Understanding neighborhood physical and social environments in relation to blood pressure changes in the Multi-Ethnic Study of Atherosclerosis

by

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BMI	Body mass index
DAG	Directed acyclic graph
MESA	Multi-Ethnic Study of Atherosclerosis
SBP	Systolic blood pressure
SES	Socioeconomic status

Abstract

Neighborhood environments have been associated with a variety of health outcomes, but much of the existing research has relied on cross-sectional data or used non-specific measures of the neighborhood. This dissertation uses longitudinal data on specific measures of neighborhood physical and social environments from the Multi-Ethnic Study of Atherosclerosis (MESA) to explore how neighborhood environments change over time and how specific neighborhood environments affect blood pressure. The first analysis investigated how changes in four survey-based measures of neighborhood environments (availability of healthy food, walking environment, social cohesion, and safety) were patterned by area socio-demographic characteristics (area socioeconomic status [SES], percentage of Black residents, and percentage of Hispanic residents). After adjusting for individual-level characteristics, we found that lower SES neighborhoods and neighborhoods with more minority residents generally had poorer physical and social environments, and that these disparities were stable or increasing over time. The second analysis used proportional hazards models to explore neighborhood physical and social environments in relation to incident hypertension using survey-based measures of neighborhood environments and GIS-based measures of the density of favorable food stores and recreational activity resources. After adjustment for individual and neighborhood-level covariates, one standard deviation higher healthy food availability was associated with a 12% lower rate of hypertension (HR = 0.88, 95% CI 0.82-0.95); other neighborhood environment measures were not related to incidence of hypertension. The third analysis used linear mixed models to describe how neighborhood survey- and GIS-based measures of physical and social environments were associated with baseline levels and changes over time in systolic blood pressure (SBP). Using imputed values for SBPs influenced by antihypertensive medication use, we found that better neighborhood food and physical activity environments were associated with lower SBPs at baseline, while better neighborhood social environments were associated with higher SBPs at baseline. There was little evidence that neighborhood environments affected SBP trajectories over time. The results of this dissertation add new evidence on the way that neighborhood socio-demographic characteristics relate to neighborhood physical and social environments, and how those environments affect cardiovascular health; these results may shape interventions to reduce social disparities in health.

Chapter 1

Introduction

Scholarly investigation of how neighborhood environments affect health has increased substantially in recent decades.[1] Much of this research has documented that various neighborhood characteristics are associated with a range of health outcomes, including cardiovascular morbidity and mortality.[2] However, causal inferences from current research are generally limited by cross-sectional data and reliance on broad measures of the neighborhood environment. Developing a better understanding of the causal mechanisms underlying neighborhood effects on health is key to designing effective interventions that can improve population health and reduce place-based disparities in health.

There are a variety of methodological challenges to understanding how characteristics of residential environments affect health. One of the most fundamental challenges is defining and quantifying residential environments. A lot of research on neighborhood health effects has used Census data to summarize the socioeconomic status of an area. While this data is easily accessible and useful for providing a broad proxy for neighborhood quality, it is less ideal for understanding mechanisms or designing targeted interventions to improve population health. Measuring specific aspects of neighborhood environments, including physical and social environments, is an important element of improving causal inference about neighborhood health effects.[2,3]

Two common methods to measure more specific aspects of the neighborhood environment are surveys and geographic information systems (GIS) data. Survey measures of neighborhood characteristics can be used to measure many different aspects of the neighborhood environment, including aspects of the social environment. While surveys typically collect residents' perceptions of their neighborhood environment and can thus be biased by subjective opinions, aggregating individual perception often produces more objective area-level measures. GIS data have been used to quantify neighborhood physical environments in a variety of ways, including measures of street connectivity, residential density, transportation networks, land use patterns, and access to retail stores or services.[4] However, the additional specificity gained by using survey- or GIS-based measures of neighborhood environments is offset by the additional expense and logistical challenges of acquiring the data, in contrast to routinely collected administrative data (such as the Census).

An additional limitation of existing research on neighborhood health effects is the paucity of longitudinal studies. Studies that identify the development of a disease in a cohort eliminate the potential for reverse causation bias, in which an observed association is the result of the outcome driving a change in the exposure. Additionally, longitudinal information on neighborhood changes in relation to individual health changes can help to avoid the 'context vs. composition' debate that has accompanied much of the research on neighborhood health effects.[5] Observing how neighborhoods change around individuals, and how those changes are associated with health, minimizes the likelihood that individual characteristics and the sorting of individuals into neighborhoods is solely responsible for observed neighborhood-level associations.

Understanding how neighborhoods affect blood pressure is a relevant public health issue because of the substantial health burden attributable to high blood pressure. High blood pressure is strongly predictive of cardiovascular disease,[6,7] and heart disease and stroke are two of the top five causes of mortality in the US.[8] Blood pressure is also strongly patterned by socioeconomic and race/ethnic groups in the US, and may contribute to social disparities in morbidity and mortality.[9] In addition, blood pressure has several properties that make it a useful outcome for exploring neighborhood effects on health; blood pressure can be measured quickly, non-invasively, and reliably. There are also multiple mechanisms through which neighborhood environments plausibly influence blood pressure (detailed below).

Data source, specific aims & hypotheses

The overreaching goal of this research is to contribute to our understanding of neighborhood influences on health, specifically blood pressure, and address some of the limitations presented above. The data used for this dissertation are from the Multi-Ethnic Study of Atherosclerosis (MESA), a prospective cohort study of 6,814 adults over age 45 in six sites across the U.S. from 2000 through 2011. MESA provides unique longitudinal health data on a multi-ethnic, multi-site cohort as well as rich longitudinal data on neighborhood environments, thanks to the ancillary MESA Neighborhood Study. The specific aims of this dissertation are as follows:

Aim 1: To describe how census tract socio-demographic characteristics are associated with levels and trajectories of change in four dimensions of neighborhood quality (healthy food availability, walking environment, social cohesion, and safety) over the MESA study period.

Hypothesis: High SES and low minority composition tracts will have better healthy food availability, walking environments, social cohesion, and safety at baseline and more positive changes over time than low SES and high minority composition tracts.

Aim 2: To investigate if time-varying neighborhood food, physical activity, and social environments are associated with incidence of hypertension in MESA.

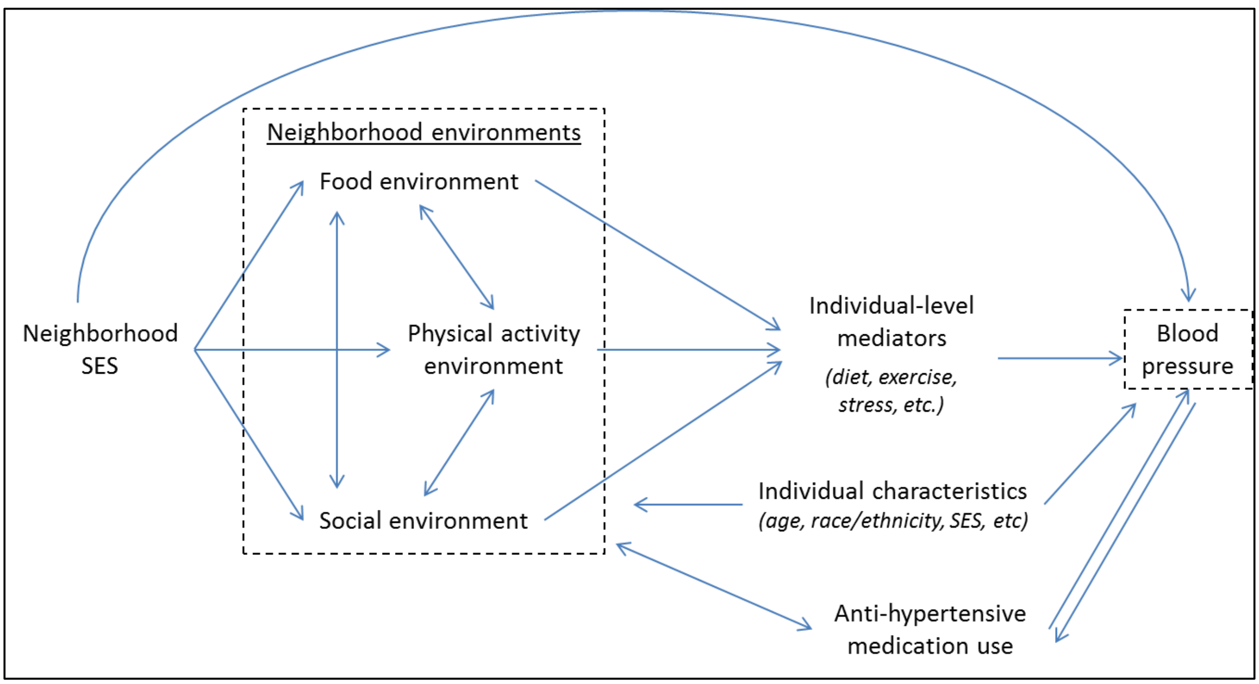
Hypothesis: Residents of neighborhoods with better food, physical activity, and social environments will have lower incidence of hypertension than residents of neighborhoods with poorer food, physical activity, and social environments after accounting for individual-level confounders.

Aim 3: To investigate if time-varying neighborhood food, physical activity, and social environments are associated with changes in systolic blood pressure in MESA, accounting for anti-hypertensive medication use.

Hypothesis: Residents of neighborhoods with better food, physical activity, and social environments will have lower systolic blood pressure at baseline and slower increases in systolic blood pressure over time than residents of neighborhoods with poorer food, physical activity, and social environments, after accounting for individual-level confounders and anti-hypertensive medication use.

The conceptual relationships underlying these aims are presented in Figure 1-1. These relationships guided the development of regression models to isolate the associations between specific features of neighborhood environments and blood pressure.

Figure 1-1. Conceptual diagram of the relationships between neighborhood environments and blood pressure.



Single-headed arrows reflect causal relationships, while double-headed arrows reflect associations that are not causal but are observed due to common causes of the factors. We posit that neighborhood food, physical activity, and social environments are all associated with each other, but are all downstream of neighborhood SES. Neighborhood food, physical activity, and social environments are causally related to individual-level intermediates including diet, exercise, and stress, which in turn are causally related to blood pressure through biological mechanisms elucidated below.

Neighborhood SES is also associated with blood pressure through pathways that do not involved neighborhood food, physical activity, and social environments (for example, air pollution[10] or noise pollution[11]), making neighborhood SES a possible confounder of the relationship between neighborhood food, physical activity, and social environments and blood pressure. In reality, all measures of neighborhood-level characteristics (SES as well as specific neighborhood environments) tend to be correlated with each other, so adjusting for multiple neighborhood-level measures as well as neighborhood SES in regression models can reduce power and statistical efficiency.

Individual-level characteristics, including age, race/ethnicity, education, and income, are related to both blood pressure and affect the sorting of individuals into neighborhoods; these characteristics are confounders of the relationship between neighborhood environments and blood pressure, and will be included as covariates in all models. Anti-hypertensive medication use is depicted as associated with neighborhood environments and both a cause and a result of blood pressure. Medication use may be influenced by the availability of medical resources, including doctors and pharmacies, in a neighborhood; availability of medical resources is likely associated with availability of other resources in the neighborhood. Anti-hypertensive medication is often prescribed when an individual's blood pressure exceeds a recognized threshold; the goal of medication use is to lower blood pressure. Thus, anti-hypertensive medication use is both a confounder and a collider of the association between neighborhood food, physical activity, and social environments and blood pressure. Using incident hypertension as the outcome of interest in a proportional hazards model sidesteps this issue because antihypertensive medication use is sufficient for being classified as hypertensive. In linear regression models with systolic blood pressure as a continuous outcome, adjusting for medication use and not adjusting for medication use will both induce bias in the association of interest. To avoid this, we use multiply imputed values of blood pressure for those observations influenced by medication use to estimate the association between neighborhood environments and underlying blood pressure not influenced by medication use.

Public health significance of high blood pressure

Approximately 25% of the world's adult population is hypertensive. Ischemic heart disease and cerebrovascular disease are leadings causes of mortality around the world;[12] approximately 54% of all stroke and 47% of all ischemic heart disease is attributable to high blood pressure.[13] Reducing the burden of high blood pressure is an important public health goal.[14] As Geoffrey Rose argued in 1985, understanding the causes of population-level distributions – and targeting interventions to shift population-level distributions – can have large impacts on overall population health.[15] Neighborhood environments represent a potential avenue for a population-based strategy to reduce blood pressure.

Neighborhoods may also be an important opportunity to reduce persistent social disparities in health. In the U.S., there are substantial racial/ethnic differences in blood pressure, such that African-Americans and Mexican-Americans are more likely to be hypertensive – and less likely to have their blood pressure controlled – than non-Hispanic whites.[9,16] Interventions or policies to improve neighborhood environments with the goal of reducing blood pressure, implemented in places where health disparities are large, may provide new traction to reduce those disparities.

Pathophysiology of neighborhoods effects on blood pressure

Blood pressure, defined as the force of blood against artery walls as blood circulates throughout the body, typically fluctuates depending on a variety of conditions, but chronically elevated levels of blood pressure can cause cardiovascular disease including heart attack and stroke.[7] Blood pressure is largely determined by two main components: cardiac output and arterial resistance. When the heart contracts, blood is pushed out of the ventricles and into circulation (known as systole; the maximum pressure in the arteries as a result of systole is the systolic blood pressure); when the heart relaxes and fills with blood (known as diastole), blood pressure in the arteries drops, giving the diastolic blood pressure. Stiffness of arteries is determined by many non-modifiable factors, including age and genetic factors, as well as modifiable lifestyle risk factors.

Common lifestyle changes recommended for reducing blood pressure include reduced salt intake, increased physical activity, maintaining a healthy weight, and lowering stress.[17] Reducing dietary sodium intake and increasing potassium intake cause the kidneys to eliminate more water and lead to reduced blood volume. Regular physical activity is associated with lowered systemic vascular resistance, likely as a result of decreased activity of the sympathetic nervous system and decreased renin production in the kidneys.[18] Chronic stress is likely to cause chronic activation of the sympathetic nervous system but may also affect baroreceptor sensitivity.[19]

The mechanisms by which neighborhood environments get 'under the skin' are broadly defined but not fully elucidated. As outlined in Figure 1-1, neighborhood environments are likely to shape individual-level mediators including diet, physical activity, and stress.[2] Research has shown that people living in neighborhoods with better food environments are more likely to have healthier diets[20,21] and that better physical activity environments are associated with more physical activity and walking.[22-24] The mechanisms through which the social environment affects health are less clear. Neighborhood safety, specifically the lack thereof, may be a source of stress itself. Additionally, living in an unsafe neighborhood may influence the amount of time people spend outside including for exercise.[2] Neighborhood social cohesion may affect the dissemination of health-related knowledge and norms, and may also be related to individual-level social support that can act as a buffer against the harmful effects of other stressors.[2,25]

Research on neighborhoods & blood pressure

A substantial body of research has linked neighborhood environments to cardiovascular health and health behaviors, but relatively little has focused on blood pressure. Most of the studies on blood pressure have used neighborhood SES to quantify neighborhood environments, and have shown that high SES neighborhoods have lower prevalence[26-28] and incidence of hypertension[29,30] than lower SES neighborhoods, though other studies have found no association between area affluence and blood pressure.[31,32]

Studies investigating more specific aspects of neighborhood environments in relation to blood pressure have also produced mixed results. Part of the complexity of understanding how specific neighborhood environments affect health is due to the variability in measurement of neighborhood food, physical activity, and social environments. Both survey-based and GIS-based measurement of neighborhood environments have been operationalized in a variety of ways.[4,33]

Survey-based neighborhood walkability was not associated with blood pressure among a sample of African-American women;[34] a GIS-based measure of walkability was not associated with hypertension in Western Australia,[35] but a small prospective study with one year of follow up found that greater GIS-based neighborhood walkability was associated with smaller increases or decreases in blood pressure compared with neighborhoods with poorer neighborhood walkability.[36] In a large observational study using data from the Women's Health Initiative Clinical Trial, densities of grocery stores or fast-food restaurants were not associated with systolic blood pressure levels.[37] However, previous research in MESA has found that better neighborhood walking environments, healthy food availability, social cohesion, and safety were all associated with lower prevalence of hypertension, though these findings were substantially attenuated after adjustment for race/ethnicity.[38] Neighborhood food, physical activity, and social environments have also been associated with major risk factors for hypertension, including obesity, diet, and physical activity.[39-42] The paucity of research using longitudinal data and specific measures of neighborhood environments is a limitation of existing work; this dissertation addresses these limitations and contributes new knowledge to enhance our understanding of how neighborhood environments influence blood pressure.

Additionally, developing a better understanding of the relationship between socio-demographic composition of a neighborhood and change in neighborhood physical and social environments can help to further our understanding of how neighborhoods may perpetuate social disparities in health. Research has found that racial/ethnic disparities in health are minimized or eliminated when neighborhood conditions are similar.[43] However, neighborhood environments are generally strongly patterned by socio-demographic characteristics in the U.S.[44] A substantial body of research documents that low-SES areas and minority neighborhoods have less favorable food and physical activity environments.[45-47] Less research has focused on patterning of the social environment, but neighborhood poverty has been associated with less social cohesion[48] and less perceived safety.[49] To our knowledge, no studies to date have explored how neighborhood socio-demographic characteristics are associated with changes in neighborhood quality.

By exploring how neighborhood socio-demographic characteristics are associated with changes in neighborhood physical and social environments over time, and how those neighborhood environments are associated with blood pressure outcomes over time, we contribute new information to address the limitations of previous research described above. This information improves our knowledge of the causal processes underpinning neighborhood effects on health and can inform future interventions to improve population health.

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Chapter 2

Associations of neighborhood socio-demographic characteristics with changes in survey-based neighborhood environments, 2000-2011

Introduction

Neighborhood quality – including characteristics of the physical environment and the social environment – has been associated with health outcomes ranging from behaviors to incident disease to mortality.[1] Neighborhood quality may also be an important factor in understanding persistent social gradients in health in the U.S., since neighborhood environments are strongly patterned by the socio-demographic composition of residents.[1-3] As a consequence, persons of different socioeconomic position and race/ethnicity may be exposed to very different neighborhood environments and changes in environments over time, with possible consequences for heath disparities. In addition, the composition of an area has implications for political advocacy and buying power, which can influence the location of beneficial and hazardous resources and services that shape the physical and social environment of a neighborhood, as well as changes in these resources over time.

A number of studies have documented differences in neighborhood physical and social environments associated with area socioeconomic or racial/ethnic composition. For example, low socioeconomic status (SES) and minority neighborhoods tend to have fewer supermarkets and more fast food restaurants[4-9] and fewer resources for physical activity.[10-12] Research on the social environment is less abundant, but neighborhood poverty has been associated with lower levels of safety[13,14] and with less social cohesion.[11] Research from sociology also suggests that higher racial segregation may be associated with lower neighborhood social cohesion.[15-17]

However, existing research on the relationship between neighborhood composition and neighborhood quality is largely limited to cross-sectional investigations in single urban areas; no research to date has investigated how changes in the physical or social environment are patterned by neighborhood SES or racial/ethnic composition. We used ten years of data from the Multi-Ethnic Study of Atherosclerosis (MESA) to describe the associations between neighborhood SES and racial/ethnic composition and changes in neighborhood quality over time. Exploring these associations will improve our understanding of the determinants of neighborhood environments and help to identify populations most at risk of the detrimental health consequences of harmful neighborhood conditions.

Methods

Study population

Data on neighborhood quality come from two datasets. The first dataset, the MESA Neighborhood Study, enrolled a cohort of 6,191 adults aged 45-84 at baseline at six field sites (Forsyth County, NC; New York City, NY; Baltimore, MD; St Paul, MN; Chicago, IL; and Los Angeles, CA) as an ancillary study to MESA. MESA Neighborhood participants completed a questionnaire about their neighborhood environments at three times (2000-2002, 2003-2005, and 2010-2011).

The second dataset, the Community Surveys (CS), were phone surveys administered to adults over age 18 who lived in the MESA study sites (but who were not MESA participants themselves). Three cross-sectional surveys were completed in 2004 (CS 1), 2006-2008 (CS 2), and 2011-2012 (CS 3); the surveys included 5,988, 5,409, and 4,212 respondents, respectively. CS 1 included the Maryland, New York, and North Carolina study sites; CS 2 included the California and New York sites, and CS 3 included a subsample of tracts in all six MESA sites. The samples were derived through random digit dialing and list-based sampling. As a result of the design, each study site had data from the three MESA data collection time periods and at least one community survey. In addition, each data collection period was spread out in time over at least a year (often a couple of years) ensuring adequate temporal representation in each site for the estimation of trends. In addition, analyses were adjusted for site in order to account for any site variations. The studies were approved by the Institutional Review Boards at each site and all participants gave informed consent.[18]

Neighborhood data

Two survey scales related to the physical environment (healthy food environment and walking environment) and two survey scales related to the social environment (social cohesion and safety) were selected for investigation because of their relevance to health outcomes[19-23] and because they had been assessed using identical items across the MESA and CS questionnaires at multiple time points. Each CS included all four survey scales of interest, while MESA participants responded to each scale twice (social cohesion in 2000-2002; safety, healthy food, and walking environment in 2003-2005; and all four scales in 2010-2011). In responding to the items, participants in all surveys were asked to refer to the area about one mile around their home.

The social cohesion scale included four questions relating to trust in neighbors, shared values with neighbors, willingness to help neighbors, and extent to which neighbors get along. The safety scale included two items about neighborhood violence and ability to walk in the neighborhood without fear. The healthy food environment scale included two questions on the availability of fresh fruits and vegetables and low-fat foods. The walking environment scale included four questions about the pleasantness of walking in the neighborhood, ease of walking to destinations, and frequency of seeing others walking or exercising in the neighborhood. Scales were based on previous work and have acceptable internal consistency, ecometric properties, and reliability.[24]

All survey scales used a 5-point Likert scale with response options ranging from 'strongly agree' to 'strongly disagree.' Each participant's ratings for each question in the scale were averaged to produce a summary score, such that higher scores indicate a higher quality neighborhood environment (greater social cohesion, greater safety, better access to healthy foods, and better walking environment). Summary scores ranged from 1-5, and were not calculated for participants who did not answer one or more of the questions within a scale.

The key predictors were census tract SES and racial/ethnic composition (percentage of non-Hispanic Black residents and percentage of Hispanic residents). A summary measure of census tract SES was derived via principal factor analysis with orthogonal rotation of 16 tract-level variables related to income, wealth, education, occupation, poverty, employment, and housing. The first factor explains 47.9% of the total variance, and represents education, occupation, housing value, and income; this factor score was used to summarize tract-level SES, such that a higher score represents increasing socioeconomic advantage. Census tract characteristics were obtained from the U.S. Census in 2000[25] and from the American Community Survey (ACS) for 2005-2009[26] and 2007-2011.[27] Tract characteristics were linked to individuals based on their address at the time they responded to the survey. Data from the 2000 Census was applied to 2000-2004; data from ACS 2005-2009 were linked to survey years 2005-2007, and data from ACS 2007-2011 were linked to survey years 2008-2011.

Additional covariates

Individual-level characteristics of respondents were considered potential confounders of the relationships between neighborhood characteristics (SES and racial/ethnic composition) and neighborhood quality, because perception of neighborhood quality varies by individual-level characteristics and persons are sorted into neighborhoods based on individual-level attributes.[24] Individual-level covariates included age (centered at 55), gender, race/ethnicity, education level (as years of education based on mid-point of educational attainment categories), income level in six categories (including a missing category, since 7.2% of observations were missing income), and data source (MESA participant or CS participant). Time was measured as the number of years since 2000.

Statistical methods

We used MESA and CS respondents as “informers” of the conditions of their neighborhoods (just as an air pollution monitor would provide information on air pollution levels in the surrounding area). In order to investigate how area-level socio-demographic characteristics are related to neighborhood environments, we modeled survey responses as a function of area characteristics using multilevel models. We adjusted for individual-level characteristics of respondents in order to eliminate biases related to systematic differences in the ways that individuals with different characteristics (e.g. age, gender, or whether they are a MESA or CS participant) may perceive a similar neighborhood. This approach allows us to make the best of use of all available data on neighborhood environments while making inferences about associations between neighborhood socio-demographic characteristics and neighborhood quality over time, accounting for the individual characteristics of the respondents themselves.

All observations of neighborhood quality from the MESA Neighborhood Study and CS 1-3 that described census tracts included in the baseline MESA exam were eligible for this analysis (30,081 observations from 20,351 participants). Observations with missing data on site, age, gender, education, race/ethnicity, or any of the tract-level predictors were excluded (917 observations from 884 participants). To keep the analytic sample as comparable as possible across survey scales, participants with missing data on any of the neighborhood scales for a given time period were also excluded (93 MESA participants [1.5%] and 2,288 CS participants [17.1%]). (More than half of the excluded CS participants were only missing the social cohesion scale; inclusion of these participants did not affect the results.) The final analytic sample consisted of 26,769 observations (15,714 from 6,170 MESA participants and 11,055 from CS participants) describing 1,171 census tracts over an approximately 10-year period. Due to variable timing of assessment of the four survey scales, there were 20,998 observations of social cohesion and 20,624 observations for safety, food environment, and walking environment.

Tract SES, percentage of Black residents and percentage of Hispanic residents were categorized into tertiles for descriptive analyses. ANOVA (or equivalent non-parametric tests) and χ^2 tests were used to compare differences among census tracts and individuals at baseline by tertiles of the tract predictors. There was no evidence of non-linearity with the neighborhood quality survey scales so tract characteristics were modeled as continuous variables, standardized to mean 0 and standard deviation 1 to facilitate comparisons.

Mixed linear regression models were used to estimate associations of tract SES and racial/ethnic composition with neighborhood quality over time. The four domains of neighborhood quality were considered in separate sets of models. Each individual's summary score for each scale was modeled as a function of individual-level characteristics, site, tract-level characteristics, time, the interaction of site with time, and the interaction of tract-level characteristics with time. A random intercept for each census tract was included to account for within-neighborhood correlations. We were unable to account for the repeated observations from MESA participants as only 18% of the sample contributed multiple observations; sensitivity analyses restricted to MESA participants only with random intercepts for individual found similar results. All models adjusted for individual-level covariates, while each tract-level predictor was evaluated independently and then in mutually adjusted models that included all three tract-level predictors.

Results

Table 2–1 shows characteristics of the 1,171 census tracts included in the analysis at baseline (year 2000) overall and across tertiles of tract SES, percentage of Black residents, and percentage of Hispanic residents. The median household income was $37,670 (IQR: $26,670-$51,678), the median percentage of Black residents was 6.7% (IQR: 1.4% to 40.3%), and the median percentage of Hispanic residents was 15.8% (IQR: 3.1% to 55.3%). The correlations among tract SES and racial/ethnic composition were moderate: between tract SES and percentage Black, -0.24; tract SES and percentage Hispanic, -0.42; and percentage Black and percentage Hispanic, -0.29.

Table 2–2 shows respondent characteristics and summary scale scores by the SES and racial/ethnic composition of the respondent's census tract (at the time when they completed the survey). Observations about high-SES tracts tended to come from older, white, more educated people with higher incomes. Observations about high percentage Black neighborhoods were less clearly patterned by individual characteristics, though they were more likely to come from Black respondents and less likely to come from high income or highly educated respondents. Observations of high percentage Hispanic neighborhoods were more likely to come from Hispanic and younger, less educated respondents with lower incomes. All four of the survey scales of interest were correlated with tract socioeconomic and racial/ethnic characteristics, such that tracts with low SES, high percentage of Black residents, and high percentage of Hispanic residents had lower scores for neighborhood social cohesion, safety, healthy food environment, and walking environment.

Healthy food environment scores were the lowest of any of the domains at baseline (Table 2–3; 3.30 [3.25, 3.34]) but increased the most over the study period, with an average 5-

year change of 0.19 (0.17, 0.21) points. Social cohesion and safety had similar baseline average scores that were mostly stable over follow-up. The walking environment scores were highest at baseline (3.86 [3.83, 3.89]) and increased slightly over time (0.04 [0.03, 0.06] points over 5 years).

Regression models adjusted for individual-level covariates and each tract-level predictor separately (Table 2–3, Model 1) found consistent patterns across all four domains of neighborhood quality. Higher tract SES was associated with higher levels at baseline and more positive changes over time, while higher percentage of Black or Hispanic residents was associated with lower levels at baseline and more negative changes over time. The magnitude of the differences at baseline were largest for safety (0.24, -0.23, and -0.28 points per standard deviation higher SES, percent Black, and percent Hispanic, respectively), while the differences in the 5-year change were largest for the healthy food environment (0.06, -0.05, and -0.01 points per 5 years for every standard deviation higher SES, percent Black, and percent Hispanic, respectively).

In models including all three tract-level predictors (Table 2–3, Model 2), social cohesion levels at baseline remained strongly associated with tract-level minority composition but not SES (one standard deviation higher in percentage of Black residents was associated with -0.06 [-0.09, -0.04] points lower social cohesion at baseline; for percentage Hispanic, -0.08 [-0.11, -0.04] points), while higher SES tracts had more positive changes in social cohesion over time than lower SES tracts. Figure 2-1 shows the increasing disparity in social cohesion between high- and low-SES tracts over time while disparities between high- and low-minority tracts were stable over time.

After adjustment for all three tract characteristics, levels of safety at baseline remained strongly patterned by tract SES and minority composition at baseline (0.07 [0.01, 0.12], -0.26 [-0.30, -0.21], and -0.29 [-0.35, -0.23] points per standard deviation higher SES, percentage Black and percentage Hispanic, respectively). Only the percentage of Black residents remained a significant predictor of changes over time, such that tracts with higher percentage Black residents experienced steeper declines in safety than lower percentage Black tracts (-0.05 [-0.07, -0.02] points over 5 years per standard deviation higher in percentage of Black residents). The net effect, as shown in Figure 2-1, is small and stable differences in safety by tract SES, large and increasing differences in safety by tract percentage of Black residents, and large but stable differences in safety by tract percentage of Hispanic residents.

The association between tract SES and healthy food availability at baseline was attenuated by adjustment for tract percentage of Black residents and tract percentage of Hispanic residents, though higher SES tracts did have larger improvements over time in healthy food environment scores than lower SES tracts (difference in 5-year change, 0.08 [0.04, 0.11] per standard deviation higher tract SES). Tract minority composition was strongly associated with baseline levels of healthy food environment summary scores (-0.16 [-0.21, -0.10] and -0.18 [-0.25, -0.10] points per standard deviation higher percentage Black residents and percentage Hispanic residents, respectively), but not with changes over time in healthy food environment summary scores. Figure 2-1 shows the increasing disparity in healthy food environment scores by tract SES over time and the wide but generally stable differences by percentage of Black residents and percentage of Hispanic residents.

The walking environment was the only survey scale in which a one-standard deviation difference in tract SES had a larger impact on summary scores at baseline than a one-standard deviation in percentage of Black or Hispanic residents (0.14 points vs. -0.09 and -0.06, respectively). Only percentage of Black residents was associated with change over time, such that high percentage Black tracts had smaller increases or decreases in walking environment scores over time (-0.03 [-0.05, -0.01] points per standard deviation higher percentage of Black residents). Figure 2-1 illustrates the large differences at baseline based on tract SES and the increasing disparity over time between high- and low-Black tracts.

Discussion

Census tract SES and racial/ethnic composition were associated with survey measures of neighborhood physical and social environments and with changes in these environments over time. After adjusting for individual covariates and all three tract-level predictors of interest, higher tract SES was associated with higher levels of all four survey scales at baseline, though the differences were only statistically significant for the walking environment and safety. In addition, high SES areas had increasing social cohesion and more pronounced increases in the healthy food environment over time compared with lower SES areas. As a result, disparities in social cohesion and the food environment by tract SES widened over time, while disparities in safety and the walking environment were stable.

Areas with a high percentage of Black residents and Hispanic residents had lower levels of social cohesion, safety, healthy food environment, and walking environment at baseline. Additionally, percentage of Black residents was inversely associated with changes in safety and the walking environment over time, such that high percentage Black areas experienced declines over time while the overall trends were stable (for safety) or increasing over time (for the walking environment). After adjustment for tract SES and percentage of Black residents, the percentage of Hispanic residents was not a significant predictor of changes over time in any of the survey scales investigated.

Our results showing that higher percentage Black or Hispanic residents is associated with lower levels of social cohesion is consistent with prior work reporting that minority racial composition and concentrated disadvantage are associated with lower levels of trust or social capital.[15-17,28] However, associations were generally weak. Social cohesion declined slightly over time, and we observed a weak patterning in changes over time by SES such that the decline was greater in lower SES compared with higher SES areas. To our knowledge, no previous studies have examined how neighborhood socio-demographic characteristics relate to changes over time in social cohesion.

Safety was strongly associated with minority composition of the neighborhood, even after adjusting for tract SES; this fits with previous research showing that minority neighborhoods experience a disproportionate burden of crime and violence.[29-31] Differences in safety may also reflect neighborhood aesthetics and incivilities that were not measured.[32-33] Levels of safety in the full sample declined slightly over time; the decline was more pronounced in neighborhoods with higher percentages of Black residents. Additional research is needed to identify the specific social and/or structural factors that drive differences (and changes over time) in social cohesion and safety by racial/ethnic composition and the implications of these differences for health.

A large body of previous research has shown that low SES and predominantly minority areas tend to have poorer access to healthy foods[6-9] and poorer environments for physical activity.[10,34-36] Our results support and extend this research to suggest that disparities in healthy food environments by neighborhood SES may be widening over time. Neighborhood food environments improved substantially on average over the 10-year period, but more quickly in high SES areas than in lower SES areas. Baseline differences in the food environment associated with the percent of minority residents (particularly Black residents) did not diminish substantially over time.

Few studies have investigated predictors of neighborhood differences in the walking environment.[37-38] We found that all three tract characteristics investigated were associated with walking environments such that lower SES tracts and tracts with more minority residents had lower baseline scores for walking environment. Although walking environment scores did not change substantially over the 10 year study period, we observed small increases in these differences by race/ethnic composition over time, particularly for the percent of Black residents.

The magnitude of differences in neighborhood quality in this analysis may be relevant for health. Previous work in MESA found that better walking and food environments, measured by a difference equivalent to the interquartile range (slightly larger than the standard deviation differences used in this analysis) was associated with 20% lower incidence of diabetes over five years of follow up.[39] Similarly, one standard deviation increase in the food environment was associated with 10% lower obesity incidence over five years of follow up in MESA.[40] Thus, some of the differences we report could have health consequences.

Limitations of this analysis include the reliance on survey data, which may introduce measurement error in quantifying neighborhood quality and the fact that the availability of supplementary community survey data was not identical across sites. However, the design was such that each site had sufficient temporal representation to estimate trends and site adjustment minimized confounding effects of site. Future research should verify these results with other measures of neighborhood quality as appropriate (though some domains, e.g. social cohesion, can be assessed only through participant reporting). Additionally, there may be residual confounding that we were not able to adjust for in this analysis, by characteristics such as personal social connectedness or residential stability. Finally, given the extensive racial/ethnic residential segregation in the US, estimating the effect of percentage of Black residents after adjusting for tract SES and percentage of Hispanic residents may be subject to structural confounding and lead to off-support inferences.[41] However, with the large sample size and racial/ethnic diversity in our data set, the three tract-level predictors were only moderately correlated. Still, much additional research is needed to narrow in on the causal factors, downstream of area SES and racial/ethnic composition, which drive variability in neighborhood quality.

Strengths of this analysis include the use of a large, multi-ethnic, and geographically diverse data set with observations of neighborhood quality in specific domains related to the physical environment and the social environment. With a ten-year observation period, we were able to observe changes in neighborhood quality in six diverse regions of the US.

This research supports the body of evidence that disadvantaged and minority neighborhoods tend to have lower quality environments, and adds new information about the ways that these inequalities are evolving over time. It is plausible that lower quality neighborhood environments may be related to the persistent health disparities observed among disadvantaged and minority individuals. The solutions to disparities in neighborhood quality are as complex as their causes, but identifying policies that can most effectively mitigate the social patterning of neighborhood quality may be important in reducing racial/ethnic disparities in health.

Table 2–1. Characteristics of census tracts at baseline (year 2000) by census tract socioeconomic status (SES) and racial/ethnic composition.

	Overall	Tract SES			Tract % Black			Tract % Hispanic		
		Low	*Med*	*High*	*Low*	*Med*	*High*	*Low*	*Med*	*High*
TRACT	*N=1171*	*N=400*	*N=385*	*N=386*	*N=389*	*N=383*	*N=399*	*N=387*	*N=386*	*N=398*
Median SES Factor Score [a]	0.17	1.11	0.13	-1.29	0.23	-0.27	0.43	-0.32	-0.29	0.98
Median of median household income [a]	$37,670	$29,399	$36,311	$56,189	$45,373	$41,579	$27,355	$47,978	$40,950	$27,995
Median % residents with HS education or more [a]	74.0	51.8	73.0	91.4	74.0	82.6	67.8	87.8	81.5	50.1
Median % residents with BA or more [a]	19.4	7.4	20.0	49.9	20.6	29.9	13.8	32.8	27.1	8.1
Median % Black residents [a]	6.7	7.2	14.2	4.2	0.7	6.4	58.3	10.4	7.1	3.3
Median % Hispanic residents [a]	15.8	59.8	21.1	4.8	30.3	12.5	11.5	1.9	15.5	67.7
Site (%) [b]										
Los Angeles, CA	35.2	53.2	28.3	23.3	64.5	23.5	17.8	1.8	41.5	61.6
Chicago, IL	12.9	4.8	10.6	23.6	12.3	11.0	15.3	24.3	11.9	2.8
Baltimore, MD	12.4	11.2	15.3	10.6	3.1	9.7	24.1	35.4	2.1	0
St Paul, MN	10.5	6.2	12.5	13.0	12.9	17.8	1.3	20.9	10.6	0.3
New York, NY	22.5	18.0	26.0	23.6	6.7	26.6	33.8	5.2	26.4	35.4
Forsyth County, NC	6.6	6.5	7.3	6.0	0.5	11.5	7.8	12.4	7.5	0

[a] *ANOVA tests (for SES Factor Score) and Kruskal-Wallis tests (for other characteristics) to compare medians across tertiles of tract SES, % Black, and % Hispanic were all significant at p<0.0001*

[b] *χ2 tests to compare the distribution across tertiles of tract SES, % Black, and % Hispanic were all significant at p<0.0001*

Table 2–2. Characteristics of survey respondents (at the time they responded to the survey), by census tract socioeconomic status (SES) and racial/ethnic composition.

INDIVIDUAL	Overall (N=26,769)	Tract SES Low (N=7487)	Tract SES Med (N=8911)	Tract SES High (N=10371)	Tract % Black Low (N=6178)	Tract % Black Med (N=11559)	Tract % Black High (N=9032)	Tract % Hispanic Low (N=9810)	Tract % Hispanic Med (N=10344)	Tract % Hispanic High (N=6615)
Age [a]	57.6	56.5	57.6	58.4	57.6	57.9	57.3	60.4	57.6	53.4
Male [b]	43.7	42.3	43.5	44.8	46.6	43.7	41.5	44.7	44.7	40.5
Education (%) [b]										
Less than HS	14.7	27.4	14.9	5.2	19.3	12.7	14.1	7.0	11.9	30.4
HS/some college	44.7	52.6	51.8	32.9	41.5	42.4	49.8	43.5	43.7	47.9
BA+	40.6	19.9	33.3	61.9	39.2	44.9	36.1	49.5	44.4	21.7
Annual income (%) [b]										
<$12,000	11.2	17.8	12.2	5.5	11.9	9.5	12.7	6.1	9.6	21.0
$12,000-24,999	15.4	23.2	16.1	9.0	18.6	12.8	16.4	10.7	15.0	22.7
$25,000-34,999	11.8	14.3	13.8	8.3	11.2	11.3	12.9	9.5	12.4	14.3
$35,999-$74,999	30.2	27.9	33.8	29.0	25.0	31.5	32.1	32.8	31.0	25.3
$75,000+	24.8	9.1	18.0	41.9	26.2	29.1	18.3	33.7	25.6	10.2
Missing	6.7	7.7	6.3	6.2	7.1	5.7	7.5	7.1	6.3	6.5
Race/ethnicity (%) [b]										
White	41.4	20.0	34.8	62.4	34.7	59.4	22.9	56.3	44.9	13.8
Asian	9.5	6.1	11.4	10.4	27.8	6.3	1.2	4.7	15.4	7.4
Black	25.4	32.3	29.7	16.7	0.9	9.9	61.9	34.7	21.1	18.3
Hispanic	22.5	40.5	22.9	9.3	35.5	23.6	12.4	3.6	17.3	58.8
Other/mixed	1.2	1.1	1.3	1.1	1.1	0.9	1.6	0.7	1.3	1.7
Study source (%) [b]										
MESA participant	58.7	59.1	60.8	56.7	52.2	62.4	58.4	67.9	59.6	43.6
CS participant	41.3	40.9	39.2	43.3	47.8	37.6	41.6	32.1	40.4	56.4
Site (%) [b]										
Los Angeles, CA	22.0	32.9	21.6	14.5	65.9	9.7	7.8	1.7	26.9	44.5
Chicago, IL	11.6	1.6	7.0	22.6	6.7	12.4	13.8	23.5	6.8	1.3
Baltimore, MD	13.9	10.6	17.8	13.0	2.0	8.4	29.1	36.6	1.3	0
St Paul, MN	10.3	13.2	15.4	3.9	11.0	17.9	0.2	6.1	19.5	2.1
New York, NY	26.3	24.4	22.8	30.6	12.3	30.3	30.7	4.9	30.2	0
Forsyth County, NC	15.9	17.2	15.3	15.4	2.1	21.2	18.4	27.2	15.3	52.1

Neighborhood scales (mean) [a]										
Social cohesion	3.54 (N=20998)	3.36 (N=5822)	3.50 (N=6943)	3.71 (N=8233)	3.58 (N=4983)	3.61 (N=8957)	3.43 (N=7058)	3.72 (N=7377)	3.57 (N=8080)	3.27 (N=5541)
Safety	3.65 (N=20624)	3.30 (N=5721)	3.61 (N=6795)	3.93 (N=8108)	3.85 (N=4895)	3.78 (N=8766)	3.34 (N=6963)	3.83 (N=7241)	3.75 (N=7940)	3.25 (N=5443)
Healthy food environment	3.57 (N=20624)	3.32 (N=5721)	3.43 (N=6795)	3.88 (N=8108)	3.77 (N=4895)	3.66 (N=8766)	3.32 (N=6963)	3.56 (N=7241)	3.65 (N=7940)	3.48 (N=5443)
Walking environment	3.95 (N=20624)	3.67 (N=5721)	3.84 (N=6795)	4.24 (N=8108)	3.98 (N=4895)	4.05 (N=8766)	3.80 (N=6963)	4.01 (N=7241)	4.03 (N=7940)	3.75 (N=5443)

[a] *ANOVA tests to compare means across tertiles of tract SES and % Hispanic were significant at $p<0.0001$; for % Black, $p<0.05$*

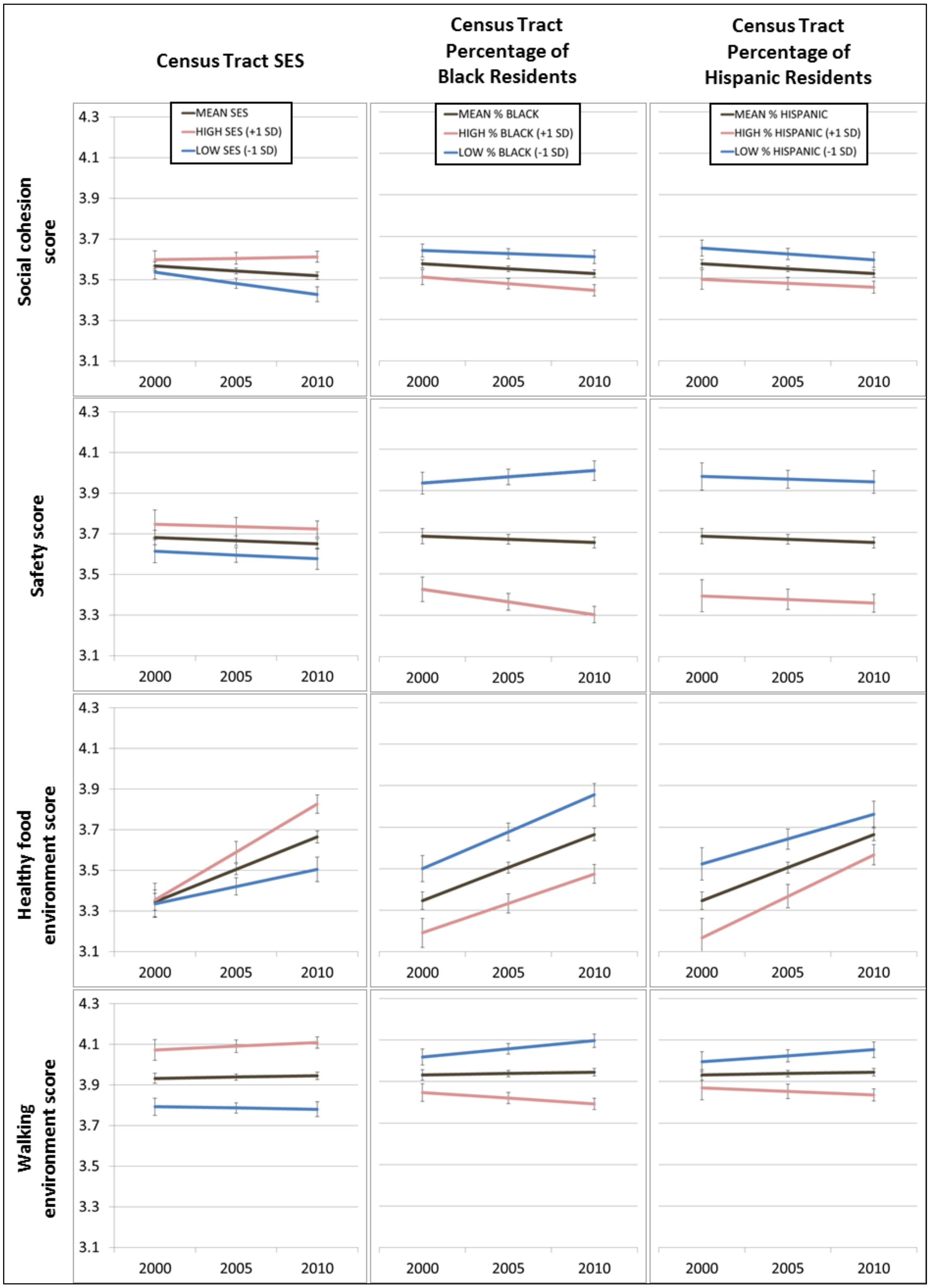
[b] *$\chi2$ tests to compare the distribution across tertiles of tract SES, % Black, and % Hispanic were all significant at $p<0.0001$*

Table 2–3. Mean differences (95% CI) at baseline and mean differences (95% CI) in 5-year changes in survey-based neighborhood quality per standard deviation increase[1] in tract characteristic.

Domain	Tract-level characteristic	MODEL 1[2] *Difference (95% CI) at baseline*	MODEL 1[2] *Difference (95% CI) in 5-yr change[4]*	MODEL 2[3] *Difference (95% CI) at baseline*	MODEL 2[3] *Difference (95% CI) in 5-yr change[4]*
Social cohesion *Mean at baseline: 3.55 (3.53, 3.57)* *Mean 5-year change: -0.01 (-0.02, 0.00)*	SES factor score	**0.08 (0.06, 0.11)**	**0.03 (0.02, 0.04)**	0.03 (0.00, 0.06)	**0.03 (0.01, 0.05)**
	Percent Black	**-0.06 (-0.08, -0.03)**	**-0.02 (-0.03, -0.01)**	**-0.06 (-0.09, -0.04)**	-0.01 (-0.02, 0.01)
	Percent Hispanic	**-0.09 (-0.11, -0.06)**	-0.01 (-0.03, 0.00)	**-0.08 (-0.11, -0.04)**	0.00 (-0.02, 0.03)
Safety *Mean at baseline: 3.64 (3.60, 3.69)* *Mean 5-year change: -0.01 (-0.03, 0.01)*	SES factor score	**0.24 (0.20, 0.28)**	**0.03 (0.01, 0.05)**	**0.07 (0.01, 0.12)**	0.00 (-0.03, 0.03)
	Percent Black	**-0.23 (-0.27, -0.19)**	**-0.05 (-0.07, -0.02)**	**-0.26 (-0.30, -0.21)**	**-0.05 (-0.07, -0.02)**
	Percent Hispanic	**-0.28 (-0.33, -0.23)**	0.00 (-0.02, 0.03)	**-0.29 (-0.35, -0.23)**	0.00 (-0.04, 0.03)
Healthy food environment *Mean at baseline: 3.30 (3.25, 3.34)* *Mean 5-year change: 0.19 (0.17, 0.21)*	SES factor score	**0.12 (0.08, 0.17)**	**0.06 (0.04, 0.09)**	0.01 (-0.05, 0.07)	**0.08 (0.04, 0.11)**
	Percent Black	**-0.12 (-0.16, -0.07)**	**-0.05 (-0.07, -0.02)**	**-0.16 (-0.21, -0.10)**	-0.02 (-0.05, 0.01)
	Percent Hispanic	**-0.15 (-0.2, -0.09)**	-0.01 (-0.04, 0.02)	**-0.18 (-0.25, -0.10)**	0.04 (0.00, 0.08)
Walking environment *Mean at baseline: 3.86 (3.83, 3.89)* *Mean 5-year change: 0.04 (0.03, 0.06)*	SES factor score	**0.18 (0.16, 0.21)**	**0.04 (0.02, 0.05)**	**0.14 (0.10, 0.18)**	0.01 (-0.01, 0.04)
	Percent Black	**-0.11 (-0.14, -0.08)**	**-0.03 (-0.05, -0.02)**	**-0.09 (-0.12, -0.05)**	**-0.03 (-0.05, -0.01)**
	Percent Hispanic	**-0.14 (-0.18, -0.11)**	-0.02 (-0.04, 0.00)	**-0.06 (-0.11, -0.02)**	-0.02 (-0.05, 0.00)

[1] One standard deviation is equivalent to 1.38 units on the factor scale for tract SES, 30 percentage points for proportion of Black residents and 28 percentage points for proportion of Hispanic residents
[2] Adjusted for individual-level characteristics (mean-centered age, gender, race, education, income, study source, and site), time, tract characteristic, and interaction of site with time and tract characteristic with time. Tract characteristics were each considered in separate models.
[3] Model 1 + all three neighborhood-level predictors and their interactions with time.
[4] The difference in 5-yr change is defined as the coefficient for the interaction term between time (since baseline, in 5-yr increments) and the neighborhood characteristic.

Figure 2-1. Estimated neighborhood quality (and 95% CIs) by levels of each tract characteristic, from mutually adjusted models (Table 3, Model 2).



One standard deviation is equivalent to 1.38 units on the factor scale for tract SES, a 30% difference in percentage of Black residents, and a 28% difference in percentage of Hispanic residents. Intercepts reflect mean values for all covariates.

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Chapter 3

Neighborhood environments and incident hypertension

Introduction

Characteristics of residential environments have been associated with a variety of health outcomes, including cardiovascular disease incidence and mortality.[1] As a major risk factor for cardiovascular disease, hypertension is an important public health outcome.[2,3] Existing research on how neighborhood environments affect blood pressure has been largely limited to cross-sectional analyses and use of generic measures of the neighborhood environment that shed little light on the specific processes involved.[4,5]

Studies of neighborhoods and hypertension using indicators of neighborhood socioeconomic status (SES) to characterize the neighborhood environment have generally, though not always,[6,7] found area-level affluence to be associated with lower prevalence[8-11] and incidence of hypertension.[12,13] Fewer studies have investigated how specific measures of neighborhood physical and social environments are related to hypertension.

Studies that have investigated specific neighborhood environments typically use either survey data to aggregate resident perceptions of their environment or geographic information systems (GIS) data to summarize the presence of resources. Cross-sectional results have been mixed. Some studies have reported no association between survey-based neighborhood walkability and prevalence of hypertension[14] but others have found a protective effect of more favorable walking environments and greater neighborhood availability of healthy foods.[15] GIS-based local densities of grocery stores and fast-food restaurants were not associated with systolic blood pressure levels in the Women's Health Initiative Clinical Trial,[16] but a small prospective study with one year of follow up found that high walkability (characterized by land use mix, street connectivity, public transportation and green space) was associated with smaller increases or decreases in blood pressure and that high density of fast food stores in the neighborhood was associated with larger increases in blood pressure, but only in low-walkability neighborhoods.[17] Neighborhood effects on blood pressure are plausible given that neighborhood food and physical activity environments have also been associated with major risk factors for hypertension, including obesity, diet, and physical activity in cross-sectional[18-20] and longitudinal analyses,[21,22] although findings have not always been consistent.[23,24]

Less research has focused on how neighborhood social environments affect blood pressure, though one study found that chronic neighborhood-level stressors[25] explain some or all of disparities between African Americans and whites in hypertension prevalence. In cross-sectional analyses of the Multi-Ethnic Study of Atherosclerosis (MESA), survey-based measures of greater neighborhood safety and greater social cohesion, as well as greater neighborhood availability of healthy foods and more favorable walking environments, were each associated with lower prevalence of hypertension, though associations were not robust to adjustment for race/ethnicity.[15]

Investigating how specific measures of neighborhood physical and social environments are related to hypertension is important for improving our understanding of the mechanisms through which neighborhood environments influence health. We use longitudinal data from the

Multi-Ethnic Study of Atherosclerosis (MESA) to examine how survey and GIS measures of specific neighborhood physical and social environments are related to incidence of hypertension in a diverse cohort sampled across six study sites with over ten years of follow-up.

Methods

Study Population

MESA is a prospective study of 6,814 men and women from six study sites (Los Angeles County, CA; St. Paul, MN; Chicago, IL; Forsyth County, NC; Baltimore, MD; and New York City, NY) who were aged 45-84 years at baseline (between August 2000 and July 2002). Participants were free of clinical cardiovascular disease at baseline (e.g. no history of heart attack, stroke, heart failure, or atrial fibrillation); participation among those eligible was 60%. Participants attended four additional follow-up examinations in 2002-2004, 2004-2005, 2005-5007, and 2010-2011. Residential histories were collected at each exam, and participant addresses were geocoded at the monthly level. The study was approved by the institutional review board at each participating site, and participants provided informed consent.[26]

Hypertension

Blood pressure was measured at each of the five exams, following a standardized protocol; after 5 minutes of seated rest, three measurements were taken at 2-minute intervals with an automated oscillometric sphygmomanometer.[27] The average of the second and third measurements was used for analysis. Hypertension was defined as systolic blood pressure above 140 mmHg, diastolic blood pressure above 90 mmHg, or reported use of antihypertensive medications.[28] The date of incident hypertension was assigned to the midpoint between the last non-hypertensive exam and the first hypertensive exam; participants who did not develop hypertension were censored at the date of their last exam.

Neighborhood Environments

Measures of neighborhood environments came from three data sources: surveys of MESA participants, surveys of individuals living in MESA sites (Community Surveys), and GIS-based densities of resources. Community Surveys were cross-sectional phone surveys that collected information from non-MESA participants over age 18 who lived in the MESA sites; the first Community Survey was completed in 2004 in the Maryland, New York, and North Carolina sites by 5,988 individuals, and the 2011 Community Survey included 4,122 respondents in a subsample of tracts in all six sites. Respondents were sampled using random digit dialing and list-based sampling.

Two survey scales related to the physical environment (healthy food availability and walking environment) and two survey scales related to the social environment (social cohesion and safety) were selected for investigation because of their potential relevance to hypertension[20,25,29,30] and because they were assessed consistently across MESA and Community Survey questionnaires at multiple time points. Each Community Survey included all four survey scales of interest, while MESA participants responded to each scale twice (social cohesion in 2000-2002; safety, healthy food, and walking environment in 2003-2005; and all four scales in 2010-2011).

The healthy food availability scale included two questions on the availability of fresh fruits and vegetables and low-fat foods in the neighborhood. The walking environment scale included four questions about the pleasantness of walking in the neighborhood, ease of walking to destinations, and frequency of seeing others walking or exercising in the neighborhood. The social cohesion scale included four questions relating to trust in neighbors, shared values with neighbors, willingness to help neighbors, and extent to which neighbors get along. The safety scale included two items about neighborhood violence and ability to walk in the neighborhood without fear. All survey scales used a 5-point Likert scale with response options from 'strongly agree' to 'strongly disagree.' In responding to the items, all participants were asked to refer to the area about one mile around their home. Scales were based on previous work and have acceptable internal consistency, ecometric properties, and reliability.[31]

The survey scales were summarized as the average of all responses from participants who lived within one mile of each MESA participant's home address. These one-mile crude means were calculated for two time periods: 2000-2005, using data from MESA participants in that time frame and the 2004 Community Survey, and 2006-2011, combining data from MESA participants with the 2011 Community Survey.

GIS-based densities of resources were derived from commercially available business listings through the National Establishment Time-Series database from Walls & Associates (Oakland, CA). Standard Industrial Classification codes (U.S. Occupational Safety and Health Administration, Washington DC) related to indoor conditioning, dance, bowling, golf, biking, hiking, team and racquet sports, swimming, physical activity instruction, and water activities were defined as physical activity resources; favorable food stores included chain and non-chain supermarkets and fruit and vegetable markets.[32,33] Data were obtained for each year from 2000-2011. Annual data were attributed to all months in the year. The simple density of favorable food stores and physical activity resources per square mile were calculated for a one-mile buffer around each participant's home address using ArcGIS software (ESRI, Redmonds, CA).

We also created environmental summary measures that combined survey and GIS measures (or multiple survey measures) related to the same domain. Survey-based healthy food availability and GIS-based density of favorable food stores were combined to capture the food environment; survey-based walking environment and GIS-based density of recreational resources were combined to capture the physical activity environment; and survey-based safety and social cohesion were combined to capture the social environment. These environmental summary measures were created by standardizing and summing together scores from the component measures. Chronbach's alpha for the summary measures were: 0.44 for the food environment, 0.75 for the physical activity environment, and 0.75 for the social environment. Table 4–1 shows details of the neighborhood measures used.

In order to better reflect the long-term accumulation of neighborhood exposures, we calculated the time-varying average of each neighborhood measure (survey-based, GIS-based, and environmental summary measures) from baseline through each month of follow-up (henceforth referred to as the cumulative average). Because hypertension is a progressive disease that develops gradually, we chose to emphasize long-term trends in neighborhood environments rather than short-term changes.

Additional Covariates

Individual-level covariates included age, race/ethnicity, and education. Race/ethnicity was self-reported as white, African American, Hispanic, or Chinese, based on questions adapted from the 2000 Census. Education was used as a proxy for individual-level SES, based on previous work showing that education is more important than income as a predictor of incident hypertension;[34] educational attainment was measured as years of education based on the midpoint of nine categories (reduced educational categories were used for descriptive statistics).

The role of neighborhood SES in understanding the relationship between specific features of the neighborhood environment and hypertension is complex.[35] Neighborhood SES may be a confounder if it is associated with neighborhood physical and social environments and has an independent effect on hypertension (through pathways that do not involve the neighborhood physical and social environments being measured).[36-38] However, if neighborhood SES captures the same underlying constructs as the specific measures of neighborhood features, adjusting for neighborhood SES may result in over-adjustment. Neighborhood SES was moderately correlated with the specific neighborhood features in this analysis (ranging from r=0.13, with the density of favorable food stores, to r=0.76, with the survey-based walking environment scale). We present models with and without adjustment for neighborhood SES for transparency. Neighborhood SES was characterized based on principal factor analysis of all US census tracts with orthogonal rotation of 16 census tract-level variables. The first factor explained 49.2% of total variance and represents education, occupation, housing value, and income; this factor score was used to summarize tract-level SES, such that a higher score represents increasing socioeconomic advantage. Data came from the 2000 Census[39] (linked to 2000-2004) and the American Community Survey in 2005-2009 and 2007-2011 (linked to 2005-2007 and 2008-2011, respectively).[40,41]

Potential mediators included body mass index (BMI), physical activity, and diet. BMI was considered a mediator of all neighborhood features, while physical activity was considered a mediator of the physical activity environment and diet was considered a mediator of the food environment. BMI was measured using height and weight measurements obtained at each MESA exam; BMI was modeled continuously. Physical activity was measured as total metabolic-equivalent hours per week of intentional exercise, and categorized into none, low, medium, and high (defined by tertiles of non-zero values). Diet was measured at the baseline exam with a food frequency questionnaire and summarized according to the Healthy Eating Index (2005 guidelines).[42]

Statistical Analysis

Descriptive analyses examined the distribution of the environmental summary measures by relevant participant characteristics. Incidence rates were calculated by tertile of the environmental summary scores using Poisson models adjusted for the mean age at baseline and the sex distribution of the sample; we also tested for linear trends in rates of hypertension by tertiles of environmental summary scores.

Cox models were used to estimate associations of time-varying cumulative average neighborhood measures with incident hypertension, before and after adjustment for individual- and neighborhood-level covariates. Neighborhood measures were modeled continuously, as exploratory analyses found no evidence of non-linearity in relationships with hypertension. Initial models adjusted for baseline age, gender, education, income, and each neighborhood measure separately, with additional covariates added in stages to illustrate their potential confounding effects. Race/ethnicity was added separately due to previous work in which residential environments were strongly patterned by race/ethnicity in relation to hypertension prevalence.[15] Mutual adjustment for all six neighborhood measures, and subsequent adjustment for neighborhood SES, was used to identify the independent effects of each neighborhood measure.

Schoenfeld residuals provided evidence that baseline age violated the proportional hazards assumption, so an interaction term between age and log-time was added to all models in addition to the main effect. Robust standard errors were used to account for dependencies among individuals within the same census tract. Effect modification was investigated by adding interaction terms between neighborhood measures and gender, baseline age, and time-varying working status. Mediation was explored by adding relevant covariates to regression models.

Results

Of the 6,191 MESA Neighborhood participants, 2,718 (43.9%) were hypertensive at baseline and were excluded from this analysis. Another 91 people (2.6%) were unable to be geocoded to a census tract or were missing key individual covariates or neighborhood environmental data, leaving a final analytic sample size of 3,382 individuals. The median person-time contributed was 7.2 years (IQR: 5.8); 17% of the sample was lost to follow up or death before the final exam.

Descriptive information about the neighborhood measures are available in Table 3–1, including the crude baseline values before standardization for use in analysis. Correlations between the neighborhood measures at baseline were moderate, ranging from 0.07 (healthy food availability and safety scales) to 0.65 (healthy food availability and walking environment scales).

Socio-demographic and neighborhood characteristics of the 3,382 participants in the study sample at baseline are presented in Table 3–2. The average age was 59.1 years at baseline; 43.6% were white, 22.5% Hispanic, 20.6% Black and 13.4% Chinese. Older participants and white participants tended to live in areas with better physical activity and social environments at baseline, and Hispanic participants lived in healthier food environments than participants of other racial/ethnic groups. Participants with more education and those living in higher SES neighborhoods had better food, physical activity, and social environments compared to participants with less education and those who lived in lower SES neighborhoods (tests for linear trend, $p<0.0001$). Quality of neighborhood environments varied by site; New York had the highest food environment scores and Winston-Salem had the lowest, while Winston-Salem had the highest social environment scores and New York had the lowest. Physical activity environment scores were slightly more equally distributed; Chicago had the highest scores and Los Angeles had the lowest.

During 21,340 person-years of observation, 1,335 incident cases of hypertension were identified. Table 3–3 shows differences in participant characteristics between those who developed hypertension and those who did not. As expected, older participants, Black participants, participants with less education, and those living in low-SES census tracts were over-represented in the incident hypertension group. Those who developed hypertension lived in areas with significantly lower healthy food, physical activity, and social environment summary scores at baseline than those who remained hypertension-free.

Age- and sex-adjusted incidence rates of hypertension (Table 3–4) showed clear patterns by tertiles of neighborhood environmental summary scores, such that better food, physical activity, and social environment summary scores were each associated with lower hypertension incidence rates (all tests for trend <0.01). These patterns persisted in Cox models adjusted for age, sex, education, income, and neighborhood environment summary scores as continuous measures (Table 3–5, Model 1; HR [95% CI] per standard deviation increase: 0.94 [0.89-0.99], 0.92 [0.86-0.98] and 0.93 [0.88-0.99] for healthy food, physical activity, and social environment summary scores, respectively). Additional adjustment for race/ethnicity attenuated most associations, though summary scores for the healthy food environment remained significantly protective (Table 3–5, Model 2; HR 0.95 [0.89-1.00]). Associations with the summary physical activity and social environment scores did not (HR 0.95 [0.89-1.01] and 0.98 [0.93-1.04], respectively).

When individual GIS and survey measures were examined, GIS-based densities related to the food environment and physical activity environment were not associated with incident hypertension, while the survey-based healthy food, walking environment, and safety scales were all significantly associated with lower rates of hypertension in models adjusted for age, gender, education, and income (HR 0.88 [0.84-0.93], 0.91 [0.86-0.97], and 0.91 [0.86-0.97], respectively). The associations with survey-based healthy food and walking environment scales persisted after additional adjustment for race/ethnicity (HR 0.91 [0.86-0.96] and 0.94 [0.88-1.00], respectively), but associations with safety did not (HR 0.98 [0.92-1.04]).

When all six neighborhood measures were simultaneously included in the model (Table 3–5, Model 3), the survey-based healthy food scale remained significantly associated with lower rate of hypertension (HR 0.89 [0.82-0.96]) but the association with the survey-based walking environment scale was attenuated and no longer statistically significant (HR 1.03 [0.93-1.12]). Adjusting for neighborhood SES (Table 3–5, Model 4) did not substantially affect these associations.

We evaluated BMI and diet as potential mediators of the relationship between the healthy food availability scale and hypertension; in a subsample with complete data on BMI (time-varying) and diet (measured at baseline) (N=2,979), the association between the survey measure of healthy food availability and incident hypertension was unchanged by adjustment for these mediators (HR 0.90 [0.83-0.98]). Interaction terms between the healthy food survey scale and gender, baseline age, and time-varying working status were all non-significant (p>0.10).

Sensitivity analyses explored the effects of using baseline measures of neighborhood quality; time-varying measures of neighborhood quality; kernel-based resource densities; density buffer sizes of 0.5 miles and 3 miles; conditional empirical Bayes estimates of survey measures for census tracts (instead of one mile crude means); restricting analyses to only those participants with at least 5 survey respondents within a one mile buffer; and adjusting for site. Estimated associations between neighborhood environments and hypertension did not change substantially.

Discussion

In this sample of middle-aged and older adults across six sites in the U.S., residents of neighborhoods with better healthy food, physical activity, and social environments had lower rates of incident hypertension than residents of lower-quality neighborhoods. After adjustment for age, sex, education, income, and race/ethnicity, the survey-based healthy food availability and walking environments scales remained significant predictors of hypertension risk. After simultaneously accounting for all neighborhood variables, only healthy food availability remained associated with hypertension such that each standard deviation higher cumulative average of survey-based healthy food score was associated with a 12% lower rate of hypertension. GIS-based densities of favorable food stores and physical activity resources, and the survey measure of social cohesion, were not associated with hypertension incidence. Safer environments were associated with lower rates of hypertension, but this association was attenuated after adjustment for race/ethnicity. We also presented results before and after adjusting for neighborhood SES, as neighborhood SES may be operating as a confounder; adjustment for neighborhood SES did not have much impact on the associations of interest.

These results concur with previous findings in MESA that better neighborhood physical environments are associated with lower prevalence of hypertension.[15] Our results add to this prior work by showing that the physical neighborhood environments (particularly the healthy food environment) are related to incidence of hypertension over an average of 7.2 years of follow up. The finding that the healthy food environment was more strongly associated with incident hypertension than the walking environment in fully adjusted models is consistent with previous work in MESA that found similar patterns with incident obesity[21] and incident diabetes.[29] Similarly to prior cross sectional analyses in MESA, we found that higher safety was associated with a lower incidence of hypertension, but as in prior work[15] this association was not robust to adjustment for race/ethnicity.

Associations of other neighborhood factors with hypertension incidence were attenuated after adjustment for race/ethnicity, suggesting that race/ethnicity may be acting as a confounder (especially in the case of social environment factors, which were strongly patterned by race/ethnicity). Alternatively, neighborhood environments may partly mediate racial disparities in hypertension. Neighborhood chronic stressors have been shown to explain some of the disparity in the prevalence of hypertension among African Americans and Hispanics compared to whites in MESA,[25] while adjustment for neighborhood socio-demographic context eliminated the disparity in hypertension prevalence between African Americans and whites in the Chicago Community Adult Health Study.[9] Reducing the disparities in neighborhood environments may contribute to reducing disparities in hypertension between African Americans and whites.

To our knowledge, this is the first study to investigate both survey-based and GIS-based measures of neighborhood physical environments in relation to incident hypertension. Survey-based measures of the food environment and physical activity environment were more strongly associated with hypertension than GIS-based measures related to the same domains. GIS-based measures are generally limited to the presence or absence of resources; survey-based measures can capture additional considerations, such as quality and ease of access, which may be important in how neighborhood environments shape various health outcomes.

Only one prior study has investigated GIS-based measures in relation to changes in blood pressure or hypertension incidence.[17] The study concluded that residents of more walkable neighborhoods (defined by land use mix, street connectivity, public transportation, and green space) had smaller increases in systolic blood pressure over one year of follow up. It is possible that walkability-related constructs may be more relevant to blood pressure outcomes than the presence of commercial businesses in the GIS measures that we used. This may also explain why the survey measure of the physical environments (which included some walkability items) was related to hypertension incidence (although results were not robust to adjustment for other neighborhood variables). The possible impact of the walking environment on hypertension is consistent with recent MESA work showing that changes in walking environments (based on distances to various amenities) are related to changes in BMI.[43]

Though additional research is needed to document the pathways through which neighborhood environments affect health, it is likely that neighborhoods influence hypertension through intermediaries including diet, physical activity, stress and BMI.[10,44] We adjusted for diet and BMI, but found that these variables did little to affect the observed association between the neighborhood healthy food environment and hypertension. However, our measure of diet was only assessed at baseline, and is subject to measurement error like all food frequency questionnaires based on participant recall. In addition, our analyses of mediation are limited by challenges inherent in estimating direct and indirect effects from regression analyses.[45,46] The observed association between neighborhood healthy food environment and hypertension is plausible in the context of data showing that healthy food environments are associated with better diets[47,48] and that better diets can lower hypertension risk.[49,50]

Differential measurement validity and reliability is of potential concern and should be considered in interpreting the relative strength of associations between different neighborhood factors. Our survey-based measure of the walking environment focused on the ease and pleasantness of walking and frequency of seeing others walking in the neighborhood; this scale may not fully capture relevant aspects of the neighborhood physical activity environment related to hypertension. It is similarly possible that measurement limitations in our social environment measures may have limited our ability to detect associations with safety or social cohesion. Additionally, the healthy food environment and walking environment scales were correlated (r=0.65) at baseline, which may limit our ability to statistically disentangle their effects.

Some relevant limitations include the possibility of confounding by individual-level characteristics not included in the models that may be patterned by neighborhood environments and affect hypertension risk, such as occupational factor. In any longitudinal study, loss to follow up is a concern; in MESA, participants who were lost were more likely to be hypertensive and live in lower quality neighborhood environments, suggesting that any bias in our results would likely be towards the null. Additionally, multiple hypotheses were examined in this analysis.

Hypertension is a multi-factorial disease that develops over decades; despite the relatively long follow-up time in this study, we likely did not capture the total relevant exposure period. To best capture the chronic exposure to neighborhood environments, we used the cumulative average of neighborhood measures throughout the study. These measures are likely to reflect the longer-term environments of MESA participants, as MESA participants were largely stable with a median duration of residence in their neighborhood at baseline of 14 years.

Strengths of this analysis include the unique availability of longitudinal data for both GIS-based and survey-based measures of specific domains of the neighborhood environment, in addition to the large, multi-ethnic cohort and long follow-up time. This analysis contributes to our knowledge of the relationship between neighborhood environments and hypertension that has been observed in cross-sectional studies, and highlights the importance of collecting survey-based measures of neighborhood environments rather than relying exclusively on indicators of the presence or absence of various types of resources. Neighborhood food environments may be a useful target for public health intervention to reduce the population-level burden of hypertension.

Table 3–1. Characteristics of the neighborhood environment summary measures and their component measures.

Measure	Scale	Baseline value (95% CI)
Food environment summary score	Sum of standardized component measures	-0.10 (-0.15, -0.04)
Survey measure of healthy food availability	Likert scale, 1-5 (5 is best)	3.52 (3.50, 3.54)
Density of favorable food stores	Number of stores per square mile	2.33 (2.21, 2.45)
Physical activity environment summary score	Sum of standardized component measures	-0.08 (-0.13, -0.02)
Survey measure of walking environment	Likert scale, 1-5 (5 is best)	3.93 (3.92, 3.95)
Density of commercial physical activity resources	Number of businesses per square mile	4.48 (4.24, 4.72)
Social environment summary score	Sum of standardized component measures	-0.04 (-0.09, 0.02)
Survey measure of social cohesion	Likert scale, 1-5 (5 is best)	3.54 (3.53, 3.55)
Survey measure of safety	Likert scale, 1-5 (5 is best)	3.68 3.66, 3.69)

Table 3–2. Participant characteristics and environmental summary scores among participants without hypertension at baseline (2000-2002).

Characteristic	N	%	Healthy food environment Mean (SD)	Physical activity environment Mean (SD)	Social environment Mean (SD)
Overall	3382	100%	-0.10 (1.58)	-0.08 (1.65)	-0.04 (1.62)
Age					
<60	1886	55.8%	-0.11 (1.57)	-0.14 (1.58)	-0.09 (1.61)
60+	1496	44.2%	-0.09 (1.59)	-0.01 (1.72)	0.03 (1.63)
P-value[1]			*0.735*	*0.022*	*0.039*
Gender					
Female	1737	51.4%	-0.05 (1.60)	-0.02 (1.67)	-0.05 (1.62)
Male	1645	48.6%	-0.15 (1.55)	-0.14 (1.62)	-0.03 (1.62)
P-value[1]			*0.060*	*0.032*	*0.835*
Race/ethnicity					
White	1473	43.6%	-0.18 (1.75)	0.46 (2.02)	0.56 (1.44)
Chinese	453	13.4%	-0.09 (0.69)	-0.62 (0.89)	0.12 (1.20)
Black	695	20.6%	-0.30 (1.59)	-0.48 (1.16)	-0.55 (1.78)
Hispanic	761	22.5%	0.25 (1.54)	-0.43 (1.22)	-0.82 (1.53)
P-value[1]			*<0.001*	*<0.001*	*<0.001*
Education					
High school or less	1046	30.9%	-0.18 (1.44)	-0.63 (1.10)	-0.56 (1.56)
Some college or Associate's degree	945	27.9%	-0.25 (1.47)	-0.27 (1.43)	-0.04 (1.59)
Bachelor's degree or more	1391	41.1%	0.07 (1.73)	0.47 (1.93)	0.36 (1.57)
P-value for trend[1]			*<0.001*	*<0.001*	*<0.001*
Annual income					
<$20,000	671	19.8%	-0.21 (1.27)	-0.63 (1.06)	-0.69 (1.47)
$20-40,000	831	24.6%	-0.06 (1.56)	-0.39 (1.31)	-0.37 (1.55)
$40-65,000	946	28.0%	-0.23 (1.62)	-0.16 (1.53)	0.01 (1.61)
≥$65,000	934	27.6%	0.09 (1.73)	0.67 (2.06)	0.67 (1.51)
P-value for trend[1]			*0.003*	*<0.001*	*<0.001*
BMI categories					
<25	1183	35.0%	0.09 (1.60)	0.18 (1.88)	0.14 (1.55)
25-29.9	1315	38.9%	-0.12 (1.58)	-0.14 (1.58)	-0.07 (1.61)
30+	884	26.1%	-0.31 (1.53)	-0.34 (1.31)	-0.25 (1.69)
P-value for trend[1]			*<0.001*	*<0.001*	*<0.001*
Tract SES					
Low	1133	33.5%	-0.44 (1.48)	-0.96 (0.78)	-0.94 (1.45)
Medium	1123	33.2%	-0.51 (1.11)	-0.58 (0.66)	0.00 (1.43)
High	1126	33.3%	0.66 (1.79)	1.31 (2.03)	0.83 (1.47)
P-value for trend[1]			*<0.001*	*<0.001*	*<0.001*

Site					
Winston-Salem, NC	438	13.0%	-1.72 (0.96)	-0.94 (0.87)	1.72 (1.38)
New York, NY	538	15.9%	2.23 (1.37)	1.04 (2.20)	-1.53 (1.43)
Baltimore, MD	458	13.5%	-0.99 (0.68)	-0.80 (0.56)	-0.02 (1.80)
St Paul, MN	618	18.3%	-1.18 (0.64)	-0.55 (0.57)	-0.08 (1.13)
Chicago, IL	666	19.7%	0.71 (0.99)	1.45 (1.77)	0.17 (1.21)
Los Angeles, CA	664	19.6%	-0.10 (0.69)	-1.00 (0.66)	-0.18 (1.30)
P-value[1]			*<0.001*	*<0.001*	*<0.001*

[1] P-values correspond to ANOVA tests or linear tests of trend.

Table 3–3. Participant characteristics at baseline (2000-2002) by incident hypertension status through 2011.

Characteristic	No hypertension (N=2047)	Incident hypertension (N=1335)	p-value[1]
Mean healthy food environment summary score	-0.05	-0.17	0.037
Mean physical activity environment summary score	-0.00	-0.19	0.001
Mean social environment summary score	0.02	-0.13	0.006
Mean age	57.6	61.0	<0.001
% Male	49.0%	48.1%	0.605
Race/ethnicity			
White	46.5%	39.0%	
Chinese	14.2%	12.1%	
Black	16.9%	26.1%	
Hispanic	22.4%	22.7%	<0.001
Education			
High school or less	28.1%	35.2%	
Some college or Associate's degree	27.6%	28.5%	
Bachelor's degree or more	44.3%	36.3%	<0.001
BMI categories			
<25	39.2%	28.5%	
25-29.9	39.3%	38.3%	
30+	21.5%	33.3%	<0.001
Tract SES			
Low	30.5%	38.0%	
Medium	33.2%	33.3%	
High	36.3%	28.7%	<0.001
Site			
Winston-Salem, NC	11.9%	14.5%	
New York, NY	15.4%	16.6%	
Baltimore, MD	13.1%	14.2%	
St Paul, MN	18.4%	18.1%	
Chicago, IL	21.0%	17.7%	
Los Angeles, CA	20.1%	19.0%	0.057

[1] P-values correspond to tests for differences between hypertension outcome groups (ANOVA for continuous variables, χ2 tests for categorical variables).

Table 3–4. Age- and sex- adjusted incidence rates per 1,000 person-years (95% CI) by tertiles of environmental summary scores in the Multi-Ethnic Study of Atherosclerosis, 2000-2010 (N=3,382).

	Environmental summary scores			p-value for trend[1]
	Low	Medium	High	
Healthy food environment	69.1 (63.1, 75.7)	58.3 (52.8, 64.4)	58.3 (52.9, 64.2)	0.009
Physical activity environment	70.0 (63.9, 76.7)	63.1 (57.4, 69.4)	52.7 (47.6, 58.4)	<0.001
Social environment	72.7 (66.4, 79.5)	59.8 (54.3, 65.8)	53.7 (48.6, 59.4)	<0.001

[1] p-values for neighborhood summary scores entered as ordinal variables in Poisson model.

Table 3–5. Adjusted hazard ratios (95% CI) for hypertension incidence corresponding to one standard deviation higher cumulative average of neighborhood environmental measures.

Food environment	*Healthy food environment summary score*	*Survey measure of healthy food*	*GIS density of favorable food stores*
Model 1: age, age-time interaction, sex, education, income, and neighborhood measure	0.94 (0.89, 0.99)	0.88 (0.84, 0.93)	1.02 (0.97, 1.08)
Model 2: Model 1 + race/ethnicity	0.95 (0.89, 1.00)	0.91 (0.86, 0.96)	1.00 (0.95, 1.06)
Model 3: Model 2 + mutual adjustment for all neighborhood measures	--	0.89 (0.82, 0.96)	1.03 (0.94, 1.13)
Model 4: Model 3 + neighborhood SES	--	0.90 (0.83, 0.97)	1.03 (0.94, 1.13)

Physical activity environment	*Physical activity environment summary score*	*Survey measure of walking environment*	*GIS density of physical activity resources*
Model 1: age, age-time interaction, sex, education, income, and neighborhood measure	0.92 (0.86, 0.98)	0.91 (0.86, 0.97)	0.95 (0.89, 1.01)
Model 2: Model 1 + race/ethnicity	0.95 (0.89, 1.01)	0.94 (0.88, 1.00)	0.97 (0.91, 1.03)
Model 3: Model 2 + mutual adjustment for all neighborhood measures	--	1.03 (0.93, 1.12)	1.00 (0.89, 1.11)
Model 4: Model 3 + neighborhood SES	--	1.07 (0.96, 1.18)	1.02 (0.92, 1.14)

Social environment	*Social environment summary score*	*Survey measure of safety*	*Survey measure of social cohesion*
Model 1: age, age-time interaction, sex, education, income, and neighborhood measure	0.93 (0.88, 0.99)	0.91 (0.86, 0.97)	0.97 (0.92, 1.03)
Model 2: Model 1 + race/ethnicity	0.98 (0.93, 1.04)	0.98 (0.92, 1.04)	0.99 (0.94, 1.05)
Model 3: Model 2 + mutual adjustment for all neighborhood measures	--	0.97 (0.89, 1.05)	1.01 (0.93, 1.09)
Model 4: Model 3 + neighborhood SES	--	0.97 (0.89, 1.05)	1.01 (0.93, 1.10)

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Chapter 4

Neighborhood environments and changes in systolic blood pressure over 10 years

Introduction

Neighborhood environments have been associated with a variety of health outcomes,[1] but most research to date has used cross-sectional data and/or non-specific measures of neighborhood environments.[2] Investigating specific neighborhood features in relation to longitudinal health changes has the potential to inform our understanding of the causal pathways and best intervention targets to improve population health.

Blood pressure is an important risk factor for cardiovascular morbidity and mortality.[3,4] Intervening on neighborhood environments could provide an opportunity to shift the population distributions of blood pressure, with potential public health benefits. However, existing research on neighborhood physical and social environments and blood pressure has reported mixed results. Survey-based measures of the physical and social environments have been associated with the prevalence of hypertension in MESA,[5] while another study found that survey-based walkability was not associated with blood pressure levels among African-American women.[6] Measures of neighborhood walkability using geographic information systems (GIS) data were not associated with systolic blood pressure (SBP) levels[7] or incident hypertension over five years in Australia,[8] but a study in the U.S. found that greater walkability (as assessed by a GIS-based summary measure of land use mix, street connectivity, public transportation, and green space) was associated with smaller one-year increases in blood pressure compared with lower walkability.[9] Density of fast food outlets and density of grocery stores were not associated with SBP levels among a cohort of older, predominantly well-educated white women.[10] Little research has focused on the role of the social environment in shaping blood pressure; research on social cohesion and stroke (high blood pressure is the most important risk factor for stroke) has found that more neighborhood social cohesion is associated with lower stroke mortality among whites[11] though results related to stroke incidence are mixed.[11,12]

A methodological complication in understanding neighborhood effects on blood pressure is the role of antihypertensive medication use. Medication use is associated with neighborhood characteristics and affects blood pressure, and thus can be considered a confounder. However, because blood pressure levels often determine medication use, it is also a collider.[13] Adjusting for medication use in regression models may induce collider bias, but ignoring medication use may result in confounded associations. One validated strategy to account for medication use without adjustment is to use multiple imputation techniques to impute underlying blood pressures.[14,15] No research to date has used multiple imputation to evaluate the impact of neighborhood environments on blood pressure trajectories.

We investigated how neighborhood physical and social environments affect baseline levels and trajectories of SBP in a multi-ethnic cohort in six sites in the U.S. over 10 years of follow-up, using multiply imputed blood pressure for those on antihypertensive medication. SBP was selected as the key blood pressure outcome because it is a stronger predictor of cardiovascular morbidity and mortality than other aspects of blood pressure in older populations.[16] Risk of cardiovascular morbidity and mortality increases linearly with SBP, even below established thresholds used to define hypertension.[17,18] Thus, understanding the causes of elevated SBP is an important public health question.

Methods

Multi-Ethnic Study of Atherosclerosis (MESA)

MESA participants were recruited in 2000-2002 in six field centers (Los Angeles, CA; St. Paul, MN; Chicago, IL; Winston-Salem, NC; Baltimore, MD; and New York, NY). Participants were aged 45-84 at baseline and free of clinical cardiovascular disease (e.g. no history of heart attack, stroke, heart failure, or atrial fibrillation). Participants were followed through four follow-up exams in 2004-2005, 2005-2007, and 2010-2011. The study was approved by the institutional review board at each participating site, and participants provided informed consent.

Blood pressure measurement and imputation

Blood pressure was measured at each of the five exams, following a standardized protocol. After five minutes of seated rest, blood pressure was measured three times, at two-minute intervals, using an automated oscillometric sphygmomanometer.[19] The average of the second and third measurements was considered the observed blood pressure.

For people taking anti-hypertensive medications, observed blood pressure measurements were replaced with imputed blood pressure. The imputation model included observed systolic and diastolic blood pressures, age, gender, race/ethnicity, body mass index, diabetes status, high density lipoproteins and total cholesterol, smoking status (never, former, or current), each class of antihypertensive medication (beta blockers, calcium channel blockers, diuretics, ACE inhibitors/angiotensin II receptor blockers, and vasodilators), all two-way interactions between medication classes, and all two-way interactions between gender and race/ethnicity with each medication class.[20] Ten imputations were created following the algorithm of Van Buuren et al[21] as implemented and described by Royston.[22,23] Models were run separately for each of the 10 imputations, and results were pooled using rules proposed by Rubin.[24]

Neighborhood environments

Information on neighborhood environments came from three data sources: surveys of MESA participants, cross-sectional surveys of individuals living in MESA sites (Community Surveys), and GIS-based densities of resources. Community Survey participants were over age 18, were not MESA participants, and were recruited through random digit dialing and list-based sampling. The first Community Survey, in 2004, included 5,988 participants in the Maryland, New York, and North Carolina sites; the 2011 Community Survey included 4,122 respondents in a subsample of tracts in all six sites.

Four survey scales (measuring neighborhood healthy food availability, walking environment, social cohesion, and safety) were chosen because of their potential relevance to blood pressure[5,25-28] and because they were assessed consistently at multiple time points from MESA participants and Community Survey participants. The healthy food availability scale included two questions on the availability of fresh fruit and vegetables and low-fat foods. The walking environment scale included four questions on the pleasantness and ease of walking in the neighborhood, and frequency of seeing others walking or exercising in the neighborhood. The social cohesion scale included four questions about trust, shared values, willingness to help neighbors, and the extent to which neighbors generally get along. The safety scale included two questions about feeling safe walking in the neighborhood and extent to which violence was a problem in the neighborhood. **Error! Reference source not found.** includes details on the survey scales used. Participants were directed to answer the questions about the area around their house or the area within a 20-minute walk. Scales were based on previous work and have acceptable internal consistency, reliability, and ecometric properties.[29]

The survey scales were summarized as the average of all responses from participants who lived within one mile of each MESA participant's home address (one-mile crude means), calculated for two time periods: 2000-2005 and 2006-2011; the values were assigned to each month in the time period. Each time period includes MESA and Community Survey participant responses to all four scales.

GIS-based densities of physical activity resources and favorable food destinations were derived from commercially available business listings through the National Establishment Time-Series database from Walls & Associates (Oakland, CA). Standard Industrial Classification codes (U.S. Occupational Safety and Health Administration, Washington DC) related to indoor conditioning, dance, bowling, golf, biking, hiking, team and racquet sports, swimming, physical activity instruction, and water activities were defined as physical activity resources; favorable food stores included chain and non-chain supermarkets and fruit and vegetable markets. [30] [31] Data were obtained for each year from 2000-2011. The simple density of favorable food stores and physical activity resources per square mile were calculated for a one-mile buffer around each participant’s home address using ArcGIS software (ESRI, Redmonds, CA). Values were assigned to each month in the year.

Three neighborhood environmental summary measures (for the food environment, physical activity environment, and social environment) were created by combining component measures related to the same domain (see **Error! Reference source not found.**). Component measures were standardized and then summed to calculate environmental summary scores. Chronbach’s alpha for the summary measures were: 0.44 for the food environment, 0.75 for the physical activity environment, and 0.75 for the social environment.

Residential histories were available at the monthly level, so neighborhood measures reflected the month of relocation for participants that moved during follow-up. To better capture the long-term accumulation of neighborhood exposures, all neighborhood measures (the four survey measures, two GIS-based measures, and the three environmental summary measures) were operationalized as the time-varying average of the monthly values of each measure from baseline through time t (referred to as the cumulative average). For example, at baseline the cumulative average reflects the baseline values; at exam 5, the cumulative average reflects the average value of the neighborhood measure from baseline through the month of the exam. Using the cumulative average of neighborhood measures allows investigation of chronic neighborhood exposures on changes in SBP.

Other covariates

Individual level covariates used include baseline age, sex, race (white, Black, Hispanic, or Chinese), education (collected as a categorical variable with nine categories), and gross family income (collected at each exam as a categorical variable with 13 categories). Use of antihypertensive medication was also assessed at each exam.

Neighborhood SES was considered as a confounder of the relationship between specific neighborhood features and SBP, as neighborhood SES may be associated with the specific features of interest and may affect blood pressure through pathways other than neighborhood food, physical activity, and social environments (e.g. air or noise pollution).[32-35] Neighborhood SES was measured with the first factor from a principal components analysis of 16 Census variables related to tract education, income, wealth, and occupation; this factor explained 47.9% of the total variance. A higher score represents increasing socioeconomic advantage. Data came from 2000 Census[36] (linked to 2000-2004) and the American Community Survey in 2005-2009[37] (linked to 2005-2007) and 2007-2011[38] (linked to 2008-2011).

Potential mediators included body mass index (BMI), diet, and physical activity. Height and weight were measured at each MESA exam; BMI was modeled continuously. Diet was assessed with a food frequency questionnaire at baseline and summarized according to the Health Eating Index (2005 guidelines); due to limited information, diet was assumed to be time invariant.[39] Physical activity was measured as the total metabolic-equivalent minutes per week of moderate and vigorous exercise, collected at four of the five study exams, and classified into quartiles for analysis.

Statistical methods

Differences in mean neighborhood environmental summary scores by participant characteristics were evaluated with ANOVA. Education and family income (as gross income) were categorized for descriptive analysis; neighborhood SES was categorized into tertiles. We then examined associations of participant and neighborhood characteristics with SBP at baseline and with five-year changes in SBP. Neighborhood food, physical activity, and social environments were categorized into tertiles for these analyses.

Each neighborhood measure was then evaluated in a linear mixed model that included individual-level covariates and neighborhood SES, to explore the associations of each measure with changes in SBP after adjustment for neighborhood SES and individual-level confounders. The neighborhood environmental summary measures were each modeled separately and then adjusted for each other in order to evaluate potential confounding by other neighborhood measures. Correlations between the neighborhood summary measures were moderate, with the food and physical activity summary measures most highly correlated with Pearson's r=0.68. All neighborhood measures were investigated as continuous variables and standardized in all analyses, for comparability across measures with different scales.

All linear mixed models included random intercepts and random slopes for time with an unstructured covariance matrix, to account for repeated measurements of individuals and to capture variability in individual SBP trajectories. There was little clustering in SBP among individuals in the same census tract (neighborhood ICC from three-level model = 0.04). Baseline age and time were both modeled linearly because bivariate associations with SBP trajectories appeared linear in qualitative exploration and inclusion of non-linear effects did not change inferences on the neighborhood parameters of interest. Other individual-level covariates were modelled continuously, including time-invariant years of education and time-varying per capita family income and neighborhood SES. Interactions between individual covariates (time-invariant baseline age, gender, race, and time-varying income and antihypertensive medication use) and time were included to ensure that systematic variability in SBP trajectories was captured.[40-43] No main effect for antihypertensive medication use was included in the models because the objective of imputing blood pressures was to remove the influence of medication use at one point in time; however, the imputed data do not account for potential differences in trajectories of SBP among those on medication and those not on medication, so the interaction between medication use and time was included in all models.

We also ran models adjusting for baseline SBP (and baseline SBP by time interaction) in order to control for the influence of baseline SBP on trajectories of SBP.[44,45] Adjusting for baseline values in analyses of change is important when baseline levels affect change, but can also introduce bias when baseline values are measured with error. Since observed baseline SBP values are influenced by both true baseline SBP and measurement error (see Figure 4-2), and measurement error at baseline is also related to changes in observed SBP (since observed change reflects observed baseline values, including measurement error), adjusting for observed baseline SBP can induce collider bias and create confounded associations between neighborhood environments and change in SBP.[46]

Potential mediators were added to separately to models adjusted for the three neighborhood summary measures concurrently to assess whether the associations between neighborhood measures and SBP were affected. Sensitivity analyses explored using 0.5- and 2-mile buffers (instead of one mile) for the GIS density measures, using conditional empirical Bayes estimates summarizing survey-based neighborhood environment measures to the tract level, and adjusting for site. We also compared alternative strategies for accounting for medication use, including covariate adjustment, exclusion of those on antihypertensive medications, and a nonparametric method in which treated values are replaced with the average of all treated values larger than the index value. This nonparametric method has been used in previous genetic studies of hypertension, and assumes that treated blood pressures are lower than counterfactual untreated blood pressures and that treatment is more effective in those with lower treated values than in those with higher treated values.[47]

Results

Of the 6,191 participants in the MESA Neighborhood study, 194 participants with missing information on key individual (128 participants) and neighborhood-level (66 participants) covariates were excluded, leaving an analytic sample size of 5,997. Median follow up was 9.2 years (IQR 4.5). Across the 11-year study period, 91.3% of participants completed at least three exams and 69.7% of participants completed all five exams. A total of 27,323 observations were used in these analyses.

Table 4–2 shows that neighborhood environment summary scores were not strongly patterned by baseline age. Male participants lived in neighborhoods with less favorable food environments but more favorable social environments than female participants. White participants lived in more favorable social environments and physical activity environments than participants in other racial/ethnic groups but had the lowest average food environment summary score of any race-ethnic group. Neighborhood environments were strongly patterned by education, income, and neighborhood SES, such that participants with more education, higher income, and those living in higher SES neighborhoods had more favorable average food environments, physical activity environments, and social environments. Participants with higher observed SBPs and higher BMI at baseline lived in neighborhoods with less favorable average food and physical activity environments than those with lower SBPs and BMIs at baseline.

For the 12,082 observations of SBP influenced by anti-hypertensive medication use, Figure 4-1 compares observed SBPs to imputed SBPs. Panel A shows all 10 imputations for each observation, while Panel B shows the mean imputed value in order to more easily visualize the results of the imputation. For those with lower observed values of SBP, the imputed values tend to be higher than the observed values; for those with high observed values (e.g. 180-200 mmHg), the imputed values tend to be slightly lower than the observed values.

Baseline SBPs and mean five-year change in SBPs varied by individual characteristics (Table 4–3). Younger, more educated, and higher income individuals had lower SBPs at baseline than older, less educated, and lower income individuals; five-year change in SBP was not patterned by age, education, or income. SBPs at baseline were similar between males and females, but females had larger five-year increases in SBP. Black participants had substantially higher SBPs at baseline than non-Black participants, but mean five-year changes in SBP were not significantly different by race/ethnicity. As expected, SBPs were higher among those taking antihypertensive medications at baseline than those not taking antihypertensive medications; participants not on medication had larger mean five-year increases in SBP. Participants in higher SES neighborhoods and neighborhoods with higher food, physical activity, and social environment summary scores had lower blood pressures at baseline than those in less advantaged neighborhoods and neighborhoods with lower food, physical activity, and social environment summary scores. Participants in neighborhoods with higher food environment summary scores had larger mean five-year increases in SBP than participants in neighborhoods with less favorable food environments; five-year changes in SBP were not patterned by neighborhood SES, physical activity environments, or social environments.

After adjusting for individual-level characteristics and neighborhood SES, better food and physical activity environments were associated with lower SBPs at baseline but larger increases in SBP over time (Table 4–4). For example, each standard deviation higher score on the survey scale of healthy food availability was associated with -1.29 (95% CI: -1.85, -0.74) mmHg lower SBP at baseline and 0.65 (0.0, 1.10) mmHg larger increase in SBP over 5 years. Better neighborhood social environments were associated with higher SBP at baseline, but with smaller increases in SBP over time; e.g. each standard deviation higher score for social cohesion was associated with 1.15 [0.56, 1.73] mmHg higher SBP at baseline and -0.43 [-0.96, 0.10] mmHg smaller increase in SBP over 5 years.

When the neighborhood measures were combined into environmental summary scores and run in separate models (Table 4–5), more favorable food and physical activity environments were associated with lower baseline levels of SBP (-1.34 [-1.90, -0.77] mmHg and -1.57 [-2.25, -0.88] mmHg per standard deviation higher cumulative average neighborhood food and physical activity environment summary score, respectively). More favorable food and physical activity environments were also associated with larger five-year increases in SBP, so that each standard deviation higher cumulative average neighborhood environment summary score was associated with approximately 0.5 mmHg larger increase in SBP over five years (0.57 [0.12, 1.02] and 0.69 [0.26, 1.12] mmHg, respectively). More favorable social environments were associated with higher SBP at baseline (1.12 [0.56, 1.68] mmHg per standard deviation higher cumulative average) but with smaller five-year increases in SBP (though this difference was not statistically significant).

In models that were mutually adjusted for all three neighborhood environment summary scores, the food environment was no longer significantly associated with baseline levels of SBP. The physical activity environment remained an important predictor of baseline SBP levels but the association attenuated slightly (-1.34 [-2.24, -0.45] mmHg lower per standard deviation higher physical activity environment summary score). The social environment also remained an important predictor of baseline SBP levels, such that each standard deviation higher social environment summary score was associated with 1.00 (0.39, 1.63) mmHg higher SBP at baseline. None of the neighborhood environment summary scores were associated with five-year changes in SBP after adjustment for each other.

Additionally adjusting for baseline SBP and the interaction of baseline SBP and time (Table 4–6) attenuated observed associations between neighborhood environments and SBP trajectories, such that none of the neighborhood environment measures were significantly associated with trajectories of SBP in models including neighborhood environments separately or together.

Addition of potential mediators (BMI, diet, and physical activity) did not affect associations between neighborhood environmental summary measures and blood pressure. Sensitivity analyses using 0.5- and 2-mile buffer zones for GIS measures, conditional empirical Bayes estimates for survey measures, and adjusting for site found results similar to the primary analyses. In mixed models adjusting for all three neighborhood environmental summary scores, adjustment for medication use as a time-varying covariate produced similar associations between neighborhood environments and blood pressure as ignoring medication use (based on observed blood pressures rather than imputed blood pressures). The non-parametric adjustment method resulted in stronger associations for the physical activity environment but weaker associations for the social environment compared to both covariate adjustment and imputation. The non-parametric method also found stronger associations between neighborhood food and physical activity environments and five-year changes in SBP than any of the other methods. Using imputed SBPs produced larger standard errors than the other methods, since it reflects the variability in estimating underlying blood pressures. Overall, results were largely consistent across the methods for addressing medication use.

Discussion

We found some evidence that neighborhood food, physical activity, and social environments are associated with SBP levels over a median of 9.2 years of follow up in a large, multi-ethnic, multi-site sample, although associations were not always in the hypothesized direction. In models adjusting for individual characteristics and neighborhood SES, participants living in neighborhoods with better food and physical activity environments had lower SBP at baseline but larger increases in SBP over time, while participants living in neighborhoods with better social environments had higher SBP at baseline but smaller increases in SBP over time. Accounting for all neighborhood environmental summary scores, the physical activity environment and the social environment remained significant predictors of baseline SBP levels, such that more favorable physical activity environments were associated with lower SBP levels and better social environments were associated with higher SBP levels. None of the neighborhood environmental summary scores were associated with changes in SBP after concurrent adjustment for all three summary scores. After adjustment for baseline SBP, associations between neighborhood environments and SBP trajectories were insignificant when each neighborhood summary score was evaluated in separate models and when all three summary scores were evaluated concurrently.

Our findings concur with previous cross-sectional research that better food and physical activity environments are associated with lower prevalence of hypertension in MESA (though our results were robust to adjustment for race/ethnicity, likely due to larger sample size and use of longitudinal data).[5] Additionally, unpublished work in MESA has found that better survey-based healthy food availability and (to a lesser extent) walking environment scores were associated with lower incidence of hypertension. We found that better food and physical activity environments were associated with lower SBP levels at baseline; the association with the physical activity environment persisted in models including all three summary scores, though the association with the food environment attenuated substantially.

In other studies, cross-sectional studies of SBP in relation to neighborhood food and physical activity environments have generally found null associations, using survey-based measures of neighborhood walkability in a sample of African-American women,[6] GIS-based densities of fast food and supermarkets in predominantly white women,[10] and GIS-based densities of walkability in western Australia.[7] The few studies of neighborhood food and physical activity environments in relation to incident blood pressure outcomes have found mixed results; in southern Australia, GIS-based food environments and walkability were not associated with incident hypertension,[8] but a study of middle aged and older adults in Portland, Oregon found that residents of highly walkable neighborhoods (defined by GIS) had average decreases in SBP after one year of follow up, while residents of low-walkability neighborhoods had increases in SBP.[9] Differences in study populations and in the measures used to quantify neighborhood environments limit the comparability of these results, and more research is needed to understand which aspects of neighborhood food and physical activity environments are most relevant for SBP.

The finding that better social environments were associated with higher baseline SBPs was contrary to expectation, though no previous research has examined neighborhood social environments in relation to blood pressure. In contrast to our findings, studies on stroke have reported that more neighborhood social cohesion was associated with lower stroke incidence over four years of follow up among Americans over age 50[12] and that more social cohesion was not associated with stroke incidence but was associated with lower stroke mortality over 11 years of follow up among adults over 65 in Chicago.[11] In support of our findings, previous cross-sectional research in MESA has found that better social environments were associated with higher BMIs among men.[25] Post-hoc analysis of our results also found that the association between the social environment and SBP was stronger in men, but otherwise consistent among different subgroups. Additional research is needed to attempt to replicate these findings in other datasets and better evaluate non-causal explanations, as better neighborhood social environments have generally been found to be associated with better health outcomes.[48,49]

The mechanisms proposed to explain beneficial effects of better social environments associations generally posit that positive relationships between neighbors allow information about health behaviors and norms to spread. However, it is possible that these relationships can support health-harming norms (e.g. smoking, alcohol use, diet quality) as well as health-supporting norms, which may be a potential explanation for our findings.[49]

The mixed findings from models unadjusted for baseline SBP that neighborhood food and physical activity environments were associated with lower SBPs at baseline but larger increases in SBP over time, while neighborhood social environments were associated with higher SBPs at baseline but smaller increases in SBP over time, may reflect two distinct phenomena: the influence of baseline blood pressures on trajectories of blood pressure and regression to the mean. The association between baseline SBP and change in SBP is supported by the observation that most characteristics associated with higher baseline SBPs were also associated with smaller five-year increases in SBP (e.g. age, BMI; Table 4–3). The influence of baseline blood pressures on trajectories of blood pressure is also biologically plausible, as low SBPs at baseline are closer to the physiological 'floor' for blood pressure and have higher to rise in comparison to higher blood pressures. The observed pattern between neighborhood environments and changes in SBP was also adjusted for interactions between individual-level covariates (baseline age, gender, race, income, and medication use) and time that may have affected baseline levels and changes over time in SBP. If the link between baseline SBP and change in SBP is causal, as depicted in Figure 4-2, then we would need to control for baseline SBP in order to identify the direct effect of neighborhood environments on change in SBP.

However, adjusting for baseline SBP can induce bias in estimating the association between neighborhood environments and change in SBP, because of regression to the mean. Regression to the mean is a statistical phenomenon found when repeated observations are measured with error, in which extreme observations at baseline tend to be less extreme at follow-up. In our example, observed baseline SBP reflects both true baseline SBP and measurement error at baseline (as illustrated in Figure 4-2), making observed baseline SBP is a collider. Baseline measurement error also affects the change in measured SBP, as change in measured SBP is the difference between observed baseline SBP (reflecting true baseline SBP and baseline measurement error) and observed follow-up SBP (reflecting true follow-up SBP and follow-up measurement error). Thus, adjusting for observed baseline SBP (as our best proxy of true baseline SBP), in order to isolate the direct effect of neighborhood environments on change in SBP, will induce an association between true baseline SBP and measurement error and produce a confounded estimate of the association between neighborhood environments and change in observed SBP.[46]

With these issues in mind, we ran models unadjusted for baseline SBP and adjusted for baseline SBP. In unadjusted models, we found statistically significant associations between neighborhood environments and changes in SBP, while in adjusted models (accounting for the association between baseline SBP and changes in SBP), we found no statistically significant associations between neighborhood environments and changes in SBP. Therefore, we concluded that most of the differences in SBP trajectories in the models not adjusted for baseline SBP were explained by the influence of baseline SBP itself on the trajectories; based on our findings, there is little evidence to conclude that neighborhood environments have a meaningful impact on trajectories of blood pressure.

Future research should employ alternative methods to better understand the influence of neighborhood environments on trajectories of SBP. Statistical methods to correct for baseline measurement error, such as regression calibration based on the reliability of blood pressure measurement, would reduce the bias from adjusting for baseline SBP; alternative modeling strategies, such as modeling the difference in SBP from baseline, would negate the need to adjust for baseline SBP altogether.[46,50,51]

The use of imputed data to avoid adjusting for antihypertensive medication use is a novel technique in research on neighborhood environments and blood pressure. We compared the results obtained with imputed blood pressures to four other methods: ignoring medication use, restricting analysis to participants that never took antihypertensive medication, adjusting for medication use as a covariate, and a nonparametric approach where observed SBP values influenced by treatment were replaced by the average of all higher treated values. Results were broadly consistent across the methods, though results using imputed data had the widest confidence intervals (reflecting the built-in variability in estimating blood pressure). The nonparametric method also produced stronger associations between neighborhood food and physical activity environments and five-year change in SBP; this finding may reflect the influence of people who were put on medication during follow-up, so their treated values were replaced with larger values (the average of all treated values above their observed value), creating a larger five-year change. Restricting analyses to participants who never take antihypertensive medication produced weaker associations between neighborhood environments and baseline SBP as well as neighborhood environments and trajectories of SBP; though the sample size was substantially reduced, it is possible that neighborhood environments are less important for blood pressure in this healthy subset of the analytic sample. In situations where the exposure of interest is more strongly associated with medication use than in the current example (neighborhood-level characteristics are not strong determinants of antihypertensive medication use), the bias introduced by adjusting for medication is likely to be larger. In post-hoc analysis, we considered the association between neighborhood characteristics and medication use in our population; after accounting for individual-level covariates, higher neighborhood SES was associated with lower use of antihypertensive medication while associations between specific neighborhood environments and antihypertensive medication use were weaker. However, using the imputed data is still conceptually more appropriate than naïve methods, since it prevents potential bias from conditioning on a collider.

Some important limitations may affect the results of this study. With any longitudinal study, loss to follow up is an important consideration. Participants who were lost to follow up lived in less favorable neighborhood environments and had higher blood pressures than participants who remained in the study; thus it is likely that any bias from loss to follow up is towards the null (if more favorable neighborhood environments lower SBP). Measurement error is a concern with measuring blood pressure,[52] despite the detailed study protocol used, but it is likely to be non-differential with respect to participants' neighborhood environments. The imputation methods used to estimate blood pressure among those on anti-hypertensive medication may also have affected our results, because high observed SBP values produced lower imputed values. If these imputed values are under-estimates of true blood pressure not influenced by medication use, then our findings may be conservative estimates of the true association between neighborhood environments and blood pressure over time. Also, neighborhood summary measures were moderately correlated (particularly the food and physical activity summary measures), hampering our ability to identify their independent effects. Using one-mile crude means to summarize neighborhood environments reduced the number of time points available, so most of the within-individual variability in neighborhood environments came from participants who moved during follow up. This work may not be generalizable to other populations of older adults, particularly if the association between neighborhood environments and SBP is different among older adults with clinical cardiovascular disease who were excluded from MESA.

This work extends previous research by using longitudinal data including both survey- and GIS-based measures of neighborhood food, physical activity, and social environments in relation to changes in SBP. We found that more favorable neighborhood food and physical activity environments were associated with lower baseline SBP levels, while better social environments were associated with higher SBP levels at baseline. We also found some evidence that more favorable neighborhood food and physical activity environments were associated with larger increases in SBP over time and more favorable social environments were associated with smaller increases in SBP, though these results were likely influenced by the issue of regression to the mean. Still, our cross-sectional findings support previous work showing that neighborhood environments are associated with blood pressure and contribute new evidence that neighborhood physical environments may be a useful intervention target for shifting population distributions of blood pressure.

Table 4–1. Neighborhood environmental summary measures and component measures used.

Measure	Description	Original scale
Food environment summary	Summary measure created by standardizing and summing the 2 measures listed below	
Healthy food availability	Survey scale including the following questions: 1. A large selection of fresh fruits and vegetables is available in my neighborhood 2. A large selection of low fat foods is available in my neighborhood	Likert scale, 1-5 (strongly disagree to strongly agree)
Density of favorable food stores	Number of favorable food stores within a one-mile buffer	Stores per square mile
Physical activity environment summary	Summary measure created by standardizing and summing the 2 measures listed below	
Walking environment	Survey scale including the following questions: 1. It is pleasant to walk in my neighborhood 2. In my neighborhood it is easy to walk to places 3. I often see other people walking in my neighborhood 4. I often see other people exercise in my neighborhood	Likert scale, 1-5 (strongly disagree to strongly agree)
Density of physical activity resources	Number of physical activity resources within a one-mile buffer	Resources per square mile
Social environment summary	Summary measure created by standardizing and summing the 2 measures listed below	
Social cohesion	Survey scale including the following questions: 1. People around here are willing to help their neighbors 2. People in my neighborhood generally get along with each other 3. People in my neighborhood can be trusted 4. People in my neighborhood share the same values	Likert scale, 1-5 (strongly disagree to strongly agree)
Safety	Survey scale including the following questions: 1. I feel safe walking in my neighborhood day or night 2. Violence is a problem in my neighborhood	Likert scale, 1-5 (strongly disagree to strongly agree)

Table 4–2. Neighborhood environmental summary scores by participant characteristics at baseline (2000-2002).

Characteristic	N	%	Mean (SD) food envt score	P value[1]	Mean (SD) phys act envt. score	P value[1]	Mean (SD) social envt score	P value[1]
Age categories								
45-54	1768	29.5%	-0.05 (0.97)		-0.09 (0.89)		-0.07 (0.99)	
55-64	1683	28.1%	-0.04 (1.02)		-0.05 (0.98)		0.00 (1.01)	
65-74	1760	29.4%	-0.05 (1.04)		-0.07 (0.95)		-0.02 (0.97)	
74+	786	13.1%	0.02 (0.99)	0.37	0.01 (1.03)	0.09	-0.06 (0.95)	0.14
Gender								
Female	3151	52.5%	0.00 (1.02)		-0.04 (0.96)		-0.07 (0.98)	
Male	2846	47.5%	-0.08 (0.99)	0.01	-0.08 (0.95)	0.12	0.00 (1.00)	0.01
Race								
White	2347	39.1%	-0.10 (1.08)		0.25 (1.18)		0.38 (0.88)	
Black	1639	11.9%	-0.21 (1.05)		-0.29 (0.69)		-0.34 (1.04)	
Hispanic	1299	27.3%	0.26 (0.98)		-0.19 (0.80)		-0.47 (0.92)	
Chinese	712	21.7%	0.03 (0.42)	<0.001	-0.34 (0.51)	<0.001	0.08 (0.70)	<0.001
Education								
Less than H.S.	2099	35.0%	-0.05 (0.94)		-0.33 (0.69)		-0.34 (0.94)	
Some college	1696	28.3%	-0.12 (0.94)		-0.13 (0.84)		0.00 (0.98)	
B.A. or more	2202	36.7%	0.04 (1.10)	<0.001	0.25 (1.15)	<0.001	0.23 (0.96)	<0.001
Annual gross family income								
Less than $20,000	1373	22.9%	-0.04 (0.87)		-0.32 (0.68)		-0.42 (0.87)	
$20,000-$40,000	1598	26.7%	0.00 (1.00)		-0.20 (0.79)		-0.22 (0.95)	
$40,000-$65,000	1637	27.3%	-0.17 (1.01)		-0.12 (0.87)		0.07 (0.98)	
More than $65,000	1389	23.2%	0.08 (1.11)	<0.001	0.42 (1.24)	<0.001	0.44 (0.94)	<0.001
BMI								
<25	1725	28.8%	0.1 (0.99)		0.09 (1.10)		0.07 (0.95)	
25-29.9	2348	39.2%	-0.04 (1.01)		-0.07 (0.95)		-0.02 (0.99)	
30+	1924	32.1%	-0.15 (1.00)	<0.001	-0.18 (0.80)	<0.001	-0.14 (1.02)	<0.001
Antihypertensive medication use								
Yes	2182	36.4%	-0.06 (1.03)		-0.11 (0.92)		-0.06 (1.00)	
No	3815	63.6%	-0.02 (0.99)	0.13	-0.03 (0.97)	<0.01	-0.02 (0.98)	0.10
Neighborhood SES								
Low	2009	33.5%	-0.21 (0.97)		-0.55 (0.49)		-0.58 (0.86)	
Medium	1986	33.1%	-0.29 (0.77)		-0.33 (0.42)		0.01 (0.88)	
High	2002	33.4%	0.39 (1.11)	<0.001	0.69 (1.20)	<0.001	0.47 (0.92)	<0.001
Observed SBP								
<120 mm Hg	2649	44.2%	0.06 (1.02)		0.05 (1.04)		-0.04 (0.95)	
120-139 mm Hg	1897	31.6%	-0.10 (1.00)		-0.11 (0.88)		0.00 (1.01)	
≥140 mm Hg	1451	24.2%	-0.13 (0.96)	<0.001	-0.20 (0.86)	<0.001	-0.06 (1.02)	0.23

[1] P values reflect ANOVA tests

Figure 4-1. Observed and imputed systolic blood pressures; for observations not influenced by antihypertensive medication, imputed blood pressure is equal to observed blood pressure.

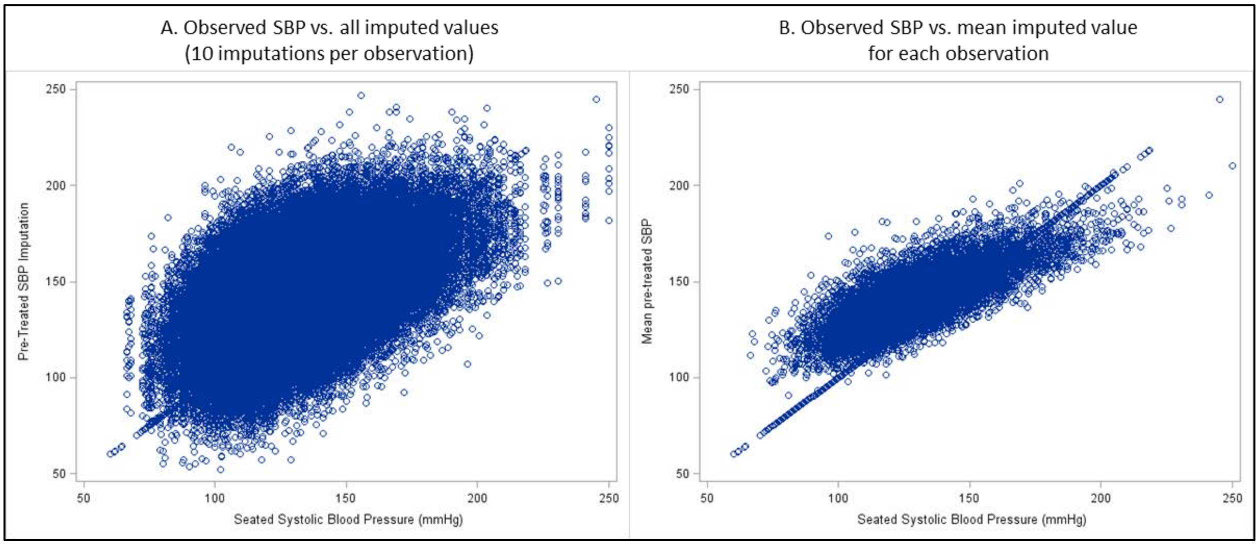


Table 4–3. Mean systolic blood pressures[1] at baseline and mean five-year changes by participant characteristics (N=5,997).

	Mean (SE) SBP at baseline	P value[2]	Mean (SE) five-year change in SBP	P value[2]
Overall	127.93 (0.30)	-	2.22 (0.23)	-
Age categories				
45-54	117.29 (0.47)		2.56 (0.38)	
55-64	126.31 (0.55)		2.86 (0.43)	
65-74	134.49 (0.50)		1.97 (0.47)	
74+	140.05 (0.79)	<0.001	1.86 (0.89)	0.47
Gender				
Female	128.09 (0.44)		2.77 (0.29)	
Male	127.77 (0.43)	0.61	1.65 (0.38)	0.03
Race				
White	124.89 (0.44)		2.21 (0.34)	
Black	134.20 (0.65)		1.68 (0.50)	
Hispanic	127.49 (0.65)		2.56 (0.55)	
Chinese	124.29 (0.87)	<0.001	3.29 (0.69)	0.28
Education				
Less than H.S.	132.00 (0.55)		2.27 (0.45)	
Some college	127.67 (0.52)		2.38 (0.41)	
B.A. or more	124.25 (0.46)	<0.001	2.22 (0.31)	0.96
Gross family income				
Less than $20,000	130.96 (0.62)		2.10 (0.63)	
$20,000-$40,000	129.38 (0.55)		2.40 (0.45)	
$40,000-$65,000	126.96 (0.50)		2.07 (0.45)	
More than $65,000	124.29 (0.51)	<0.001	2.52 (0.43)	0.89
BMI				
<25	123.23 (0.49)		3.15 (0.44)	
25-29.9	128.00 (0.45)		1.95 (0.35)	
30+	132.10 (0.54)	<0.001	1.75 (0.48)	0.07
Antihypertensive medication use				
Yes	136.64 (0.45)		0.13 (0.40)	
No	122.90 (0.31)	<0.001	1.41 (0.26)	0.01
Neighborhood SES				
Low	130.18 (0.53)		2.26 (0.43)	
Medium	127.65 (0.49)		2.49 (0.36)	
High	125.97 (0.49)	<0.001	2.04 (0.32)	0.66
Food environment				
Low	128.96 (0.46)		1.26 (0.45)	
Medium	128.35 (0.48)		2.42 (0.38)	
High	126.50 (0.57)	0.003	2.93 (0.44)	0.03
Physical activity environment				
Low	129.76 (0.45)		1.79 (0.41)	
Medium	127.12 (0.49)		2.60 (0.37)	
High	126.62 (0.50)	<0.001	2.66 (0.39)	0.21
Social environment				
Low	128.94 (0.50)		2.46 (0.42)	
Medium	127.56 (0.46)		2.22 (0.43)	

High	127.23 (0.49)	0.03	2.16 (0.33)	0.85

[1] Imputed values used for observations influenced by antihypertensive medication use
[2] P values reflect Wald tests for multivariate inference from linear mixed models

Table 4–4. Mean differences systolic blood pressure at baseline and mean differences in 5 year change (in mmHg) associated with one standard deviation higher cumulative average for each neighborhood environment measure, in separate models adjusted for individual-level characteristics and neighborhood SES.[1]

	Difference (95% CI) in SBP at baseline	Difference (95% CI) in five-year change in SBP
Healthy food availability	**-1.29 (-1.85, -0.74)**	**0.65 (0.20, 1.10)**
Density of favorable food stores	**-0.88 (-1.43, -0.32)**	0.35 (-0.10, 0.81)
Walking environment	**-1.18 (-1.85, -0.51)**	**0.60 (0.13, 1.06)**
Density of physical activity resources	**-1.28 (-1.91, -0.66)**	**0.62 (0.25, 1.00)**
Social cohesion	**1.15 (0.56, 1.73)**	-0.43 (-0.96, 0.10)
Safety	**0.83 (0.28, 1.38)**	-0.17 (-0.59, 0.25)

[1] Adjusted for baseline age, gender, race, education, time-varying adjusted household income, time-varying neighborhood SES, interactions by time (baseline age, gender, race, income, and antihypertensive medication use), and neighborhood environment measure.

Table 4–5. Mean differences systolic blood pressure at baseline and mean differences in 5 year change (in mmHg) associated with one standard deviation higher cumulative average neighborhood environmental summary score.

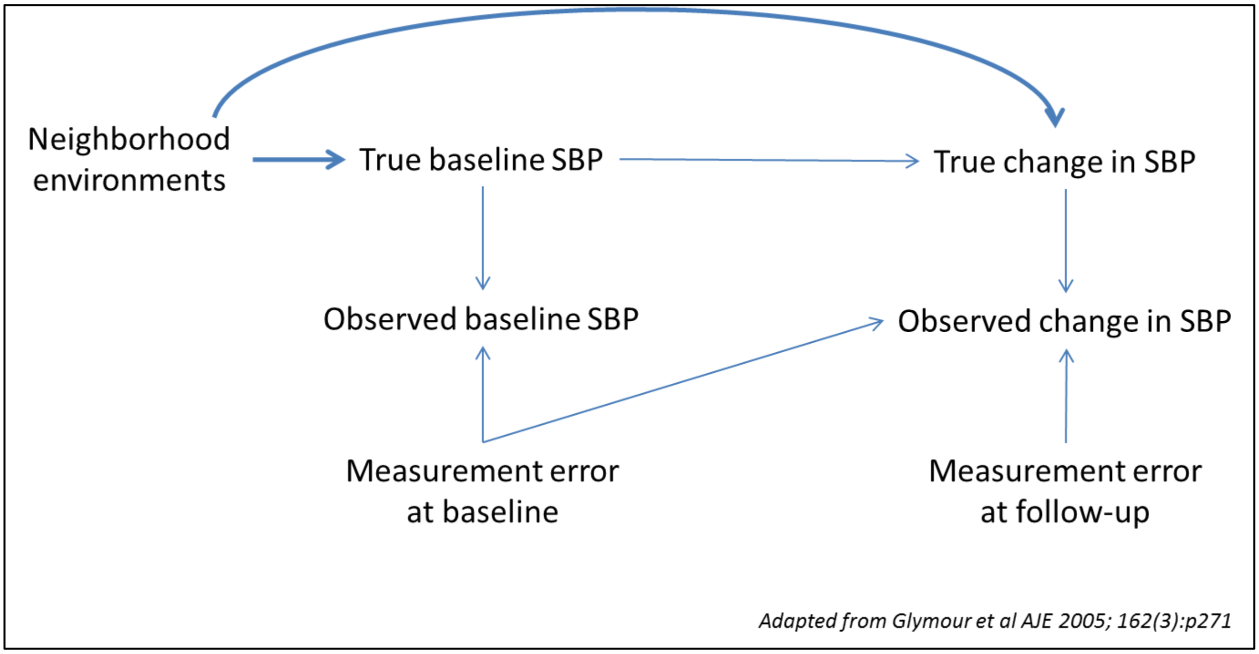
	Difference (95% CI) in SBP at baseline	Difference (95% CI) in five-year change in SBP
In separate models: [1]		
Food environment	**-1.34 (-1.90, -0.77)**	**0.57 (0.12, 1.02)**
Physical activity environment	**-1.57 (-2.25, -0.88)**	**0.69 (0.26, 1.12)**
Social environment	**1.12 (0.56, 1.68)**	-0.34 (-0.81, 0.13)
Concurrent adjustment: [2]		
Food environment	-0.19 (-0.96, 0.58)	0.11 (-0.58, 0.81)
Physical activity environment	**-1.34 (-2.24, -0.45)**	0.55 (-0.11, 1.22)
Social environment	**1.00 (0.39, 1.63)**	-0.29 (-0.78, 0.20)

[1] Adjusted for baseline age, gender, race, education, time-varying adjusted household income, time-varying neighborhood SES, interactions by time (baseline age, gender, race, income, and antihypertensive medication use), and environmental summary score in separate models.
2 Same covariates as above with all three environmental summary scores in the same model.

Table 4–6. Mean differences in 5 year change (in mmHg) associated with one standard deviation higher cumulative average neighborhood environmental summary score, adjusted for systolic blood pressure at baseline.

	Difference (95% CI) in five-year change in SBP
In separate models: [1]	
Food environment	0.13 (-0.31, 0.57)
Physical activity environment	0.17 (-0.26, 0.59)
Social environment	0.00 (-0.43, 0.44)
Concurrent adjustment: [2]	
Food environment	0.03 (-0.69, 0.76)
Physical activity environment	0.13 (-0.55, 0.81)
Social environment	0.02 (-0.49, 0.52)

Figure 4-2. Directed Acyclic Graph (DAG) for understanding neighborhood effects on blood pressure.[1]



[1] Solid lines indicate causal relationships; bold lines indicate the primary associations of interest for this analysis.

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Chapter 5

Discussion

Summary of findings

This dissertation contributes new knowledge to our understanding of changes in neighborhood environments and how specific features of neighborhood environments affect the incidence of hypertension and blood pressure changes over time in addition to how socio-demographic characteristics impact changes in neighborhood environments. Taken together, the results of these analyses imply that socio-demographic characteristics of neighborhoods have implications for the health of their residents. In Aim 1, we found that high SES and low density minority neighborhoods had better physical and social environments than low SES and high density minority neighborhoods. In Aims 2 and 3, better physical environments were associated with more favorable blood pressure outcomes including lower rates of hypertension and lower baseline values of SBP. The results of this dissertation have implications for future research and interventions to shape population health and reduce social disparities in health.

Summary of Aim 1

In Aim 1 (Chapter 2), we found that socio-demographic characteristics of census tracts were associated with neighborhood environments after adjusting for individual-level characteristics. In models that were mutually adjusted for tract SES, percent Black residents, and percent Hispanic residents, tracts with higher minority composition had poorer physical and social environments at baseline compared to lower minority areas. Tracts with more Black residents also had larger decreases in safety and walking environment scores over time compared to tracts with fewer Black residents. High SES tracts had better safety and walking environments at baseline, and larger increases in social cohesion and in the food environment over time compared to lower SES neighborhoods.

Aim 1 in context

Our findings broadly concur with the substantial body of research showing that minority and low SES neighborhoods tend to have lower-quality environments than low-minority, high SES neighborhoods.[1-3] In the U.S., racial residential segregation and the spatial concentration of poverty – in addition to a plethora of other historical, political, and societal trends – have produced stark differences in neighborhood environments, particularly between white communities and black communities. Using data from 1980, Robert Sampson concluded that among 171 U.S. cities, "the worst urban contexts in which whites reside with respect to poverty and family disruption are considerably better off than the mean levels for black communities."[4(p353-354)] Race/ethnic residential segregation has been labelled as a fundamental cause of racial disparities in health, in part because of segregation's influence on access to education and employment opportunities that contribute to socioeconomic status.[5,6]

Most research on socio-demographic patterning of neighborhood environments has focused on the physical environment, and shown that low SES and minority areas have poorer food and physical activity environments than their high SES and low-minority counterparts.[7-10]

We found similar patterns, and provide new information on how physical and social environments are changing over time. Notably, healthy food availability scores were similar between low SES and high SES tracts at baseline, but over time differences increased such that low SES tracts had significantly lower scores by the end of the study. Differences in healthy food availability scores between high-minority and low-minority tracts were apparent at baseline and stable over time. Walking environment scores were lower in low SES and high minority areas than in high SES and low minority areas, and were stable or increasing over time.

Research on socio-demographic patterning of neighborhood social environments has suggested that low-income areas tend to be less safe[11] and have less social cohesion[12] than higher-income areas. We found small differences in safety and social cohesion between low-SES and high-SES areas, using a multi-dimensional measure of SES. Previous research has also found that social environments are patterned by minority composition, such that minority neighborhoods are less safe than non-minority neighborhoods and experience a disproportionate burden of violent crime.[13-15] We found striking differences in safety by minority composition, and widening disparities over time between low percentage Black and high percentage Black tracts. Evidence on minority composition and social cohesion is more mixed, but suggests that minority racial composition and concentrated disadvantage are associated with lower levels of trust or social capital.[16,17] We found small but stable differences in social cohesion between low-minority and high-minority neighborhoods.

A unique contribution of this analysis is the ability to explore how neighborhood socio-demographic characteristics pattern changes in food and physical activity environments, to provide evidence of narrowing or widening of disparities over time. We show that healthy food availability increased overall during the course of follow-up, but that existing disparities by neighborhood minority status were unchanged and disparities by neighborhood SES widened over time. Disparities in walking environment and safety scores between low percentage Black and high percentage Black areas also increased over time. Documenting these increasing disparities by area SES and minority composition adds urgency to calls that interventions to improve neighborhood environments should be targeted to the communities that need them most.[18]

Summary of Aims 2 & 3

In Aim 2 (Chapter 3), more favorable neighborhood environments were associated with lower incidence of hypertension among MESA participants who were not hypertensive at baseline. The survey-based measure of the food environment remained significantly protective for hypertension after adjustment for individual-level covariates, neighborhood SES, and all other measures of the neighborhood environment. In Aim 3 (Chapter 4), more favorable food and physical activity environments were associated with lower baseline levels of systolic blood pressure, while better social environments were associated with higher baseline levels of blood pressure in models adjusted for individual-level covariates and neighborhood SES. However, the influence of neighborhood environments on trajectories of blood pressure were in the opposite direction as the baseline effects, with better food and physical activity environments associated with larger increases in SBP over time and better social environments associated with smaller increases in SBP over time. After additional adjustment for baseline SBP, associations between neighborhood environments and SBP trajectories were close to null.

Assessing the impact of neighborhood environments on change in SBP over time in Aim 3 was complicated by the potential influence of baseline SBP on trajectories of SBP. If baseline SBP is a causal factor in determining SBP changes over time and if error in baseline is associated with the change over time, then both baseline-adjusted and baseline-unadjusted analyses will be biased (see Figure 4-2). More complex methods may be needed to account for baseline levels without introducing bias. However, based on sensitivity analyses we conducted, we believe that baseline SBP values are driving some of the paradoxical differences in SBP trajectories that we observed, and concluded that we have little evidence to suggest that neighborhood environments affect SBP trajectories.

Aims 2 & 3 in context

Aims 2 and 3 (Chapters 3 and 4, respectively) both found that neighborhood environments were associated with blood pressure outcomes, but the nuance of which environments were most relevant varied slightly between outcomes. In Aim 2, after concurrent adjustment for individual-level covariates and all neighborhood measures only the survey-based measure of healthy food availability remained significantly associated with incident hypertension. In Aim 3, after concurrent adjustment for the three neighborhood environment summary measures, more favorable food and walking environments (each defined using GIS and survey measures combined) remained associated with lower baseline systolic blood pressure levels, though only the association with the walking environment was statistically significant.

No other research has explored how survey-based measures of specific neighborhood environments are associated with incident hypertension. Previous research in MESA found that the walking environment and food environment were both inversely associated with the prevalence of hypertension. However, these results attenuated and were not significant after adjustment for race/ethnicity, likely a result of the strong patterning of neighborhood environments by race/ethnicity in the U.S.[19] Another study used a survey-based walkability scale, composed of questions focused on presence of sidewalks and trails for pedestrians and cyclists, that found that walkability was not associated with blood pressure.[20] Studies using GIS-based measures of neighborhood walkability and food environments have found mixed results in relation to both systolic blood pressure levels and incident hypertension.[21,22]

One possibility to explain the inconsistency in neighborhood domains relevant to blood pressure is that the different analytic samples in Aim 2 and Aim 3 reveal that different neighborhood environments are important at different stages of hypertension progression. Aim 2 excluded all participants with hypertension at baseline (44% of the cohort), and the results reflect the impact of the food environment on the development of hypertension. Aim 3 included participants with all ranges of blood pressure at baseline; perhaps the physical activity environment is more relevant for blood pressure outcomes among those with hypertension.

The results of Aim 2 and Aim 3 are also incongruent regarding the social environment. In Aim 2, better social environments were associated with a slightly lower hypertension rate in models adjusted for most individual-level covariates, but the associations attenuated to non-significance after adjustment for race/ethnicity. In Aim 3, better social environments (more social cohesion and more safety) were associated with higher systolic blood pressures at baseline after adjustment for individual-level covariates, neighborhood SES, and summary measures of the neighborhood food and physical activity environments. Post-hoc analyses showed that this association was stronger among men than women and stronger among those who were hypertensive at baseline than those who were not hypertensive at baseline. The positive association between the social environment and baseline SBP was broadly consistent across levels of individual-level characteristics and neighborhood SES, reducing the likelihood that the pooled association is being driven by one or more subgroups where associations exist. Again, differences in the analytic samples may explain the discrepancies in the role of the social environment on blood pressure between Aims 2 and 3. However, a substantial amount of research has shown that better social environments, including more socially cohesive and safer environments, are associated with better distribution of health-promoting norms and more social support as well as health-related outcomes including physical activity and obesity.[23-25] Yet previous work in MESA has found that the better social environments were associated with higher BMI among men in cross-sectional analyses.[26] Additional research should continue to explore the association between social environments and measures of cardio-metabolic health in MESA and attempt to replicate these findings outside of MESA, to clarify whether these findings are robust to other settings or whether non-causal explanations such as residual confounding are involved. It is possible that neighborhood social environments can facilitate the dissemination of health-damaging norms as well as health-promoting norms;[16] future research could also look for the intermediary pathways through which the social environment might negatively affect cardio-metabolic health (e.g. individual-level stress or harmful health behaviors), particularly among men.

Another contribution of this dissertation is the ability to compare and contrast survey-based and GIS-based measures of neighborhood environments. Little research has explored how different data sources for measuring neighborhood environments affect observed associations between neighborhoods and health outcomes, and wide variability in the methods used to quantify neighborhood environments hampers comparability.[27] In Aim 2, GIS-based measures did little to explain variability in hypertension incidence. In Aim 3, GIS-based measures were associated with systolic blood pressure in models adjusted for individual characteristics and neighborhood SES, but not in models also adjusted for other neighborhood environment measures.

Generally, GIS-based measures of neighborhood food and physical activity environments were less strongly associated with blood pressure than survey-based measures of neighborhood food and physical activity environments. This may suggest that survey-based measures, and their ability to pick up on qualitative aspects of environments like quality, access, and pleasantness, are more relevant to health outcomes than GIS-based measures which are typically limited to presence or absence of resources. Additionally, the GIS-based measures as constructed for these analyses do not include whether or not residents were aware of available resources or used them. Given the time and cost required to collect survey data on neighborhood environments, documenting their benefits in understanding neighborhood effects on health is important. Research that consistently shows that survey-based measures are a meaningful way to quantify and compare neighborhood environments in relation to health will help to make the case for continued funding of data collection methods including community-based surveys such as the one used in this research.

Strengths and limitations

Key strengths of this dissertation include the unique data source, with rich longitudinal data on neighborhood environments and health outcomes. No other study has been able to compare different sources of neighborhood data over time, in relation to individual-level health changes over time, in a multi-ethnic and multi-site cohort. Also, the availability of imputed blood pressure was key in addressing a fundamental methodological challenge to estimating the association between neighborhood environments and blood pressure.

As always, the results of these analyses should be considered in light of limitations that could affect the validity of the results. Measuring neighborhood environments for the purposes of understanding neighborhood health effects is challenging due to lack of conceptual clarity on the specific aspects of neighborhoods that are important, and inconsistent measures used in previous research makes comparability across studies difficult. Survey-based approaches to measuring neighborhoods are subject to variability in respondents' interpretations of the questions and subjective experiences in their neighborhood. The lack of precision in survey measures is offset by the capacity to capture broader information about quality, access, and other harder-to-quantify aspects of the environment. It is possible that measurement error in survey-based perceptions of neighborhood environments is differential with respect to individual- or neighborhood-level characteristics (e.g. race or neighborhood SES); the use of aggregated measures, combining responses from all nearby MESA and Community Survey participants, may help to reduce this measurement error. The aggregation of survey data also reduced the time-varying resolution of the available measures, which may mask temporal variability in neighborhood environments.

GIS-based approaches to measuring neighborhood environments are easier to calculate but can only be applied to quantify the presence or absence of resources. GIS databases are also subject to inaccuracies; validation studies have documented substantial errors in commercial data sources, but have also shown that errors are generally not differential by tract socio-demographic characteristics.[28-30]

In Aims 2 and 3, some degree of error in the measurement of blood pressure is likely. It is also possible that blood pressure as measured during a study exam is not reflective of usual blood pressure due to white coat hypertension or daily fluctuations in diet and activity patterns. The study protocol included multiple measurements to even out short-term variability in blood pressure. However, if this measurement error is differential by characteristics of participants' neighborhood environments, associations between neighborhood environments and blood pressure could be biased. For example, if residents of low-SES neighborhoods are less comfortable in clinical settings and more prone to 'white coat' hypertension, associations between neighborhood environments and blood pressure could be artificially inflated. In this situation, because neighborhood SES is not the exposure of interest, adjustment for neighborhood SES will help to address possible confounding.

Measurement error in blood pressure is also problematic because it can produce patterns of regression to the mean. As we observed in Aim 3, adjusting for baseline SBP in order to isolate the direct effect of neighborhood environments on change in SBP can create confounded associations by inducing an association between true baseline SBP and measurement error at baseline.[31] Statistical methods to account for measurement error in baseline values (either regression calibration incorporating information about the reliability of blood pressure measurement, or incorporating measurement error into the models with structural equation modeling) or alternative approaches to avoid adjusting for baseline measures (by modeling change from baseline as the outcome of interest) would be useful for learning more about the impact of neighborhood environments on trajectories of blood pressure.

Another limitation of Aims 2 and 3 is the potential temporal mismatch between the available data on neighborhood environments and the relevant time frame for influencing blood pressure outcomes. Despite the longitudinal data on neighborhood environments available, blood pressure outcomes during the study were likely influenced by neighborhood environments prior to the MESA baseline exam. Hypertension is a chronic disease that develops over decades, and without longer-term information on neighborhood environments, we may have under-estimated the true impact of neighborhood environments on blood pressure.[32] However, individuals are likely to live in broadly similar neighborhood environments throughout their life,[32] so neighborhood environments measured during the MESA study may be a reasonable proxy for longer-term exposure to neighborhood environments. We also used cumulative average measures of neighborhood environments to reduce the short-term variability in neighborhood environments. Future research should consider whether time-lagged measures of neighborhood environments might be more strongly associated with health outcomes, though a long lag might be necessary which might be challenging within the context of traditional epidemiologic study designs. Alternatively, life-course frameworks could be used to explore whether there are specific periods of life during which neighborhood environments have larger influence on later blood pressure outcomes, for example, if neighborhood environments in childhood can influence dietary behaviors throughout life or whether neighborhood effects accumulate through life.[33]

Ideally, we would find that the neighborhood-level associations with blood pressure outcomes that we detected are mediated through individual-level intermediaries, as evidence of the proposed pathways through which neighborhood environments affect blood pressure. We attempted to identify mediators by adjusting for diet, physical activity, and BMI where appropriate; these adjustments did not attenuate the neighborhood-level associations of interest. However, we had significant limitations to the data available to measure some of these variables, including limited sample size and measurement error in the use of a food frequency questionnaire. Additionally, separating direct and indirect effects in regression models is inherently challenging.[34,35] Further research should use more advanced mediation techniques to confirm the proposed causal pathways through which neighborhood environments affect blood pressure.

Another concern is residual confounding by individual-level characteristics, a concern common to many studies of neighborhood effects on health that try to isolate contextual effects from compositional effects. This issue is also complicated by the lack of uni-directional relationships between individual characteristics and neighborhood characteristics – that both "people create places, and places create people." [36(p26)] Additionally, modifiable individual-level characteristics may be both confounders and mediators of neighborhood effects on health. We adjusted for key demographic and socioeconomic characteristics of individuals to minimize the likelihood that observed differences in blood pressure outcomes by neighborhood environments are a result of individual-level characteristics, but it is possible that our measurement of individual-level characteristics was imprecise or that we were unable to adjust for all of the relevant characteristics. For example, healthy individuals may seek healthier environments, causing the observed association between healthier environments and lower incidence of hypertension and lower SBP that we observed. With most MESA participants having lived in their neighborhood for 14 years prior to the MESA baseline exam, we were unable to account for the reasons that MESA participants ended up the environments where they were observed.

The multi-site and multi-ethnic composition of the MESA cohort increases our confidence that the findings are likely generalizable to middle-aged and older adults in the U.S. and other Western countries. However, the relationship between neighborhood environments and blood pressure changes may be different among younger populations, because younger people may spend less time in their neighborhood than older people and the influence of neighborhood environments on blood pressure may be cumulative over extended periods of time. We did not find statistically significant differences in the associations between neighborhood environments and blood pressure changes by racial/ethnic groups or other individual-level characteristics, but some research has suggested that neighborhood influences on heath may differ by gender or race/ethnicity.[32,37] If neighborhood environments affect different types of people in different ways, the expected association between neighborhood environments and blood pressure in different populations with different distributions of these individual characteristics would change.

Future directions

This research contributes to the large body of evidence that neighborhood environments shape the health of their residents. However, additional work is needed to overcome methodological issues in the study of neighborhood effects on health and translate our knowledge into meaningful interventions for improving population health and reducing health disparities.

Methodological considerations

This dissertation highlights two key methodological issues that deserve additional consideration: determining the best data sources for measuring neighborhood environments and accounting for medication use in analysis blood pressure outcomes.

Though GIS-based measures tend to be cheaper and easier to produce than survey-based measures of neighborhood environments, the results of this dissertation illustrate the limitations of relying solely on GIS-based measures of neighborhood food and physical activity environments. GIS-based measures of neighborhood environments were not associated with incident hypertension in Aim 2, though survey-based measures of more favorable food and physical activity environments were inversely associated with incident hypertension. Additionally, survey-based approaches have particular utility for measuring aspects of the social environment, which is less directly related to objective neighborhood features than the physical environment.

However, GIS-based measures do capture some truth about neighborhood environments, and will likely continue to be used in studies of area-level effects on health. But it is not yet clear how GIS-based measures can be used effectively to understand neighborhood health effects. It may be that GIS-based measures are useful for categorizing neighborhood environments broadly, as a neighborhood with zero grocery stores likely has a poorer food environment than a neighborhood with multiple grocery stores, but the difference between a neighborhood with four grocery stores and a neighborhood with five grocery stores may be minimal. Also, some evidence suggests that GIS-based measures of environments that reflect street connectivity, land use mix, transportation networks, and other indicators of the built environment may be more correlated with health behaviors and outcomes than GIS-based measures of environments that focus on commercial stores, which was used in these analyses.[38-40] Measures related to presence or absence of commercial resources are limited by their inability to differentiate between qualitative dimensions (quality, access, cost) that may be important in relation to health.

It is increasingly clear that GIS- and survey-based measures of neighborhood environments do not capture the same information, even when they are related to the same conceptual domains. Previous research has compared survey-based measures and GIS-based measures of neighborhood food environments in three MESA sites, and found that the two types of measures were associated but not collinear.[41] Researchers should carefully consider which aspects of neighborhood environments are most conceptually relevant to their research question, and consider the strengths and limitations of available measures for capturing those aspects of neighborhood environments. The relative utility of different measures likely varies depending on the health outcome of interest, adding further complexity.

Another methodological issue, addressed in Aim 3, is the role of medication use. Researchers interested in continuously-measured outcomes affected by medication, including blood pressure as well as cholesterol, glucose, and other important health markers, should carefully consider the conceptual relationships between exposure, outcome, and medication use. If medication use both affects and is affected by the outcome, and is associated with the exposure, then medication use is both a collider and a confounder; even if medication use is not associated with the exposure of interest, it is likely to still cause measurement error in the true outcome of interest. A variety of approaches have been proposed to address this issue,[42] though few empirical studies have evaluated or compared different methods. In our analyses, results using multiply imputed blood pressures to replace observed blood pressure influenced by medication use were largely comparable to results adjusting for medication use as a covariate. Future research should refine and clarify the settings in which medication use has the largest effect on associations of interest, which likely depends on the strength of associations between medication use and the exposure of interest and the outcome of interest. In situations where the exposure of interest is more strongly associated with medication use than in our analyses (for example, if the exposure is more directly related to access to medical care or personal characteristics associated with medication use), researchers could quantify the impact of different methods of accounting for medication use to provide a sense of the maximum bias produced by naïve methods.

Future research on neighborhoods and blood pressure

Research should continue to investigate how neighborhood environments affect population health. A particularly fruitful area for research may be in understanding the role of neighborhoods in perpetuating social disparities in health. Residential racial segregation, and the discrepancy in neighborhood environments by racial composition, has been labeled as a fundamental cause of health disparities,[5,6] and research has shown that racial/ethnic disparities in health are minimized when neighborhood environments are similar.[43] Because neighborhood environments affect everyone in the neighborhood, and are likely to affect a broad range of health outcomes, neighborhood environments could constitute an efficient and effective means of minimizing health disparities.

To explicitly quantify the contribution of neighborhood environments to social disparities in health, structural equation models or other mediation techniques would be useful. For example, structural equation modeling can be used to quantify how much of the observed association between tract percentage of Black residents and incident hypertension is mediated by specific neighborhood environments. MESA would be a useful data source for such analyses because of the extensive longitudinal data for health outcomes and neighborhood environments, as well as the multi-site and multi-ethnic sample.

Future research on neighborhoods and blood pressure in particular should build on the results of this dissertation. Using different statistical methods to isolate the influence of neighborhood environments on SBP trajectories could provide new evidence on the potential health effects of neighborhood environments. Future research should also explore the association between neighborhood social environments and blood pressure, including potential differences in men and women. Studies incorporating better time-varying information about health intermediaries (e.g. diet, physical activity, stress) could identify the relevant physiological pathways through which neighborhoods influence health, contributing to our knowledge of the causal processes at work. We can also extend our understanding of neighborhood effects on health throughout the life course, including potential sensitive periods and cumulative effects. Future research should also consider non-linear effects of neighborhood environments as well as joint effects of multiple dimensions of neighborhood environments.

Intervention and policy implications

In most Western societies – and increasingly, across the globe – high blood pressure in particular and chronic diseases in general are a major public health concern. Interventions that adopt a population-based strategy to reduce the burden of disease are ideally situated to maximize population benefit for minimal resource investment per capita. Meta-analysis of randomized controlled trials concluded that reducing blood pressure by 10 mmHg was associated with a 31% reduction of stroke;[44] the seventh report of the joint national committee on high blood pressure reported that a 2 mmHg reduction of SBP causes a 6% reduction in stroke mortality and a 4% reduction in mortality attributable to coronary heart disease.[45] If a one standard deviation difference in neighborhood physical activity environment (equivalent to 0.33 points on a 5-point Likert scale on the pleasantness and frequency of seeing people walking in the neighborhood, or 6.7 more physical activity resources per square mile) is associated with 1 mmHg lower SBP, improving neighborhood environments may be an important avenue for public health interventions. The Moving to Opportunity study provides quasi-experimental evidence that changing neighborhood environments (specifically, moving to a lower-poverty area) can reduce cardiometabolic risk,[46] adding to our confidence that neighborhoods can be meaningful targets for population-level interventions.

However, large-scale community-based interventions for CVD prevention aimed at shifting the distribution of risk factors levels have had mixed success. The Stanford Five-City Project, which began in 1978 and tapered off in the late 1980s, implemented a massive community intervention that included mass media campaigns, individual-, group-, and provider-education programs, and efforts to improve availability of healthy food options. Evaluation of the intervention concluded that knowledge of CVD risk factors increased, while CVD risk factors (cholesterol, blood pressure) improved modestly. In light of large secular trends apparent in control cities, the magnitude of the intervention was considered modest.[47] Additional intervention programs inspired by the Stanford Five-City project, including the Minnesota Heart Health Program and the Pawtucket Heart Health Project, had similar lackluster effects.[48,49] Future interventions should focus on higher levels of a social-ecological model, rather than relying on individual motivation and capacity to overcome structural and environmental threats to health. New tools such as health impact assessments should be used to consider the health implications of a variety of policies, from housing to transportation to taxation. Shaping environments so that the healthy choice is the easy choice may be a more efficient and sustainable way to shift population health than relying on individual willpower.

Conclusion

This dissertation addresses how neighborhood composition affects neighborhood physical and social environments, and how those physical and social environments pattern blood pressure outcomes. The results of this research add to the substantial body of knowledge on neighborhood health effects and overcome previous limitations using unique longitudinal data in a multi-ethnic, multi-site cohort study. This evidence can be used to inform epidemiologic approaches to studying neighborhood effects on health as well as potential interventions to leverage neighborhood environments to improve population health or address social disparities in health.

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