.30 (13.04)	51.79 (22.62)
Change (2000 to 2010)								
Destinations								
Social Engagement (count)	10.46 (15.62)	12.79 (18.42)	7.25 (12.53)	10.18 (11.14)	6.46 (7.95)	9.73 (10.14)	12.76 (11.16)	10.82 (15.33)
Walking (count)	1.58 (4.93)	1.44 (4.99)	0.79 (4.65)	0.06 (3.84)	0.75 (4.06)	-0.73 (4.77)	2.35 (5.15)	3.15 (5.15)
Physical Activity Facilities (count)	0.92 (1.95)	1.08 (2.20)	0.78 (1.88)	0.66 (1.43)	1.13 (2.06)	0.63 (1.32)	1.07 (1.83)	0.77 (1.59)
Land-Uses								
Percent Retail	-0.35 (4.09)	0.28 (2.78)	0.01 (1.45)	-7.26 (9.63)	-4.43 (6.41)	-0.04 (1.14)	-0.09 (1.13)	1.01 (2.17)
Percent Residential	-0.30 (7.07)	-1.45 (5.18)	0.59 (2.72)	-0.28 (11.86)	-3.13 (17.15)	-0.89 (6.11)	-12.89 (8.60)	2.22 (2.71)
Sociodemographics								
Total Population (1000 people)	0.25 (1.51)	0.44 (1.92)	0.12 (1.58)	0.06 (0.72)	0.30 (1.08)	-0.09 (0.88)	0.60 (1.01)	0.05 (0.68)
Percent over 65	0.35 (3.67)	0.55 (3.10)	0.12 (4.11)	-0.83 (4.18)	0.71 (3.13)	-0.30 (2.94)	0.00 (0.03)	0.36 (4.13)
Percent non-Hispanic white	-2.92 (8.40)	-4.08 (7.14)	-3.10 (9.40)	-3.87 (7.65)	-4.13 (7.18)	-7.69 (11.65)	0.02 (2.89)	-0.09 (9.10)
Median Household Income (1000 USD)	3.30 (10.57)	4.17 (9.21)	0.72 (12.09)	3.79 (8.45)	0.08 (7.31)	-2.23 (4.91)	-1.64 (6.64)	5.50 (11.88)
Percent without a vehicle	-2.50 (7.69)	-2.79 (5.29)	-2.39 (9.16)	-3.79 (8.13)	-0.75 (4.47)	-1.08 (5.00)	-1.30 (3.50)	-2.52 (10.05)

Table 5-3 Comparison of sociodemographic characteristics between clusters of high change and other neighborhoods in the built environment from local Moran's I.

	Social Destinations (Area Adjusted)			Walking Destinations (Area Adjusted)			Phys Activity Destinations (Area Adjusted)		
	HH	**Other**	**p-value**	**HH**	**Other**	**p-value**	**HH**	**Other**	**p-value**
N	444	7939		261	8122		372	8011	
Baseline (2000)									
Percent over 65	10.95 (6.29)	11.11 (6.78)	0.6193	8.04 (4.10)	11.20 (6.80)	**<0.0001**	10.35 (5.98)	11.14 (6.79)	**0.0280**
Percent non-Hispanic white	54.91 (29.32)	44.75 (33.67)	**<0.0001**	21.30 (25.06)	46.06 (33.49)	**<0.0001**	56.18 (27.84)	44.79 (33.69)	**<0.0001**
Median Household Income (1000 USD)	47.62 (27.74)	47.88 (23.05)	0.0788	28.89 (14.00)	48.48 (23.30)	**<0.0001**	49.14 (24.09)	47.81 (23.28)	0.1614
Percent without a vehicle	41.12 (27.85)	21.63 (22.70)	**<0.0001**	51.23 (25.58)	21.75 (22.75)	**<0.0001**	41.22 (28.86)	21.80 (22.77)	**<0.0001**
Change (2000 to 2010)									
Percent over 65	0.16 (3.88)	0.36 (3.65)	0.2816	0.23 (3.81)	0.35 (3.66)	0.6146	0.04 (3.42)	0.36 (3.68)	0.1035
Percent non-Hispanic white	2.65 (7.62)	-3.23 (8.33)	**<0.0001**	2.61 (6.62)	-3.10 (8.39)	**<0.0001**	3.16 (8.42)	-3.21 (8.29)	**<0.0001**
Median Household Income (1000 USD)	8.24 (13.47)	3.03 (10.32)	**<0.0001**	5.31 (8.85)	3.24 (10.62)	**0.0002**	9.52 (12.53)	3.01 (10.39)	**<0.0001**
Percent without a vehicle	-3.63 (9.05)	-2.43 (7.60)	**0.0015**	-4.46 (7.86)	-2.43 (7.67)	**<0.0001**	-3.17 (8.66)	-2.46 (7.64)	0.0854

HH=Neighborhoods (census tracts) with high values clustered with tracts with high values; Other includes: LL (Tracts with low values clustered with tracts with low values), HL/LH (discordant tracts with high values surrounded by tracts with low values or tracts with low values surrounded by tracts with high values) and NS (Not statistically significant, not in a cluster).
P-values from Analysis of Variance (ANOVA) or Wilcoxon Two-Sample Test (for Median Household Income)

Table 5-4 Differences in change in the built environment between 2000 and 2010 associated with census tract characteristics in 2000 (estimates correspond to the difference in 2000-2010 change for an IQR increase in percentile of the characteristic at baseline).

	Social Engagement		Walking Destinations		Physical Activity Facilities	
Predictor	Independent	Mutually Adjusted	Independent	Mutually Adjusted	Independent	Mutually Adjusted
Percent over 65 in 2000	**1.12 (0.78, 1.45)*** **	0.35 (-0.01, 0.70)	**-0.25 (-0.36, -0.15)*** **	**-0.18 (-0.30, -0.07)** **	**0.07 (0.03, 0.11)** **	**-0.10 (-0.14, -0.05)*** **
Percent NHW in 2000	**5.89 (5.20, 6.57)*** **	**5.22 (4.25, 6.18)*** **	**-0.45 (-0.68, -0.23)*** **	**-0.56 (-0.88, -0.24)** **	**0.92 (0.83, 1.01)*** **	**0.97 (0.85, 1.10)*** **
Median household income in 2000	**3.16 (2.78, 3.55)*** **	**3.68 (3.15, 4.20)*** **	-0.04 (-0.17, 0.08)	0.06 (-0.11, 0.23)	**0.43 (0.38, 0.48)*** **	**0.31 (0.24, 0.38)*** **
Percent with no vehicle in 2000	**0.99 (0.42, 1.56)*** **	**6.22 (5.54, 6.90)*** **	-0.08 (-0.26, 0.10)	**-0.30 (-0.53, -0.08)** **	**-0.08 (-0.16, -0.01)* **	**0.54 (0.45, 0.63)*** **

***= p<0.05; **=p<0.01; ***=p<0.0001**
Controls for city, population in 2000, land area

Table 5-5 Mean within tract changes in the built environment associated with a within tract IQR increases in census tract sociodemograhic characteristic.

		Social Engagement		Walking Destinations		Physical Activity Facilities	
	Predictor	Independent	Mutually Adjusted	Independent	Mutually Adjusted	Independent	Mutually Adjusted
At 25th Percentile of the Baseline level of the Sociodemographic characteristic	Percent over 65 between 2000 and 2010	0.34 (-0.09,0.77)	0.27 (-0.17, 0.70)	0.34 (0.20, 0.48)***	0.28 (0.14, 0.42)***	0.05 (0.00, 0.11)	0.04 (-0.02, 0.09)
	Percent NHW between 2000 and 2010	0.79 (0.24, 1.34)**	0.45 (-0.12, 1.01)	0.37 (0.19, 0.54)***	0.30 (0.12, 0.48)**	0.21 (0.14, 0.28)***	0.21 (0.14, 0.28)***
	Median household income between 2000 and 2010	1.28 (0.91, 1.66)***	1.32 (0.92, 1.72)***	0.05 (-0.07, 0.17)	0.02 (-0.11, 0.15)	0.06 (0.02, 0.11)**	0.08 (0.03, 0.13)**
	Percent with no vehicle between 2000 and 2010	0.95 (0.49, 1.40)***	1.18 (0.72, 1.64)***	0.26 (0.11, 0.40)**	0.23 (0.09, 0.38)**	0.08 (0.02, 0.14)**	0.09 (0.03, 0.15)**
At 75th Percentile of the Baseline level of the Sociodemographic characteristic	Percent over 65 between 2000 and 2010	0.48 (0.13, 0.83)**	0.38 (0.02, 0.74)*	0.29 (0.17, 0.40)***	0.23 (0.12, 0.35)***	0.06 (0.02, 0.11)**	0.05 (0.00, 0.09)*
	Percent NHW between 2000 and 2010	1.62 (1.18, 2.06)***	1.46 (1.01, 1.91)***	0.25 (0.11, 0.39)**	0.23 (0.09, 0.38)**	0.05 (-0.01, 0.10)	0.04 (-0.02, 0.10)
	Median household income between 2000 and 2010	1.08 (0.77, 1.38)***	1.13 (0.81, 1.45)***	0.04 (-0.06, 0.13)	0.03 (-0.07, 0.14)	0.10 (0.06, 0.14)***	0.11 (0.07, 0.15)***
	Percent with no vehicle between 2000 and 2010	0.47 (0.19, 0.74)**	0.76 (0.48, 1.04)***	0.10 (0.01, 0.19)*	0.10 (0.01, 0.19)*	0.07 (0.04, 0.11)***	0.09 (0.06, 0.13)***

*= p<0.05; **=p<0.01; ***=p<0.0001

All models control for change in population

Figure 5-1 Census tracts (2000) included in analyses by metropolitan area

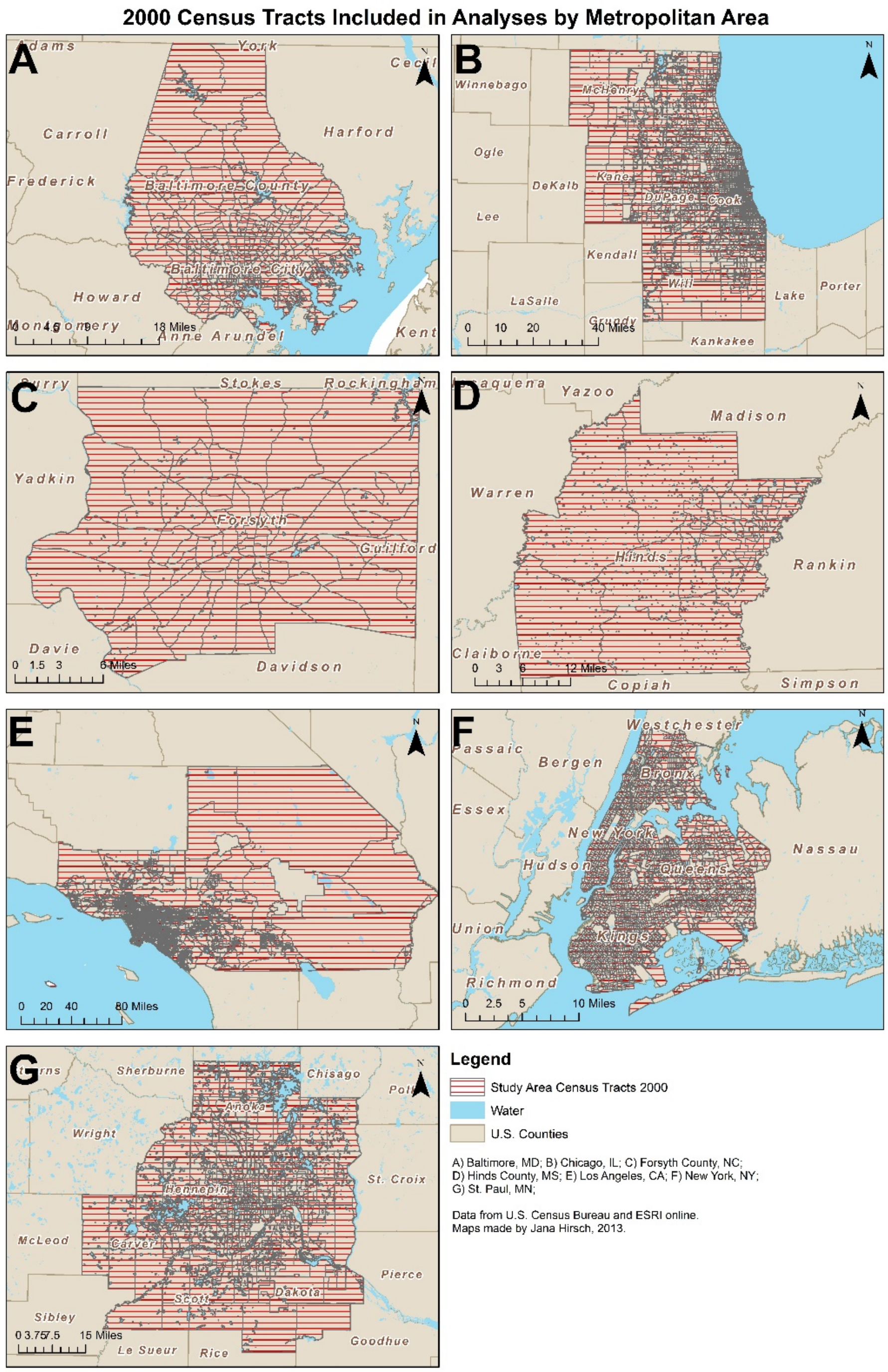


Figure 5-2 Change in destinations (2000-2010) for baseline differences in sociodemographics

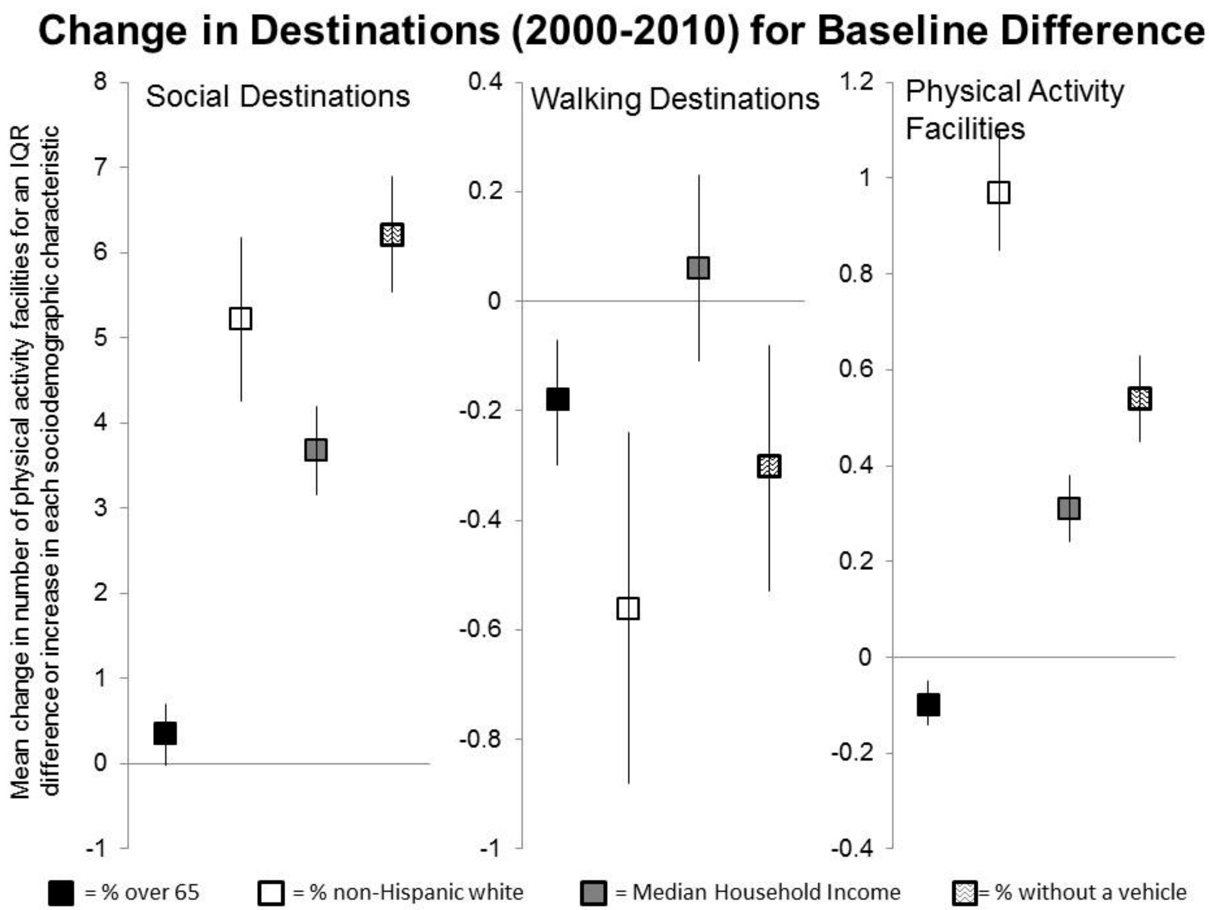


Figure 5-3 Change in destinations for social engagement (2000-2010) for change in sociodemographics

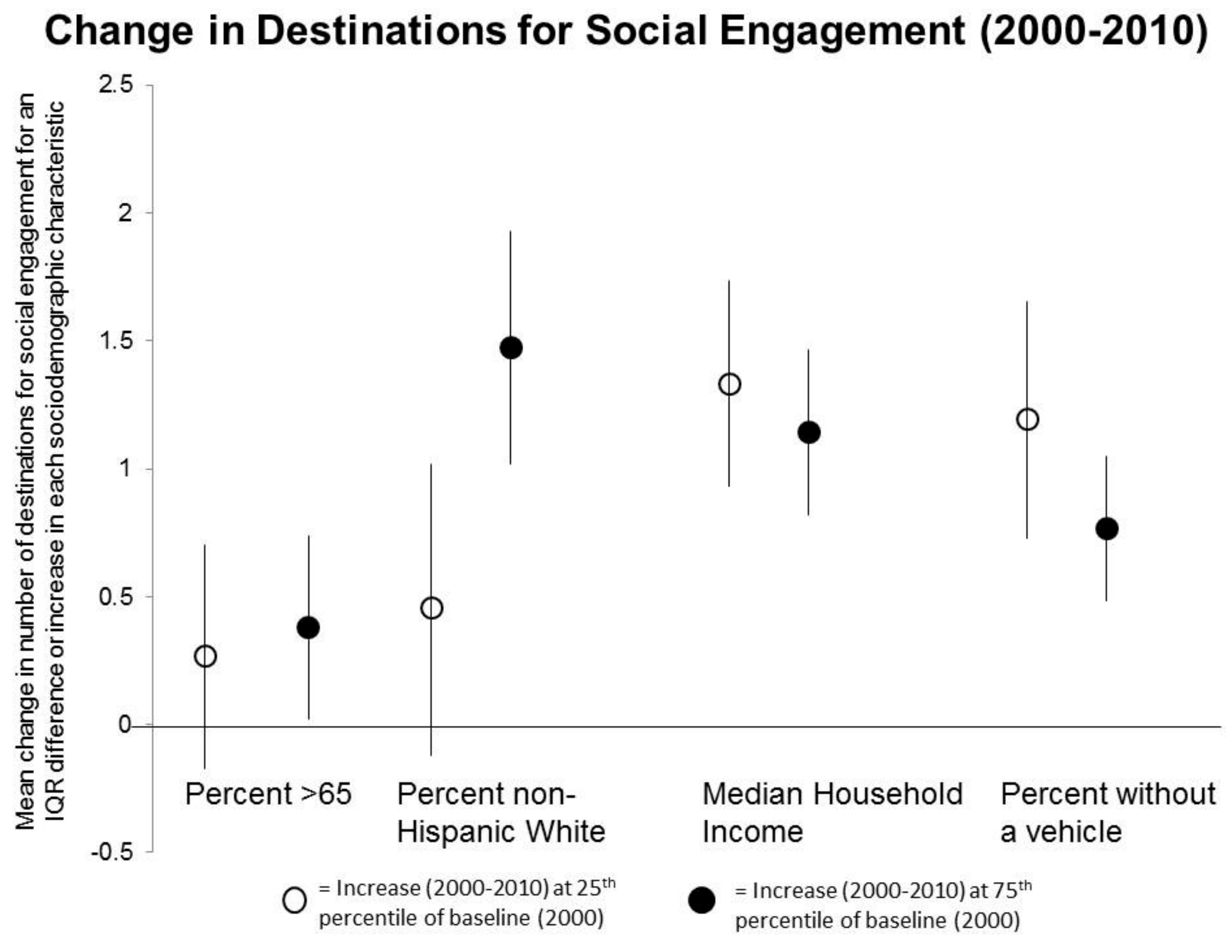


Figure 5-4 Change in physical activity facility destinations (2000-2010) for change in sociodemographics

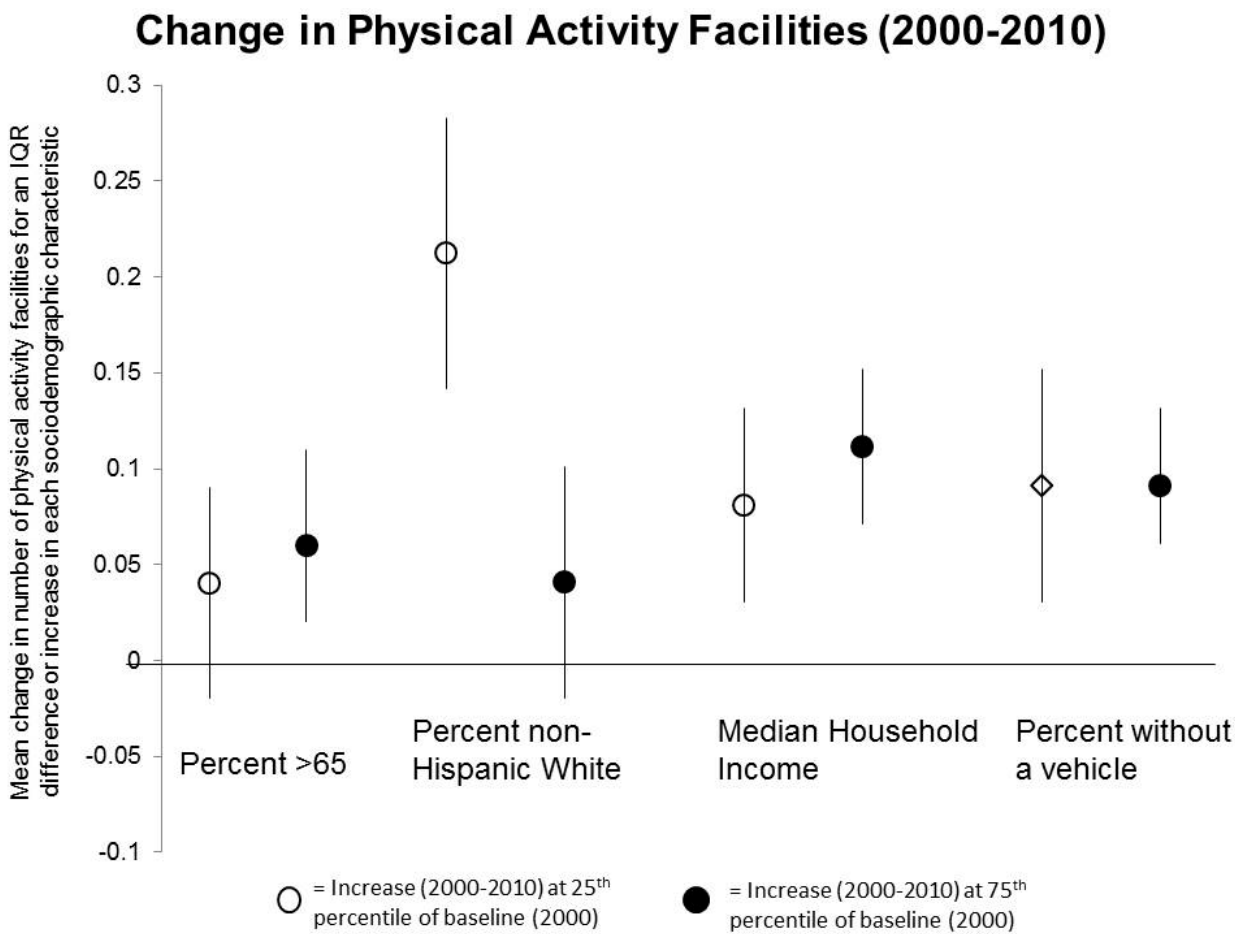
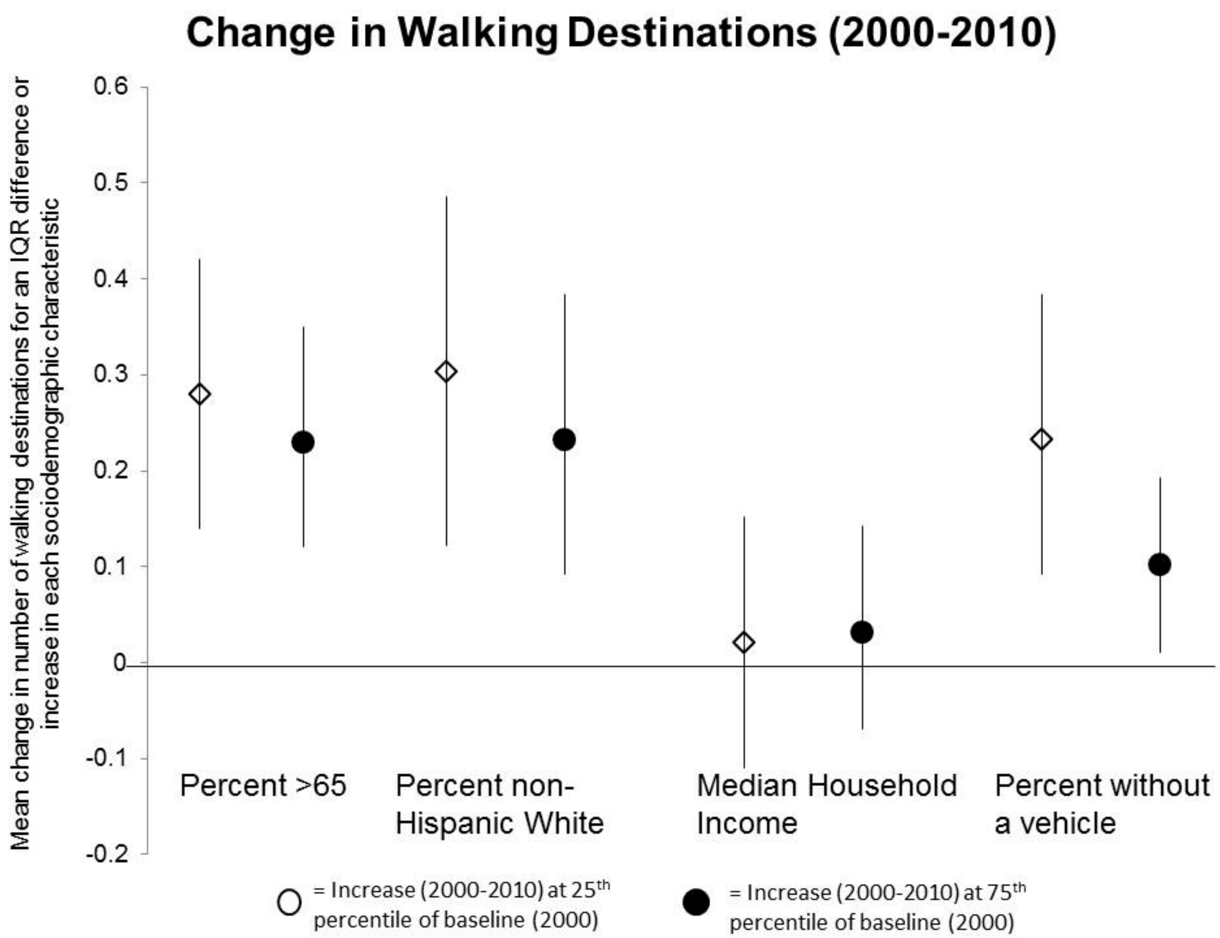


Figure 5-5 Change in walking destinations (2000-2010) for change in sociodemographics



Chapter 6 Conclusion

This concluding chapter begins with the findings from each dissertation aim considered within the hypotheses that formed the foundation for each analysis (Table 6-1) and places these findings within the existent literature. This chapter then discusses the significance and implication of these findings. This chapter concludes with the strengths and limitations of the dissertation as a whole, and possible future research directions.

Review of Main Findings

Consistent with our hypotheses, aim 1 found that moving to an area with higher walkability was associated with an increase in transport walking (Table 6-1). Similarly, aim 2 found that changes over time in walking were influenced by baseline levels and changes in built environment features in a larger cohort of both non-moving and moving participants. There was no association between changes in the built environment and changes in leisure walking in either aim 1 or aim 2. Both of these aims contribute to our understanding of the longitudinal association between the built environment and walking, but these are several key differences. The first difference is in the measurement of the built environment: aim 1 used Walk Score®, a composite and commercial measure of walkability, while aim 2 helped to identify which specific built environment features were associated with walking trajectories through GIS-based population density, land-use, destinations, access to buses, and street characteristics. The second difference is in sample and method, including which participants were including, length of study, and modeling approach. Aim 1 used residential relocation to investigate change, restricting the analysis to only participants who moved between exams 3 and 5. Since these individuals exhibit a large amount of change in both exposure (walkability) and outcome (walking), a fixed effects analysis was possible for aim 1. Yet examining change that is the product of residential relocation does not help policy-makers to understand the potential impact of changing neighborhoods around the people who live there. Aim 2 was able to look at changes occurring around a non-moving and moving population to clarify how interventions in the environment may influence behavior change. Unfortunately, since many participants have very little measurable change in their neighborhood environments or their walking behaviors, fixed effects models did not converge and multi-level marginal models were used instead.

Extending beyond walking levels and consistent with hypotheses, aim 1 found that moving to an area with higher walkability was associated with a decrease in BMI. Similarly, aim 3 found that changes in the built environment were associated with decreases (or less steep increases) in BMI and WC. Comparable differences exist between aims 1 and 3, including Walk Score® versus GIS-based built environment metrics, and sample differences reflecting movers and non-movers. However, even among the full cohort of movers and non-movers, participants exhibited enough change in BMI and WC for fixed effects models to be used in the analysis of aim 3.

Overall, the findings from aims 1-3 suggest a link between changes in the built environment and changes in walking behavior and obesity. This indicates that changes in the built environment may be a viable option for increasing physical activity and decreasing obesity at the population level. However, as hypothesized, aim 4 found that while the number of destinations for social engagement, walking, and physical activity all increased between 2000 and 2010, changes in the built environment are spatially clustered in advantaged neighborhoods. Clusters experiencing greater change had higher percent non-Hispanic white residents, higher incomes and more housing units without vehicles at baseline. They also tended to show greater increase in non-Hispanic white residents and income over time. This has the potential to increase existent neighborhood health disparities.

Overall Comparison to Previous Literature

The association between change in built environment and change in transport walking extended previous research that showed that living in a more highly walkable neighborhood helped individuals to maintain or increase walking levels over time.[24, 95-97] Our results for aims 1 and 2 were consistent with previous residential relocation research indicating that moving to an area with higher walkability,[10, 117] lower sprawl index[11], higher street connectivity[18], increased access to destinations[12, 16, 17, 21, 22] and higher population density[20] was associated with increases in walking, overall physical activity, and travel behavior. In particular, the increase in transport walking after moving to a more supportive environment seen in aim 1 was concordant with previous research in other countries[16] and select United States cities.[10, 12, 18, 22] While limited longitudinal literature exists examining longitudinal changes in the built environment not caused by residential relocation, results from aim 2 are consistent with the findings from residential relocation studies, including aim 1.

The lack of associations in aims 1 and 2 between change in built environment and change in leisure walking was consistent with previous cross-sectional research[88] and with the measures used in aims 1 and 2. Both Walk Score and the GIS-derived measures of the built environment were designed to measure elements that influence whether errands or other transportation could occur on foot. They do not capture other components of the built environment that may encourage leisure-time walking, such as aesthetic quality, street traffic, or availability of walking trails. As stated previously, differences in the associations of walkability with transport and leisure walking highlight the importance of matching environmental measures to specific behaviors when studying associations between health behaviors and the environment.[98]

The finding that changes in the built environment was associated with declines in BMI and WC must be taken within a broader, and inconsistent, literature. Previous research on neighborhood walkability and weight trajectories showed the importance of the environmental context in maintaining a healthy weight,[30, 31, 95, 99, 100] but longitudinal evidence linking changes in the environment to changes in weight and BMI was inconsistent.[29, 34, 36] Conflicting results might be because of different definitions of neighborhoods[29, 34, 36] or the types of measures the built environment used. [29, 34, 36] In both aims 1 and 3, the effects of change in the built environment on change in BMI or WC was not reduced after controlling for change in transport walking, suggesting that the BMI effect was not mediated through the effects on walking found in aims 1 and 2. This may be due to measurement error in amount of walking, or to changes in dietary patterns or another health behavior. It may also be advantageous to examine alternate outcomes, such as blood pressure, cholesterol, or cancer, which may be associated with physical activity above and beyond associations with obesity.[166]

Aims 2 and 3 help to identify and isolate which specific features encourage walking behavior and decrease obesity. Results from aim 2 suggested that changes to higher percent retail, population density, and access to destinations were comparatively stronger and more consistently associated with changes in transport walking than street characteristics and bus access. This pattern is consistent with cross-sectional research[7, 74] and highlights the greater importance of walking destinations over street or transportation networks. The strong associations with density of destinations was also consistent with previous work on the perceived environment, showing the importance of convenience and access to mixed services to walking,[16, 17, 19] cycling,[20] and overall physical activity.[12] In aim 3, factor 1, representing density and primarily composed of population density, density of walking destinations, and a lower %residential, was the only built environment factor to significantly decrease BMI. Although results were not attenuated by transport walking, this is consistent with the findings from aim 2 that population density and access to destinations were the most consistently associated with transport walking.

The patterning of changes in the built environment by racial composition, socioeconomic status and vehicle ownership was consistent with cross-sectional evidence that shows that white, high-income neighborhoods are already advantaged with regards to physical activity facilities,[153-156, 160] parks,[153, 154] and aesthetics[41, 151, 152]. It was also consistent with previous research on the types of neighborhoods that implement master plans relating to bicycle and pedestrian infrastructure. One study showed that the degree of racial diversity among communities with master plans for non-motorized transportation was lower than the United States average.[157] Lack of a plan may lead to a lower likelihood of positive changes in the built environment to encourage walking and cycling, which is consistent with the patterning of change observed in aim 4. The change in destinations that was observed with changes in racial composition or socioeconomic status may be part of a process of gentrification. Many new urban developments have targeted young middle-class adults, many of whom are non-Hispanic white, without regulations for affordable housing to ensure they do not displace current residents. Similarly, non-Hispanic white and high socioeconomic status individuals may move to an area and retail may follow this new base of patrons. Alternative, the patterns seen in aim 4 are also potentially consistent with a story of urban growth. Areas on the edges of these seven cities may be less dense to begin with and thus have more “room to improve.” These more suburban rings are often also predominantly white, middle-class neighborhoods. Ultimately, without on-the-ground knowledge of each census tract experiencing these positive changes, it is hard to discuss the process behind these changes.

Significance and Implications

Physical inactivity and obesity remain prominent public health concerns within the United States. The United States differs starkly from many other high-income countries in the extent to which residents engage in active travel, such as through walking or bicycling.[55, 56] Similarly, despite recent leveling of obesity trends in the United States,[125] 35.7% of all adults aged 20 years or older are still classified as obese (body mass index (BMI $\geq$30 kg/m^2) and an additional 33.1% are overweight (BMI 25-29.9 kg/m^2).[125] Numerous studies show links between physical inactivity, excess weight and several chronic comorbidities, most notably cardiovascular disease, diabetes, and cancers.[126, 167, 168] Walking may be an important component of physical activity[57-60] and incorporating walking into daily life, through active travel, may be a viable way to decrease physical inactivity, obesity, and chronic disease.

While individual behavior change remains important for addressing physical inactivity and obesity, interventions at the community level hold the potential to impact broader populations, in a more sustained way. Changes to the infrastructure of a neighborhood conceivably can encourage all residents of that neighborhood to change their behavior. Even if these changes are small, shifts in the entire population towards slightly more activity may have a large influence on population burden of chronic diseases. Additionally, changes to the infrastructure are sustainable across time, potentially influencing not just the current, but also the future residents. This dissertation supports neighborhood- and community-level interventions by illustrating the potential changes in physical activity from changes in the built environment. Additional work should attempt to tease apart the relative strengths of individual- and neighborhood-level interventions.

Density and destinations were consistently found to be associated with transport walking and obesity across aims 1-3. This is consistent and supports anecdotal urban planning knowledge that "many problems can be solved with density." Increases to population density allow for economic support of additional destinations and amenities, user support for public transportation, and compact, well-laid out street networks. It is also noteworthy that these features were associated with transport but not leisure walking. This may also be due to the fact that leisure walking may occur elsewhere so that measures of the residential environment are not very reflective of where the walking takes place. As research continues to identify elements of the built environment to intervene on, it is important to match features and elements with outcomes that make theoretical sense. Being close to additional destinations may not influence leisure walking but being close to parks and green space may.

This dissertation helped elucidate the complex relationship between the built environment and health behaviors. Expanding research beyond cross-sectional associations furthered our causal evidence while enhancing our understanding of which neighborhoods are most likely to change and why. The findings of this dissertation help to build a stronger evidence base for practitioners attempting to understand which modifiable features of the built environment may impact health behavior changes. By clarifying the mechanism that links built environment with health, this research encourages public health practitioners and urban planners to work together towards designing and building healthier communities. Finally, research on neighborhood-level predictors of built environment change may inform policies to include strategies that are more suitable at combatting not only chronic diseases, but also health inequalities.

Overall Strengths

This is one of the first studies to use time-varying GIS-based measures to examine associations of the built environment (and changes in the built environment) with changes in walking and obesity over time in a geographically and ethnically diverse United States sample. In contrast to cross-sectional studies, longitudinal analyses allow us to establish whether a built environment feature or a change in a built environment feature is associated with change in walking over time. Although longitudinal studies do not completely overcome the effect of self-selection on the associations observed,[38] they have the potential to improve causal evidence, especially if they investigate the impact of changes in neighborhood conditions on changes in health. Use of a multi-city and multi-ethnic sample makes the results of this dissertation more generalizable to the United States public than studies conducted in a single city with majority non-Hispanic white participants.

Dissertation Limitations

Limitations of this dissertation include the use of self-reported walking (either interviewer- or self-administered), potential residual confounding by individual-level factors and other neighborhood features, limited generalizability to other ages and cities or countries, and limitations in the built environment data used. Self-reported measures of walking might not be as accurate as those assessed objectively using pedometers or accelerometers. However, because our analyses investigated change in walking within participants, stable overestimates and underestimates of walking by a given person were accounted for. This may also be an issue in determining the extent to which walking mediated the pathway between built environments and obesity. While neither aim 1 nor aim 3 found a large attenuation of the association when walking was added, this may, in part, be due to inaccurate measurement rather than a lack of causal mechanism.

In all of the aims there was low power to examine the association of change in the built environment within cities, and threshold effects. Limited sample size also prevented an investigation of whether a minimum change in the environment was necessary for an effect on walking behavior or obesity (i.e., whether a threshold effect was present). Self-selection continues to be a potential threat to internal validity. Participants were included in aims 2 and 3 if they attended the baseline visit and one other. However, those who stay in the MESA cohort are more likely to be non-Hispanic white and likely also healthier. This selective loss to follow-up may lead to a potential bias in built environment estimates if also patterned by walking or built environment attributes. In addition, although all aims controlled for several time- varying covariates and aims 1,3 and 4 used fixed effects models that tightly controlled for time-invariant person characteristics, residual confounding by other time- varying factors could not be ruled out. There may be additional effect modification of the influence of the built environment by site, safety, or other individual and neighborhood level characteristics.

Our study was limited to a middle-age and older adult population and results from this study may not be generalizable to younger samples or other cities. This sample of adults had a higher percentage engaged in walking than national samples,[122] which could have affected their responsiveness to built environment features. However, this pattern is consistent with some evidence proposing walking as a replacement for more strenuous physical activity as people age.[123] Additionally, while the entire MESA cohort is multi-ethnic the distribution of races and ethnicities within sites does not include all four ethnicities. This makes disentangling the differences in race and site challenging. The MESA sample may have a number of other key differences from the general population. As the cohort was sampled as adults free of clinical cardiovascular disease at baseline (2000) they may represent a healthier subset of the United States public. These individuals may be better suited to respond positively to changes in the built environment that may occur. Additionally MESA participants were sampled to have specific racial/ethnic composition, and were not sampled to be geographically representative of the cities from which they were recruited. This ultimately may mean that they have less geographic variability within each city, making it hard to estimate within-city associations.

Several limitations are inherent to the built environment data we used. First, we relied on land-use and transportation information collected from various sources at various years. However, as different regional and municipalities collect and revise land-use files sporadically, this data is a representation of the land-use codes on file. Additionally, some study area's land-use classification systems are more detailed than others. However, categorization was done to harmonize codes to the most broad land-use codes. Second, using parcel area for land-use patterns penalizes vertical development (e.g. this method treats a parcel with a four-story building the same way as a parcel with a one-story building). Third, the use of zoning to infer existing land-uses may not accurately reflect what is on the ground. Finally, although sensitivity analyses with ½-mile and 3-mile buffers showed similar results, the use of 1-mile buffers may have led to misspecification of the relevant geographic area in some cities. Similarly, in the area-level analyses, census tracts may not accurately reflect neighborhood boundaries. Ultimately, changes in the built environment may take longer than ten years or may occur in small-scale design features that are difficult to measure across multiple study areas, such as crosswalks, bicycle lanes, and sidewalks.

Future Work

Policy changes relating to urban planning are increasingly thought of as health policies. As the result of current research, organizations are increasingly pushing land-use zoning and licensing to regulate and improve the environment.[169] Public health departments, such as in Philadelphia, are collaborating with city planners to update zoning codes to incorporate various health and sustainability provisions including 1) density bonuses, allowing developers to build taller buildings or buildings with more floor area for fresh foods and mixed-use developments, 2) density bonuses for including mixed income housing at transit nodes, 3) built-in assessment of large projects for their effect on pedestrians, and 4) new parking regulations with maximums for cars and requirements for bicycles and hybrid vehicles. Policies across the county are being passed that support complete streets, with rapid acceleration in the past decade. The number of communities adopting complete streets policies roughly doubled each year in 2008, 2009, and 2010, and by the end of 2010, 46 states had adopted at least one policy.[170] Other feasible solutions suggested include retrofitting cul-de-sacs using walking or biking paths to create increased connectivity while maintaining safety and low street traffic.[171]

The actions of Americans and their response in polls show that the public supports these movements. Between 2000 and 2009 bicycle commuting increased by 57 percent[172] and a recent poll (May 2012) by America Bikes indicates that 83% of those polled would like to see federal funding for bicycling and walking maintain or increased.[173] More importantly, this desire to maintain or increase funding was equal across political parties, age groups, community types (urban, suburban, rural), and geographic region (Northeast, Midwest, South, and West).[173]

However, as governments search federal, state, and local budgets for excess costs, non-automobile focused transportation funds remain limited. On average, states spend 20 percent of their federal transportation dollars on transit, 2 percent on bicycle/pedestrian projects, 39 percent on projects that maintain roads and bridges, and 23 percent on projects that add capacity to roads and bridges.[174] Without adequate research (along with public support, and popular media) built environment advances may become less salient and decrease in priority. As more policies arise to change the built environment, I plan to evaluate the effectiveness of these strategies in changing the environment and improving overall health. The use of health impact assessments or natural experiments would allow me to investigate the way non-health policies influence health and compare the effectiveness of various urban planning policies. Collaborative work with experts across economics, planning, and public policy will help the field to understand the complex process and numerous stakeholders involved in translating built environment research to successful policy changes. This research, in combination with previous and future studies, will add strength to the many campaigns and projects already underway, help keep improvements in the built environment on the policy agenda, and may even encourage new changes into the future.

Changes to the built environment are likely to persist many decades after they are implemented. Therefore, as we move towards advocating new policies, it is crucial that we understand and acknowledge the complex ways that the built environment may influence a multitude of health outcomes in order to avoid unintended negative consequences. As the built environment may play an important role in multiple aspects of health, including mental health, substance use, cognitive and physical decline, future work should expand beyond cardiovascular risk to examine the full spectrum of health. Little literature exists on the built environment's influence on mental health. However, a recent study from Australia showed that the built environment way independently associated with depression through land-use mix, and specifically through retail availability.[175] Although local retail facilitates walking, our these findings suggest that it may increase the odds of depression, potentially leading to worse health outcomes for a population experiencing increases in these features. In my future work, I hope to collaborate with psychologists, social workers, gerontologists, and physicians to explore the numerous pathways between the environment and overall health. In combination with health behaviors, such as sleep and physical activity, biomarkers may help to elucidate some of the underlying mechanisms that link neighborhoods to health.

Similarly, continued attention needs to be paid to equity in policies to change the built environment to ensure that changes do not have the unintended consequence of increased health disparities. Allowing the market (real estate and financial) to dictate which changes occur where is likely to encourage change in already-advantaged neighborhoods. Increasing the health of *all* Americans will require a coordinated approach to environmental change. Real estate developers, financial institutions, civil engineers, urban planners, and public health advocates need to come together to assess, measure, and evaluate changes in the environment. Future work should focus on creating metrics of change in the built environment, including equitable distribution of those changes, then work to benchmark existent conditions, and track changes over time.

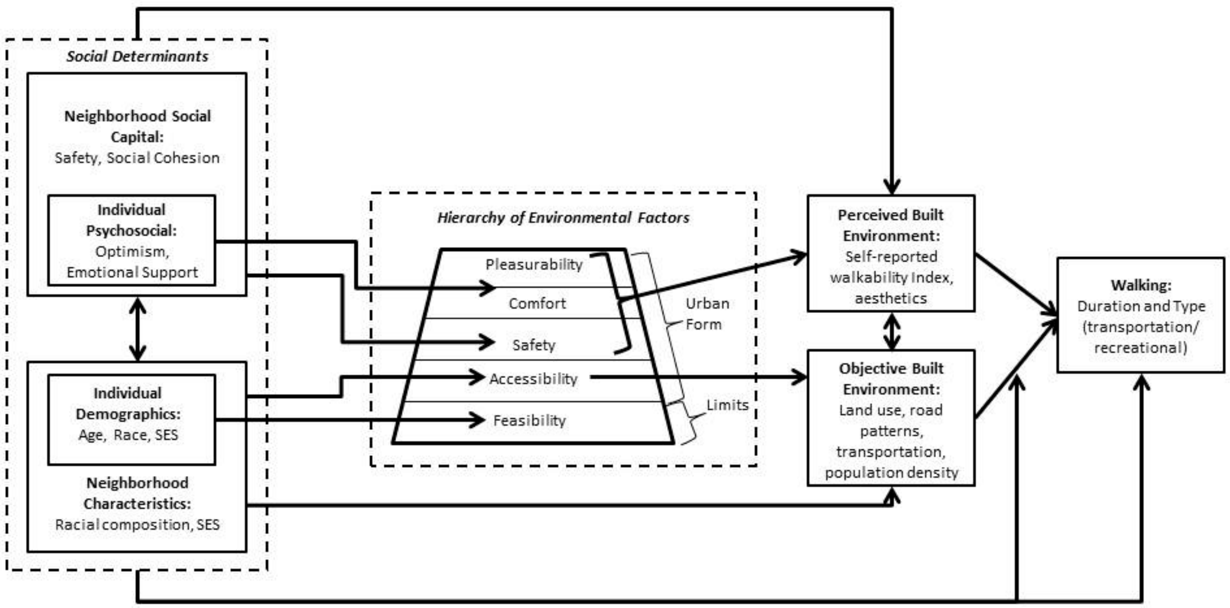
Tables

Table 6-1 Summary of main aims and findings

Aim	Exposure	Outcome(s)	Sample	Timing	Model	Hypothesis	Findings
1: To assess the effect of moving to a different built environment on changes in walking and obesity among MESA participants.	Walk Score®	Walking; BMI	Movers between exams 3 and 5	Exams 3 & 5	Fixed Effects Models	Moving to ↑ walkability = ↑walking and ↓BMI	Moving to ↑ walkability = ↑transport walking and ↓BMI. Walkability ≠ leisure walking
2: To investigate the effect of change in the built environment on changes in walking among both moving and non-moving MESA participants.	Specific GIS-based	Walking	All movers and non-movers	Exams 1, 2, 3, & 5	Multi-level Marginal Models	↑population density, % retail, destinations, and netratio = ↑walking ↓%residential and distance to bus = ↑walking	↑population density, % retail, destinations, and netratio = ↑ transport walking ↓%residential and distance to bus = ↑transport walking Population density, % retail, %residential, destinations, distance to bus, and netratio ≠ leisure walking
3: To investigate the effect of change in the built environment on changes in obesity among both moving and non-moving MESA participants.	GIS-based factors	BMI; WC	All movers and non-movers	Exams 1, 2, 3, 4, & 5	Fixed Effects Models	↑factor 1 (density of development) and factor 2 (downtown retail districts) = ↓BMI and ↓WC ↑factor 3 (distance to public transportation) = ↑BMI and ↑WC	↑factor 1 = ↓BMI and ↓WC factor 2 and factor 3 ≠ BMI or WC
4: To identify whether changes in the built environment are patterned by initial neighborhood sociodemographic characteristics and changes in neighborhood sociodemographic characteristics.	Census Sociodemographics	GIS-based destinations and land uses	All census tracts within the available land use data	2000 & 2010	Linear Models Fixed Effects Models	Change in destinations > change in land use, and streets ↑baseline median household income, %NHW and %households without a vehicle = ↑change in the built environment ↑baseline % over 65=↓change in the built environment ↑change in median household income, %NHW, and %households without a vehicle = ↑change in the built environment ↑change in % over 65=↓change in the built environment	Change in destinations > change in land use, and streets ↑baseline median household income, %NHW and %households without a vehicle = ↑change in the built environment ↑baseline % over 65=↓change in the built environment ↑change in median household income, %NHW, % over 65, and %households without a vehicle = ↑change in the built environment

Appendixes

Appendix A Causal Model



Appendix B Matching built environment data by year

<table>
<tr><th colspan="14">Matching built environment data by year for each data source at each site.</th></tr>
<tr><th>BE Data</th><th>Site</th><th>2000</th><th>2001</th><th>2002</th><th>2003</th><th>2004</th><th>2005</th><th>2006</th><th>2007</th><th>2008</th><th>2009</th><th>2010</th><th>2011</th></tr>
<tr><td rowspan="7">Land Use</td><td>CA</td><td colspan="3">2001</td><td>2001/2005*</td><td colspan="3">2005</td><td colspan="5">2008</td></tr>
<tr><td>IL</td><td colspan="3">2001</td><td>2001/2005</td><td colspan="8">2005</td></tr>
<tr><td>MD (Cny)</td><td colspan="3">2002</td><td>2002/2004</td><td colspan="2">2004</td><td>2004/2008</td><td colspan="5">2008</td></tr>
<tr><td>MD (Cty)</td><td colspan="4">2002</td><td>2002/2006</td><td colspan="3">2006</td><td>2006/2010</td><td colspan="3">2010</td></tr>
<tr><td>MN</td><td colspan="8">2005</td><td colspan="4">2010</td></tr>
<tr><td>NC</td><td colspan="8">2005</td><td colspan="4">2010</td></tr>
<tr><td>NY</td><td colspan="2">2001</td><td>2001/2003</td><td>2003</td><td>2004</td><td>2004/2006</td><td colspan="3">2006</td><td colspan="3">2011</td></tr>
<tr><td rowspan="6">Bus Routes</td><td>CA</td><td colspan="6">2005</td><td>2005/2007</td><td colspan="5">2007</td></tr>
<tr><td>IL</td><td colspan="12">2005</td></tr>
<tr><td>MD (Cty)</td><td colspan="12">2009</td></tr>
<tr><td>MN</td><td colspan="8">2005</td><td colspan="4">2010</td></tr>
<tr><td>NC</td><td colspan="5">2001</td><td>2001/2009</td><td colspan="6">2009</td></tr>
<tr><td>NY</td><td colspan="12">2010</td></tr>
<tr><td rowspan="6">Trains/ Subway</td><td>CA</td><td colspan="8">2006</td><td>2006/2010</td><td colspan="3">2010</td></tr>
<tr><td>IL</td><td colspan="12">2005</td></tr>
<tr><td>MD (Cty)</td><td colspan="12">2009</td></tr>
<tr><td>MN</td><td colspan="12">2004</td></tr>
<tr><td>NC</td><td colspan="12">2009</td></tr>
<tr><td>NY</td><td colspan="12">2010</td></tr>
<tr><td>TIGER roads</td><td>ALL</td><td colspan="5">2000</td><td>2000/2010</td><td colspan="6">2010</td></tr>
<tr><td>Census</td><td>ALL</td><td colspan="5">2000</td><td>2000/2010</td><td colspan="6">2010</td></tr>
<tr><td rowspan="5">Buildings</td><td>IL</td><td colspan="12">2010</td></tr>
<tr><td>MD (Cny)</td><td colspan="6">2004</td><td>2004/2008</td><td colspan="5">2008</td></tr>
<tr><td>MD (Cty)</td><td colspan="8">2006</td><td>2006/2010</td><td colspan="3">2010</td></tr>
<tr><td>NC</td><td>1997</td><td>1997/2005</td><td colspan="10">2005</td></tr>
<tr><td>NY</td><td colspan="10">2009</td><td colspan="2">2010</td></tr>
</table>

MD Cny= Baltimore County   MD Cty=Baltimore City

*Years with slashes indicate a cutpoint on June of that year

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