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Original Contribution

Associations Between the Built Environment and Objective Measures of Sleep

The Multi-Ethnic Study of Atherosclerosis

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Although dense neighborhood built environments support increased physical activity and lower obesity, these features may also disturb sleep. Therefore, we sought to understand the association between the built environment and objectively measured sleep. From 2010 to 2013, we analyzed data from examination 5 of the Multi-Ethnic Study of Atherosclerosis, a diverse population from 6 US cities. We fit multilevel models that assessed the association between the built environment (Street Smart Walk Score, social engagement destinations, street intersections, and population density) and sleep duration or efficiency from 1-week wrist actigraphy in 1,889 individuals. After adjustment for covariates, a 1-standard-deviation increase in Street Smart Walk Score was associated with 23% higher odds of short sleep duration (≤6 hours; odds ratio = 1.2, 95% confidence interval: 1.0, 1.4), as well as shorter average sleep duration (mean difference = −8.1 minutes, 95% confidence interval: −12.1, −4.2). Results were consistent across other built environment measures. Associations were attenuated after adjustment for survey-based measure of neighborhood noise. Dense neighborhood development may have multiple health consequence. In promoting denser neighborhoods to increase walkability, it is important to also implement strategies that reduce the adverse impacts of this development on sleep, such as noise reductions efforts.

cohort; neighborhoods; noise; sleep

Abbreviations: BE, built environment; CI, confidence interval; MESA, Multi-Ethnic Study of Atherosclerosis; SD, standard deviation; SS, Street Smart.

Sleep disturbances and sleep loss are prevalent in the United States (1). It is estimated that 25% of American adults report insufficient sleep or rest at least 15 out of every 30 days, whereas 29% report sleeping less than 7 hours per night (2). Sleep problems are associated with lost productivity, motor vehicle crashes, and health outcomes that include heart disease, high blood pressure, obesity, diabetes, stroke, and all-cause mortality (3, 4). Population strategies to improve sleep require an understanding of risk factors for poor sleep, which include contextual factors such as built environments (BE).

Neighborhood BE may influence sleep through a myriad of complex pathways. BE characterized by high density and more destinations could be beneficial for sleep by promoting physical activity (which can have direct beneficial effects on sleep quality), or by affecting pathways that involve adiposity or propensity for sleep apnea (5–7). Conversely, BE could have adverse effects on sleep through associations with noise, traffic, air pollution, and inopportune light exposures, which are all associated with poor sleep (8, 9). Air pollution may influence inflammation and neurotransmitters involved in sleep and sleep-related breathing disorders (9). High traffic, noise, or inopportune light exposures may lead to heightened arousal, which may result in decreased sleep efficiency and increased awakenings (10). Older populations may be more vulnerable to the effects of neighborhood environment and sleep because of underlying chronic health conditions.

Understanding the link between BE and sleep is especially important given recent policies promoting high density development for health and sustainability (11). To date, there has been limited investigation of the relationships between BE and sleep, with existing work that broadly examines access to recreational facilities (12), green space (13), and urbanization (10, 14, 15). Using objectively measured BE and sleep data, we investigated the associations of BE with sleep duration and efficiency in the Multi-Ethnic Study of Atherosclerosis (MESA). In secondary analyses, we explored survey-reported measures of neighborhood noise as a factor that could partially explain the influence of BE on sleep outcomes. Because of previous research that showed sleep differences by sex (16) and the potential sex differences in coping mechanisms for environmental sleep disturbances, we investigated sex interactions in our exploratory analyses.

METHODS

MESA is a longitudinal study of 6,814 US adults between the ages of 45 and 84 years from 6 communities (Baltimore, Maryland; Chicago, Illinois; Forsyth County, North Carolina; Los Angeles, California; New York, New York; and Minneapolis-St. Paul, Minnesota) (17). MESA was designed to prospectively investigate risk factors for subclinical cardiovascular disease and progression to clinical disease across racial/ethnic groups including non-Hispanic white, African-American or black, Hispanic, and Asian/Chinese. Participants without cardiovascular diseases were recruited between July 2000 and August 2002, and were administered 4 follow-up examinations. Current analyses utilize data on sleep measures and neighborhood characteristics from 2 MESA ancillary studies that were collected with the fourth follow-up examination (examination 5) between April 2010 and February 2012. Institutional Review Board approval was obtained at each study site and written informed consent was obtained from all participants.

Neighborhood built environment

Neighborhood BE was characterized using Geographic Information Systems and linked to MESA households as part of the MESA Neighborhood Ancillary study. Examination 5 residential addresses were geocoded using the TeleAtlas EZ-Locate web-based software (Lebanon, New Hampshire). We analyzed walkability using the Street Smart (SS) Walk Score (www.walkscore.com) for each residential address, obtained from Redfin (Seattle, Washington) in August 2015. As a composite measure, SS Walk Score may be challenging for urban planners who are trying to translate research into policy. Therefore, we also analyzed 3 specific BE indicators that capture walkability (18) and that have previously been associated with walking in MESA (19–21): 1) population density, 2) street connectivity, and 3) social engagement destinations. These measures were used for 2 reasons. First, they are similar to components of the SS Walk Score, which allowed us to determine which specific features influence sleep. Second, they may be related to higher exposures to noise, light, or air pollution that may explain the association between walkability and sleep. The SS Walk Score algorithm produces scores ranging from 0 to 100 (higher scores indicate better walkability), on the basis of a distance decay to various destinations (e.g., restaurants, shopping, schools, parks, or entertainment) within 1.5 miles and was adjusted for street network characteristics (e.g. low intersection density and high block length) (22). SS Walk Score utilizes network distances by following streets to amenities and allows for multiple amenities within each category. We used standard developer SS Walk Score cutpoints, where 0–24 indicated "very car-dependent," 25–49 indicated "car-dependent," 50–69 indicated "somewhat walkable," 70–89 indicated "very walkable," and 90–100 indicated "walker's paradise."

For population density, street connectivity, and social engagement destinations, neighborhoods were defined as half-mile Euclidean buffers. Half mile was chosen because BE elements which might influence sleep (e.g., noise, light, or traffic) are at close proximity. Sensitivity analyses were performed using 1-mile and quarter-mile Euclidean buffers; results were similar (not shown). Population density was measured as population per square mile, obtained from the 2010 US Census at block level divided by land area. When a block was not fully contained within a participant's buffer, the population was assumed to be uniform within each block. Street network was obtained using the 2012 StreetMap Premium for ArcGIS (Esri, Redlands, California). Street connectivity was measured by intersection density, counting the number of intersections within the buffer divided by land area in hectares. Destinations that promote social engagement were purchased from the National Establishment Time-Series database (Walls & Associates, Denver, Colorado) and classified using 8-digit standard industry classification codes. From previous work, 430 standard industry classification codes were selected on the basis of likelihood of facilitating social interaction and promoting social engagement (e.g., beauty shops/barbers, entertainment venues, recreation clubs, libraries, museums, civil and political clubs, religious locations, night clubs and dining places) (23). Density (count per square mile) was created as the number of locations in business in 2010 within the buffer divided by land area. Sensitivity analyses were performed using only nighttime locations (e.g., bars or nightclubs). Results were similar for these types of locations and all other locations (Web Tables 1 and 2, available at https://academic.oup.com/aje). Exposures were transformed to z scores for ease of comparison.

Neighborhood survey-based noise

Survey-based noise was assessed by administering questionnaires to participants. Participants described their neighborhood (defined as a 20-minute walk, or about a mile) by responding to the question "There is a lot of noise in my neighborhood" on a 5-point scale ranging from (1) "strongly agree" to (5) "strongly disagree." To obtain a neighborhood aggregate noise measure, the same question was administered to a random sample of residents of selected census tracts in the 6 study sites between August 2011 and May 2012. Values were reverse coded so higher scores indicated more noise. Neighborhood-level noise was measured by taking the mean of responses for all respondents living within a 1-mile buffer of the participant, excluding their own response. By averaging across individuals, a more valid measure of the objective reality of neighborhoods was obtained. This was also transformed to z score for comparison.

Sleep measures

Between 2010 and 2013, sleep patterns were assessed using a 1-week wrist actigraphy as part of the MESA Sleep

Ancillary study. Participants wore Actiwatch Spectrum devices (Philips Respironics, Murrysville, Pennsylvania) on their nondominant wrists for 7 consecutive days, while completing a sleep diary (24). A centralized reading center at Brigham and Women's Hospital (Boston, Massachusetts) scored all records. Details regarding measurement and scoring of actigraphic data have been previously published (25). In brief, sleep-wake status for each 30-second epoch within each rest period was computed using Actiware-Sleep scoring algorithm (version 5.59). Sleep onset was defined as 5 immobile minutes, and sleep offset was defined as 0 immobile minutes and a wake threshold of 40 counts. We examined sleep duration as the sum of all epochs scored as sleep in the main sleep period, measured in minutes. We also examined sleep efficiency, a measure of sleep continuity and disturbed sleep, which was defined as the proportion of epochs between sleep onset and offset scored as sleep. Each actigraphy-measured sleep variable was computed for each recording night and averaged across all recorded nights. Individuals with at least 5 nights of data were included, which composed 95.4% of the MESA sleep study population.

Covariates

Covariates that were selected a priori as potential confounders included individual sociodemographics (age, sex, race/ethnicity, education, household income), neighborhood socioeconomic status, health-related behaviors (smoking, alcohol use, physical activity), body mass index, and depressive symptoms.

Age and sex were self-reported. Race/ethnicity was classified as non-Hispanic white, non-Hispanic black, Hispanic, and Asian/Chinese. Education was selected from 8 categories and a continuous measure of education years was derived using midpoints of selected categories. Similarly, combined family income was selected from 15 categories and a continuous measure was derived using category midpoints.

Smoking status was self-reported and categorized as current, former, or never smoker. Alcohol use was categorized as never (0 drinks/week), moderate (≤7 drinks/week for women; <14 drinks/week for men) and heavy (>7 drinks/week for women; >15 drinks/week for men) (26). Physical activity, assessed by a questionnaire adapted from the Cross-Cultural Activity Participation Study (27), was measured as moderate to vigorous in metabolic equivalent minutes per week and categorized into quartiles. Height and weight were measured and body mass index was calculated as ratio of weight to height squared. Depressive symptomology was assessed with the Center for Epidemiologic Studies of Depression scale (after removal of the sleep item) and modeled continuously (28).

Neighborhood socioeconomic status was characterized on the basis of a factor score derived from principal components analysis of US census tract-level data from the American Community Survey 5-year estimates for the years 2007–2011 (29). The factor score includes median household income, percentage of homes with interest and dividends, median value of owner-occupied housing, percentage of residents with at least a high school diploma, percentage of residents with at least a bachelor's degree, and percentage of residents employed in managerial professions.

Statistical analysis

Participants with complete neighborhood and sleep data and geocodes accurate to the street or zip code +4 level were included in analyses, which accounted for 40.1% of the examination 5 sample. This resulted in a sample size of 1,889 individuals. Because of missing data, analyses including neighborhood-level noise had a sample size of 1,767 individuals.

We used χ^2 or analysis of variance to test for differences in covariates, BE exposures, and outcomes by 5 categories of SS Walk Score. To examine the relationship between BE and sleep, we used a series of multilevel models. Linear and logistic multi-level models, with a random intercept for each census tract (as a proxy for neighborhood), were used in the main analyses. See the Web Appendix for more details and for the intraclass correlations (Web Table 3). Sleep duration was categorized as short (≤6 hours), normal (>6 but <9 hours), and long (≥9 hours) in some analyses and analyzed continuously in minutes in other analyses. In logistic regression models, because of small sample size for long sleep ($n = 33$), we compared short versus normal or long sleep. Sleep efficiency was analyzed continuously.

We utilized a sequential modeling approach. BE measures were model-adjusted for individual sociodemographics and neighborhood socioeconomic status (model 1), and then were further adjusted for smoking, alcohol use, body mass index, and depressive symptoms (model 2). Additionally, an adjustment for physical activity (quartiles) was included (model 3). Physical activity was examined in a separate model because it could function as a potential negative confounder of the association between greater walkability and adverse sleep outcomes, as greater walkability has been shown to be linked to more physical activity, which could in turn result in better sleep. Sensitivity analyses were performed with the addition of chronic illness, as measured by hypertension (systolic blood pressure ≥140 mmHg, diastolic blood pressure ≥90 mmHg, or use of antihypertensive medication), diabetes (fasting glucose ≥126 mg/dL or use of insulin or oral hypoglycemic medication), and emphysema/chronic obstructive pulmonary disease (self-reported). Results were similar to model 3 (not shown).

Each BE measure was modeled in separate models. To test the impact of neighborhood-level survey-based noise on the association between BE and sleep measures, noise was added to all models described above. Because results are consistent across models, and results from fully adjusted models (model 3 described above) are shown. All analyses were performed using SAS software, version 9.3 (SAS Institute, Inc., Cary, North Carolina).

RESULTS

Just over half of all participants were women (53.8%), and also composed a higher percentage of those in "walker's paradise" (60.3%) (Table 1). Residents of "car dependent" neighborhoods were more likely to be non-Hispanic white and non-Hispanic black and less likely to be Hispanic and Chinese than residents of other neighborhoods. Neighborhood disadvantage scores had a U-shape relationship with SS Walk Score; disadvantage was less frequent in both low- and high-walkability neighborhoods. Although all walkability categories were represented in Maryland, Minnesota, Illinois, and California, the North Carolina study site had no "very walkable" or "walker's paradise" neighborhoods and the New York study site had almost no "car dependent" neighborhoods. More than 90% of the sample were former or never smokers, and over 50% did not currently drink alcohol. The mean depressive symptoms score was highest in the most walkable neighborhoods (6.3 (standard deviation (SD), 6.8)) compared with the least walkable neighborhoods (9.0 (SD, 8.3)). As expected, social engagement destinations, intersection density, population density, and neighborhood-level survey-based noise all increased with walkability as measured by the SS Walk Score.

Average sleep duration was 6.5 hours, or 390.4 minutes (SD, 80.6). In unadjusted analyses, mean sleep duration was highest among participants in "car-dependent" neighborhoods (400.3 (SD, 76.6)) and decreased with increasing walkability (Table 1). Higher social engagement destination density, intersection density, population density, and SS Walk Score were associated with shorter average sleep time, higher odds of short sleep duration, and lower average sleep efficiency (Table 2). After adjustment for individual- and neighborhood-level sociodemographic characteristics, as well as individual health behaviors and outcomes, a standard deviation higher SS Walk Score was estimated to be associated with a mean 8.1 minutes of fewer sleep (95% confidence interval (CI): −12.1, −4.2). Qualitatively similar associations were observed for a standard deviation difference in social engagement destinations (−6.5 minutes, 95% CI: −11.2, −1.7), intersection density (−4.7 minutes, 95% CI: −8.7, −0.7), and population density (−7.7 minutes, 95% CI: −11.9, −3.6).

A standard deviation higher social engagement destination, population density, and SS Walk Score was associated with 21% higher odds (adjusted odds ratio = 1.2, CI: 1.0, 1.4), 17% higher odds (adjusted odds ratio = 1.2, 95% CI: 1.0, 1.3), and 23% higher odds (adjusted odds ratio = 1.2, 95% CI: 1.0, 1.4) of short sleep duration, respectively. After adjusting for all covariates, only intersection density was statistically significantly associated with decreased average sleep efficiency (adjusted mean difference = −0.2, 95% CI: −0.4, −0.1).

Higher neighborhood-level survey-based noise was associated with shorter average sleep time (adjusted mean difference = −7.7, 95% CI: −11.7, −3.7), higher odds of short sleep duration (adjusted odds ratio = 1.2, 95% CI: 1.0, 1.3) and decreased average sleep efficiency (adjusted mean difference = −0.2%, 95% CI: −0.4, 0.0). Neighborhood-level noise was correlated with BE measures (Spearman correlations: 0.7–0.8). Models that included noise resulted in attenuated associations of BE features with sleep (Table 3). For sleep duration, the association of SS Walk Score was reduced by 22.9% (−9.1 minutes (95% CI: −13.2, −5.0) versus −7.0 minutes (95% CI: −12.7, −1.3)), with a similar reduction observed in population density (−8.7 minutes (95% CI: −12.9, −4.6) versus −6.2 minutes (95% CI: −11.4, −0.9)). Larger relative reductions in the associations for social engagement destinations (−7.6 minutes (95% CI: −12.4, −2.8) versus −3.5 minutes (95% CI: −9.4, 2.3)) and intersection density (−6.0 minutes (95% CI: −10.1, −1.9) versus −2.3 minutes (95% CI: −7.3, 2.7)) were observed. The association of BE measures with odds of shorter sleep was also attenuated with the adjustment for neighborhood-level noise, with observed reductions ranging between 1% and 6%.

There was no evidence of effect modification by sex in any analysis. Also, in sensitivity analyses we adjusted for site, and found that results were in the same direction but attenuated (see Web Tables 4 and 5).

DISCUSSION

In geographically and racially/ethnically diverse middle-aged and older adults, higher neighborhood walkability (characterized by SS Walk Score, population density, intersection density, and social destinations) was associated with shorter average sleep duration. Other measures of sleep continuity and quality were weakly associated with indices of neighborhood walkability, where the only significant adjusted association observed was for sleep efficiency and intersection density. This is among the first studies to report associations of BE with sleep. It provides evidence indicating that characteristics associated with walkability are associated with small average decreases in nightly sleep duration. The associations of more walkable environments with poorer sleep outcomes were attenuated when noise was taken into consideration. On average, a standard deviation higher walkability was associated with 23% higher odds of short sleep. A standard deviation higher walkability score was associated with an average of 8 minutes less sleep at night.

Although the magnitudes of these associations are small, they are comparable to the sizes of the associations observed for other important sleep risk factors. For example, in the same data, a 5-unit higher body mass index is associated with 26% higher odds of short sleep. Short sleep duration has been linked to higher prevalence of cardiovascular risk factors, as well as increased risk of cardiovascular disease (30–35). Future research is needed to replicate our findings and determine the implications for health.

Although previous work has not directly examined associations of neighborhood BE features with objectively measured sleep-wake patterns among adults, our findings are consistent with existing literature that show that residence in urban environments is associated with shorter sleep duration for both adults (10) and infants (14). Despite evidence that neighborhood social environment or physical disorder influences other sleep outcomes such as insomnia and daytime sleepiness (36, 37), we found no statistically significant associations between BE and wake after sleep onset, sleep latency, insomnia, and daytime sleepiness. This may reflect differences in the environmental measurements assessed in each study. Attention should be paid to the myriad of features that compose neighborhood environments as they may have differing impacts on sleep.

The pathways through which neighborhood BE may influence sleep are complex. Various intervening mechanisms could result in opposing effects. There are numerous potential pathways through which more walkable neighborhoods could negatively influence sleep, including noise, inopportune light exposure, traffic, air pollution, and stress. Conversely, dense neighborhood BE have been shown to be associated with increased walking or physical activity, as well as decreased obesity, all of which have been associated with better sleep (7).

Table 1. Sociodemographic, Built Environment, and Sleep Characteristics by Street Smart Walk Score Walkability Category, Examination 5, Multi-Ethnic Study of Atherosclerosis, 2010–2012

Characteristic	Overall (n = 1,889)		0–24: Car Dependent (n = 452)		25–49: Car Dependent (n = 349)		50–69: Somewhat Walkable (n = 376)		70–89: Very Walkable (n = 337)		90–100: Walker's Paradise (n = 375)		*P* Value
	Mean (SD)	%	Mean (SD)	%	Mean (SD)	%	Mean (SD)	%	Mean (SD)	%	Mean (SD)	%	
Sociodemographic													
Age, years	68.6 (9.2)		68.4 (8.8)		68.0 (9.3)		68.3 (9.1)		69.0 (9.2)		69.5 (9.6)		0.16
Women		53.8		51.1		52.1		55.8		49.5		60.3	0.03
Race/ethnicity													<0.01
White		38.9		49.8		41.5		32.4		32.6		35.5	
Chinese		12.2		8.2		12.0		18.3		20.2		4.0	
African-American/black		27.0		32.1		23.8		27.4		27.0		23.5	
Hispanic		21.9		10.0		22.6		21.8		20.2		37.1	
Education, years	13.6 (3.9)		14.6 (2.7)		13.4 (3.6)		13.1 (4.0)		13.4 (4.5)		13.1 (4.4)		<0.01
Income (per $1,000)	55.0 (35.6)		64.2 (35.8)		54.3 (33.8)		47.8 (33.4)		53.6 (35.9)		52.9 (36.7)		<0.01
Neighborhood disadvantage score	−0.5 (1.2)		−0.3 (0.9)		−0.2 (0.8)		−0.0 (1.0)		−0.5 (1.2)		−1.5 (1.5)		<0.01
Study site													<0.01
Forsyth County, North Carolina		15.7		49.1		16.0		5.0		0.0		0.0	
New York, New York		16.1		0.7		0.6		2.4		9.8		68.8	
Baltimore, Maryland		14.9		17.3		20.9		18.3		14.0		3.7	
St. Paul, Minnesota		18.2		17.7		39.3		26.3		7.7		0.3	
Chicago, Illinois		18.6		8.0		6.9		16.2		39.2		26.1	
Los Angeles, California		16.5		7.3		16.3		31.6		29.4		1.1	
Health													
Smoking status													0.16
Never smoker		46.8		42.9		47.8		47.6		46.0		50.7	
Former smoker		46.3		51.3		44.4		43.3		48.1		43.2	
Current smoker		6.9		5.7		7.7		9.0		5.9		6.1	
Alcohol consumption													0.01
Not current user		56.5		52.6		55.9		56.1		58.2		60.8	
Moderate		36.2		42.0		38.4		35.9		33.8		29.3	
Heavy		7.3		5.3		5.7		8.0		8.0		9.9	
BMI[a]	28.7 (5.5)		29.3 (5.9)		28.8 (5.1)		28.5 (5.3)		28.1 (5.5)		28.7 (5.6)		0.06
Depressive symptoms (CES-D (excluding sleep score))	7.4 (7.2)		6.3 (6.8)		6.9 (6.7)		7.1 (7.2)		7.6 (6.6)		9.0 (8.3)		<0.01

Table continues

Table 1. Continued

Characteristic	Overall (n = 1,889)		0–24: Car Dependent (n = 452)		25–49: Car Dependent (n = 349)		50–69: Somewhat Walkable (n = 376)		70–89: Very Walkable (n = 337)		90–100: Walker's Paradise (n = 375)		*P* Value
	Mean (SD)	%	Mean (SD)	%	Mean (SD)	%	Mean (SD)	%	Mean (SD)	%	Mean (SD)	%	
Moderate-vigorous physical activity, METs													
0–1,724		24.9		18.6		23.8		31.6		27.6		24.5	0.01
1,725–3,456		25.0		29.6		25.2		21.8		24.0		23.2	
3,457–6,629		25.1		26.1		23.8		24.2		27.0		24.3	
6,630–34,290		25.0		25.7		27.2		22.3		21.4		28.0	
Built environment													
Social engagement destinations per mile^{2}[b]	141.2 (222.5)		11.3 (10.3)		31.3 (23.0)		65.0 (84.4)		113.9 (55.5)		501.1 (267.3)		<0.01
Intersection density per hectare[b]	0.8 (0.5)		0.3 (0.2)		0.6 (0.2)		0.7 (0.2)		1.0 (0.5)		1.4 (0.5)		<0.01
Population density per mile^{2}[b]	18.2 (25.6)		2.2 (1.5)		5.3 (2.6)		8.9 (6.9)		15.1 (7.7)		61.4 (27.6)		<0.01
SS Walk Score	54.4 (31.8)		—[c]		—[c]		—[c]		—[c]		—[c]		—[c]
Neighborhood survey-based noise[d]	1.5 (0.6)		0.9 (0.4)		1.2 (0.4)		1.4 (0.4)		1.6 (0.4)		2.2 (0.3)		<0.01
Sleep outcomes													
Average sleep time, minutes	390.4 (80.6)		400.3 (76.6)		391.8 (81.1)		393.9 (75.6)		383.3 (83.8)		380.0 (85.3)		<0.01
Average sleep time, hours													
≤6		29.8		24.1		28.6		29.3		34.1		34.4	0.03
>6 but <9		68.4		74.3		68.5		69.1		64.7		64.0	
≥9		1.7		1.5		2.9		1.6		1.2		1.6	
Average sleep efficiency, %	89.9 (3.6)		90.2 (3.4)		89.6 (4.0)		90.0 (3.4)		89.7 (3.4)		89.8 (3.8)		0.17

Abbreviations: BMI, body mass index; CES-D, Center for Epidemiologic Studies Depression; MET, metabolic equivalent of task; SD, standard deviation; SS, Street Smart.
[a] Weight (kg)/height (m)^2.
[b] Density measured within a half mile of the study participant's home address.
[c] SS Walk Score is not shown in bivariate association with itself.
[d] Mean of respondents within 1 mile of the study participant's home address (n = 1,767).

Table 2. Mean Differences in Average Sleep Time, Odds Ratios of Short Sleep, and Mean Differences in Average Sleep Efficiency for a 1-Standard-Deviation Difference in Built Environment Features (*n* = 1,889), Multi-Ethnic Study of Atherosclerosis, 2010–2012

Sleep Parameter	Model 1[a]		Model 2[b]		Model 3[c]	
	β	95% CI	β	95% CI	β	95% CI
Average sleep time, minutes						
Social engagement destinations per mile^2	−6.6	−11.3, −1.8	−6.4	−11.1, −1.7	−6.5	−11.2, −1.7
Intersection density per hectare	−4.8	−8.8, −0.7	−4.7	−8.7, −0.7	−4.7	−8.7, −0.7
Population density per mile^2	−8.0	−12.2, −3.9	−7.8	−11.9, −3.6	−7.7	−11.9, −3.6
SS Walk Score	−8.0	−11.9, −4.0	−8.1	−12.1, −4.2	−8.1	−12.1, −4.2
Average efficiency, %						
Social engagement destinations per mile^2	0.0	−0.3, 0.2	0.0	−0.3, 0.2	0.0	−0.3, 0.2
Intersection density per hectare	−0.2	−0.4, −0.1	−0.2	−0.4, −0.1	−0.2	−0.4, −0.1
Population density per mile^2	−0.2	−0.4, 0.0	−0.2	−0.4, 0.0	−0.2	−0.4, 0.0
SS Walk Score	−0.1	−0.3, 0.1	−0.1	−0.3, 0.1	−0.1	−0.3, 0.1
	OR	**95% CI**	**OR**	**95% CI**	**OR**	**95% CI**
Short sleep[d]						
Social engagement destinations per mile^2	1.2	1.1, 1.4	1.2	1.0, 1.4	1.2	1.0, 1.4
Intersection density per hectare	1.1	1.0, 1.3	1.1	1.0, 1.3	1.1	1.0, 1.3
Population density per mile^2	1.2	1.1, 1.3	1.2	1.0, 1.3	1.2	1.0, 1.3
SS Walk Score	1.2	1.1, 1.4	1.2	1.0, 1.4	1.2	1.0, 1.4

Abbreviations: CI, confidence interval; OR, odds ratio; SS, Street Smart.

[a] Model 1 was adjusted for sex, race, age, age squared, educational level, income, and neighborhood socioeconomic status.

[b] Model 2 was adjusted for the variables in model 1 and smoking, alcohol consumption, body mass index, and depressive symptoms, as measured using the Center for Epidemiologic Studies–Depression Scale.

[c] Model 3 was adjusted for the variables in model 2 and physical activity level.

[d] Short sleep was defined as ≤6 hours (vs. >6 hours).

Previous evidence has shown both noise and light exposure to be associated with shorter sleep duration across various populations (8). Places with more people and destinations could generate additional disturbances that do not exist in less populated, more isolated neighborhoods. Furthermore, mixed-use neighborhoods with retail interspersed with residential areas may have more turnover of businesses, causing intermittent disturbances such as construction. Residing in neighborhoods proximate to transportation routes may be sources of nighttime noise (8). When adjusting for neighborhood-level survey-based noise, we observed an attenuated association between the BE and sleep duration, which suggests that noise may explain some of the association. Our noise measure was limited as it was determined on the basis of a single question, and we potentially underestimated its contribution to sleep disturbance. Additional research that uses more comprehensive noise measures is needed to better quantify its contributions to sleep across neighborhoods.

In the present study, intersection and population density were both associated with sleep duration. These associations deserve further exploration as they could represent the impact of traffic and air pollution. Intersection density could result in higher volume of cars and increased stop-and-go traffic, which could result in both increased noise and air pollution. Air pollution may activate pulmonary and systemic inflammation, which adversely affects sleep (9). Emerging literature has begun to examine the competing risks of walkability and air pollution (38), but future work should continue to expand on this with particular attention to their subsequent influence on sleep.

Despite evidence in the MESA cohort that BE are associated with more walking (19–21) and less obesity (21, 39), it is plausible that the amounts of increase in physical activity and decrease in obesity may not be sufficient to generate better sleep outcomes. In sensitivity analyses that adjusted for physical activity, the negative association between BE measures and sleep persisted.

Strengths and limitations

To our knowledge, the present study is the first to quantify the association between objectively measured BE characteristics and objective measures of sleep-wake patterns by using numerous BE metrics derived from geographic information systems and 7-day wrist actigraphy. However, our metrics do not capture smaller-scale aesthetic features, such as green space or sidewalks, which may be related to sleep (13). Our measure of walkability is highly correlated with urbanicity

Table 3. Mean Differences in Average Sleep Time, Odds Ratios of Short Sleep, and Mean Differences in Average Sleep Efficiency for a 1-Standard-Deviation Difference in Built Environment Features and Neighborhood Survey-Based Noise (*n* = 1,767), Multi-Ethnic Study of Atherosclerosis, 2010–2012

Exposure	Model 1[a]		Model 2[b]	
	β	95% CI	β	95% CI
Average sleep time, minutes				
Social engagement destinations per mile^2	−7.6	−12.4, −2.8	−3.5	−9.4, 2.3
Intersection density per hectare	−6.0	−10.1, −1.9	−2.3	−7.3, 2.7
Population density per mile^2	−8.7	−12.9, −4.6	−6.2	−11.4, −0.9
SS Walk Score	−9.1	−13.2, −5.0	−7.0	−12.7, −1.3
Average efficiency, %				
Social engagement destinations per mile^2	−0.1	−0.3, 0.2	0.1	−0.2, 0.4
Intersection density per hectare	−0.2	−0.4, 0.0	−0.1	−0.4, 0.1
Population density per mile^2	−0.2	−0.4, 0.0	−0.1	−0.4, 0.1
SS Walk Score	−0.1	−0.3, 0.1	0.1	−0.2, 0.4
	OR	**95% CI**	**OR**	**95% CI**
Short sleep[c]				
Social engagement destinations per mile^2	1.2	1.1, 1.4	1.2	1.0, 1.4
Intersection density per hectare	1.1	1.0, 1.3	1.1	0.9, 1.2
Population density per mile^2	1.2	1.0, 1.3	1.1	0.9, 1.3
SS Walk Score	1.3	1.1, 1.4	1.3	1.0, 1.5

Abbreviations: CI, confidence interval; OR, odds ratio; SS, Street Smart.

[a] Model 1 includes only the built environment exposure, which was adjusted for sex, race, age, age squared, educational level, income, neighborhood socioeconomic status, smoking, alcohol consumption, body mass index, depressive symptoms (as measured using the Center for Epidemiologic Studies–Depression Scale), and physical activity level.

[b] Model 2 was adjusted for the variables in model 1 and neighborhood noise exposure. Values for neighborhood aggregate noise are as follows: average sleep time (minutes), mean difference = −7.7, 95% CI: −11.7, −3.7; for short sleep, odds ratio = 1.2, 95% CI: 1.0, 1.3; and for average efficiency (%), mean difference = −0.2, 95% CI: −0.4, 0.0.

[c] Short sleep was defined as ≤6 hours (vs. >6 hours).

and therefore may be capturing sleep consequences of urbanicity mediated by factors such as noise, light, and air pollution.

Although we tested the association at varying buffer sizes, some misspecification of spatial context relevant to sleep is likely to be present (40, 41). We accounted for correlation in the errors of participants living in the same census tract, but some residual correlation may exist with participants in neighboring tracts. Although polysomnography is the gold standard for sleep measurement, actigraphy has been shown to be valid and correlates with sleep estimations made by polysomnography (42). There are other psychosocial measures (such as anxiety) and environmental measures (such as light) which may confound or mediate the association between the BE and sleep. The present study uses a diverse population of individuals, across numerous geographic locations in the United States. However, this sample is not a population-representative sample and results may not be generalizable to other populations that include adolescents, younger adults, or those in other geographic regions. Future work should utilize longitudinal methods to establish temporality, as our cross-sectional analyses cannot determine causality.

Lastly, residual confounding by unmeasured individual and neighborhood characteristics is always a possibility in observational studies such as ours. Given strong associations between site and BE features, it was not possible to reliably estimate associations of BE features with sleep after adjusting for site, as site is essentially a rough proxy for BE. We have no reason to believe that site affects sleep through pathways not involving other factors present in the models (including BE features themselves); therefore we believe models unadjusted for site are our best approximations of the causal effects of BE within constraints of observational studies and data at our disposal.

Public health implications

We found evidence of associations between neighborhood walkability and shorter sleep duration, which were partially explained by noise. Although BE measures have been associated with better health outcomes (43), our results suggest the need for a deeper consideration of BE influences (including potential adverse effects on noise, light and air pollution) as policies are developed for dense, urban form. By focusing on select outcomes, previous work may have failed to capture the full realm of health impacts of BE. Potential countervailing influences of promoting higher density and street connectivity on physical activity and sleep should be further considered. Given the benefits of walkability, future studies should identify factors that may buffer the negative effects of BE characteristics and noise on sleep health.

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REFERENCES

1. Colten H, Altevogt BM, eds. *Sleep Disorders and Sleep Deprivation: An Unmet Public Health Problem*. Washington, DC: National Academies Press; 2006.
2. Centers for Disease Control and Prevention (CDC). Perceived insufficient rest or sleep among adults – United States, 2008. *MMWR Morb Mortal Wkly Rep*. 2009;58(42):1175–1179.
3. Centers for Disease Control and Prevention (CDC). Effect of short sleep duration on daily activites–United States, 2005–2009. *MMWR Morb Mortal Wkly Rep*. 2011;60(8):239–242.
4. Buxton OM, Marcelli E. Short and long sleep are positively associated with obesity, diabetes, hypertension, and cardiovascular disease among adults in the United States. *Soc Sci Med*. 2010;71(5):1027–1036.
5. Chambers EC, Schechter C, Tow A, et al. Household density and obesity in young black and white adults. *Ethn Dis*. 2010; 20(4):366–369.
6. Johnson DA, Drake C, Joseph CL, et al. Influence of neighbourhood-level crowding on sleep-disordered breathing severity: mediation by body size. *J Sleep Res*. 2005;24(5):559–565.
7. Kredlow MA, Capozzoli MC, Hearon BA, et al. The effects of physical activity on sleep: a meta-analytic review. *J Behav Med*. 2015;38(3):427–449.
8. Muzet A. Environmental noise, sleep and health. *Sleep Med Rev*. 2007;11(2):135–142.
9. Zanobetti A, Redline S, Schwartz J, et al. Associations of PM10 with sleep and sleep-disordered breathing in adults from seven US urban areas. *Am J Respir Crit Care Med*. 2010; 182(6):819–825.
10. Hale L, Do DP. Racial differences in self-reports of sleep duration in a population-based study. *Sleep*. 2007;30(9):1096–1103.
11. Geller AL. Smart growth: a prescription for livable cities. *Am J Public Health*. 2003;93(9):1410–1415.
12. Philbrook LE, El-Sheikh M. Associations between neighborhood context, physical activity, and sleep in adolescents. *Sleep Health*. 2016;2(3):205–210.
13. Astell-Burt T, Feng X, Kolt GS. Does access to neighbourhood green space promote a healthy duration of sleep? Novel findings from a cross-sectional study of 259 319 Australians. *BMJ Open*. 2013;3(8):e003094.
14. Bottino CJ, Rifas-Shiman SL, Kleinman KP, et al. The association of urbanicity with infant sleep duration. *Health Place*. 2012;18(5):1000–1005.
15. DeSantis A, Troxel WM, Beckman R, et al. Is the association between neighborhood characteristics and sleep quality mediated by psychological distress? An analysis of perceived and objective measures of 2 Pittsburgh neighborhoods. *Sleep Health*. 2016;2(4):277–282.
16. Krishnan V, Collop NA. Gender differences in sleep disorders. *Curr Opin Pulm Med*. 2006;12(6):383–389.
17. Bild DE, Bluemke DA, Burke GL, et al. Multi-Ethnic Study of Atherosclerosis: objectives and design. *Am J Epidemiol*. 2002; 156(9):871–881.
18. Leslie E, Coffee N, Frank L, et al. Walkability of local communities: using geographic information systems to objectively assess relevant environmental attributes. *Health Place*. 2007;13(1):111–122.
19. Hirsch JA, Moore KA, Clarke PJ, et al. Changes in the built environment and changes in the amount of walking over time: longitudinal results from the Multi-Ethnic Study of Atherosclerosis. *Am J Epidemiol*. 2014;180(8):799–809.
20. Hirsch JA, Moore KA., Evenson KR, et al. Walk score® and transit score® and walking in the Multi-Ethnic Study of Atherosclerosis. *Am J Prev Med*. 2013;45(2):158–166.
21. Hirsch JA, Diez Roux AV, Moore KA, et al. Change in walking and body mass index following residential relocation: the Multi-Ethnic Study of Atherosclerosis. *Am J Public Health*. 2014;104(3):e49–e56.
22. Walk Score. Walk Score methodology. https://www.walkscore.com/methodology.shtml. Accessed February 24, 2016.
23. Hoehner CM, Schootman M. Concordance of commercial data sources for neighborhood-effects studies. *J Urban Health*. 2010;87(4):713–725.
24. Morgenthaler T, Alessi C, Friedman L, et al. Practice parameters for the use of actigraphy in the assessment of sleep and sleep disorders: an update for 2007. *Sleep*. 2007;30(4): 519–529.

25. Chen X, Wang R, Zee P, et al. Racial/ethnic differences in sleep disturbances: the Multi-Ethnic Study of Atherosclerosis (MESA). *Sleep*. 2015;38(6):877–888.
26. Allen JP, Wilson V, eds. *Assessing Alcohol Problems: A Guide for Clinicians and Researchers*. 2nd ed. Bethesda, MD: National Institute on Alcohol Abuse and Alcoholism; 2003.
27. LaMonte MJ, Durstine JL, Addy CL, et al. Physical activity, physical fitness, and Framingham 10-year risk score: the cross-cultural activity participation study. *J Cardiopulm Rehabil*. 2001;21(2):63–70.
28. Radloff LS. The CES-D scale: a self-report depression scale for research in the general population. *Appl Psychol Meas*. 1977; 1(3):385–401.
29. Mujahid MS, Diez Roux AV, Morenoff JD, et al. Assessing the measurement properties of neighborhood scales: from psychometrics to ecometrics. *Am J Epidemiol*. 2007;165(8): 858–867.
30. Taheri S, Lin L, Austin D, et al. Short sleep duration is associated with reduced leptin, elevated ghrelin, and increased body mass index. *PLoS Med*. 2004;1(3):e62.
31. Vgontzas AN, Liao D, Bixler EO, et al. Insomnia with objective short sleep duration is associated with a high risk for hypertension. *Sleep*. 2009;32(4):491–497.
32. King CR, Knutson KL, Rathouz PJ, et al. Short sleep duration and incident coronary artery calcification. *JAMA*. 2008; 300(24):2859–2866.
33. Knutson KL, Ryden AM, Mander BA, et al. Role of sleep duration and quality in the risk and severity of type 2 diabetes mellitus. *Arch Intern Med*. 2006;166(16):1768–1774.
34. Leng Y, Cappuccio FP, Wainwright NW, et al. Sleep duration and risk of fatal and nonfatal stroke: a prospective study and meta-analysis. *Neurology*. 2015;84(11):1072–1079.
35. Ikehara S, Iso H, Date C, et al. Association of sleep duration with mortality from cardiovascular disease and other causes for Japanese men and women: the JACC study. *Sleep*. 2009;32(3): 295–301.
36. Desantis AS, Diez Roux AV, Moore K, et al. Associations of neighborhood characteristics with sleep timing and quality: the Multi-Ethnic Study of Atherosclerosis. *Sleep*. 2013;36(10): 1543–1551.
37. Johnson DA, Brown DL, Morgenstern LB, et al. The association of neighborhood characteristics with sleep duration and daytime sleepiness. *Sleep Health*. 2015;1(3):148–155.
38. Marshall JD, Brauer M, Frank LD. Healthy neighborhoods: walkability and air pollution. *Environ Health Perspect*. 2009; 117(11):1752–1759.
39. Hirsch JA, Moore KA, Barrientos-Gutierrez T, et al. Built environment change and change in BMI and waist circumference: Multi-Ethnic Study of Atherosclerosis. *Obesity (Silver Spring)*. 2014;22(11):2450–2457.
40. James P, Berrigan D, Hart JE, et al. Effects of buffer size and shape on associations between the built environment and energy balance. *Health Place*. 2014;27:162–170.
41. Hirsch JA, Winters M, Clarke P, et al. Generating GPS activity spaces that shed light upon the mobility habits of older adults: a descriptive analysis. *Int J Health Geogr*. 2014;13:51.
42. Jean-Louis G, von Gizycki H, Zizi F, et al. The actigraph data analysis software: I. A novel approach to scoring and interpreting sleep-wake activity. *Percept Mot Skills*. 1997; 85(1):219–226.
43. Leal C, Chaix B. The influence of geographic life environments on cardiometabolic risk factors: a systematic review, a methodological assessment and a research agenda. *Obes Rev*. 2011;12(3):217–230.