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Byoungjun Kim, Wendy M Troxel, Tamara Dubowitz, Gerald P Hunter, Bonnie Ghosh-Dastidar, et al.. Neighborhood Built Environments and Sleep Health: A Longitudinal Study in Low-Income and Predominantly African-American Neighborhoods. *American Journal of Epidemiology*, 2023, 10.1093/aje/kwad016 . hal-03976347

**HAL Id: hal-03976347**

**<https://hal.science/hal-03976347v1>**

Submitted on 7 Feb 2023

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*American Journal of Epidemiology* Submitted Manuscript

**Title:** Neighborhood Built Environments and Sleep Health: A Longitudinal Study in Low-Income and Predominantly African-American Neighborhoods

**Authors:** Byoungjun Kim, Wendy M. Troxel, Tamara Dubowitz, Gerald P. Hunter, Bonnie Ghosh-Dastidar, Basile Chaix, Kara E. Rudolph, Christopher N. Morrison, Charles C. Branas, Dustin T. Duncan

**Correspondence Address:** Correspondence to Dr. Byoungjun Kim, Department of Population Health, New York University Grossman School of Medicine, 180 Madison Ave 5th Floor, New York, NY 10016. Email: [Byoungjun.kim@nyulangone.org](mailto:Byoungjun.kim@nyulangone.org)

**Affiliations:** Department of Epidemiology, Columbia University Mailman School of Public Health, New York, New York, United States (Byoungjun Kim, Kara E. Rudolph, Christopher N. Morrison, Charles C. Branas, Dustin T. Duncan); Department of Population Health, New York University Grossman School of Medicine, New York, New York, United States (Byoungjun Kim); RAND Corporation, Health Division, Pittsburgh, Pennsylvania, United States (Wendy M. Troxel, Tamara Dubowitz, Gerald P. Hunter, Bonnie Ghosh-Dastidar); Sorbonne Université, INSERM, Institut Pierre Louis d'Epidémiologie et de Santé Publique IPLESP, Nemesis team, F75012 Paris, France (Basile Chaix); Department of Epidemiology and Preventive Medicine, School of Public Health and Preventive Medicine, Monash University, Melbourne, Victoria, Australia (Christopher N. Morrison)

**Funding:** Funding for PHRESH Zzz study was provided by the National Heart Lung Blood Institute (Grant No. R01 HL122460 and HL131531) and the National Cancer Institute (Grant No. R01CA164137). BK was supported in part by the NYU Training Program in Healthcare Delivery Science and Population Health funded by Agency for Healthcare Research and Quality (Grant No. T32HS026120).

**Data Availability Statement:** The data set is available from the corresponding author.

**Thanks:** N/A

**Conference presentation:** N/A

**Preprint Information:** N/A

**Disclaimer:** The views expressed in this article are those of the authors and do not reflect those of the funders

**Conflict of Interest:** All authors report no conflicts.

**Running Head:** Neighborhood Built Environments and Sleep Health

**Key words:** neighborhood, built environments, walkability, urban design, sleep, actigraphy, physical activity, mediation analysis

**Abbreviations:** PA: physical activity, KA: Krippendorff's alpha, PO: percentage inter-observer agreement, WASO: wakefulness after sleep onset, IPAQ: International Physical Activity Questionnaire, MET: standard metabolic equivalent level, SNMM: structured nested mean models, RD: risk difference, RR: risk ratio, CI: confidence interval, SD: standard deviation

**Abstract:**

The present study examined the associations between physical characteristics of neighborhoods and sleep health outcomes and assessed the mediating role of physical activity on these associations. A longitudinal study (PHRESH Zzz, n=1,051) was conducted in two low-income, predominately African-American neighborhoods with repeated measures of neighborhood characteristics and sleep health outcomes from 2013 to 2018. Built environment measures of walkability, urban design, and physical neighborhood disorder were captured from systematic field observations. Sleep health outcomes included insufficient sleep, sleep duration, wakefulness after sleep onset (WASO), and sleep efficiency measured from 7-day actigraphy data. G-computations based on structural nested mean models were used to examine the total effects of each built environment feature and causal mediation analyses were used to evaluate direct and indirect effects through physical activity. Urban design features were associated with decreased WASO ( $\beta$ : -1.26, 95% confidence interval [-4.31, -0.33]). Neighborhood disorder ( $\beta$ : -0.46, CI [-0.86, -0.07]) and crime rate ( $\beta$ : -0.54, CI [-0.93, -0.08]) were negatively associated with sleep efficiency. Neighborhood walkability was not associated with sleep outcomes. We did not find a strong and consistent mediating role of physical activity. Interventions to improve sleep should target modifiable factors, including urban design and neighborhood disorder.

**Keywords:** neighborhood, built environments, walkability, urban design, sleep, actigraphy, physical activity, mediation analysis

## **Introduction**

Neighborhood characteristics are important factors of various health outcomes and health behaviors (1, 2), and recent studies have consistently shown the associations between residential environments and sleep health (3-6). Socioeconomic disadvantage, neighborhood disorders, and crime are associated with poorer sleep health outcomes (7-9), and built environments, defined as the human-made physical characteristics in which daily activity happens, are recognized as potentially important factors of sleep health (10-13).

Physical characteristics of neighborhoods may influence sleep health through multiple pathways. Neighborhood walkability may have positive effects on sleep health (3, 10, 11, 14), as acute and regular physical activities have positive impacts on sleep health (15). In this sense, accessibilities to recreational facilities and green space are identified as other determinants of sleep health (16). Furthermore, sedentary lifestyles and physical inactivity can cause obesity which is an established risk factor of sleep apnea and sleep disordered breathing (17-22).

Physical neighborhood disorders, defined as perceived physical conditions of neighborhoods that indicate the breakdown of order and social control, can modify sleep behaviors and sleep health. The negative impacts of physical neighborhood disorder and deteriorated environments, such as graffiti, abandoned properties, and litter, on perceived neighborhood conditions, can prompt altered health behaviors and adverse health outcomes (23, 24). Dilapidated physical conditions of neighborhood may discourage outdoor physical activity (PA) (24, 25), and physical neighborhood disorders increase psychological and physical stresses in daily activity which is closely related to sleep health (26, 27). Recent studies have investigated the associations between the physical

neighborhood disorders and sleep health, covering sidewalk conditions (28) and housing characteristics as measures of physical disorder (29-31).

Sleep health measures, including sleep duration, quality, and disorders, show disproportionate distributions in relation to sociodemographic factors, similar to other chronic conditions (32, 33). The African-American population in the United States has higher prevalence of poor sleep health compared to their White counterparts (34-36). Racial/ethnic and income minority groups are likely to reside in disadvantaged neighborhood environments, and the adverse conditions they face may be an important contributing factors that cause the disproportionate sleep outcomes, in addition to individual-level characteristics such as income and occupation (3).

Despite abundant studies on neighborhood characteristics and sleep health, the causal identification and mechanisms in these studies still remain unclear. Most existing studies employ a cross-sectional study design which is vulnerable to reverse causality. In addition, the majority of studies use self-reported sleep measures and survey-measured neighborhood characteristics (i.e. perceived neighborhood) which are susceptible to measurement errors. Moreover, the common neighborhood definitions are static administrative boundaries, such as census tracts, which introduce potential problems due to spatial misclassifications and the well-known modifiable areal unit problems (37). Recent studies from the Multi-Ethnic Study of Atherosclerosis investigated the impact of walking environments on sleep duration and sleep disorders using objective measurements of sleep health (10, 11), but the metrics for neighborhood characteristics were limited to administrative boundaries or self-reported conditions. Troxel and colleagues examined impact of physical conditions of neighborhood on objectively measured sleep health using

systematic audit tools for street conditions (28). However, the above-mentioned studies employed cross-sectional study designs. Therefore, careful examination of rigorous causal relationships and mechanisms are now required, based on refined neighborhood measurements and objective measures of sleep health, along with advanced study designs and statistical analyses (38).

The present study thus contributes to the existing literature by analyzing repeated measures of neighborhood characteristics and actigraphy-based sleep measures. The actigraphy-based measures capture sleep/active cycles via wristwatch-like accelerometer devices, and serve as a validated method to quantify sleep and wake patterns (39, 40). We hypothesized that adverse built environments in residential areas are negatively associated with sleep health, and that the relationships between built environments and sleep health are mediated by PA.

## **Methods**

### **Data**

The PHRESH Zzz (=1,051) is a part of original study of Pittsburgh Hill/Homewood Research on Eating, Shopping, and Health (PHRESH). The participants of PHRESH study were randomly recruited in 2011 based on households in two low-income, predominantly African American neighborhoods in Pittsburgh, Pennsylvania (41). From 2013, there has been significant neighborhood revitalization projects, such as housing and greenspace improvements and retail and business developments, in one neighborhood (the Hill District) compared to the other neighborhood (Homewood). The PHRESH Zzz, was designed to examine the impact of neighborhood changes on various health behaviors including sleep. The PHRESH Zzz data were

collected in 2013, 2016, and 2018 based on in-person household survey. There was a total of 1,051 participants in 2013 data collection wave. In 2016 and 2018, the number of participants were 828 and 820, respectively, resulting in 22% attrition rate which is similar with other longitudinal actigraphy studies (42, 43).

The PHRESH Zzz study incorporated micro-level street audit data collection on neighborhood environments. This objective assessment utilized a wide-range of items based on validated audit tools, including Systematic Pedestrian and Cycling Environmental Scan (44), St. Louis Analytic Audit Tool and Checklist (45), and Systematic Social Observation protocol (46). The PHRESH Zzz street audit tools emphasized on neighborhood-level features that have bearings on PA, sleep, and obesogenic behaviors (47). The auditing was conducted on 25% of randomly selected street segments ( $n=511$ ) in each neighborhood, plus oversamples of 85 street segments in the areas where the revitalization projects were planned. One year prior to the PHRESH Zzz data collection waves, pairs of trained observers who were community members familiar with the neighborhoods recorded the status of various physical features including urban design, walking environments, and neighborhood disorders. The majority of audit items indicated more than good reliability based on Krippendorff's alpha (KA) test ( $>0.4$ ) (48) and percentage inter-observer (PO) agreement ( $>75\%$ ) across waves (49, 50). The KA is an index that indicates whether the agreement exceeds chance levels, and  $KA > 0.4$  is regarded as intermediate to excellent agreement (51). As KA is sensitive to prevalence rate, percentage inter-observer agreement was also tested, and  $PO > 75\%$  indicates good to excellent agreement (52, 53). Recorded neighborhood conditions from the street audit tools were spatially joined to participants' address as average scores of street segments within or



intersecting with ¼-mile network buffers (47). The 1/4-mile distance was selected as a “walking distance” (54, 55).

### *Sleep*

An actigraphy-based sleep outcome was collected in all waves of PHRESH Zzz study. Actigraph GT3X model was used, which is a validated device to detect sleep and wake patterns compared to polysomnography (56-58). Participants were asked to wear the wrist-watch device for 7 consecutive days. Data were classified into sleep and wake periods based on bedtimes and waketimes from daily sleep diaries, and further validated by visual inspection of the actigraphy data. Sleep and wake rhythms were calculated based on Cole-Kripke algorithm resulting in total sleep time, sleep efficiency, and wakefulness after sleep onset (WASO). The sleep health measures were averaged across all nights (59), and data of participants who wore less than 4 nights were excluded as 4 or more nights of data are required to establish reliable sleep patterns via actigraphy (60). It is assumed that the actigraphy-based outcome data were missing not at random, as the missingness was due to adherence to actigraphy monitoring for 7 consecutive days, therefore we did not employ imputation for the missing outcome (61).

The total minutes spent sleeping during the time in bed was defined as total sleep duration which was analyzed as a continuous variable. Sleep duration less than 360 minutes (6 hours) was categorized as insufficient sleep (62), which was used as a binary variable. WASO was measured as the total minutes recorded as awake after sleep onset based upon the Cole–Kripke algorithm. WASO was analyzed as a continuous variable. Sleep efficiency was proportion of the sleep

duration divided by the total time in bed in percentage based on self-reported sleep diaries and actigraphy data. Higher values of sleep efficiency mean better sleep continuity.

### ***Physical Activity***

A validated score that evaluates the level of PA was derived from International Physical Activity Questionnaire (IPAQ) Short Form (63). Questions on frequencies and times spending on vigorous, moderate, and walking PAs with examples during the last 7 days were asked to all participants. A standard metabolic equivalent (MET) level was assigned to each activity (moderate PA = 4.0, vigorous = 8.0, and walking = 3.3), and a combined total PA in MET-min/week was computed as a continuous variable by weighting the reported frequency (events per week) and duration (minutes per event) (63). The IPAQ was measured during each data collection wave followed by the consecutive monitoring of sleep duration and quality through actigraphy device, thus there was sequential temporal order between the PA and sleep measures.

### ***Neighborhood characteristics***

#### ***Urban Design***

As described above, the street segments were randomly selected (25% of all streets) one-year prior to each data collection wave, and the urban design index was derived from the audit data on street segments within ¼-mile street network buffer around participants' home addresses. The urban design index was scored based on the previous literature on street characteristics associated with PA and walking (64). Three items with good to excellent reliability and internal consistency were assessed from the street audit and summed: (1) presence of public/street art (KA > 0.7) (2), landscaping including small garden and planters (KA > 0.7), and (3) neighborhood signages (PO

> 90%) (47). The urban design index ranges from 0 to 3, and higher score indicates better urban design features.

### *Walkability*

The walkability index was derived from the audit data. The items to evaluate walkability covered presences of traffic lights and signs at the intersection, pedestrian crossings, sidewalks conditions (e.g. presences of sidewalk, sidewalk buffer, continuous sidewalk, and tree shading), street lightings, public transit amenities (e.g. bus stop and light rail stop), and mixed land use (65). Each item showed good to excellent agreement (KA > 0.4; PO >75%) (48). For each street segment, the scores of all items were summed, and the average across the street segments within the buffer area was used as continuous variable (Cronbach's Alpha = 0.77). The index ranged from 0 to 22, with higher scores indicating greater walkability.

### *Neighborhood disorders*

Physical characteristics that may indicates neighborhood disorders were also derived from the street audit data. The data collectors logged adverse physical conditions of each street segments, such as litters on streets, vacant lots or housing, bars on windows, and broken windows (66). The items consistently showed moderate to high agreement (KA > 0.4, PO > 75%) except for litters on streets which may be easy to miss and change quickly (KA < 0.4). The items were summed for each street segment, and average scores were derived. A higher score indicates more adverse physical conditions.

### *Crime*

Point-level crime data for 2012, 2015, and 2017 were obtained from the City of Pittsburgh Police Department. Each incident was geocoded, and the success rate was 95%. The total number of crimes within a 1/4-mile network buffer was summed for each year.

### *Covariates*

Several individual-level sociodemographic factors were examined as a priori potential confounders. The selected covariates included age, gender, per capita annual household income, education (less than high school, high school diploma, some college, and bachelor's degree or above), employment status (employed full-time, employed part-time, unemployed or retired), marital status (married or living with partner, never married, and widowed or separated), family structure (any child(ren) in household) and vehicle availability (owned or had access to a car). In addition, the number of years lived in the current neighborhoods was included as a covariate.

### *Statistical Analysis*

Summary statistics were provided to describe the characteristics of PHRESH Zzz study. All exposure measures were standardized as z-scores. The joint additive effects of built environments on sleep health across 3 waves (2013, 2016, and 2018) were estimated using g-estimation with structured nested mean models (SNMM), utilizing the repeated measures of built environments and sleep health (67). In notation, the joint effects is defined as  $E(Y_s^{a_t,0} - Y_s^{a_{t-1},0} | A = a_{t-1}, C = c_t)$ , for all  $s=1, \dots, T$  and all  $t < s$  with covariate  $c$ , which assumes that the exposure at each time has the same effect on all subsequent outcomes. In other words, the joint causal effect is the counterfactual outcome with exposure set to the observed up to time  $t$  and 0 afterwards, estimating expected the effect (e.g. causal mean difference) of exposure at any time  $t$  on all subsequent

outcome periods. For this analysis, it is assumed that the exposure at each time has the same effect on all subsequent outcomes. Given the time interval between data collection years (three years on average), the effect of built environments at prior time can consistently affect the sleep health (68, 69). When Y is a dichotomized outcome (e.g. insufficient sleep), the SNMM fits the causal risk ratio (70). Percentile-based 95% confidence intervals (CI) for each parameter were calculated based on 500 bootstrapping samples.

The mediating roles of PA on the associations between neighborhood characteristics and sleep health were examined by employing natural direct and indirect effects based on potential outcome frame. To define the direct and indirect effects, let A denote an exposure variable (e.g. neighborhood characteristics), Y an outcome variable (e.g. insufficient sleep), M a mediator variable (e.g. PA). Under this notation, the direct effect is the effect  $A \rightarrow Y$ , not through M, and the indirect effect is the effect  $A \rightarrow M \rightarrow Y$ . The conditional natural direct/indirect effects are defined as  $E(Y_{ij}^{a,M_{ij}^{a*}} - Y_{ij}^{a^*,M_{ij}^{a*}} | C_{ij} = c)$ , and  $E(Y_{ij}^{a,M_{ij}^a} - Y_{ij}^{a,M_{ij}^{a*}} | C_{ij} = c)$ , where  $Y^{a,M^{a*}}$  denotes the potential outcome that would have been observed if A were set to a and M were set to the value it would have taken if A were set to a\*. To pool within-wave mediation analysis across the three waves, two generalized mixed-effects models for both the mediator and the outcome were fitted and used for the mediation analyses (71). The both models for the mediator and outcome have subject-specific random intercepts and random exposure slopes for each participant (Equation 1 and 2).

$$Eq.1 : M_{i,j} = \beta_0 + u_i + \beta_1 X_{1i,j} + \dots + \beta_\rho X_{\rho i,j} + \beta_{NBHD} NBHD_{i,j} + \varepsilon_{i,j}$$

$$Eq.2 : Y_{i,j} = \gamma_0 + g_{0i} + \gamma_1 X_{1i,j} + \dots + \gamma_\rho X_{\rho i,j} + \gamma_{NBHD} NBHD_{i,j} + \gamma_M M_{i,j} + \eta_{i,j}$$

where  $i$  corresponds to each participant and  $j$  to each visit;  $\beta_0$  and  $\gamma_0$  to the intercept for the sample mean;  $u_i$  and  $g_{0i}$  to the subject-specific random intercept.  $\beta_1 X_{1i,j}$  to  $\beta_{\rho} X_{\rho i,j}$  and  $\gamma_1 X_{1i,j}$  to  $\gamma_{\rho} X_{\rho i,j}$  correspond to the covariates we selected.  $M_{i,j}$  corresponds to PA, and  $Y_{i,j}$  corresponds to sleep health outcomes.  $\beta_{NBHD} NBHD$  and  $\gamma_{NBHD} NBHD$  correspond to neighborhood built environments, and  $\gamma_M M_{i,j}$  corresponds to PA in the mediator-outcome association.  $\varepsilon_{i,j}$  and  $\eta_{i,j}$  are the within-subject, within-visit error terms.

In the equations,  $\gamma_{NBHD}$  corresponds to the natural direct effect, and the natural indirect effect is given by the product of  $\beta_{NBHD} \times \gamma_M$ . The delta method was used to calculate the variance of the natural indirect effect (71), which corresponds to  $Var(\gamma_M) \beta_{NBHD}^2 + 2Cov(\beta_{NBHD}, \gamma_M) \beta_{NBHD} \gamma_M + Var(\beta_{NBHD}) \gamma_M^2$ . Lastly, proportion mediated is calculated as the percentage of natural indirect effect over the total effect.

A valid mediation analyses requires the following criteria: a) an association between exposure (e.g. neighborhood built environments) and mediator (e.g. PA); and b) an association between mediator and outcome (e.g. sleep health) (72). The two associations were tested using generalized mixed-effects models. In addition, natural direct and indirect effects require following underlying assumptions: no unmeasured confounding between exposure (A) – outcome (Y) (denoted as  $C_1$ ), no unmeasured confounding between A – mediator (M) (denoted as  $C_2$ ), no unmeasured confounding between M – Y (denoted as  $C_3$ ), and no measured or unmeasured confounder between M – Y that itself affected by A (denoted as  $C_4$ ). The covariates adjusted for potential  $C_1$ ,  $C_2$ , and  $C_3$ , which included in all analysis (Figure 1). Given the longitudinal setting, sleep health outcomes at one visit may potentially affect PA at the subsequent visit ( $C_4$ , dotted arrow in Figure 1), which may potentially bias the mediator–outcome association and the mediation estimates (i.e. post-

treatment confounding) (72, 73). We tested the association between prior sleep health and subsequent PA from Equation 3.

$$Eq. 3 : M_{i,j+1} = \alpha_0 + u_i + \alpha_1 X_{1i,j} + \dots + \alpha_\rho X_{\rho i,j} + \alpha_Y Y_{i,j} + \alpha_M M_{i,j} + \beta_{NBHD} NBHD_{i,j} + \varepsilon_{i,j}$$

where  $M_{i,j+1}$  corresponds to PA at subsequent visit.

For the mediation analysis, a total of 570 participants who completed the three waves of data collection was utilized.

## Results

Table 1 shows the descriptive characteristics of the PHRESH Zzz participants across three waves of data collection. The majority of participants were African-American (92%), and 76% were female in 2013. The mean sleep durations were 344, 334, and 327 minutes in 2013, 2016, and 2018, respectively. The average WASO were 89, 111, and 123 minutes in each waves.

### *Overall association between built environments and sleep health*

The g-computations to estimate joint average effects of built environments on sleep health found negative associations between urban design index and WASO (Risk Difference (RD): -1.26, 95% CI [-4.31, -0.33]) (Table 2). One standard deviation increase (0.37) in urban design index in 1/4-mile network buffer of residential address was associated with 1.26 minutes decrease (i.e. having one more positive urban design features which is equivalent to 2.7 SD was associated with 3.4 minutes decrease) in WASO after adjusting for the covariates. Neighborhood walkability was not associated with sleep outcomes in the analysis. Neighborhood disorder was negatively associated with sleep efficiency (RD: -0.46 percent point [-0.86, -0.07]). Lastly, crime rate in the 1/4-mile

network buffer was associated with increased risk of insufficient sleep (Risk Ratio: 1.05 [1.01, 1.10]), increased WASO (RD: 3.62 minutes [0.16, 5.89]), and decreased sleep efficiency (RD: -0.54 percent point [-0.93, -0.08]).

### *Mediation Analysis*

The characteristics of complete case samples used for mediation analysis are provided in Web Table 1. Figure 2 shows the associations between exposure and mediator, as well as mediator and outcome after adjusting for covariates. The urban design index and neighborhood disorder scale showed associations with PA, the mediator. PA (in MET-min/week) was associated with sleep duration and WASO (p-value < 0.1). The results supported the valid longitudinal mediation analysis on the associations of urban design and neighborhood disorder with sleep duration and WASO, based on the abovementioned criteria.

The additional analysis results to support the longitudinal mediation analysis from equation 3 were provided in the supplemental table 1 (Web Table 2). The post-exposure confounding for the M-Y association (dotted arrow in Figure 1) due to previous sleep measures was tested using multivariable mixed-effect models with lagged variable for PA, and PA levels at subsequent visits did not show associations with previous sleep health outcomes.

Table 3 shows the natural direct and indirect effects between neighborhood characteristics and sleep health as well as proportion mediated by PA. The natural direct/indirect effects were presented in Figure 3. The association between urban design and sleep duration was mediated by PA ( $\beta$ : 0.57 [0.14, 1.08], proportion mediated 0.21%), however, the total effect and direct effect were not significant (Figure 3-B). The relationship between urban design and WASO was partially



mediated by PA ( $\beta$ : 0.37 [0.06, 0.78], proportion mediated 0.14%), but the direction of mediating effect was opposite to the direct effect ( $\beta$ : -2.90 [-5.99, -0.68]) (Figure 3-C). Despite the weak total effects of neighborhood disorder on sleep duration ( $\beta$ : -2.79 [-7.84, 2.4]), PA played small mediating roles between the associations ( $\beta$ : -0.63 [-1.40, -0.10], proportion mediated 0.17%) (Figure 3-B).

## **Discussion**

Prior studies have demonstrated that adverse physical conditions in a neighborhood are associated with poor sleep health (14, 38), and our analyses showed consistent associations of neighborhood disorder with decreased sleep efficiency, and neighborhood urban design with decreased WASO. Despite the small magnitudes of the associations, such neighborhood features can provide positive sleep environments for numerous residents living in the area, along with other potential benefits of improved built environments (74). Previous studies on built environments and sleep health found negative or null associations between neighborhood walkability and sleep duration (8, 10, 12), and we found the similar relationships. Our null findings on walkability and sleep health may be explained by concurrent neighborhood characteristics with walkability, such as increased noise and light pollution (10). That is, the walkability index measured street connectivity and land use mix which may be related to increased traffic, ambient noise, and nocturnal light. We also hypothesized that PA may mediate the associations between built environments and sleep health, yet the mediating role of PA was found to be weak or not significant. The average level of PA was significantly less than the recommended levels of moderate intensity activity (75), which is consistent with other population-based studies among older females in the U.S. (76, 77). Due to

the significantly low level of PA from the baseline, our PA measures may not have had enough variation to examine the mediating role among the participants.

Adverse built environments are more salient risk factors of multiple health outcomes and behaviors especially in low-income and racial/ethnic minority communities (78, 79), and this may also contribute to sleep health disparities among those populations. Our findings revisited potential neighborhood-level determinants of sleep health disparities among predominantly African-American communities, which may contribute to the disproportionate burden of cardiovascular diseases and other chronic conditions (80). Neighborhood built environments are modifiable, and improving urban aesthetic and enhancing neighborhood built environments in disadvantaged neighborhood can help directly reducing the sleep health disparities, which may in turn contribute to addressing the health inequalities (81). Such modifiable built environments of neighborhoods may also alter the social capital and ties in the neighborhoods, which may, in turn, further address prevailing health inequality (82, 83).

The present study is the first to examine that the associations between repeated measures of built environments and objectively measured sleep health. In addition, we employed systematic street audit tools to evaluate micro-level changes in built environments in two low-income, predominantly African-American communities. The focus on these neighborhoods is particularly important, as adverse neighborhood conditions in historically marginalized communities is a fundamental, structural cause of health inequality (84-86). We also employed g-computations to establish temporality, which can help determine causality, and is a technique that has been rarely if ever applied to study this topic in the past.

This study has several limitations. We examined diverse built environments separately, hypothesizing the distinct model may estimate the total effects of each variable on sleep health. However, in real world, various social and physical characteristics of neighborhoods co-occur, and we did not adjust for aspects of the social environment, so these represent unmeasured confounders that may bias our results.

The exposure variables, neighborhood characteristics, were derived based on participants' residential address. However, individuals travel multiple neighborhoods in their daily activities, and appropriate assessments of neighborhood characteristics based on such daily mobility is critical in quantifying actual exposures to neighborhood characteristics. In addition, individuals have prior propensity to select where to live according their life needs and preference, and this residential self-selection may serve as a confounder between the neighborhood and sleep (87). The systematic field observations have relative strengths in capturing actual neighborhood conditions (88), but consistent rigor and attention of the data collectors still remain as a potential limitation. However, the observers were community members familiar with the local contexts, and our inter-observer agreements showed relatively reliable agreements. Although we collected 24-hour wrist accelerometer data, the data was processed only for sleep-wake patterns (not PA) in 2018 due to funding limitations. Instead, the validated IPAQ was utilized, but it may still susceptible to recall bias. Two neighborhoods in the study were small communities with little geographic variations resulting in less power and covariation. The participants were predominately African-American female, which unlikely represent other populations in different communities. However, the Hill

District underwent extensive urban revitalization projects, and the results can propose the relationships of urban development projects with sleep health in other cities.

To summarize, we found that built environments were related to objectively-measured sleep health. Since sleep deficits are associated with several poor health outcomes including obesity, cardiovascular diseases, and psychiatric illnesses, improving sleep health be a primary opportunity to reduce a variety of public health challenges. Based on our findings, interventions to improve sleep could include place-based strategies that target the modifiable factors in the built environmental, including via urban design, which are easy to intervene compared to other individual-level characteristics, such as income. Furthermore, enhancing such physical neighborhood environments in this way has the potential to directly improve other health outcomes, not only through sleep health but also via various causal mechanisms as co-benefits (89).

**Acknowledgments:** Funding for PHRESH Zzz study was provided by the National Heart Lung Blood Institute (Grant No. R01 HL122460 and HL131531) and the National Cancer Institute (Grant No. R01CA164137). BK was supported in part by the NYU Training Program in Healthcare Delivery Science and Population Health funded by Agency for Healthcare Research and Quality (Grant No. T32HS026120).

**Financial Disclosure:** none.

**Non-financial Disclosure:** none

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**Table 1.** PHRESH Zzz Study Characteristics (2012-2018)

Variables	PHRESH Zzz								
	2012 (n=1,051)			2016 (n=828)			2018 (n=820)		
	count	%	mean (SD)	count	%	mean (SD)	count	%	mean (SD)
Age			54.6 (16.5)			57.9 (15.5)			59.8 (15.0)
Race									
African-American	963	91.6		765	92.4		734	89.5	
Non African-American	88	8.4		63	7.6		86	10.5	
Female	803	76.4		656	79.2		658	80.2	
Per capita annual household income (in 1,000)			13.5 (13.9)			14.0 (13.5)			14.3 (14.1)
Education									
Less than high school	145	13.8		104	12.6		89	10.9	
High school	432	41.1		348	42.0		311	37.9	
Some college	324	30.8		264	31.9		318	38.8	
College	150	14.3		112	13.5		102	12.4	
Marital status									
Married or living with partner	212	20.2		137	16.5		123	15.0	
Never married	417	39.7		349	42.1		351	42.8	
Widowed, divorced, separated	422	40.2		342	41.3		346	42.2	
Household with child(ren)	290	27.6		207	25.0		172	21.0	
Employment									
Full-time	245	23.3		195	23.6		179	21.8	
Part-time	142	13.5		117	14.1		110	13.4	
Not employed	664	63.2		516	62.3		531	64.8	
Car owner or access to a car	595	56.6		506	61.1		518	63.2	
Years in current neighborhood			29.7 (23.3)			28.5 (22.5)			31.6 (23.0)
Sleep health									
Mean minutes sleep duration			344 (84.7)			334 (77.5)			327 (82.5)
Insufficient sleep (<6hr)	229	21.8		201	24.3		208	25.4	
Mean minutes of WASO			88.8 (54.1)			111 (62.6)			123 (71.5)
Mean sleep efficiency (%)			78.0 (11.2)			73.0 (11.9)			70.8 (12.6)
Physical activity (MET-min/week)			3,362 (3,833)			3,647 (4,005)			2,400 (3,363)
Urban design score <sup>a</sup>			0.81 (0.37)			0.39 (0.32)			0.77 (0.22)
Walkability score <sup>a</sup>			7.74 (2.13)			8.74 (1.87)			8.24 (1.92)
Neighborhood disorder score <sup>a</sup>			4.66 (1.21)			4.82 (1.10)			4.54 (1.0)
Total Crime <sup>a</sup>			23.1 (18.1)			23.7 (17.5)			23.9 (21.0)

WASO: wakefulness after sleep onset, MET: standard metabolic equivalent level, <sup>a</sup> in ¼-mile buffer of residential address

**Table 2.** Joint causal effects of neighborhood built environments on sleep health<sup>a</sup>, PHRESH Zzz Study (2012-2018)

Exposure - Outcome	Risk Ratio	Risk Difference	95% CI
<b>Urban Design Score</b>			
Insufficient Sleep	1.03		0.96, 1.11
Total Sleep		-0.92	-4.62, 2.12
WASO		-1.26	-4.31, -0.33
Sleep Efficiency		0.25	-0.3, 0.77
<b>Walkability Score</b>			
Insufficient Sleep	0.98		0.92, 1.03
Total Sleep		0.93	-1.97, 4.61
WASO		-0.12	-2.01, 1.73
Sleep Efficiency		0.07	-0.29, 0.61
<b>Neighborhood Disorder Score</b>			
Insufficient Sleep	0.99		0.93, 1.07
Total Sleep		-1.02	-3.98, 2.56
WASO		1.64	-0.58, 4.48
Sleep Efficiency		-0.46	-0.86, -0.07
<b>Crime</b>			
Insufficient Sleep	1.05		1.01, 1.10
Total Sleep		-1.12	-3.59, 1.29
WASO		3.62	0.16, 5.89
Sleep Efficiency		-0.54	-0.93, -0.08

WASO: wakefulness after sleep onset, CI: confidence interval, <sup>a</sup> All models were adjusted for age, sex, education, marital status, family structure, vehicle availability, and number of years in current neighborhood.

**Table 3.** Causal mediation analysis<sup>a</sup> results (complete case analysis), PHRESH Zzz Study (2012-2018)

Effect decomposition	Insufficient Sleep		Sleep Duration		WASO		Efficiency	
	ORs	95% CI	$\beta$	95% CI	$\beta$	95% CI	$\beta$	95% CI
<b>Urban Design</b>								
Total	1.01	0.98, 1.03	1.37	-2.53, 5.45	-2.53	-5.59, -0.36	0.91	0.36, 1.41
NDE	1.01	0.98, 1.03	0.81	-3.00, 4.8	-2.90	-5.99, -0.68	0.90	0.34, 1.40
NIE	1.00	0.99, 1.00	0.57	0.14, 1.08	0.37	0.06, 0.78	0.01	-0.05, 0.07
Proportion Mediated	-0.10	-0.91, 1.67	0.21	-1.74, 4.15	-0.14	-1.03, 0.05	0.01	-0.07, 0.09
<b>Walkability</b>								
Total	0.99	0.96, 1.01	-0.67	-5.18, 3.94	1.35	-2.38, 4.73	-0.08	-0.74, 0.53
NDE	0.99	0.96, 1.01	-0.86	-5.43, 3.77	1.22	-2.52, 4.67	-0.08	-0.75, 0.54
NIE	1.00	1.00, 1.00	0.19	-0.19, 0.67	0.13	-0.13, 0.49	0.01	-0.02, 0.05
Proportion Mediated	0.02	-1.56, 0.97	0.02	-1.00, 1.35	0.04	-0.26, 1.00	0.00	-0.67, 0.45
<b>Neighborhood Disorder</b>								
Total	0.99	0.97, 1.02	-2.79	-7.84, 2.4	1.99	-1.84, 5.41	-0.77	-1.45, -0.14
NDE	0.99	0.96, 1.02	-2.15	-7.27, 3.11	2.40	-1.3, 6.05	-0.75	-1.43, -0.09
NIE	1.00	1.00, 1.01	-0.63	-1.40, -0.10	-0.42	-0.97, 0.00	-0.01	-0.08, 0.05
Proportion Mediated	-0.07	-11.6, 1.03	0.17	-1.21, 1.31	-0.15	-1.13, 0.88	0.02	-0.12, 0.31
<b>Crime</b>								
Total	1.03	1.00, 1.06	0.68	-3.96, 5.44	5.23	1.41, 8.53	-0.75	-1.43, -0.17
NDE	1.03	1.00, 1.06	0.61	-3.95, 5.33	5.17	1.19, 8.51	-0.76	-1.46, -0.17
NIE	1.00	1.00, 1.00	0.07	-0.17, 0.39	0.06	-0.12, 0.26	0.00	-0.01, 0.02
Proportion Mediated	0.00	-0.08, 0.11	0.01	-0.79, 0.29	0.01	-0.03, 0.11	0.00	-0.07, 0.04

WASO: wakefulness after sleep onset, NDE: natural direct effect, NIE: natural indirect effect, OR: odds ratio, CI: confidence interval, <sup>a</sup> All models were adjusted for age, sex, education, marital status, family structure, vehicle availability, and number of years in current neighborhood.