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Neighborhood built environment and cognition in non-demented older adults: The Multi-Ethnic Study of Atherosclerosis

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ABSTRACT

Preliminary studies suggest that neighborhood social and built environment (BE) characteristics may affect cognition in older adults. Older adults are particularly vulnerable to the neighborhood environment due to a decreasing range of routine travel with increasing age. We examined if multiple neighborhood BE characteristics are cross-sectionally associated with cognition in a diverse sample of older adults, and if the BE-cognition associations vary by individual-level demographics. The sample included 4539 participants from the Multi-Ethnic Study of Atherosclerosis. Multivariable linear regression was used to examine the associations between five BE measures and four cognitive measures, and effect modification by individual-level education and race/ethnicity. In the overall sample, increasing social destination density, walking destination density, and intersection density were associated with worse overall cognition, whereas increasing proportion of land dedicated to retail was associated with better processing speed. Effect modification results suggest that the association between urban density and worse cognition may be limited to or strongest in those of non-white race/ethnicity. Although an increase in neighborhood retail destinations was associated with better cognition in the overall sample, these results suggest that certain BE characteristics in dense urban environments may have a disproportionately negative association with cognition in vulnerable populations. However, our findings must be replicated in longitudinal studies and other regional samples.

1. Introduction

Cognitive impairment, present in ≥10% of adults 65 years and older (Unverzagt et al., 2001), is associated with lower quality of life (Muangpaisan et al., 2008) and increased nursing home placement (Gaugler et al., 2007). The impending rise in the population of older adults (US Census) will be accompanied by an increase in the prevalence of cognition impairment, calling for strategies to address the associated economic, health, and social burden. Interventions focused on improving diet and reducing vascular risks may simultaneously delay the onset of cognitive impairment (Nelson and Tabet, 2015). Additionally, there is emerging recognition that residential environments are important in shaping health behaviors and health outcomes (Koohsari et al., 2015; Sallis et al., 2009). For example, lower neighborhood socioeconomic status has been associated with worse cognition in older adults in previous studies (Clarke et al., 2012). Older adults may be particularly influenced by their neighborhood environment due to a smaller range of routine travel and thus increased exposure to proximal environments (Marottoli et al., 2000). Therefore, policies that promote a safe and walkable neighborhood environment may help older adults age in place and delay the onset of cognitive impairment by providing an environment that is socially and mentally engaging (Cassarino and Setti, 2015) and supportive of a healthy lifestyle (Clarke et al., 2012).

The neighborhood built environment (BE) comprises all of the physical aspects of the environment (Oxford University Press)

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surrounding the home, including the road network, buildings, sidewalks and bike paths, parks and public spaces, and amenities such as lighting. The mechanisms by which the neighborhood BE affects cognition are likely complex and multifaceted, and thus the direction of the associations may depend on individual-level characteristics and the BE features under consideration. BE-cognition associations have been explored little to date, with prior studies providing little explication on likely mechanism(s) for any observed associations. Below we outline a number of causal mechanisms, each of which may individually or jointly help explain associations between a specific BE characteristic and cognition.

The neighborhood BE may influence health behaviors such as physical activity (PA) and diet, factors that have been associated with cognition (Boone-Heinonen et al., 2011; Groot et al., 2016). Additionally, urban environments may be associated with increased vehicular pollutant exposure due to decreased distances to busy roadways (Buonocore et al., 2009) and decreased air ventilation created by buildings (Yuan et al., 2014). Airborne pollutants (Power et al., 2011) have been associated with worse cognition and brain structure in older adults. Neighborhoods with more social engagement opportunities may improve well-being and decrease stress, anxiety, and depression, consequently improving cognition. On the other hand, neighborhood psychosocial disorder (e.g., crime, graffiti), fear of falls, and sensory overload (e.g., confusing spaces, noise, crowds) may increase social isolation (Aneshensel et al., 2011; James, 2009) and negatively impact cognition if residents minimize time spent in the neighborhood. In addition, neighborhood BE factors such as land use mix, population density, traffic, and noise may improve or worsen quality of life and associated mental health outcomes (e.g., stress) (Fassio et al., 2013; Sarmiento et al., 2010; Stansfeld et al., 1996), thereby affecting cognition. Stress in late-life has been associated with worse cognition in older adults (Aggarwal et al., 2014) and a decrease in stressors has been associated with improved cognition (Dickinson et al., 2011). Lastly, neighborhood BEs may provide cognitive stimulation, which can either improve cognition or cause cognitive overload that worsens cognition. Living in a complex neighborhood environment in older age may provide mental stimulation that helps delay cognitive decline by requiring constant but passive adaptation (Cassarino and Setti, 2015). However, the neighborhood BE may cause cognitive overload (Lindenberger et al., 2000) among those with physical or mental disabilities or cognitive impairment.

The few published studies on the BE and cognition in older adults found associations between cognition and the presence of a community center or transit stop, condition of public spaces, distance to community resources, street connectivity, land use mix, and area dedicated to the natural environment (Besser et al., 2017; Wu et al., 2017). Some but not all of these studies suggest a positive association between increasing urban density and better cognitive functioning. However, the types of BE and cognitive measures used and methods of defining neighborhoods differed markedly in the studies, and additional work is needed to narrow down the BE features that may have the greatest influence on cognition, to examine potential effect modifiers, and to investigate associations in diverse samples.

In this study, we examine if five neighborhood BE characteristics representing increased density, street accessibility, and land use mix, typically consistent with increasing urban density/less sprawl (Smart Growth America), are associated with better cognition. We additionally aimed to investigate if the BE-cognition associations vary by individual-level education or race/ethnicity, characteristics previously found to modify the association between neighborhood SES and health (Merkin et al., 2009; Wight et al., 2006). We focused on density of social destinations, walking destinations, and intersections, as well as proportion of land dedicated to residences and retail, because similar measures have been associated with walking in older adults (Cerin et al., 2013; Hall and McAuley, 2010; Li et al., 2005; Michael et al., 2006; Troped et al., 2017), aiming to investigate characteristics that are simultaneously associated with PA and cognition. Urban planners consider diverse implications of plans and policies, including economic, social, environmental, and health-related considerations. Therefore, it will be useful for studies to narrow down specific BE characteristics that may benefit multiple aspects of health (e.g., PA and cognition), to strengthen arguments for future plans and policies aimed at improving health.

2. Materials and methods

2.1. Sample

The analytic sample originated from 4716 participants who completed Exam 5 (2010–2012) of the Multi-Ethnic Study of Atherosclerosis (MESA), a longitudinal, population-based cohort study of subclinical cardiovascular disease. MESA has completed five exams since 2000, with a sixth exam currently underway. Participants aged 45- to 84-years-old were enrolled from six US regions (Forsyth County, North Carolina; New York, New York; Baltimore, Maryland; St. Paul, Minnesota; Chicago, Illinois; Los Angeles, California) and individuals of African American, Chinese, and Hispanic race/ethnicity were oversampled. Details about MESA have been published previously (Bild et al., 2002). The final sample excluded those (n = 357) who: 1) were missing all cognitive test scores; 2) were missing all BE measures; 3) were taking Alzheimer's disease medication at any exam (acetylcholinesterase inhibitors or *N*-methyl-D asparate receptor blocker); 4) had an International Classification of Disease (ICD) code suggesting dementia in death certificate and hospitalization records (Fujiyoshi et al., 2016); or 5) had a Cognitive Abilities Screening Instrument (CASI) score < 20, which lacks face validity.

2.2. Cognitive measures

MESA's Exam 5 was the only available exam that included cognitive measures (Fitzpatrick et al., 2015). The cognitive tests included: 1) the CASI (Teng et al., 1994) (version 2), a brief test of global cognition (range: 0–100); 2 and 3) Digit Span Forward (DSF) and Backward (DSB) (Wechsler Adult Intelligence Scale subtests [WAIS-III] (Wechsler, 1997)) (ranges: 0–16, 0–14, respectively), measures of attention, short term and working memory; and 4) Digit Symbol (DS; subtest of WAIS-III (Wechsler, 1997)), a measure of processing speed (range: 0–133). For the regression analyses, z-scores were calculated for each neuropsychological test by subtracting an individual's score from the entire sample's mean score and dividing the difference by the entire sample's standard deviation. The BE may influence certain aspects of cognition more than others (e.g., processing speed versus short-term memory), and therefore, each of the four cognitive tests were included separately in our analyses because they capture different cognitive domains.

2.3. Built environment measures

The neighborhood measures were originally developed as part of the MESA Neighborhood Study (Diez Roux et al., 2016). Land parcels for each study site were classified as residential (e.g., family homes, apartment complexes/condominiums) or retail (e.g., shopping centers, clothing stores), and the percent of the ¼-mile, ½-mile, and 1-mile buffers dedicated to residences or retail was calculated by dividing the residential/retail area by the total buffer area (Rodríguez et al., 2009). Intersection density was determined by dividing intersection counts (excluding culs-de-sac) for the ¼-mile, ½-mile, and 1-mile buffer by the total buffer area. The densities of social engagement (e.g., beauty shops/barbers, performance-based entertainment) and walking destinations (e.g., postal services, non-beverage eating/dining places) per square mile were calculated for the ¼-mile, ½-mile, and 1-mile area around the home using 2010 National Establishment Time Series (NETS) business data. Neighborhood SES, based on US Census

American Community Survey data (2007–2011) at the tract-level, was previously developed from a principal components analysis of the percent of neighborhood residents with a bachelor's degree, a high school degree, a managerial occupation, and an annual household income > $50,000, and the neighborhood's median home value, median household income, and percent rental income.

2.4. Participant characteristics

Baseline characteristics included age, sex, education, race/ethnicity, marital status, family income, and ≥1 apolipoprotein ε4 allele (APOE ε4), a genetic risk factor for Alzheimer's disease. We described certain health indicators and conditions, including depression (Center for Epidemiologic Studies Depression Scale [CES-D] score ≥ 16), self-reported diabetes, and medication use for hypertension, hypercholesterolemia, and depression.

2.5. Statistical methods

The sample's demographics, clinical characteristics and APOE genotype were detailed using descriptive statistics. Means and standard deviations (SD), ranges, and the 25th, 50th, and 75th percentiles of the BE measures were calculated, and Pearson correlation coefficients were calculated to examine the correlation between BE measures.

Unadjusted and adjusted linear regression models with generalized estimating equations (accounting for clustering by study site) were employed to examine the BE and cognition associations and effect modification by education and race/ethnicity. Twenty models were run to examine each BE measure (independent variable) and cognitive test (dependent variable) combination. Results are reported in separate tables for density/street accessibility measures (walking destination, social destination, and intersection density) and for land use measures (proportion of land dedicated to residences or retail) for ease of readability. Multiple BE measures were highly correlated in our sample; however, may not necessarily be highly correlated in other samples or neighborhoods/regions. Thus, we chose to evaluate the BE measures separately. Additionally, we aimed to avoid a composite BE measure (e.g., sprawl index) that would limit the specificity in interpreting the results and the ability to contribute to evidence suggesting specific BE features to be targeted in future plans and policies. The BE and cognitive measures were treated as continuous variables, and the multivariable models adjusted for age, sex, race/ethnicity, income, marital status, neighborhood SES, and ≥1 APOE ε4 allele.

Interaction terms (e.g., intersection density × education) were entered into the multivariable models to test for effect modification by education (≤12 years versus > 12 years) or race/ethnicity (Chinese-American, African-American, and Hispanic, versus non-Hispanic white). Our reporting of results focuses on statistically significant interactions ($p < .05$) with statistically significant ($p < .05$) associations in ≥1 of the stratified groups (e.g., among Hispanics).

The ½-mile buffers around the participants' homes were hypothesized to be the area most representative of older adult neighborhoods (i.e., a reasonable walking distance), and therefore were the primary focus. However, for the main effects analyses, we also evaluated the ¼-mile and 1-mile BE measures to assess consistency across different buffer sizes.

3. Results

The final sample included 4539 participants. The majority was 55- to 84-years of age, female, college educated, and married (Table 1). Forty-one percent were non-Hispanic whites, 12% Chinese-American, 27% African-American, and 21% Hispanic. Twenty-seven percent were APOE ε4 carriers and 14% had depression. The mean cognitive test scores were 87.8 for the CASI, 9.7 for the DSF, 5.6 for the DSB, and 50.8 for the DS (Table 2). In addition to the results presented in the main tables, additional data and sensitivity analyses are provided in the supplemental material.

Table 1
Demographics and clinical characteristics (n = 4359).

Characteristic	n (%)
Age, exam 5 (years)	
45-54	73 (1.7%)
55-64	1476 (33.9%)
65-74	1397 (32.1%)
75-84	1148 (26.3%)
≥85	265 (6.1%)
Male	2041 (46.8%)
Education	
< High school degree	588 (13.5%)
High school degree	754 (17.3%)
Some college	1273 (29.3%)
≥Bachelor's degree	1737 (39.9%)
Married	2771 (64.2%)
Race/ethnicity	
White/Caucasian	1777 (40.8%)
Chinese-American	504 (11.6%)
Black/African American	1162 (26.7%)
Hispanic	916 (21.0%)
Family income ≥$30,000/year	2839 (67.6%)
≥1 APOE ε4 allele	1083 (26.5%)
Depression (CES-D ≥16)	614 (14.4%)
Diabetes	461 (10.6%)
Hypertension medication	2402 (55.2%)
Hypercholesterolemia medication	1693 (38.8%)
Cardiovascular disease	333 (7.6%)
Cerebrovascular disease (TIA/stroke)	136 (3.1%)

Abbreviations: APOE = apolipoprotein E; CES-D = Center for Epidemiologic Studies Depression scale; TIA = transient ischemic attack.
Missing: APOE, n = 268; income, n = 156; education, n = 7; CES-D, n = 86; diabetes, n = 26; married, n = 42; cardiovascular disease, n = 2; cerebrovascular disease, n = 2.

Table 2
Cognitive test scores and built environment characteristics.

Measure	Mean ± Standard deviation
CASI	87.8 ± 8.7
DSF	9.7 ± 2.8
DSB	5.6 ± 2.4
DS	50.8 ± 18.4
Social destination density[a]	145.7 ± 228.2
Walking destination density[a]	68.7 ± 106.2
Intersection density[a]	0.79 ± 0.52
Proportion land residential[a]	0.47 ± 0.17
Proportion land retail[a]	0.048 ± 0.051

Abbreviations: CASI = Cognitive Abilities Screening Instrument; DSF = Digit Span Forward; DSB = Digit Span Backward; DS = Digit Symbol.
Missing: CASI, n = 8; DSF, n = 16; DSB, n = 16; DS, n = 405; proportion residential, n = 283; proportion retail, n = 283.
[a] ½-mile buffer.

3.1. Main effects analyses

In the unadjusted analyses, increasing social destination density was associated with better CASI scores and increasing social and walking destination densities were associated with better DSB scores (see Appendix). Lastly, increasing social destination density was associated with better DS scores.

In the adjusted analyses, compared to those living in neighborhoods with the lowest social and walking destination densities, those living in the highest social and walking destination densities in the ½-mile surrounding the home scored worse on the CASI by 0.33 and 0.29 SDs, respectively (Table 3). Compared to those living in neighborhoods with the lowest intersection densities, individuals living in the highest

Table 3
Adjusted associations between density measures and cognitive test z-scores in overall sample.

BE measure	Buffer size	Estimate (95% CI)[a] CASI[b]	DSF[b]	DSB[b]	DS[b]
Social destination density	¼-mile	−0.0001*** (−0.0002, −0.0001)	0.0000 (−0.0001, 0.0002)	−0.0001 (−0.0002, 0.0000)	0.0000 (−0.0001, 0.0002)
	½-mile	−0.0002*** (−0.0002, −0.0001)	0.0001 (−0.0002, 0.0003)	−0.0001 (−0.0003, 0.0001)	0.0001 (−0.0001, 0.0002)
	1-mile	−0.0003*** (−0.0004, −0.0002)	0.0001 (−0.0002, 0.0004)	−0.0000 (−0.0003, 0.0002)	0.0001 (−0.0001, 0.0003)
Walking destination density	¼-mile	−0.0002*** (−0.0003, −0.0001)	0.0001 (−0.0002, 0.0005)	−0.0003** (−0.0005, −0.0001)	0.0000 (−0.0002, 0.0002)
	½-mile	−0.0004*** (−0.0005, −0.0003)	0.0003 (−0.0003, 0.0008)	−0.0003 (−0.0005, 0.0000)	−0.0000 (−0.0001, 0.0000)
	1-mile	−0.0007*** (−0.0008, −0.0006)	0.0001 (−0.0007, 0.0010)	−0.0001 (−0.0006, 0.0003)	−0.0002 (−0.0004, 0.0000)
Intersection density	¼-mile	−0.05*** (−0.07, −0.03)	0.00 (−0.07, 0.07)	−0.01 (−0.04, 0.02)	−0.07 (−0.14, 0.01)
	½-mile	−0.05*** (−0.07, −0.04)	−0.00 (−0.07, 0.06)	−0.01 (−0.05, 0.03)	−0.04 (−0.09, 0.01)
	1-mile	−0.10*** (−0.12, −0.07)	−0.01 (−0.11, 0.09)	−0.02 (−0.08, 0.05)	−0.02 (−0.04, 0.01)

Abbreviations: BE = built environment; CASI = Cognitive Abilities Screening Instrument; DSF = Digit Span Forward; DSB = Digit Span Backward; DS = Digit Symbol; CI = confidence interval; Association within education group: *p < .05, **p < .01,***p < .001.
[a] Controlling for age, education, race/ethnicity, income, sex, marital status, APOE genotype, neighborhood SES.
[b] Higher scores = better cognition.

intersection densities in the ½-mile surrounding the home scored worse on the CASI by 0.25 SD. Although the magnitude of the estimates changed when examining these same associations using the ¼-mile and 1-mile BE measures, the associations were consistently in the same direction (increasing BE measure associated with worse cognition) and were all statistically significant (Table 3). Additionally, an increasing walking destination density in the ¼-mile surrounding the home (but not the ½-mile or 1-mile) was associated with worse scores on the DSB test.

The results were suggestive of an association between proportion of land dedicated to retail and cognition, although only observed using the ¼-mile measure (Table 4). Compared to those living in neighborhoods with the lowest proportion of land dedicated to retail, individuals living in neighborhoods with the highest proportion of land dedicated to retail scored better on the DS by 0.13 SD.

Table 4
Adjusted associations between land use measures and cognitive test z-scores in overall sample.

BE measure	Buffer size	Estimate (95% CI)[a] CASI[b]	DSF[b]	DSB[b]	DS[b]
Proportion land residential	¼-mile	0.03 (−0.04, 0.10)	−0.12 (−0.39, 0.15)	0.03 (−0.03, 0.10)	0.02 (−0.11, 0.15)
	½-mile	0.05 (−0.06, 0.16)	−0.10 (−0.37, 0.16)	−0.01 (−0.13, 0.11)	0.01 (−0.07, 0.09)
	1-mile	0.06 (−0.04, 0.16)	−0.18 (−0.53, 0.18)	0.01 (−0.15, 0.18)	0.10 (−0.06, 0.26)
Proportion land retail	¼-mile	−0.12 (−0.41, 0.17)	0.61 (−0.05, 1.27)	−0.19 (−0.45, 0.08)	0.27* (0.03, 0.50)
	½-mile	−0.16 (−0.72, 0.39)	0.72 (−0.17, 1.61)	−0.23 (−0.74, 0.28)	0.23 (−0.08, 0.54)
	1-mile	−0.41 (−1.52, 0.70)	0.99 (−0.00, 1.98)	−0.14 (−0.76, 0.48)	0.21 (−0.17, 0.59)

Abbreviations: see Table 3; Association within education group: *p < .05, **p < .01,***p < .001.
[a] Controlling for age, education, race/ethnicity, income, sex, marital status, APOE genotype, neighborhood SES.
[b] Higher scores = better cognition.

3.2. Effect modification by education

Education modified the association between social destination density and cognition (Table 5). Increasing social destination density was associated with worse DSF scores in those with low education but not in those with high education. Associations between proportion of land dedicated to residences/retail and cognition did not vary by education (Table 6).

Table 5
Adjusted associations between density measures and cognitive test z-scores, by education.

BE measure (½-mile buffer)	Education level[c]	Estimate[a,b] (95% CI) CASI[d]	DSF[d]	DSB[d]	DS[d]
Social destin. density	Low	−0.0003 (−0.0008, 0.0002)	−0.0005† (−0.0010, −0.0001)	0.0000 (−0.0002, 0.0002)	−0.0001 (−0.0005, 0.0003)
	High	−0.0002††† (−0.0003, −0.0001)	0.0001** (−0.0002, 0.0004)	−0.0001 (−0.0004, 0.0002)	0.0001 (−0.0001, 0.0003)
Walking destin. density	Low	−0.0004 (−0.0012, 0.0005)	−0.0001 (−0.0008, 0.0007)	0.0002 (−0.0001, 0.0004)	−0.0004 (−0.0011, 0.0003)
	High	−0.0006††† (−0.0008, −0.0004)	0.0003* (−0.0004, 0.0009)	−0.0004 (−0.0009, 0.0001)	−0.0001 (−0.0003, 0.0000)
Intersection density	Low	−0.08 (−0.37, 0.22)	−0.08 (−0.27, 0.12)	0.01 (−0.13, 0.15)	−0.08 (−0.23, 0.08)
	High	−0.05 (−0.11, 0.01)	−0.01 (−0.07, 0.05)	−0.01 (−0.11, 0.10)	−0.05 (−0.12, 0.02)

Abbreviations: see Table 3; Statistically significantly different than low education: *p < .05, **p < .01, ***p < .001; Association within given education group: †p < .05, ††p < .01, †††p < .001.
[a] Controlling for age, education, sex, race/ethnicity, income, marital status, APOE genotype, neighborhood SES.
[b] Z-score change per one-unit increase in BE measure.
[c] Education: low: ≤12 years; high: > 12 years.
[d] Higher scores = better cognition.

Table 6
Adjusted associations between land use measures and cognitive test z-scores, by education.

BE measure (½-mile buffer)	Education level[c]	Estimate[a,b] (95% CI)			
		CASI[d]	DSF[d]	DSB[d]	DS[d]
Proportion residential	Low	0.35 (−0.01, 0.72)	−0.12 (−0.59, 0.35)	−0.01 (−0.23, 0.22)	0.09 (−0.01, 0.18)
	High	−0.01 (−0.21, 0.19)	−0.03 (−0.30, 0.24)	0.01 (−0.22, 0.23)	0.02* (−0.14, 0.17)
Proportion retail	Low	−0.46 (−1.11, 0.20)	−0.75 (−1.53, 0.04)	0.20 (−0.63, 1.03)	0.27 (−1.27, 1.82)
	High	−0.21*** (−0.88, 0.47)	0.90 (−0.16, 1.96)	−0.43 (−1.04, 0.19)	0.11 (−0.60, 0.82)

Abbreviations: see Table 3; Statistically significantly different than low education: *p < .05, **p < .01, ***p < .001; Association within given education group: †p < .05, ††p < .01, †††p < .001.
[a] Controlling for age, education, sex, race/ethnicity, income, marital status, APOE genotype, neighborhood SES.
[b] Z-score change per one-unit increase in BE measure.
[c] Education: low: ≤12 years; high: > 12 years.
[d] Higher scores = better cognition.

3.3. *Effect modification by race/ethnicity*

Race/ethnicity modified numerous BE-cognition associations (Tables 7 and 8). The associations between three BE measures and cognition varied significantly when comparing Chinese and non-Hispanic white participants. Increasing social destination density was associated with worse DSB scores, whereas increasing intersection density was associated with better CASI and DS scores in Chinese but not non-Hispanic white participants (Table 7). In addition, increasing

Table 8
Adjusted associations between land use measures and cognitive test z-scores, by race/ethnicity.

BE measure (½-mile buffer)	Race/ethnicity	Estimate[a,b] (95% CI)			
		CASI[c]	DSF[c]	DSB[c]	DS[c]
Proportion residential	NH white	0.19†† (0.06, 0.33)	0.15 (−0.06, 0.37)	0.01 (−0.36, 0.38)	−0.03 (−0.14, 0.09)
	Chinese	0.06††† (0.04, 0.08)	−0.09*** (−0.28, 0.10)	0.23 (−0.13, 0.60)	−0.14 (−0.58, 0.29)
	African American	−0.17*** (−0.40, 0.06)	0.12 (−0.20, 0.43)	−0.05 (−0.27, 0.17)	−0.08 (−0.43, 0.26)
	Hispanic	0.14 (−0.12, 0.40)	−0.05 (−0.12, 0.03)	0.23†††,* (0.14, 0.33)	0.14†,** (0.03, 0.24)
Proportion retail	NH white	0.13 (−0.85, 0.59)	0.31 (−0.78, 1.40)	−0.31 (−1.20, 0.58)	0.44 (−0.28, 1.16)
	Chinese	−0.41†† (−0.68, −0.14)	−0.31 (−0.82, 0.19)	−1.74†††, * (−2.52, −0.96)	0.05 (−0.34, 0.44)
	African American	−0.57 (−2.10, 0.97)	−0.58* (−2.46, 1.30)	−0.27 (−1.65, 1.12)	1.33††† (0.61, 2.05)
	Hispanic	−0.41 (−2.18, 1.36)	0.52 (−0.35, 1.40)	−0.02 (−1.78, 1.73)	−1.47††,*** (−2.52, −0.42)

Abbreviations: NH = Non-Hispanic; other abbreviations in Table 3; Statistically significantly different than NH whites: *p < .05, **p < .01, ***p < .001; Association within a given racial/ethnic group: †p < .05, ††p < .01, †††p < .001.
[a] Controlling for age, education, sex, race/ethnicity, income, marital status, APOE genotype, neighborhood SES.
[b] Z-score change per one-unit increase in BE measure.
[c] Higher scores = better cognition.

Table 7
Adjusted associations between density measures and cognitive test z-scores, by race/ethnicity.

BE measure (½-mile buffer)	Race/ethnicity	Estimate[a,b] (95% CI)			
		CASI[c]	DSF[c]	DSB[c]	DS[c]
Social destin. density	NH white	−0.0001 (−0.0004, 0.0001)	−0.0002† (−0.0003, −0.0000)	−0.0002 (−0.0005, 0.0002)	0.0001 (−0.0001, 0.0003)
	Chinese	0.0004 (−0.0001, 0.0009)	0.0000 (−0.0007, 0.0007)	−0.0009†††, *** (−0.0013, −0.0005)	0.0002 (−0.0002, 0.0005)
	African American	−0.0006††† (−0.0009, −0.0002)	−0.0004†, ** (−0.0008, −0.0001)	−0.0003†††, ** (−0.0004, −0.0001)	0.0001 (−0.0000, 0.0002)
	Hispanic	−0.0005†††, *** (−0.0005, −0.0004)	0.0005††† (0.0004, 0.0006)	−0.0002* (−0.0004, 0.0001)	−0.0004†††, *** (−0.0004, −0.0003)
Walking destin. density	NH white	−0.0003 (−0.0008, 0.0001)	−0.0003 (−0.0008, 0.0001)	−0.0005 (−0.0012, 0.0002)	0.0002 (−0.0003, 0.0006)
	Chinese	0.0005 (−0.0006, 0.0016)	0.0001 (−0.0014, 0.0015)	−0.0013† (−0.0025, −0.0001)	0.0007† (0.0001, 0.0012)
	African American	−0.0010††† (−0.0013, −0.0006)	−0.0005†††, * (−0.0007, −0.0002)	−0.0001 (−0.0007, 0.0005)	0.0001 (−0.0000, 0.0002)
	Hispanic	−0.0008†††, ** (−0.0010, −0.0005)	0.0008††† (0.0006, 0.0009)	−0.0004†, * (−0.0007, −0.0000)	−0.0011†††,*** (−0.0016, −0.0007)
Intersection density	NH white	−0.03 (−0.06, 0.01)	−0.09†† (−0.15, −0.03)	0.01 (−0.08, 0.10)	−0.01 (−0.05, 0.02)
	Chinese	0.05†††, *** (0.04, 0.06)	0.10†† (0.04, 0.16)	0.02 (−0.02, 0.06)	0.16†††,*** (0.13, 0.19)
	African American	−0.24††† (−0.32, −0.15)	−0.06 (−0.17, 0.05)	−0.04* (−0.15, 0.07)	−0.01 (−0.04, 0.03)
	Hispanic	−0.09†††, * (−0.12, −0.06)	0.03 (−0.08, 0.13)	−0.13†,* (−0.25, −0.00)	−0.24†††,*** (−0.28, −0.20)

Abbreviations: NH = Non-Hispanic; other abbreviations in Table 3; Statistically significantly different than NH whites: *p < .05, **p < .01, ***p < .001; Association within a given racial/ethnic group: †p < .05, ††p < .01, †††p < .001.
[a] Controlling for age, education, sex, race/ethnicity, income, marital status, APOE genotype, neighborhood SES.
[b] Z-score change per one-unit increase in BE measure.
[c] Higher scores = better cognition.

proportion of land dedicated to retail was associated with worse DSB scores in Chinese but not non-Hispanic white participants (Table 8).

The associations between three BE measures and cognition varied significantly when comparing African American and non-Hispanic white participants. Increasing social destination density was associated with worse DSF and DSB scores and increasing walking destination density was associated with worse DSF scores in African Americans, associations for the most part not observed in non-Hispanic whites (Table 7). Similarly, increasing proportion of land dedicated to residences was associated with better CASI scores in non-Hispanic whites but not in African Americans (Table 8).

The associations between all five BE measures and cognition varied significantly when comparing Hispanic and non-Hispanic white participants. Increasing social destination density was associated with significantly worse CASI and DS scores, and increasing walking destination density and intersection density were associated with worse CASI, DSB, and DS scores in Hispanics (Table 7). No associations were observed between these same BE and cognitive measures among non-Hispanic whites. Also in Hispanics, increasing proportion of land dedicated to residences was associated with better DSB and DS scores and increasing proportion of land dedicated to retail was associated with worse DS scores, with no such associations observed for non-Hispanic whites (Table 8).

4. Conclusions

This study provides cross-sectional evidence for an association between the neighborhood BE and cognition in older adults, independent of individual-level demographics and neighborhood-level SES. Unexpectedly, increasing social destination density, walking destination density, and intersection density were associated with worse cognition in the overall sample and more noticeably in individuals of non-white race. The exception to this pattern was the association between increasing proportion of land dedicated to retail and better cognition in the overall sample. However, the potentially beneficial association of more retail destinations in the neighborhood on cognition appeared to be limited to non-Hispanic whites and African American participants, as it was associated with significantly worse cognition in Chinese and Hispanic participants.

Although increasing densities of social and walking destinations were associated with worse cognition in this study, the results from past studies examining similar measures and cognition have been mixed. One study found that access to a community center was associated with slower cognitive decline (Clarke et al., 2015), another found that closer access to community resources (e.g., grocery store) was associated with worse cognition (Magaziner and Cadigan, 1989), while another found no association between presence of recreation centers and institutions in the neighborhood and cognition (Clarke et al., 2012). It was initially hypothesized that increased access to neighborhood social and walking destinations would be associated with improvements in cognition by improving PA levels, social engagement, mental health, or quality of life. The unexpected findings in this study may be due to residual confounding by unmeasured factors, increased exposure to air pollution due to increased walking in the neighborhood which worsens cognition, or factors related to study design (e.g., cross-sectional nature). Thus, additional research on the topic is necessary.

The negative relationship between intersection density and cognition in this study is comparable to findings from another study that used a different measure of street connectivity (i.e., integration) (Watts et al., 2015). The authors speculated that greater integration (less navigational turns to reach a given destination) may create cognitive overload among older adults because of the greater number of initial choices, or may induce stress when walking due to the associated higher levels of traffic. In that previous study, a separate measure of street connectivity (number paths/streets connected to a given street in the network) was associated with less cognitive decline, which the authors posited to be indicative of the benefits of increased accessibility or availability of walking or social destinations. However, increased accessibility to walking and social destinations was associated with worse cognition in our study. While our results were surprising and contrary to our hypothesis, neighborhoods with higher intersection densities may be associated with unmeasured aspects of the environment that negatively impact cognition, such as traffic, noise, or air pollution. Additional studies are needed to assess whether accessibility/street connectivity is negatively and causally related to cognition.

An increased proportion of the neighborhood dedicated to retail had a positive association with cognition. No other known studies have examined this particular measure in relation to cognition; however, two studies found that increased land use mix was associated with lower odds of cognitive impairment and dementia (Wu et al., 2015, 2017). It is possible that unlike other BE characteristics often consistent with increasing urban density, the availability of more retail destinations specifically may promote increased utilitarian physical activity or social engagement that is then associated with improved cognition. In addition or alternatively, increased retail availability may encourage spending time in the neighborhood, which may increase cognitively stimulating activity or may be associated with improved quality of life overall, thereby improving cognition. This is speculative, as much more work is needed to determine if the associations are causal and the underlying mechanisms to explain them.

The associations between increasing social destination density and worse cognition was only observed in those with low education and not those with higher levels of education. Two previous studies have demonstrated similar interactions between neighborhood characteristics and individual-level education in relation to cognitive outcomes (Aneshensel et al., 2011; Wight et al., 2006). The authors found that the associations between lower neighborhood SES and worse cognition were strongest in those with lower education levels. Considering our findings together with those previous studies, individuals of lower SES may be more vulnerable to any possible negative effects on cognition from neighborhood exposures typically consistent with increasing urban density. However, it must be noted that individual-level education did not modify most of the BE-cognition associations in this study. Other measures of individual-level SES were limited in the MESA dataset, and thus investigation of effect modification by other SES measures is called for in future studies.

BE characteristics often associated with increasing urban density may differentially impact individuals of non-white race. We found that Chinese, African American, and Hispanic participants had worse cognition if they lived in neighborhoods with greater social destination, walking destination, and intersection densities. Additionally, we found that living in neighborhoods with more retail destinations was associated with worse cognition in Chinese and Hispanic participants. At least two previous studies had relevant findings. In one study, Mexican Americans living in barrios (typically higher density) had worse cognition compared to Hispanics living in suburban neighborhoods (Espino et al., 2001). The other study found that presence of institutional resources in the neighborhood was associated with worse cognition in African Americans but better cognition among whites (Clarke et al., 2012). The associations in our study were found after controlling for individual-level and neighborhood-level SES, suggesting that other factors related to non-white race/ethnicity may increase vulnerability to the potentially harmful effects of increasing urban density on cognition.

Although at least one of the BE measures consistent with increasing urban density was associated with better processing speed among non-Hispanic white, Chinese, and African American participants, the same was not true for Hispanic participants. In addition, a large percentage of the associations with worse cognition were found for Hispanics versus the other races/ethnicities. Unlike the non-Hispanic whites who were almost all US born and spoke English as their primary language, 65% of Hispanics were foreign born and approximately half spoke Spanish as their primary language (data not shown). Among whites, certain BE characteristics may be associated with improvements in cognition through improvements in PA. In contrast, among Hispanics immigrants, a compact BE may have an overall negative effect if unfamiliar cultures or languages in the neighborhood cause cognitive overload. Alternatively, other unknown factors associated with Hispanic enclaves may help explain our observed associations. For instance, the associations between dense urban environments and worse cognition may be explained by lower levels of acculturation among Hispanics. We did not further investigate ethnic enclaves/acculturation in our analyses because the available measures on acculturation/primary language were highly correlated with race/ethnicity. New studies of the BE and cognition that are focused specifically on Hispanics will be the best positioned to address the potential impact of acculturation.

While outside the scope of our study, we quickly examined available data on food environments. Although the mean density of unfavorable food stores was similar between Hispanics and non-Hispanic whites, the median and 75th percentile were higher for Hispanics. It is possible that one or more of the BE measures included in our study were partial proxies for unfavorable food environments. Greater availability of fast food options has been associated with increased fast food consumption in younger adults (Boone-Heinonen et al., 2011). In turn, diabetes, a diet-related health condition, has been associated with brain atrophy and cognitive impairment (Roberts et al., 2014). Food environments as an inherent part of the BE may be associated with changes in diet, a risk factor previously demonstrated to influence cognition in older adults. Therefore, further examination of associations between neighborhood food environments and cognition may be a fruitful avenue for future research that may help explain our observed disparities.

The causal mechanisms to explain observed associations are unclear, and as one of the first to examine BE-cognition associations, this study was not expected to tease apart the potential mechanisms. However, we observed associations with each of the four cognitive tests, suggesting that the neighborhood BE may affect multiple aspects of cognition, including attention, short-term and working memory, and processing speed. The association between increasing urban density and better processing speed may be explained by the need for greater cognitive processing of complex urban environments, or could also be related to increased levels of overall PA in dense urban environments. Typically, processing speed slows with age and is associated with less white matter integrity in the brain (Albinet et al., 2012). In turn, white matter integrity is better preserved among older adults obtaining more PA (Tian et al., 2015). The negative associations may be explained by increased access to unhealthy foods, stress, or psychosocial responses (e.g., fear of others) that can accompany increasing urban density, which may decrease healthy behaviors or quality of life, worsening cognition. Overall, our study suggests differing associations between the BE and cognition based on the cognitive domain examined. Specific aspects of the BE may affect only specific cognitive domains, and keeping these measures as explicit as possible in future studies may help elucidate the causal mechanisms.

The strengths of this study included the use a multi-ethnic, multi-site cohort recruited through population-based methods, which improves the generalizability of the findings. MESA provides a rich source of demographic, clinical, and neighborhood data that allowed for the control of important confounders. Additionally, when the ¼- and 1-mile BE measures were used instead of the ½-mile measures, the findings changed in some instances but were generally similar in the direction of the association, suggesting that the findings are relatively robust regardless of the neighborhood scale (i.e., buffer size) used.

Nevertheless, this study has limitations, first and foremost its cross-sectional nature. Our results must be replicated in other cohorts and using methods that consider longitudinal measures of the BE and cognition to provide evidence for a causal association. We were not able to account for bias due to neighborhood self-selection, in which preferences for moving to a particular BE may also be related to an individual's cognition or factors associated with cognition (James et al., 2015). However, the large majority of MESA participants did not move since their baseline exam (Hirsch et al., 2014) and almost half did not move during the 20 years preceding MESA enrollment (Murray et al., 2010), consistent with the expectation of decreased residential mobility with age (Plane et al., 2005). There is some evidence that the MESA participants tended to move between neighborhoods with similar SES levels (Murray et al., 2010), and future research should examine whether this pattern can be extrapolated to neighborhood BE characteristics. The inconsistency of findings between our study and past studies may relate to differences in the definitions of the BE characteristics, the neighborhood scales (e.g., ½-mile surrounding home versus US Census tract), the cognitive measures used, the study designs (e.g., longitudinal or cross-sectional), or the sample selection. Additionally, attrition since enrollment into the study may have affected our findings, as those who remained in MESA as of the Exam 5 were more often of higher SES, married, and non-Hispanic white (data not shown). Finally, unmeasured aspects of the neighborhood or residual confounding by individual-level factors may have biased our results. Future research must carefully consider the individual-level and neighborhood-level characteristics that are likely mediators versus confounders of the BE-cognition association, as well as which characteristics are more likely to be independent predictors of cognition and therefore not confounders. An example would be neighborhood social characteristics, which in this study were hypothesized to be either mediators or independent predictors of cognition but not confounders of the BE-cognition associations, and therefore, were not controlled for in our analyses.

Subsequent studies should employ a more expansive cognitive test battery than available in MESA, to explore other cognitive domains that may be associated with the neighborhood BE and to help address the limitations the CASI, a brief cognitive test of overall cognition. Although not available for all six MESA sites, neighborhood parks and greenspace could be examined in future studies, as they have been previously associated with increased PA (Sugiyama et al., 2010) and improved mental health (Sturm and Cohen, 2014), and thus may be associated with cognition. In addition, other BE scales may be important to consider in tandem with the immediately surrounding neighborhood environment, such as the bordering neighborhoods and their availability of social or walking destinations or transit connections. Finally, new studies may benefit from consideration of BE typologies, sets of BE characteristics that typically accompany one another (e.g., higher intersection density is correlated with higher walking destination density), given that their individual-level effects may be difficult to disentangle.

In this study, neighborhood BE characteristics were cross-sectionally associated with cognition in older adults, and many BE-cognition associations varied by race/ethnicity, suggesting these associations are complex and depend on individual-level characteristics. The findings have significant implications for urban planning for equity if replicated in future studies. Compact growth principles, which increase urban density and have been recommended as a way of allowing older adults to age in place, may have detrimental effects on the cognitive functioning of vulnerable populations. Ideally, planners and public health researchers would evaluate compact growth policy implications on diverse populations of older adults, and weigh the potentially positive (e.g., increased PA) and negative consequences to health (e.g., worse cognition). In the process, additional policies and programs could be devised to offset any potential harmful effects of increased urban density on cognition among susceptible individuals. However, before our findings can be incorporated into urban planning considerations, our results must be replicated in longitudinal studies and in other regional samples.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.socscimed.2018.01.007.

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