Neighborhoods and Sleep Health: Mediating Roles of Psychological Distress and Physical Activity

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Abstract

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Sleep has been recognized as a major determinant of physical and mental health. Emerging studies suggested that social and built environments should be considered as important determinants of sleep health, however causal mechanisms between neighborhood factors and sleep health still remain unclear. The proposed dissertation is a connected set of papers including a systematic review and longitudinal studies investigating associations between neighborhood stressors and sleep health as well as potential causal mechanisms via psychological distress and physical activity. The longitudinal studies employed comprehensive measures of neighborhood characteristics and sleep health along with g-estimation and mediation analysis techniques. Neighborhood social and built environments may contribute to poor sleep health, particularly in low-income and racial/ethnic minority neighborhoods, and psychological distress can be a salient pathway linking these neighborhood characteristics and sleep health. Based on our findings, interventions to improve sleep should target modifiable factors and enhance neighborhood environments. These sorts of strategies have the potential to improve not only sleep health but also other health outcomes.

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Chapter 1: Neighborhood and Sleep Health among Adults: A Systematic Review

Objective: Sleep is an important determinant of various health outcomes, and insufficient sleep and sleep disorders are a public health crisis in the United States. The objective of this review is to provide an update on scientific contributions to our understanding of the social/built environmental determinants of sleep health. In particular, this review focuses on the diverse measurement of neighborhood characteristics and sleep outcomes, as well as analytic approaches for quantifying the effect of neighborhood on sleep health.

Methods: Two major electronic databases were searched and reviewed for relevant articles between January 2000 to February 2021 that examined the associations of social and built environments with sleep health. Inclusion criteria included peer-reviewed quantitative studies on neighborhood-level characteristics and sleep health among adult populations.

Results: Systematic searches in MEDLINE/PubMed and SCOPUS identified 52 eligible articles (out of 11,084). Various social and built environmental characteristics of neighborhoods were identified as potential determinants of sleep health, and the majority of studies examined neighborhood social capital, safety, and environmental stressors. However, 88% of included articles employed cross-sectional study designs, limiting causal identification. We also found substantial differences in metrics of neighborhood characteristics and model specifications. While the majority of articles (48%) utilized perceived neighborhood conditions as the main exposure, more recent studies (23%) employed geographic information systems to measure neighborhood characteristics. Most studies used self-reported (rather than objective) measures of sleep health.

Conclusions: To shed light on the causal relationships between social/physical neighborhood characteristics and sleep health, more studies should be conducted with longitudinal, quasi-experimental, and randomized trial study designs coupled with objectively measured neighborhood and sleep health parameters.

1.1 Introduction

Sleep has been recognized as a major determinant of physical and mental health.[1,2] Laboratory and epidemiological studies demonstrate that sleep deficiency may contribute to a variety of adverse chronic conditions and outcomes among adults, including cardiovascular diseases (CVDs), neurocognitive disorders, and psychiatric disorders. Laboratory and physiologic studies suggest that insufficient sleep disrupts neuroendocrine controls, glucose regulation and metabolism,[3,4] and biological pathogenesis models of circadian rhythm and neurodegenerative process are suggested.[5-7] Epidemiological studies show that adults who report short sleep duration (less than 5-6 hours per day) have increased body mass index (BMI),[8] and higher risks of hypertension,[9] type-2 diabetes,[10] and other CVDs.[3] Neurocognitive disorders related to sleep deficiency include decreased executive functions, impaired vigilant attention, and memory loss, which may be due to reduced neuroplastic processes during sleep that are important for functional recovery.[11,12] Lastly, observational studies demonstrate reciprocal relationships between multiple sleep disorders and psychiatric illnesses.[13-15] Specifically, short sleep duration is associated with depression,[16] anxiety,[17] and risk of developing post-traumatic stress disorder.[18] Despite such importance of sleep, nocturnal sleep duration among adults in the United States (U.S.) has declined from 1960, and in 2014, more than one third of U.S. population had short sleep duration, defined as sleep less than 7 hours.[19] Another study from a national representative sample estimated that more than 70 million U.S. adults had less than 6 hours of sleep duration in 2012.[20]

Emerging studies recognize social and environmental factors as important determinants of sleep health.[21,22] The theory of social production of disease discusses social and structural barriers as major determinants of health outcomes and health behaviors.[23] Similar to other chronic conditions and health outcomes examined under the "social production of disease" theory, sleep health is also socially patterned by economic and political factors.[21] Sleep is comprised of three components; sleep need (i.e. biological requirement for sleep), sleep opportunity (i.e. the amount of time an individual can make available for sleep), and sleep ability (i.e. the amount of sleep an individual can achieve),[24] and these components are modified by the society to which an individual belongs. In addition, the psychosocial theory suggests that adverse environmental factors can create a vulnerability to physical and psychological stress[25] which may influence sleep health consequently.[26] Studies have reported that physical and psychological stress, operationalized as allostatic load and stress biomarkers, are associated with sleep health.[27-30] In a similar vein, the socioecological model of sleep health suggests the interwoven interactions of individual-level characteristics, including age, sex, race/ethnicity and occupation, with supra-individual factors of sleep health, such as social and built environments.[31,32]

In fact, various built and social environmental factors have been documented as potential risk factors for poor sleep health: ambient noise, artificial light, air pollution, obesogenic environments, neighborhood disinvestment, lack of green space and recreational facilities, limited social cohesion and social capital, and neighborhood violence.[22,33] Some definitions of neighborhood stressors are interchangeably used indicating different measures of neighborhood conditions. For example, the term “neighborhood disadvantage” refers to adverse socioeconomic status of a neighborhood. In addition, the methods of measuring neighborhood characteristics are substantially different across studies. The utilization of diverse methods to assess neighborhood is not a problem in itself, as each method has its own strengths and limitations. However, the splintered nature of quantifying neighborhood factors makes it difficult or even impossible to assess the consistency of findings across studies, and it is important to discuss the most appropriate approaches for sleep health research. Self-reported measures (i.e. survey-based questions) of neighborhood characteristics which are commonly employed in studies on neighborhood and sleep health have strengths in capturing subjective perceptions closely related to the lived reality,[34] however such measures are susceptible to recall bias, same-source bias when sleep outcomes are measured via self-report, threatening the reliability and validity issues of the collected data.[34,35]

To overcome abovementioned limitations, objective methods for defining and measuring neighborhood characteristics have been widely employed in sleep epidemiology. Such objective methods include systematic field observations, use of census data to characterize administrative neighborhoods, and geographic information system (GIS) techniques. Such objectively-measured social/built environments has strengths in objectively capturing actual neighborhood conditions.[34] The findings based on objectively measured neighborhood characteristics may deliver feasible and effective place-based interventions and policy implications. However, the use of administrative boundaries may introduce inadequate assessment of exposure areas and spatial misclassification which is attributable to potential biases due to the artificial aggregation of point-based data.[36-38] For example, a census tract has heterogeneity within its boundary due to the shape and scale of the aggregation unit, therefore the aggregated data is limited in capturing specific and actual exposure within the unit, and the quality of these variables also depend on where the participant lives in this area.

In addition, the measurements of sleep health vary across studies. While polysomnography, a multi-parametric measure that includes assessment of brain waves activity, blood oxygen level, heart rate and breathing, as well as eye and leg movements during sleep, is considered the gold standard, most of the current studies on neighborhood and sleep health employed self-reported sleep health or actigraphy-based measurements (i.e. monitoring sleep/active cycles via wristwatch-like accelerometer devices) of sleep duration and quality, due to logistic difficulties of employing polysomnography in population-based studies.

Moreover, there is little consensus on the analytic approaches and model specifications to employ. It is expected that the selection of covariates can be heterogeneous based on different research questions and conceptual models, however omitting relevant factors or including potential mediators or colliders may result in biased estimates or different interpretations across studies. For example, a large body of literature suggested that psychological stress can play important roles in sleep health,[29,30] and neighborhood stressors may be associated with psychosocial stress and cumulative biological risks.[39,40] In addition, epidemiological studies have reported that the level of physical activity, which may be associated with physical and social environments, plays substantial role in daily sleep duration and quality.[41,42] Adjusting the associations between neighborhood factors and sleep health for these mediating variables will yield associations with biases or different interpretations.

There are a few published systematic reviews[33,43] as well as narrative reviews[44-46], however, the extant reviews did not provide specific information on neighborhood definitions and model specifications and thus did not address these methodological concerns. Therefore, the objective of this systematic review is to synthesize the recent literature on the associations between neighborhood characteristics and sleep health and to critically assess the evidence derived from empirical studies. The present systematic review assesses the differences in measurements of neighborhood features and sleep heath as well as model specifications and variable selections to evaluate the analytic approaches that have been used and examine whether findings were appropriately interpreted.

1.2 Methods

Search Strategy and Study Selection

This systematic review was based on the literature that has been identified and referenced from a systematic search for papers published between January 2000 and February 2021, using two large data bases, PubMed and SCOPUS, which are relatively exhaustive in the biomedical and social sciences respectively. Additional relevant articles were identified and included from the reference lists of selected articles as well as from relevant review articles. The PRISMA Statement was utilized to guide the conduct of the review.[47] The neighborhood characteristics were captured from a set of terms [neighborhood, social environment, built environment, spatial, geospatial], and then we included multiple dimensions of sleep health as the outcome: [sleep, sleep disorder, sleep quality, sleep hygiene, sleep deprivation, sleep problem, obstructive sleep apnea (OSA), insomnia]. The search criteria required at least one term present from the exposure and from the outcome.

No filters or language restriction was applied within the databases. The search process was limited to empirical studies on neighborhood social/built environments and sleep, disregarding reviews or theoretical articles. The search strategy also limits the scope to studies focusing on adult populations. The neighborhood characteristics may affect children's and adolescents' sleep health via disparate mechanisms from adults, as the sleep epidemiology and etiologic processes of an individual systematically vary across life course.[21] In addition, perceptions, experiences, and potential health effects of a similar neighborhood may differ by the developmental stages , even for people residing in the same dwelling. Sequential inclusion screens were conducted based on title, abstract, and full-text review (Figure 1). The detailed inclusion criteria are the following: (1) investigation of neighborhood-level characteristics (no indoor environments), (2) investigation of human sleep health, (3) empirical study with findings published in peer-reviewed journals (i.e. no reviews, editorial letters, protocols, book chapters, etc.), (4) no ethnographic or qualitative studies, and (5) adults population only (exclude infant, child, and adolescent studies).

Data Extraction

An initial abstract review of select abstracts was conducted by one reviewer (BK), and one additional reviewer (DTD) assessed the study selection process. Articles that meet the inclusion criteria were reviewed and classified according to study design, target population, measurements of the exposure and the outcome variables as well as variable selection strategies. The main findings of each study were extracted. Specifically, data were extracted from each paper on the study characteristics including country, year of publication, study design, and sample profile (e.g. sample size and specific sub-population of studies). Detailed information on exposure and outcome assessments, such as neighborhood characteristics assessed, definitions of neighborhood (e.g. perception or residence-based boundaries), measurement tools of neighborhood exposures (e.g. survey, secondary dataset, or field observation) and outcomes (e.g. survey, objective measures), as well as covariates and intermediary variables were examined. In case of missing methodological information, further articles explaining the study design were retrieved.

Neighborhood characteristics were classified into several categories to facilitate the interpretations of study findings. To illustrate, measurements of neighborhood-level social capital and social cohesion, commonly measured from questionnaires on group memberships, neighborhood belonging, trust, and shared-values,[48] were grouped as "social capital" as the two dimensions of social environments are not fundamentally different from each other.[49] Neighborhood-level socioeconomic status, including poverty, mother-only households, unemployment, and education attainment, was classified as "neighborhood disadvantage" referring to the landscape of economic and social resources.[50] A set of physical and social conditions of neighborhoods, such as vacant lots and housings, litters on streets, graffiti/vandalism, selling/using drugs or drinking in public, and load noise, were classified as "neighborhood disorder".[51] The neighborhood disorder category comprised objectively measured neighborhood conditions as well as perceived neighborhoods. "Neighborhood safety" includes reported crime rates as well as perceived safety and observed violence collected from questionnaire. Perceived safety is commonly included as one of items for neighborhood disorder, and it is classified as neighborhood safety along with crime rates, in case the perceived safety was independently analyzed as a single exposure variable. A set of physical characteristics that provides pleasant walking environments and facilitates physical activity, such as urban design (e.g. street connectivity and sidewalk condition), accessibility to amenities and parks, and green space was classified as "walkability" category.[52] Walkability also includes survey-measured perceived conditions and quantitatively assessed physical environments. Other measures, such as neighborhood noise, light pollution, and air quality were grouped as "environmental stressors".

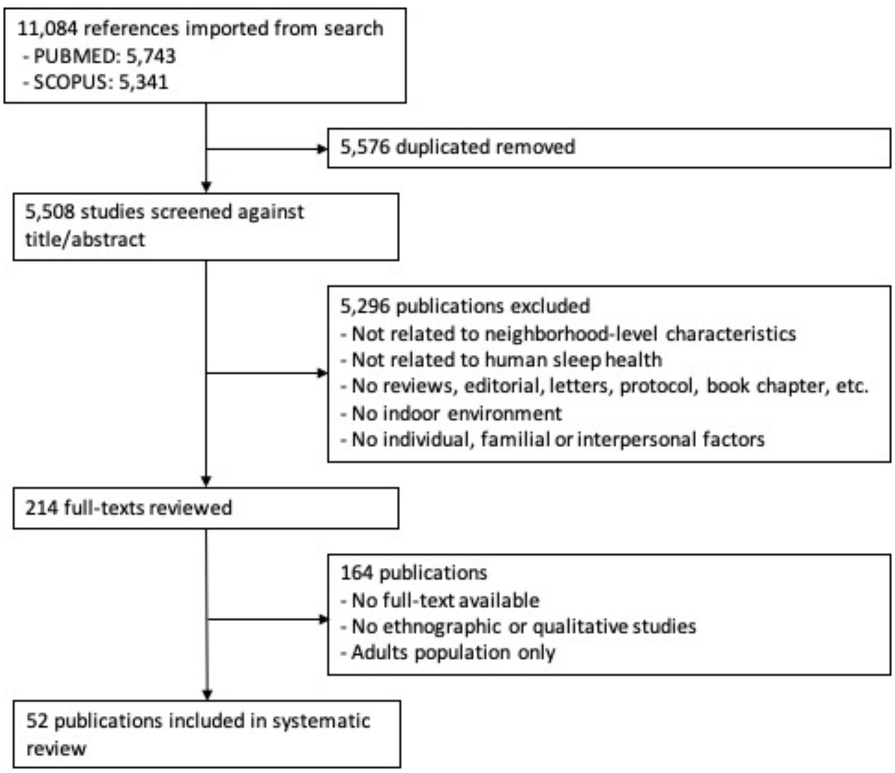

Figure 1. Results of study selection process

1.3 Results

The database search and screening resulted in 52 empirical studies from the year of 2000 to February 2021. (Figure 1) The first searches provided a total of 11,084 papers, and after excluding duplicates, 5,508 studies remained. Titles were first screened to determine eligibility. Following this, 757 abstracts were reviewed, with the full-text retrieved for 214 papers. The majority of the excluded studies from the 214 studies was targeting infants, children, and adolescents sleep health. In total, 52 studies were identified to be included in this systematic review (Figure 1). Table 1 illustrates the characteristics of the included studies.

Study Characteristics

Most of the empirical studies on neighborhood effects on sleep health have emerged from the mid-2000s and have increased in the recent years. Among the 52 included papers, 46 articles (88%) employed cross-sectional study designs whereas 6 studies (12%) utilized longitudinal settings including one natural experimental design. Among the 6 longitudinal studies, only one recent study employed a quasi-experimental design comparing two similar neighborhoods with repeated measures of sleep health. The majority of studies (71%) on this topic have been conducted in the U.S. followed by European countries (12%: 6 studies) and Asian countries (8%: 4 countries). Many of these studies focused on specific sub-populations, such as Black or Hispanics (29%), middle to older aged populations (12%), and other vulnerable populations (4%) including sexual minorities and mothers.

Among the 52 articles, 14 articles (27%) included measures of social capital as a potential determinants of sleep health, followed by neighborhood safety (13 studies: 25%), neighborhood social/physical disorder (11 studies: 21%), and neighborhood social disadvantages (8 studies: 15%). Physical neighborhood characteristics, such as neighborhood noise (10 studies: 19%) and walkability of neighborhood (6 studies: 12%), were also analyzed as the main exposure of interests.

Neighborhood Definitions and Measurements

Most of the studies (73%) investigated participants' residential neighborhoods, and 13 studies (25%) did not specifically define how participants should define their neighborhood when answering the survey. For example, most of the surveys in this category asked questions such as "In your neighborhood, is violent crime a problem?" rather than defining neighborhood as "Within 10 minutes walking distance from your home". Only one study specified neighborhood as areas of residence, work, and socializing to capture diverse experiences in daily life. In terms of the geographical boundaries of neighborhood definitions, about a half of the articles (25 studies: 48%) used perceived neighborhood boundaries without specified geographic borders, whereas 14 studies (27%) employed small administrative boundaries, such as census tract or postal codes, and 3 studies (6%) used boundaries of larger areas (e.g. city and county levels). Twelve studies (23%) used GIS-based measures involving no administrative boundaries, yet the methods for defining neighborhood boundaries were varied. For example, ego-centric circular buffers based on participants' home addresses were used in 7 studies (13%), whereas proximity (i.e. distance) to certain points of interests was employed in 5 studies (10%).

As the majority of studies employed perceived neighborhood definitions, survey-based questionnaires were the major the measurement tools of neighborhood characteristics (33 studies: 63%). Twenty-two studies (42%) utilized secondary datasets, such as census data, point-level crime data and noise measures, and 6 studies (12%) used direct measures including filed observation and direct noise measurements.

Sleep Measurements and Outcomes

Most studies used self-reported (rather than objective) measures of sleep health. The most common sleep outcomes among included studies was sleep duration including insufficient sleep (32 studies: 62%). Among the 32 studies on sleep duration, 78% (25 studies) utilized self-reported sleep duration, whereas only 10 studies used quantitatively evaluated sleep duration through actigraphy. Twenty four studies (46%) investigated sleep quality, and among those 16 studies (67%) employed self-reported sleep quality, whereas 8 studies (33%) utilized sleep efficiency as an indicator of sleep quality. Sleep problems (e.g. sleep disturbances, wake up after sleep onset (WASO), etc.) were examined in 16 studies (29%), and among those 16 studies, 5 studies (31%) utilized WASO based on actigraphy. Three studies investigated insomnia using self-reported survey items, and sleep apnea (obstructive sleep apnea) was examined in 4 studies using polysomnography or home sleep apnea testing devices.

Analytic Approaches

Most of the studies adjusted the associations of interest for basic individual characteristics, such as age, sex, race/ethnicity, income, and education attainment. However, the selection of additional covariates and confounders showed substantial inconsistency. For example, household size and type (e.g. marital status and number of household members) are potential confounders in the associations between neighborhood and sleep, as family structure over different life courses can determine sleep health,[53] as well as preferences of neighborhood characteristics.[54,55] Among included studies, 20 studies (38%) omitted the measures in the analysis. Twenty-six studies (54%) included psychological factors such as stress, depression, and anxiety as covariates with potential risk of bias due to conditioning on a mediator, whereas only 3 studies investigated the psychological factors as potential mediators or effect modifiers. In addition, it is proposed that neighborhood environments may be associated with individual's physical activity and consequently affect sleep health.[41,56,57]. Seventeen studies (33%) included physical activity as a covariate, potentially resulting in biases, yet none of the included articles examined its mediating role. Such psychological and behavioral factors may be salient mediators and/or effect modifiers on the associations between neighborhood and sleep, but they were not examined in most of current studies. Lastly, inclusions of body mass index and health behaviors such as smoking status and alcohol use were not consistent across studies.

Study findings

Most of the studies (51 studies: 98%) reported associations between neighborhood exposures of interests and sleep health. However, 15 studies reported null associations or associations in the opposite direction than expected as well as inconsistent findings within studies. Neighborhood social capital, physical/social disorders, safety, and walkability were associated with sleep duration, sleep quality, and sleep problems after adjusting for potential confounders and relevant risk factors. However, the model specifications varied considerably across studies. For example, low social capital was associated with short sleep durations in 9 cross-sectional studies. Ten cross-sectional studies reported a safe neighborhood condition as a protective factor of sleep duration, and the associations were ranged from 0 to 10 minutes increase sleep durations. Neighborhood disorder was associated with decreased sleep duration ranging from 7 to 14 minutes in 5 cross-sectional studies. Walkability measures were reported as a protective factors of short sleep duration in 6 cross-sectional studies. However, the results from cross-sectional studies cannot be directly interpreted as causal associations without well-defined temporal orders between the exposure and outcomes. Two longitudinal studies with repeated sleep assessments reported associations between neighborhood disorder and short sleep duration. Lastly, two cross-sectional studies attempted to examine intermediary mechanisms between neighborhood characteristics and sleep health considering psychological distress and they found that it had a mediating role, yet those findings may not be interpreted as causal mechanisms due to the cross-sectional study design.

1.4 Discussion

This systematic review provides comprehensive and in-depth information related to reported associations of social and physical neighborhood characteristics with sleep outcomes. Various social and physical neighborhood features have been identified as potential determinants of sleep health, and the studies that make up this knowledge space contain diverse sample populations and locations of study suggesting greater catchment and possibly generalizability of the associations reported. Neighborhood social capital and social cohesion, neighborhood safety, and physical and social disorders were frequently examined using different measures and metrics.

The use of different measurement strategies to capture such neighborhood characteristics and other differences in study designs could have contributed to varied effect sizes across studies, despite the consistent directions of the various study estimates. Most of the studies employed perceived neighborhood conditions based on residential areas, whereas several studies utilized secondary datasets using residential administrative boundaries such as census tracts or ZIP codes to define residential neighborhoods. Only one study defined neighborhood as areas of residence, work, and socializing.[58] Considering the potential spatial misclassification issues related to static administrative boundaries, several recent studies utilized ego-centric neighborhood definitions with point-level exposure measures and GIS techniques. Perceived neighborhood conditions may reflect real experiences among study participants, while some of the objective measures of neighborhood characteristics may portend modifiable risk factors and feasible place-based interventions. Optimal study design would consider both objective and subjective measures of neighborhood environments and could model the latter as mediators of the effect of the former.

In addition, divergent measures of sleep health outcomes (e.g. self-reported vs. objectively measured sleep health) make it difficult to compare the findings between studies. While most of the studies used self-reported sleep duration and sleep quality which are susceptible to recall bias and same-source bias, recent studies started employing actigraphy-measured sleep duration and efficiency, which may be regarded as improved methods from self-reported sleep. Again, optimal studies may be those collecting both objective and self-reported measurements of sleep. Of note, only a few studies investigated sleep disorders such as obstructive sleep apnea and insomnia.

Lastly, the majority of studies were based on cross-sectional designs in U.S. settings limiting inference pertaining to causal relationships between neighborhood characteristics and sleep health outcomes as well as possibly the generalizability of findings. This systematic review also compared the various model specifications used and found substantial differences in covariate selection and multivariable model building strategies across studies. The divergent nature of these models together with the different measurement strategies may result in inconsistent effect sizes that cannot be readily compared across studies.

This systematic review is not without limitations. The search strategy based on the two major scientific databases did not include a potential grey literature of unpublished studies, such as thesis and report, as well as non-English studies. Restricting the search to studies which explicitly focused on studies with individual-level exposure may have missed studies which employed ecological study designs with large-scale ambient environmental characteristics such as air pollution and noise, as such environmental stressor measures were commonly estimated with aggregated data in larger contexts, such as city- and county-levels.

Future directions

Twelve percent of the included articles employed longitudinal study settings, and only one study used a natural experimental design. In order to more fully investigate the causal relationships between social/physical neighborhood characteristics and sleep health, more studies should be conducted with longitudinal designs (i.e., with repeated sleep assessments) and experimental study designs coupled with objectively measured neighborhood and sleep health addressing above mentioned limitations of self-reported measures when those are used alone (but optimal studies may collect both objective and subjective data). Due to ethical and feasibility limitations of random assignments of neighborhood characteristics, quasi-experimental designs with recent neighborhood changes would be preferred. Also, repeated measures of neighborhood characteristics over longer period of time and utilizations of rigorous neighborhood definitions are critical in establishing valid causal inferences and suggesting feasible place-based interventions, given the limited numbers of articles that examined changes in neighborhood characteristics with refined definitions of a neighborhood. Future studies should especially take into account daily mobility patterns and activities of daily living of individuals when defining neighborhood, as neighborhood stressors not only exist in administratively defined areas but are perhaps more accurately measured in individually-defined neighborhood spaces experienced on a per person basis over daily activities. For example, utilizing activity space definitions based on global positioning system (GPS) as neighborhood boundaries can provide more accurate exposure measures reflecting daily mobility patterns [59,60]. Second, considering the distal causal pathways from neighborhood characteristics to sleep health relative to individual-level behavioral factors such as physical activity and psychological factors, studies should elaborate on identifying causal mechanisms. There have been multiple theoretical frameworks that can explain the associations between neighborhood and sleep, however, greater empirical, and certainly experimental, evidence is needed to reveal how neighborhood features more accurately modify sleep health of individuals. Lastly, the intercorrelations between multiple neighborhood characteristics and their multicollinearity should be investigated in relation to sleep health outcomes, especially in relation to whether it is possible to disentangle their effects with regression modeling. An alternative may be to use mixture modeling to explore neighborhood influences as a mixture of interrelated neighborhood components with both an overall and independent effects. Although one quasi-experimental study design was used to evaluate the impact of neighborhood investments comparing intervention and control groups,[61] further quasi-experimental, and even randomized trial designs may be helpful in providing new evidence that further shapes place-based interventions, including issues of co-occurring neighborhood environmental factors.

Conclusion

High-quality evidence regarding the impact of neighborhood effects on sleep health is required to further inform place-based preventative and policy interventions to meaningfully address potentially inequitable variation in sleep health at the neighborhood level. Quasi-experimental studies or longitudinal designs are required to improve the quality of evidence, and utilization of objective measures for sleep health and neighborhood characteristics that can better inform intervention strategies. Studies which examine the direct impact of neighborhoods without careful considerations of causal mechanisms will continue to miss important mediating variables and result in potentially biased estimates, hindering our understanding and response to neighborhood effects and poor sleep health.

1.5 Tables

Table 1. Summary of studies on social/physical environment on sleep among adults, January 2000 to February 2021

Reference	Year	Study Design	Population	Geographic context	NBHD characteristic studied	NBHD type	NBHD definition	Measure of NBHD factors	Sleep outcomes	Sleep measures	Psy. factor	Phys. Act. factor	BMI	Health Behav.	HH struc ture	Main effect estimates
Dubowitz et al. [61]	2021	Longitu dinal	Mostly black adults (n=676)	Pittsburg, PA	NBHD investment	Reside ntial area	Proximity	Secondary data	Duration, efficiency, WASO	Actigraph y	Yes	No	Yes	No	Yes	Near investment–DUR: +18.3 mins, EFFCY: +3.8%, WASO: -27.9 mins
Richardso n et al. [62]	2021	Cross-section al	Mostly black adults (n=515)	Pittsburg, PA	Safety	Reside ntial area	Buffer	Secondary data	Duration, WASO	Actigraph y	Yes	No	Yes	No	Yes	Crime–DUR: null, WASO: +5.96 mins
Alhasan et al. [63]	2020	Cross-section al	Adults (n=167,153)	United States	Social capital	Unspec ified	Perceptio n	Survey	Duration, problems	Survey	Yes	Yes	Yes	Yes	Yes	Low social capital–short sleep PR: 1.19, problems PR:1.26
Beutel et al. [64]	2020	Cross-section al	Adults (n= 11,905)	Rhine-Main, Germany	Env. Stressor	Unspec ified	Perceptio n	Survey	Problems	Survey	Yes	No	No	No	Yes	Noise–problems RR: 1.14
Dong et al. [65]	2020	Longitu dinal	Mostly Black adults (n=269)	Pittsburg, PA	Walkability	Reside ntial area	Buffer	Street Audit	Apnea	Apnea testing device	Yes	No	Yes	Yes	No	High walkability–OSA OR: 0.83
Troxel et al. [66]	2020	Cross-section al	Mostly Black adults (n=634)	Pittsburg, PA	NBHD disorder	Reside ntial area	Buffer	Street Audit	Duration, efficiency, WASO	Actigraph y	Yes	No	Yes	No	Yes	NBHD disorder–DUR: -14.0 mins, EFFCY: -2.0%, WASO: 10.7 mins
Watanabe et al. [67]	2020	Cross-section al	Older adults (n=16,650)	Japan	Social capital, walkability	Reside ntial area	Perceptio n	Survey	Quality	Survey	Yes	Yes	No	No	Yes	Social capital–poor sleep PR: null, Walkability PR: 0.59
Xiao et al. [68]	2020	Cross-section al	Middle-older adults (n=333,365)	10 sites in US	Env. stressor	Reside ntial area	Unspecifi ed	Secondary data	Duration	Survey	No	Yes	No	Yes	Yes	High lighting–short sleep OR: 1.16 (women), 1.25 (men)
Yang et al.[69]	2020	Cross-section al	Adults (n=608)	Hong Kong	Walkability	Reside ntial area	Buffer	Secondary data	Quality	Survey	Yes	Yes	No	Yes	Yes	Low green space–poor sleep quality OR: null

Murillo et al.[70]	2019	Cross-sectional	Hispanic adults (n=13,537)	United States	Social capital	Unspecified	Perception	Survey	Duration	Survey	No	No	No	No	Yes	High social capital–normal sleep OR: 1.31~1.53
Robbins et al. [71]	2019	Cross-sectional	Adults (n=1,007)	Philadelphia, PA	Social capital	Unspecified	Perception	Survey	Duration, insomnia, sleepiness	Survey	No	No	No	No	No	Low social capital–short sleep OR: 1.6, high social capital–long sleep OR:0.4
Bierman et al. [72]	2018	Longitudinal	Older adults (n = 7,130)	United States	NBHD disorder	Residential area	20-min walking	Survey	Problems	Survey	No	Yes	No	No	Yes	NBHD disorder–sleep problem index: 0.02
Johnson et al. [73]	2018	Cross-sectional	Adults (n = 2712)	Wisconsin	Walkability, Env. stressor	Residential area	Census block group	Secondary data	Duration, quality	Survey	No	No	No	No	Yes	Green space–short sleep OR: 0.76, noise OR: 1.03
Johnson et al.[74]	2018	Cross-sectional	Adults (n=1,889)	6 sites in US	Walkability	Residential area	Buffer	Survey	Duration, efficiency	Actigraphy	Yes	Yes	Yes	Yes	No	Walkability–short sleep OR: 1.2, DUR: -8.1 mins
Mellman et al.[75]	2018	Cross-sectional	Black adults (n=85)	Washington DC	NBHD disorder, safety	Residential area	Perception, census tract	Survey, census data	Nervous system activity	Electrocardiogram and actigraphy	Yes	No	No	Yes	No	NBHD disorder–normalized high frequency: -0.24 (all), safety: -0.35 (female)
Nam et al.[76]	2018	Cross-sectional	Black adults (n=252)	New Haven, CT	Social capital, walkability, safety	Unspecified	Perception	Survey	Quality, sleep behaviors	Survey	Yes	No	Yes	No	Yes	Social capital–sleep quality: +0.21, walkability: +0.22, safety: +0.15
Ruff et al.[77]	2018	Cross-sectional	Adults (n=120)	New York, NY	NBHD stigma	Unspecified	Perception	Survey	Duration, quality	Survey	No	No	Yes	No	No	Media stigma–DUR: -0.96hr, poor sleep quality RR: 2.64
Troxel et al.[78]	2018	Cross-sectional	Mostly Black adults (n=788)	Pittsburg, PA	Social capital, NBHD disorder, safety, walkable	Residential area	Buffer, perception	Street audit, survey	Duration, efficiency, WASO	Actigraphy	Yes	No	Yes	No	Yes	Capital, disorder, walkability-null, safety–DUR: null, EFFCY:1.1%, WASO:-5.7 mins
Win et al.[79]	2018	Cross-sectional	Adults (n=12,321)	Rural Japan	Social capital	Residential area	Perception	Survey	Duration	Survey	No	Yes	Yes	Yes	No	Low social capital–short sleep PR: 1.22
Xiao and Hale [80]	2018	Longitudinal	Middle-older adults (n=208,537)	8 sites in US	NBHD disadvantage	Residential area	Census Tract	Census data	Duration	Survey	No	Yes	Yes	Yes	Yes	High NBHD disadvantage–short sleep RR: 1.46 (men), 1.72 (women)
Young et al.[81]	2018	Cross-sectional	NHOPI adults (n=2,464)	United States	Social capital	Unspecified	Perception	Survey	Duration, quality	Survey	Yes	Yes	No	Yes	Yes	Low social capital–short sleep OR:

																1.14, quality OR: null
Duncan et al.[82]	2017	Cross-sectional	Sexual minority men (n=580)	Paris, France	Safety	Unspecified	Perception	Survey	Duration, quality, problems	Survey	No	No	No	No	No	Unsafe NBHD–short sleep RR:1.92, poor sleep quality RR:1.6, problems RR:1.57
Evandt et al.[83]	2017	Cross-sectional	Adults (n=13,019)	Oslo, Norway	Env. stressor	Residential area	Geographic coordinates	Noise modeling	Insomnia	Survey	No	Yes	No	Yes	Yes	Noise–insomnia symptoms OR: 1.04~1.06
Johnson et al.[84]	2017	Cross-sectional	Adults (n=1,949)	6 sites in US	Social capital, safety	Residential area	20-min walking	Survey	Duration, efficiency	Actigraphy	Yes	No	Yes	Yes	Yes	High social capital–DUR: 6.1 mins, high safety–6.1 mins, EFFCY: null
Simonelli et al.[85]	2017	Cross-sectional	Hispanic adults (n=2,156)	4 sites in US	Safety, Env. stressor	Unspecified	Perception	Survey	Duration, efficiency, insomnia	Actigraphy, survey	Yes	No	No	No	No	Unsafety NBHD–short sleep risk: +7.7%, noise–insomnia risk: +4.4%
Billings et al.[57]	2016	Cross-sectional	Adults (n=1,896)	6 sites in US	Walkability	Residential area	Perception	Survey	Apnea	Polysomnography	Yes	Yes	Yes	Yes	No	Low walkability–apnea hypopnea index: 3.21 events/h
Chambers et al.[86]	2016	Cross-sectional	Hispanic adults (n=385)	Bronx, NY	NBHD disorder	Residential area	Perception	Survey	Duration, quality, problems	Survey	No	No	No	Yes	Yes	NBHD disorder–short sleep OR: null, poor sleep quality OR: 2.12
De Santis et al.[87]	2016	Cross-sectional	Mostly Black adults (n=873)	Pittsburg, PA	Social capital, NBHD disorder, safety	Residential area	Buffer, perception	Street Audit, survey	Quality	Survey	Yes	No	Yes	No	Yes	High social capital – sleep quality rate: 0.08, safety: 0.13, NBHD disorder: null
Douglas, Murphy [88]	2016	Cross-sectional	Adults (n=208)	Dublin, Ireland	Env. stressor	Residential area	Proximity	Noise measure	Problems	Survey	No	No	No	No	No	Sleep disturbance in high noise levels (32% vs 2%)
Fuller-Rowell et al.[89]	2016	Cross-sectional	Middle aged adults (n=426)	Milwaukee Midwest	NBHD disadvantage	Residential area	Census tract	Census data	Duration, efficiency, WASO	Actigraphy	No	Yes	Yes	Yes	Yes	NBHD disadvantage – DUR: null, EFFCY: null, WASO: 3.54
Hill et al.[90]	2016	Cross-sectional	Adults (n=39,590)	7 countries	Safety	Unspecified	Perception	Survey	Duration, quality, insomnia, sleepiness	Survey	No	No	No	No	No	Safety–short sleep OR: 0.44~1.25, insomnia OR: 0.22~0.73, poor sleep quality OR: 0.49~0.79

Johnson et al.[58]	2016	Cross-sectional	Black adults (n=5,301)	Jackson, MS	Social capital, NBHD disadvantage, NBHD disorder, safety	Residential, work, socializing areas	Perception, Census tract	Survey, census data	Duration, quality	Survey	Yes	Yes	Yes	No	Yes	Social capital, NBHD disadvantage: null, low safety–DUR: -9.82 mins, NBHD disorder– DUR: -11.18 mins
Michaud et al.[91]	2016	Cross-sectional	Adults (n=1,238)	Canada	Env. stressor	Residential area	Proximity	Secondary data	Duration, efficiency, quality	Actigraphy, survey	No	No	Yes	Yes	No	Noise–sleep measures: null
Perron et al.[92]	2016	Cross-sectional	Adults (n=4,336)	Montreal, Canada	Env. stressor	Residential area	Postal Code	Secondary data	Problems	Survey	No	No	No	No	No	Near noise sources–sleep problems PR: 1.85~3.76
Chen-Edinboro et al.[93]	2015	Longitudinal	Older Adults (n=7,231)	United States	Social capital, NBHD disorder	Residential area	20-min walking	Survey	Insomnia	Survey	Yes	No	Yes	Yes	No	NBHD disorder–insomnia OR: 1.05~1.09, low social capital OR: 1.06~1.09
Fang et al.[94]	2015	Cross-sectional	Adults (n=3,591)	Boston, MA	NBHD disadvantage	Residential area	Census Tract	Census data	Duration	Survey	Yes	Yes	Yes	Yes	Yes	NBHD disadvantage–short sleep OR: 2.08
Grigsby-Toussaint et al.[95]	2015	Cross-sectional	Adults (n=255,171)	United States	Walkability	Residential area	County	Secondary data	Duration	Survey	No	No	Yes	Yes	Yes	More natural amenities–short sleep OR: 0.91~0.78
Holt et al.[96]	2015	Cross-sectional	Adults (n=745,868)	United States	Env. stressor	Residential area	ZIP code	Secondary data	Duration	Survey	No	No	Yes	Yes	No	Noise-short sleep: null
Johnson et al.[97]	2015	Cross-sectional	Mostly Hispanic (n=760)	Corpus Christi, TX	NBHD disadvantage, safety	Residential area	Census Tract, perception	Survey, Census data	Duration, sleepiness	Survey	Yes	No	Yes	Yes	No	NBHD disadvantage, safety–DUR: null, safety–sleepiness OR: 0.82
Johnson et al.[98]	2015	Cross-sectional	Adults (n=1789)	Detroit, MI	NBHD crowding	Residential area	Census tract	Census data	Apnea	Polysomnography	No	No	Yes	No	Yes	High NBHD crowding–apnea hypopnea index: 0.4
Bassett and Moore [99]	2014	Cross-sectional	Adults (n=2,643)	Montreal, Canada	Social capital, NBHD disadvantages	Residential area	Perception, Census tract	Survey, Census data	Quality	Survey	No	No	No	No	Yes	Low social capital–poor sleep quality OR: 1.25 (men), NBHD disadvantage OR: 1.18 (women)
Frei et al.[100]	2014	Longitudinal	Adults (n=1,122)	Basel, Switzerland	Env. stressor	Residential area	Geographic coordinates	Secondary data	Duration, efficiency, problems, sleepiness	Actigraphy, survey	Yes	Yes	Yes	Yes	Yes	Noise–DUR: null, EFFCY: -4.1%, sleep problem

																score: -0.44, sleepiness: null
Brown and Mellman [101]	2014	Cross-sectional	Black young adults (n=378)	Washington D.C.	NBHD disorder	Unspecified	Perception	Survey	Duration, insomnia	Survey	Yes	No	No	No	No	NBHD disorder–Insomnia severity index: +0.002
Matsumoto et al.[102]	2014	Cross-sectional	Adults (n=4,176)	Ishinomaki, Japan	Social capital	Residential area	Perception	Survey	Problems	Survey	No	No	No	No	Yes	High social capital–sleep problems OR: 0.42~0.74
Astell-Burt et al. [103]	2013	Cross-sectional	Adults (n=259,319)	New South Wales, Australia	Walkability	Residential area	Census district	Secondary data	Duration	Survey	Yes	Yes	Yes	Yes	Yes	More green space–short sleep RR: 0.68
De Santis et al. [104]	2013	Cross-sectional	Adults (n=1,406)	6 sites in US	Social capital, NBHD disorder, safety, walkable	Residential area	Perception, Census tract	Survey, Census data	Duration, sleepiness, insomnia	Survey	Yes	No	Yes	No	No	NBHD disorder–DUR: -0.11hr, safety: 0.12hr, social capital: 0.08hr
Hale et al. [105]	2013	Cross-sectional	Adults (n=1297)	Wisconsin	NBHD disorder, safety	Unspecified	Perception	Survey	Quality	Survey	Yes	No	Yes	Yes	Yes	NBHD disorder–poor sleep quality: 1.42
Bakker et al. [106]	2012	Cross-sectional	Adults (n=725)	Netherlands	Env. stressor	Residential area	ZIP code	Secondary data	Problems	Survey	Yes	No	No	No	No	Noise–sleep problems OR: 2.98
Zanobetti et al. [107]	2010	Cross-sectional	Adults (n=3,030)	6 sites in US	Env. stressor	Residential area	City boundary	Secondary data	Efficiency, Apnea	Polysomnography	No	No	Yes	Yes	No	High PM10 level–sleep-disordered breathing index: 12.9%, EFFCY: -1.2%
Hill et al. [108]	2009	Cross-sectional	Adults (n=1504)	Texas	NBHD disorder	Residential area	Unspecified	Survey	Quality	Survey	Yes	No	No	Yes	Yes	NBHD disorder–sleep quality score: -0.7
Johnson et al. [109]	2009	Cross-sectional	Mothers (n=392)	Baltimore, MD	Safety	Unspecified	Perception	Survey	Duration, problems	Survey	No	No	No	Yes	Yes	Low safety–short sleep OR: 2.06
Hale and Do [110]	2007	Cross-sectional	Adults (n=32,749)	United States	Urbanicity	Residential area	MSA	Survey	Duration	Survey	Yes	Yes	Yes	Yes	Yes	Living in urban area–short sleep OR: 1.43

NBHD: neighborhood, Psy.: psychological, Phys. Act.: physical activity, Behav.: behavior HH: household, DUR: sleep duration, EFFCY: sleep efficiency, WASO: wake up after sleep

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Chapter 2: Mediating Role of Psychological Distress in the Associations between Neighborhood Environments and Sleep Health

Study Objectives: Characteristics of neighborhood social environments, such as safety and social cohesion, have been examined as determinants of poor sleep. The current study investigates associations between neighborhood social characteristics and sleep health, as well as the mediating role of psychological distress on these possible associations.

Methods: Three waves of PHRESH Zzz (n=2,699), a longitudinal study conducted in two low-income, predominately Black neighborhoods, were utilized for this analysis. Characteristics of neighborhood social environments were measured using crime rates, a neighborhood social disorder index, and self-reported social cohesion. Sleep health was measured via 7 days of wrist-worn actigraphy as insufficient sleep, sleep duration, wake after sleep onset (WASO), and sleep efficiency. G-estimations based on structural nested mean models and mediation analyses were performed to estimate effects of neighborhood social environments on sleep as well as direct/indirect effects through psychological distress.

Results: Crime rate around residential addresses was associated with increased risk of insufficient sleep (risk ratio: 1.05 [1.02, 1.12]), increased WASO (β: 3.73 [0.26, 6.04]), and decreased sleep efficiency (β: -0.54 [-0.91, -0.09]). Perceived social cohesion was associated with decreased risk of insufficient sleep (OR: 0.93 [0.88, 0.97]). Psychological distress mediated part of the associations of crime and social cohesion with insufficient sleep.

Conclusions: Neighborhood social environments may contribute to poor sleep health in low-income, predominantly Black neighborhoods, and psychological distress can be a salient pathway linking these neighborhood characteristics and sleep health.

2.1 Introduction

Sleep is an essential determinant of physical and mental health.[1,2] A large body of studies show that sleep health is associated with body mass index,[3] hypertension,[4] type-2 diabetes,[5] and other cardiovascular diseases.[6] Furthermore, poor sleep is related to multiple neurocognitive disorders,[7,8] as well as psychiatric illnesses.[9-11] Despite this, sleep duration, a key metric of sleep health, has been decreasing in the United States (U.S.) since 1960, and in 2014, more than 30% of U.S. population had short sleep duration, defined as sleep less than 7 hours.[12] In 2018, more than 35% of working adults in the U.S. reported insufficient sleep.[13] Sleep health outcomes, including sleep duration and sleep disorders, show socially patterned distributions related to sociodemographic factors, analogous to other chronic conditions.[14,15] Specifically, Black population has higher burden of poor sleep health compared to their White counterpart.[16-18] Racial/ethnic minorities and lower socioeconomic groups are likely to reside in disadvantaged neighborhood environments, and such adverse environmental factors play important roles in the associations between neighborhood and sleep.[19]

Neighborhood characteristics are important determinants of various health outcomes and health behaviors through different causal mechanisms.[20-22] Social environments of neighborhoods, such as safety and social cohesion, are particularly relevant to psychological well-being and mental health, as features of social disorders and neighborhood disadvantages function as salient stressors.[23,24] Under the framework of the psychosocial theory, adverse neighborhood social characteristics may increase vulnerabilities to stress,[25] and such increased stress may modify sleep behavior and sleep quality (Figure 1).[26] In fact, social characteristics of neighborhoods are salient risk factors of perceived stress and psychological distress,[27,28] and various types of stresses, such as allostatic load, stress biomarkers, and psychological distress, are associated with poor sleep health outcomes.[29-32]

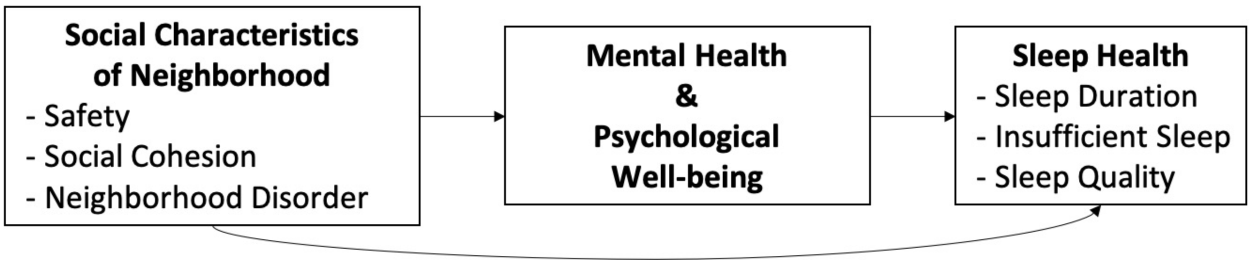


Figure 1. Conceptual Diagram

In addition to individual-level factors of sleep health including age, sex, race/ethnicity and occupation, growing evidence suggests that supra-individual and neighborhood-level factors, such as walkability, urban design, neighborhood disorder, safety and social cohesion, could shape sleep health.[19,33-37] However, most of the studies on environmental risk factors of sleep health rely on cross-sectional study designs with self-reported sleep measures and perceived neighborhood characteristics, which are susceptible to recall bias, same-source bias and reverse causality, and measurement errors. Self-reported sleep health, commonly operationalized as sleep duration and sleep disturbances, may not capture various aspects of sleep, since sleep is a comprehensive and complex behavior with multi-faceted components including sleep timing, duration, quality, and circadian rhythm.[38] In addition, most existing studies on neighborhood and sleep examined residence-based neighborhood characteristics with static administrative boundaries positing potential biases, such as spatial misclassification and modifiable areal unit problems.[39] Recently, Johnson and colleagues investigated neighborhood social characteristics characterized by social cohesion and safety as determinants of objective sleep duration measured via actigraphy device (i.e. monitoring sleep/active cycles via wristwatch-like accelerometer devices) which have been validated to evaluate sleep and wake patterns.[40-42] Troxel and colleagues examined the associations between various social and physical characteristics of neighborhoods and sleep health utilizing objective measures of sleep health via actigraphy device as well as quantitative neighborhood environment measures based on geographic information systems (GIS).[43-45] However, the previous studies are still limited to cross-sectional study designs.[43]

Due to the abovementioned limitations, the causal identification and mechanisms still remain unclear. Individual-level psychological aspects influence sleep health, yet only a few cross-sectional studies investigated these variables as a potential causal mechanism,[26,45] despite a large body of literature on neighborhood effects on mental health status. Identification of causal mechanisms is important to provide plausible and feasible intervention to improve sleep health, thus, it is critical to identify specific pathways of the impacts of neighborhood characteristics on sleep health, based on refined neighborhood assessments, psychological measures, and objective measures of sleep health, along with appropriate study design and statistical analysis.[35]

The present paper contributes to the existing literature by analyzing repeated measures of various objective measures of neighborhood characteristics and actigraphy-based sleep measures. We hypothesized that adverse social environments in residential areas are positively associated with poor sleep health, and that the association between neighborhood environments and sleep health is mediated by psychological distress. The present paper aims to explore the association of the social neighborhood stressors with sleep health and examine potential mediation via a psychological stress pathway.

2.2 Methods

Data

The PHRESH Sleep (PHRESH Zzz) is a sub-cohort study based on an original study of Pittsburgh Hill/Homewood Research on Eating, Shopping, and Health (PHRESH). The participants of PHRESH study were recruited from a random sample of households in two low-income, predominantly African American neighborhoods in Pittsburgh, Pennsylvania.[46] From 2013, one neighborhood (the Hill District) has undergone significant neighborhood revitalization projects compared with the other neighborhood (Homewood), which included housing and greenspace improvements as well as retail and business developments. The PHRESH Zzz investigated how and to what extent changes in social and built environments may impact sleep and other health behaviors. The PHRESH Zzz data were collected in 2013, 2016, and 2018 from an in-person household survey. There were 1051 participants who were in the cohort in 2013, 828 participants in 2016, and 820 in 2018 resulted in 22% attrition rate which is similar with other longitudinal actigraphy studies.[47,48] Participants with fewer than 4 nights of actigraphy data (n = 224) and/or who were missing covariates (n = 16) were excluded from the analysis. It is assumed that the missingness of actigraphy data is mainly due to the adherence to the data collection protocols (e.g. continuous monitoring during 7 days,[49] and such missing not at random outcome data would be preferred to be handled as a complete case analysis.[50] In addition, the analytic sample for mediation analysis included 570 participants who completed all the three waves of data collection (Table S2) to estimate random intercept and random slope.

The PHRESH Zzz data collection included micro-level street auditing on social and built environments characteristics 1-year prior to the actigraphy measures of sleep across the three waves in the two neighborhoods. This objective assessment employed validated audit tools, including the Systematic Pedestrian and Cycling Environmental Scan,[51] St. Louis Analytic Audit Tool and Checklist,[52] and Systematic Social Observation protocol,[53] with modifications for emphasis on physical activity, sleep, and obesogenic behaviors [54]. The auditing process covered a 25% random sample (n=511) of all street segments (n=2,027) in each neighborhood, with additional oversamples of 85 street segments in the neighborhood in which revitalization projects were anticipated. One year prior to each wave of PHRESH Zzz (2011, 2015, and 2017), pairs of trained data collectors conducted comprehensive observations on various social and physical characteristics including urban design features, neighborhood disorders, and walkability measures. Detailed information on audit variables were described elsewhere.[54] Across waves, the majority of items in the street audit tools showed good to excellent agreement (> 75% agreement) based on Krippendorff's alpha[55] and percentage inter-observer agreement.[56,57] Neighborhood characteristics from the street audit data were spatially joined to individuals based on average scores of street segments within or intersecting with 1/4-mile network buffers of each participants' residential addresses. Details of the street auditing data collection procedures are described elsewhere.[54]

Sleep

In the PHRESH Zzz study, Actigraph GT3X model was used to define sleep health outcomes, which is a validated device to measure sleep and wake rhythms relative to polysomnography.[58-60] Participants were asked to wear the wrist device for 7 consecutive days. Data of participants who wore fewer than 4 nights were excluded from the analyses based on suggested nights of data required to establish reliable sleep patterns via actigraphy.[61] Sleep and wake patterns were derived using Cole-Kripke algorithm to calculate total sleep time, sleep efficiency, and wake-after sleep onset (WASO). Sleep outcomes were averaged across all nights of each assessment period.[62]

Sleep duration (i.e. total sleep time) is the total amount of time spent sleeping during the participant's time in bed assessed by actigraphy. Sleep duration in each wave was calculated by averaging the valid actigraphy data of each participants. The averaged time of sleep was analyzed as a continuous variable. In addition, less than 7 hours of average sleep duration in each wave was classified as insufficient sleep,[63] and insufficient sleep was utilized as a dichotomized variable. WASO was measured as the total number of minutes classified as awake after sleep onset based upon the Cole–Kripke algorithm. WASO was analyzed as a continuous variable. Sleep efficiency was defined as the total duration of sleep divided by the total time in bed based on self-reported sleep diaries and visual inspection of actigraphy records. Higher values of sleep efficiency indicate better sleep continuity. Sleep efficiency was analyzed as a continuous variable.

Psychological Distress

Psychological distress was measured from the Kessler 6 (K6) scale. The K6 consists of six questions about how often the participants had felt: 1) nervous; 2) hopeless; 3) restless; 4) depressed; 5) that everything was an effort; and 6) worthless during past 30 days. The response options were: 'never', 'a little of the time', 'some of the time', 'most of the time' and 'all of the time'. Responses were scored in the range of 0 ('never') to 4 ('all of the time'), generating a scale with a range of 0–24, which indicates the presence of mild to severe distress. A K6 score above 5 points was classified as moderate distress [64], and the dichotomized variable was utilized in the analysis. The K6 scale was measured during the home visit of each data collection wave followed by the consecutive monitoring of sleep duration and quality through actigraphy device. Therefore, there was sequential temporal order between the psychological distress measure and sleep measures. Of note, previous sleep could have contributed to both psychological distress and subsequent sleep measures, representing a major source of confounding, and we tested the associations between sleep health outcomes and subsequent psychological distress.

Neighborhood characteristics

Crime

Incident-level crime data provided by the City of Pittsburgh police department were extracted and geocoded (95% geocoding rate) for 2012, 2015, and 2017 which were one year prior to the in-person household survey. For each household, the total number of crimes that occurred within a 1/4-mile network distance were summed for each year using ArcGIS 10.2 software. The 1/4-mile network distance was considered as a "short walking distance", and it was frequently used in prior neighborhoods research.[65,66] In addition to the total number of crimes, violence and property crimes were considered separately in a sub-analysis.

Social Cohesion

Participants' perceptions of social cohesion was assessed with a validated questionnaire made of five-item Likert-scale items, ranging from 1 (strongly agree) to 5 (strongly disagree). The questions include: "People in this neighborhood are willing to help their neighbors", "This is a close-knit neighborhood", "People in this neighborhood can be trusted", "People in this neighborhood generally don't get along with each other", "People in this neighborhood do not share the same values", and "People in this neighborhood look out for one another".[67,68] The average scale of the six questions were employed as a social cohesion index with higher scores indicating greater perceived social cohesion, and each item was also utilized separately for sub-analysis.

Neighborhood social disorder

Neighborhood social disorder measure was derived from the street audit data. The data collectors recorded physical conditions of each street segment that may indicate neighborhood disorders including presences of any litter on streets, any vacant lot or housing, bars on windows, and broken windows as well as perceived safety (by data collectors) on the street segment.[69] All neighborhood disorder items were summed for each street segment, and average scores for participants were calculated based on the 1/4-mile street network buffer. Higher scores indicate more neighborhood disorder, and each item was also analyzed separately in a sub-analysis.

Covariates

A set of individual-level sociodemographic variables identified as potential confounders between neighborhood characteristics and sleep health was included in the analysis as covariates. The covariates included age, sex, per capita annual household income (in $1,000), education attainment (less than high school [referent], 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), and family structure (any child(ren) in household). Additionally, the number of years lived in the current neighborhood was also included in the analysis.

Statistical Analysis

Descriptive statistics were provided to summarize data of the study. All measures in the analysis, including the characteristics of neighborhood social environments, psychological distress, and sleep health were measured repeatedly across three waves. The three waves of data were analyzed using g-estimation with structured nested mean models (SNMM), estimating the joint additive effect of each neighborhood characteristic on sleep health across all 3 waves.[70] 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,…,T and all t<s with covariate c. In other words, the joint effect is the counterfactual outcome with exposure set to the observed up to time t and 0 afterwards, estimating expected 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 social environments at prior time can consistently affect the sleep health.[71,72] When Y is a binary outcome (e.g. insufficient sleep), an SNMM fits the causal risk ratio.[73] Lastly, percentile-based confidence intervals for the causal parameters of a fitted SNMM were calculated from 500 bootstrapping samples.

To examine the mediating role of psychological distress averaged across three waves, natural direct and indirect effects were estimated using a potential outcomes frame which allows for an interaction between the exposure and the mediator.[74] 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. psychological distress). Under this notation, the direct effect is the effect A → Y, not through M, and the indirect effect is the effect A → M → Y. The conditional natural direct/indirect effects are defined as $E(Y_{ij}^{a,M_{ij}^{a^*}} - Y_{ij}^{a^*,M_{ij}^{a^*}} \mid C_{ij} = c)$, and $E(Y_{ij}^{a,M_{ij}^{a}} - Y_{ij}^{a,M_{ij}^{a^*}} \mid C_{ij} = c)$, 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 establish valid mediation analyses, the following criteria were considered: a) if there was an association between exposure and mediator; and b) if there was an association between mediator and outcome. In addition, natural direct and indirect effects require following underlying assumptions: no unmeasured confounding between A – Y (denoted as C_1), no unmeasured confounding between A – 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 abovementioned covariates were included to adjust for potential C_1, C_2, and C_3, which included in all analysis (Figure 2). And the last assumption, C_4, might be violated due to the longitudinal data. Some covariates, especially indicators of socioeconomic status, might be affected by previous neighborhood social environments at prior timepoint, violating this assumption, and these can potentially bias the results.[75-77] Sleep measures at prior timepoint can also associated with subsequent psychological distress and sleep measures, and we tested the associations by employing lagged sleep health outcome (Equation 3). To pool within-wave mediation analysis across the three waves, two generalized mixed-effects models for both the mediator and the outcome were fitted. The model for the mediator has subject-specific random intercepts and random exposure slopes for each participant (Equation 1), and the outcome model has random intercepts and random slopes for the exposure, and the mediator (Equation 2).

$$Equation\ 1 - M_{i,j} = \beta_0 + u_i + \beta_1 X_{1ij} + \cdots + \beta_\rho X_{\rho ij} + \beta_{NBHD} NBHD_{ij} + \varepsilon_{ij}$$

$$Equation\ 2 - Y_{i,j} = \gamma_0 + g_{0i} + \gamma_1 X_{1ij} + \cdots + \gamma_\rho X_{\rho ij} + \gamma_{NBHD} NBHD_{ij} + \gamma_M M_{ij} + \eta_{ij}$$

where i corresponds to each participant and j to each visit; β_0 and γ_0 to the intercept for the sample mean; u_i and g_{0i} to the subject-specific random intercept. $\beta_1 X_{1ij}$ to $\beta_p X_{pij}$ and $\gamma_p X_{pij}$ to $\gamma_p X_{pij}$ correspond to the selected covariates. M_{ij} corresponds to psychological distress, and Y_{ij} corresponds to sleep health outcomes. β_{NBHD}NBHD and γ_{NBHD}NBHD correspond to neighborhood characteristics, and $\gamma_M M_{ij}$ corresponds to psychological distress in the mediator-outcome association. ε_{ij} and η_{ij} are the within-subject and within-visit error terms.

γ_{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, which corresponds to $Var(\gamma_M)\ \beta_{NBHD}^2 + 2Cov(\beta_{NBHD}, \gamma_M)\ \beta_{NBHD}\ \gamma_M + Var(\beta_{NBHD})\ \gamma_M^2$.[74] Proportion mediated is calculated as the percentage of natural indirect effect over the total effect.

When fitting the linear mixed-effects models with subject-specific intercepts and covariate adjustment, we assumed no time-varying unmeasured confounding for M – Y relationship. However, socioeconomic status, such as income and employment status can be affected by previous social environments. In addition, sleep health outcomes at one visit could potentially affect psychological distress at the subsequent visit (dotted arrow in Figure 2), and it may potentially bias the mediator–outcome association and the mediation estimates.[78,79] Therefore, we tested the presence of an association between $Y^{i,j}$ and $M^{i,j+1}$, to check the assumption of the post-exposure M – Y confounding from Equation 3.

$$Equation\ 3 - \ M_{i,j+1}$$
$$= \alpha_0 + \ u_i + \ \alpha_1 X_{1ij} + \cdots + \ \beta_\rho X_{\rho ij} + \alpha_Y Y_{1ij} + \alpha_M M_{ij} + \ \beta_{NBHD} NBHD_{ij} + \ \varepsilon_{ij}$$

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

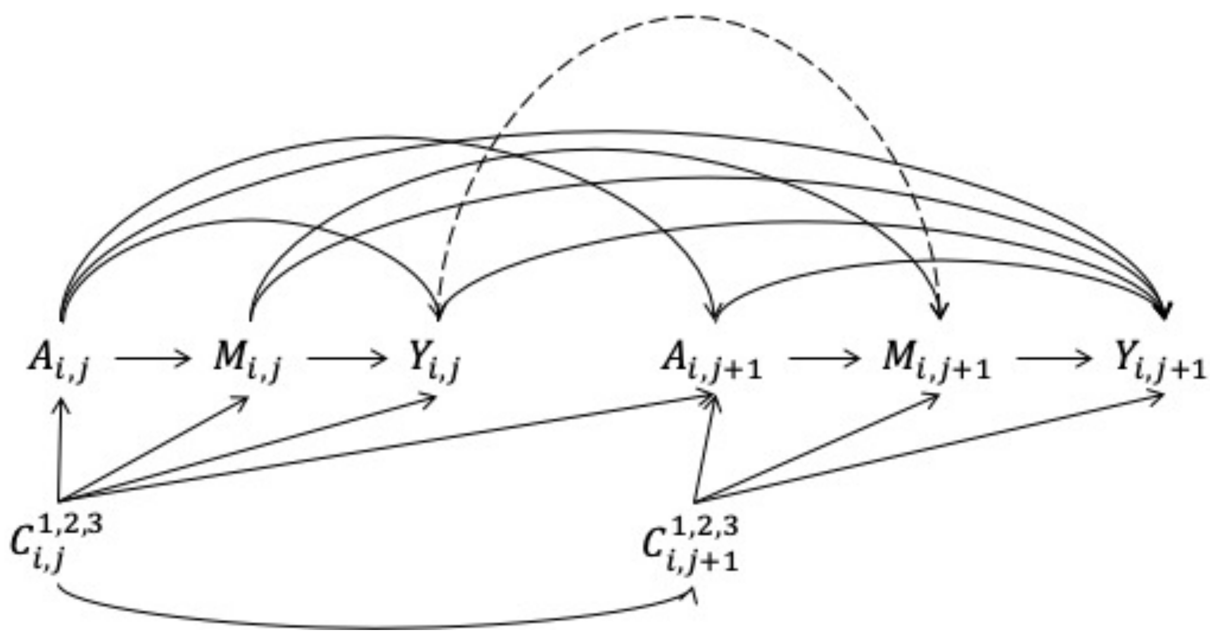


Figure 2. Directed acyclic graph (DAG) for mediation analysis. $A_{i,j}$ represents neighborhood characteristics for *i*th subject at *j*th visit; $M_{i,j}$ represents psychological distress for *i*th subject at jth visit; $Y_{i,j}$ represents sleep health outcomes for *i*th subject at jth visit. $C^{1,2,3}_{i,j}$ represents exposure outcome confounders (C_1), exposure mediator confounders (C_2), and mediator outcome confounders (C_3).

2.3 Results

There was a total of 2,699 participants in this study. The first wave in 2012 included 1,051 participants, and there were 828 participants for wave 2 in 2016, and 820 participants for wave 3 in 2018. Table 1 describes participant characteristics at each wave, and Table S2 shows 570 participants who completed all the three data collections. Ninety-two percent of participants were Black, and 76% were female at wave 1. The mean sleep duration was 344 minutes, and the prevalence of insufficient sleep (sleep duration < 6 hours) was 22% at the first wave.

Overall association between neighborhood social characteristics and sleep health

Table 2 show the joint associations of time-varying neighborhood social characteristics on sleep health. Crime rates within ¼-mile buffer of participants' home address were associated with increased risk of insufficient sleep (risk ratio (RR): 1.05, 95% confidence interval (CI) [1.02, 1.12]), increased WASO (risk difference (RD): 3.73 minutes, CI [0.26, 6.04]), and decreased sleep efficiency (RR:-0.55 percent point, CI [-0.92, -0.09]). Perceived social cohesion was associated with decreased risk of insufficient sleep (RR: 0.93, CI [0.88, 0.97]) and increased total sleep time (RD: 3.35 minutes, CI [0.88, 5.97]). Lastly, neighborhood disorder indicators on streets within or intersecting ¼-mile buffer of participants home address was associated with decreased sleep efficiency (RD: -0.46 percent point, CI [-0.85, -0.77]).

Mediation Analysis

Crime rate and social cohesion showed associations with psychological distress, however, neighborhood disorder was not associated with the mediator (Figure 3). Psychological distress was associated with insufficient sleep, WASO, and sleep efficiency, but not with sleep duration.

Therefore, the basic criteria for valid mediation analysis for psychological distress (i.e. mediator) were met for crime, social cohesion as exposures, and insufficient sleep, WASO, and sleep efficiency as outcomes.

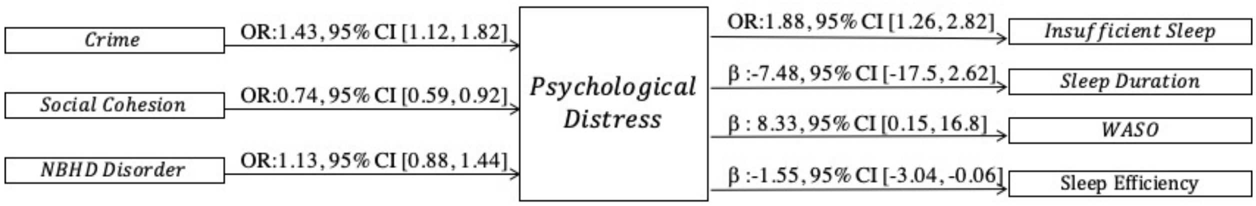
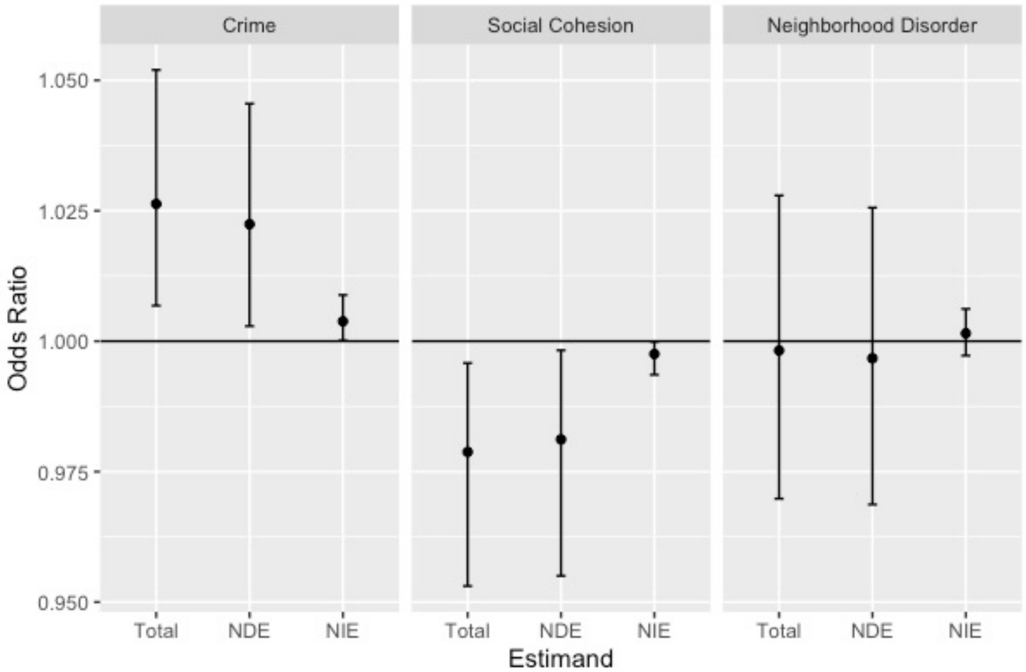


Figure 3. Exposure-mediator and mediator-outcome associations. Each mixed-effect regression models were adjusted for age, sex, income, education, employment, marital status, family structure, and number of years in current neighborhood.

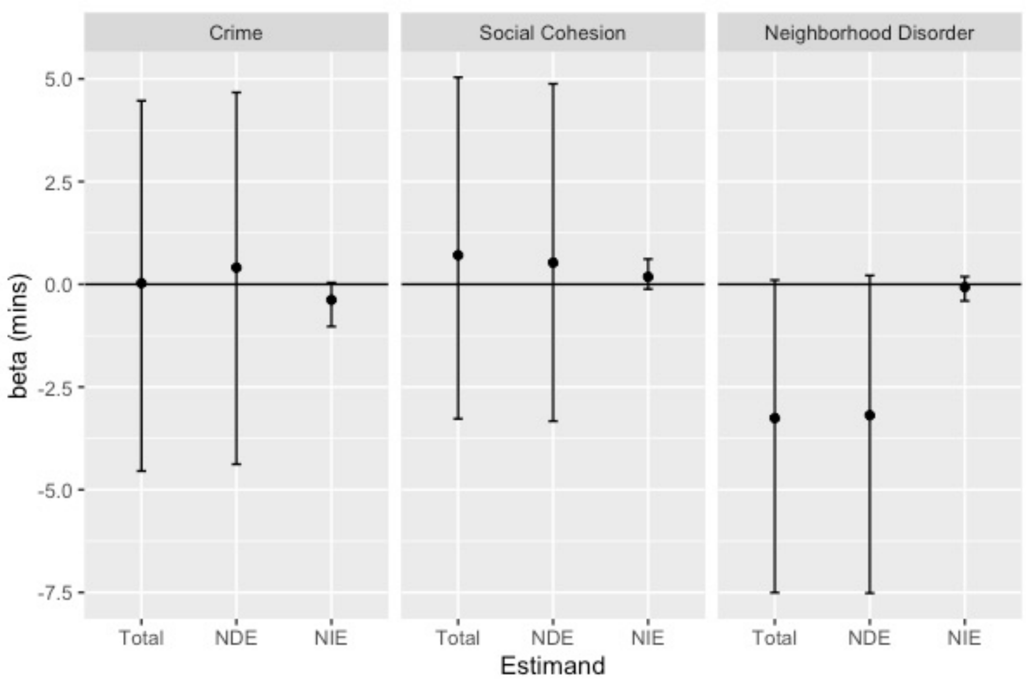
In addition, prior to fitting mixed effect models for the longitudinal mediation analysis, we examined whether there was time-varying confounding for the M-Y association due to previous sleep outcomes from equation 3 (dotted arrow in Figure 2). The psychological distress measure at the subsequent visit (M_{ij} + 1) was not associated with sleep health outcomes (Y_{ij}) at the prior visit, and all the point estimate and confidence interval were negligible (Table S1). However, other time-varying confounders, specifically covariates for socioeconomic status, still remain as potential sources of bias.

Table 3 presents the natural direct/indirect effects and proportion mediated for psychological distress. The results showed that psychological distress mediated the associations between crime rate in 1/4-mile network buffer and insufficient sleep, as well as between social cohesion score and insufficient sleep (figure 4 – a). Psychological distress was also a salient mediator in the relationships between crime and WASO (figure 4 – b), and between crime and sleep efficiency (figure 4 – c).

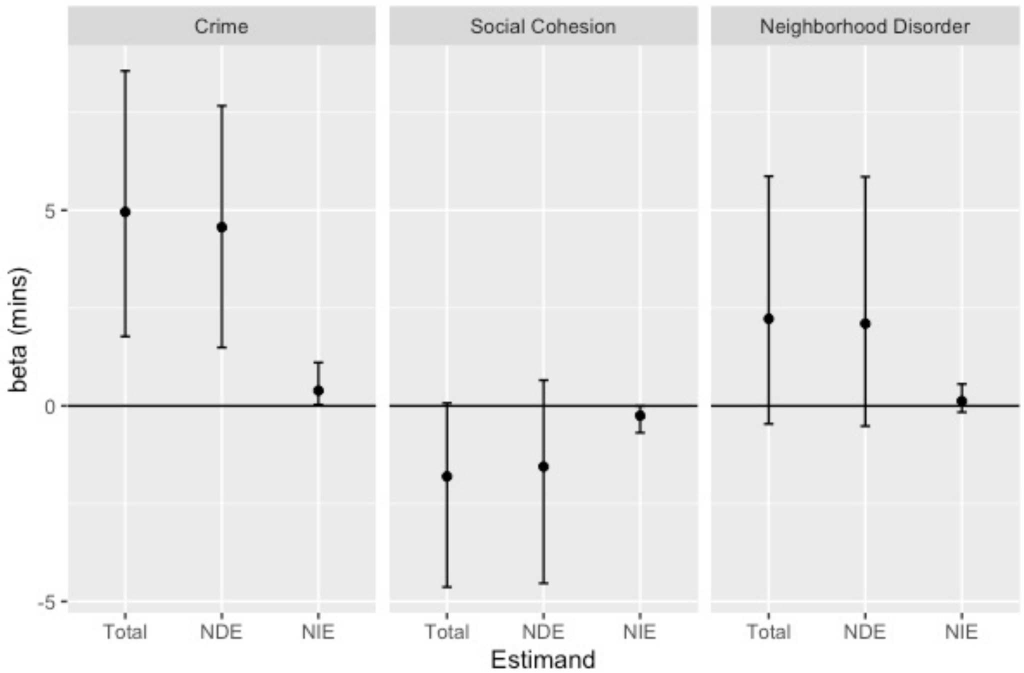
4-a Insufficient Sleep



4-a. Sleep Duration



4-c. WASO



4-d. Sleep Efficiency

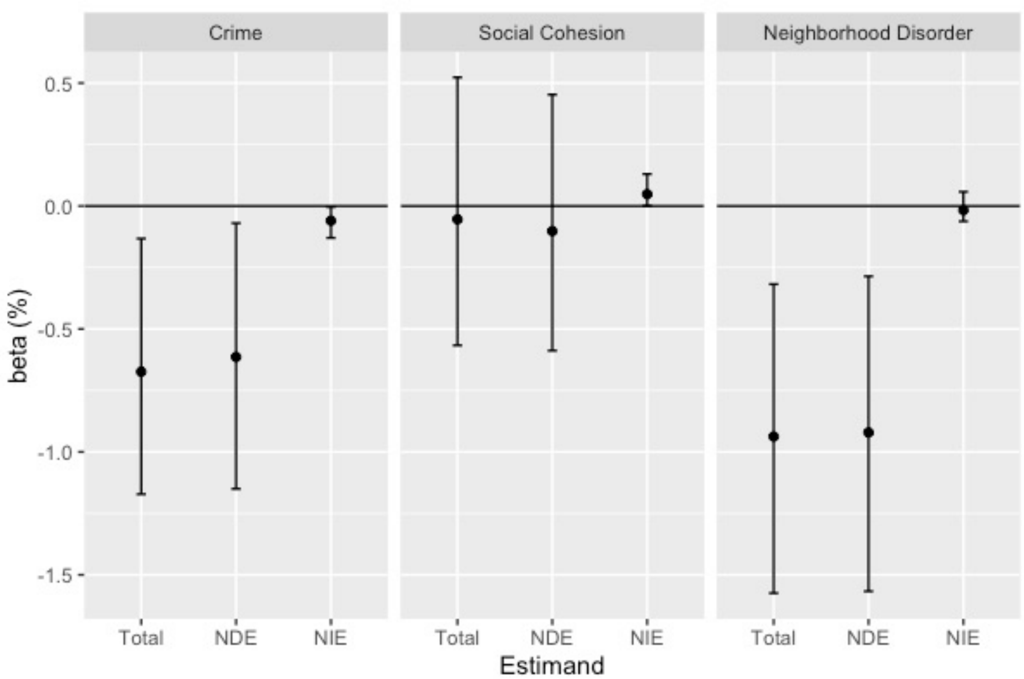


Figure 4. Mediation analysis results. Figure 4-a is for insufficient sleep, 4-b for sleep duration, 4-c for WASO, and 4-d for sleep efficiency outcomes. Each plot represents the four built

environment characteristics. Total: total effect, NDE: natural direct effect, NID: natural indirect effect

2.4 Discussion

We found associations between neighborhood social characteristics and objective measures of sleep health, consistent with previous findings.[42,43] Specifically, neighborhood crime was associated with increased risk of insufficient sleep, increased WASO, as well as decreased sleep efficiency, and neighborhood social cohesion may be a protective factor of insufficient sleep and sleep duration. Lastly, neighborhood disorder may decrease sleep efficiency in the two low-income, predominantly Black neighborhoods.

In addition, the mediation analyses found that psychological distress may play a minor but non negligible role in the associations between neighborhood social characteristics and sleep health. The associations of neighborhood social cohesion with insufficient sleep was also partially explained by psychological distress. Previous research examined the impacts of neighborhood safety and social cohesion on psychological distress and self-reported sleep duration,[26,45,80] and our findings support the mediating role of psychological distress.

We enhanced prior research on neighborhood effects on sleep health by utilizing repeated measures of neighborhood characteristics and sleep health. Along with the g-estimation based on structured nested mean model, the three waves of PHRESH Zzz data allows rigorous estimations of time-varying neighborhood characteristics and sleep health. In addition, the mediation analysis investigated a potential mechanism through psychological distress. Lastly, except the perceived social cohesion index, the measures of neighborhood social characteristics (i.e. crime rates and neighborhood disorders) were captured via systematic report data and direct observations.

Marginalized groups are likely to reside in disadvantaged environments, and such deprived social characteristics of neighborhoods have bearings on various health outcomes.[20-22,81] Considering the associations between sleep and health,[3-11] our findings suggests that disadvantaged neighborhood environments may play its role in health disparities in cardiometabolic diseases and other chronic conditions through sleep health in racial minority groups.[82] Thus, public health professionals and policy makers may consider neighborhood disorder, exposure to crimes, and perception of safety as key, modifiable, neighborhood factors that could address the poor sleep health as well as other sleep-related chronic conditions. From our analysis, we found that adverse neighborhood environments may increase psychological distress which may consequently contribute to sleep. These findings suggest place-based interventions that can enhance safety and social cohesion of a neighborhood. However, it should be interpreted with a caveat: reducing crime is not necessarily entails enforced policing.[83] For instance, increased level of social cohesion may also reduce crime rate,[84,85] therefore a set of upstream strategies to foster social capital and collective efficacy in a neighborhood may be beneficial.[68,86]

This study is not without limitations. Various neighborhood characteristics, including social and built environments, can effect changes in each other and consequently impact on sleep health. For instance, poor sidewalk conditions with abandoned buildings and empty lots may affect the sense of social cohesion in neighborhoods, and it is also possible that low social cohesion can cause poor maintenance of streets. Such interwoven associations between social and built environments are hardly separable from observational data.[87,93] We did not adjust for aspects of the built environment, so these represent unmeasured confounders that may bias our results. However, we assumed that social characteristics of neighborhoods are salient stressors which directly affect psychological distress as a distinct causal pathway and analyzing separate aspects of social environments can predict the total effect of each domain. In addition, there is might be unmeasured post-exposure confounders on the association between psychological distress and sleep health,[88] which is a violation of underlying assumption for natural direct and indirect effects. For example, neighborhood characteristics may impact on the level of physical activity of individuals, and such physical inactivity can cause psychological distress as well as sleep health. Given the longitudinal nature of the data, there are also measured post-exposure confounders, including the current wave's covariates. If any one of these measured variables or any additional unmeasured variables acted as a post-exposure confounder, the natural direct and indirect effects would not be identified, and our results could be biased. However, we hypothesize that the selected covariates were potential determinants of social characteristics of neighborhoods, rather than consequences of neighborhood environments. An alternative would be to estimate interventional direct and indirect effects, which do not need such an assumption for identification. In this analysis, the baseline sleep outcomes and psychological distress measures were not measured nor included as covariates, which may result biased estimates. However, baseline adjustment with potential measurement errors can also cause additional biases.[89]

We utilized participants' residential address which does not capture of daily mobility-based neighborhood exposures.[90] For example, individuals are exposed to multiple (e.g. residential, work, socializing) neighborhood environments in their daily lives, thus adequate capture of neighborhood characteristics based on daily mobility pattern is important in determining actual exposures to neighborhood characteristics. In addition, residential self-selection of individuals, referring individuals' propensity to choose where to live based on their life needs and preferences, may influence the neighborhood satisfaction and sleep.[91]

This study was conducted in relatively small neighborhood areas, Hill District and Homewood in Pittsburgh, and such small geographic variations are unlikely to represent diverse environmental factors across large cities. Thus, the study results may not be generalizable to other urban or rural contexts. However, as one of the neighborhoods, Hill District, experienced community-wide urban redevelopment projects, and the findings may suggest the associations of urban development changes with sleep health in large metropolitan areas. Although actigraphy data have strengths in measuring sleep health objectively, it has limitations, such as imperfect capture of sleep health due to dropping out participants with less than 4 night. Given the exclusion, the present analysis may not fully represent the characteristics of the PHRESH Zzz data.

Lastly, it is important to note that the K6 measure does not broadly capture neighborhood stressors but is used for detecting serious mental illness and disorders. Moreover, social cohesion was assessed with an individual subjective measure rather than with an objective collective measure as those provided by ecometric analyses of residents' perceptions.[92]

In summary, we found the social characteristics of neighborhoods are related to actigraphy-based sleep health measures via a potential psychological pathway. Since sleep is a salient determinant of several poor health outcomes including obesity, cardiovascular diseases, and psychiatric illnesses, improving sleep health may subsequently affect a variety of public health challenges. Based on our findings, interventions to improve sleep should target modifiable factors and enhance neighborhood environments. These sorts of strategies have the potential to improve not only sleep health but also other health outcomes.

2.5 Tables

Table 1. PHRESH Zzz Study Characteristics

	PHRESH Zzz					
	2012 (n=1,051)		2016 (n=828)		2018 (n=820)	
	Mean or count	SD or %	Mean or count	SD or %	Mean or count	SD or %
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 or 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%
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
Psychological distress (K6 score ≥ 5)	217	20.6%	168	20.3%	160	19.5%
Total crime (in ¼-mile buffer)	23.1	18.1	23.7	17.5	23.9	21.0
Social cohesion score	3.06	0.81	3.16	0.77	3.26	0.74
Neighborhood disorder score (in ¼-mile buffer)	4.66	1.21	4.82	1.10	4.54	1.0

Table 2. Joint causal effects of neighborhood social characteristics on sleep health

Exposure	Outcome	Risk Ratio (or Risk Difference)	95% Confidence Interval
Crime	Insufficient Sleep	1.05	(1.02, 1.12)*
	Total Sleep	-1.22	(-3.79, 1.48)
	WASO	3.73	(0.26, 6.04)*
	Sleep Efficiency	-0.55	(-0.92, -0.09)*
Social Cohesion	Insufficient Sleep	0.93	(0.88, 0.97)*
	Total Sleep	3.35	(0.88, 5.97)*
	WASO	-0.61	(-2.86, 1.47)
	Sleep Efficiency	0.07	(-0.3, 0.49)
Neighborhood Disorder	Insufficient Sleep	0.99	(0.94, 1.07)
	Total Sleep	-0.99	(-3.95, 2.58)
	WASO	1.61	(-0.6, 4.42)
	Sleep Efficiency	-0.46	(-0.85, -0.07)*

All models were adjusted for age, sex, education, marital status, family structure, and number of years in current neighborhood.

Table 3. Mediation Analysis Results (complete case analysis)

	Insufficient Sleep		Sleep Duration		WASO		Efficiency	
	ORs	95% CI	β	95% CI	β	95% CI	β	95% CI
Crime								
Total	1.03	(1.01, 1.05)*	0.03	(-4.55, 4.47)	4.96	(1.77, 8.56)*	-0.67	(-1.17, -0.13)*
NDE	1.02	(1.00, 1.05)*	0.41	(-4.38, 4.67)	4.57	(1.49, 7.67)*	-0.61	(-1.15, -0.07)*
NIE	1.00	(1.00, 1.01)*	-0.38	(-1.03, 0.04)	0.39	(0.03, 1.11)*	-0.06	(-0.13, 0.00)*
Proportion Mediated	0.13	(-0.02, 0.42)	0.02	(-2.35, 3.22)	0.08	(0.01, 0.3)*	0.09	(0.00, 0.57)*
Social Cohesion								
Total	0.98	(0.95, 1.00)*	0.71	(-3.27, 5.04)	-1.80	(-4.63, 0.07)	-0.05	(-0.57, 0.52)
NDE	0.98	(0.96, 1.00)*	0.52	(-3.33, 4.88)	-1.55	(-4.54, 0.66)	-0.10	(-0.59, 0.45)
NIE	1.00	(0.99, 1.00)*	0.18	(-0.12, 0.61)	-0.25	(-0.69, -0.01)*	0.05	(0.00, 0.13)*
Proportion Mediated	0.08	(-0.06, 0.66)	0.05	(-0.65, 4.51)	0.13	(-0.26, 3.16)	-0.02	(-3.3, 9.49)
Neighborhood Disorder								
Total	1.00	(0.97, 1.03)	-3.26	(-7.51, 0.10)	2.23	(-0.46, 5.87)	-0.94	(-1.57, -0.32)*
NDE	1.00	(0.97, 1.03)	-3.19	(-7.52, 0.22)	2.10	(-0.52, 5.86)	-0.92	(-1.57, -0.29)*
NIE	1.00	(1.00, 1.01)	-0.07	(-0.40, 0.19)	0.12	(-0.16, 0.56)	-0.02	(-0.06, 0.06)
Proportion Mediated	0.01	(-1.39, 2.52)	0.01	(-0.11, 0.34)	0.04	(-0.09, 8.35)	0.02	(-0.07, 0.09)

NDE: Natural Direct Effect, NIE: Natural Indirect Effect, *:p-value<0.05
All models were adjusted for age, sex, education, marital status, family structure, and number of years in current neighborhood.

Table S1. Associations of sleep health outcomes with psychological distress at the subsequent visit (t + 1)

Neighborhood Characteristic	Sleep at t	Psychological Distress at t+1	95% CI
Crime	Insufficient Sleep	0.92	(0.6, 1.39)
	Sleep Duration	1.00	(1.00, 1.00)
	WASO	1.00	(1.00, 1.00)
	Sleep Efficiency	0.99	(0.98, 1.01)
Social Cohesion	Insufficient Sleep	0.94	(0.62, 1.41)
	Sleep Duration	1.00	(1.00, 1.00)
	WASO	1.00	(1.00, 1.00)
	Sleep Efficiency	0.99	(0.98, 1.01)
Neighborhood Disorder	Insufficient Sleep	0.96	(0.62, 1.48)
	Sleep Duration	1.00	(1.00, 1.00)
	WASO	1.00	(1.00, 1.00)
	Sleep Efficiency	0.99	(0.98, 1.01)

Table S2. PHRESH Zzz Study Characteristics – Complete Cases Only

	PHRESH Zzz (n=570)					
	2012		2016		2018	
	Mean or count	SD or %	Mean or count	SD or %	Mean or count	SD or %
Age	55.8	14.2	58.9	14.1	61.6	14.2
Race						
African-American	536	94%	536	94%	536	94%
Non African-American	34	6%	34	6%	34	6%
Female	463	81.2%	463	81.2%	463	81.2%
Per capita annual household income (in 1,000)	14.1	14.3	14.6	13.6	15.2	15.1
Education						
Less than high school	71	12.5%	71	12.5%	63	11.1%
High school	242	42.5%	242	42.5%	219	38.4%
Some college	180	31.6%	180	31.6%	212	37.2%
College	77	13.5%	77	13.5%	76	13.3%
Marital status						
Married or living with partner	110	19.3%	91	16.0%	84	14.7%
Never married	234	41.1%	241	42.3%	238	41.8%
Widowed, divorced or separated	226	39.6%	238	41.8%	248	43.5%
Household with child(ren)	140	24.6%	119	20.9%	98	17.2%
Employment						
Full-time	137	24.0%	124	21.8%	127	22.3%
Part-time	81	14.2%	84	14.7%	76	13.3%
Not employed	352	61.8%	362	63.5%	367	64.4%
Years in current neighborhood	32.5	22.4	29.4	21.9	33.2	23.1
Sleep health						
Mean minutes sleep duration	342	80.5	334	74.5	327	82.4
Insufficient sleep (<6hr)	130	22.80%	143	25.10%	167	29.30%
Mean minutes of WASO	88	55.9	112	64.1	123	73.5
Mean sleep efficiency (%)	78.3	10.8	73	11.8	71.1	12.3
Psychological distress (K6 score ≥ 5)	116	20.4%	111	19.5%	105	18.4%
Total crime (in ¼-mile buffer)	23.2	17.7	24.1	18.0	23.8	21.4
Social cohesion score	3.06	0.81	3.18	0.79	3.27	0.76
Neighborhood disorder score (in ¼-mile buffer)	4.57	1.23	4.75	1.11	4.49	1.0

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Chapter 3: Mediating Role of Physical Activity in the Associations between Neighborhood Environments and Sleep Health

Study Objectives: Physical and social characteristics of neighborhoods, including walkability, urban design features and crime, may be important determinants of sleep health. The present study examined the associations between physical and social characteristics of neighborhoods and sleep health outcomes and assessed the mediating role of physical activity on these associations.

Methods: A longitudinal study (PHRESH Zzz, n=2,699) was conducted in two low-income, predominately African-American neighborhoods with repeated measures of neighborhood characteristics and sleep health outcomes. Built environment measures of walkability, urban design, and neighborhood physical disorder were captured from systematic field observations, and police-reported crime rate was analyzed. Sleep health outcomes included insufficient sleep, sleep duration, wake-up after sleep onset (WASO), and sleep efficiency measured from 7 days of wrist-worn 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.

Results: Urban design features in residential area were associated with decreased WASO (β: -1.26, 95% confidence interval [-4.31, -0.33]). Neighborhood physical disorder (β: -0.46, 95% CI [-0.86, -0.07]) and crime rate (β: -0.54, 95% 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 in the associations between built environments and sleep health outcomes.

Conclusions: Neighborhood built environments may contribute to poor sleep health. Interventions to improve sleep should target modifiable factors, including via urban design, and seek to enhance such physical and social neighborhood environments which have the potential to improve not only sleep health but also other health outcomes.

3.1 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 disorder, and crime are associated with poorer sleep health outcomes,[7-9] and built environments, such as walkability of neighborhood and neighborhood disorder, are recognized as potentially important factors of sleep health.[10-13]

Physical characteristics of neighborhoods may influence sleep health through multiple pathways. Neighborhood walkability, defined as built environments that promote physical activity, such as street connectivity, block size, transportation network, and land use patterns, 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, accessibility to recreational facilities and green space are identified as other environmental factors 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]

In addition, physical neighborhood disorder, 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 neighborhood physical 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] Recent studies have investigated the associations between the physical neighborhood disorder and sleep health, covering sidewalk conditions[25] and housing characteristics as measures of physical disorder.[26-28]

Sleep health measures, including sleep duration, sleep quality, and sleep disorders, show disproportionate distributions in relation to sociodemographic factors, similar to other chronic conditions.[29,30] The African-American population in the United States (US) has higher prevalence of poor sleep health compared to their White counterparts.[31-33] Racial/ethnic and income minority groups are likely to reside in disadvantaged neighborhood environments, and the adverse environmental conditions they face may be an important contributing factors that cause the disproportionate sleep outcomes as a mediator as well as an effect modifiers, in addition to individual-level characteristics such as income and occupation.[3]

Despite an abundance of 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 recall bias, same-source bias, and reverse causality. In addition, the majority of studies use self-reported sleep measures as well as survey-measured neighborhood characteristics (i.e. perceived neighborhood) which are susceptible to measurement errors. Moreover, the common boundaries of neighborhood characteristics are static administrative boundaries, such as census tracts and ZIP codes, which introduce potential spatial misclassification and modifiable areal unit problems.[34] Recent studies from the Multi-Ethnic Study of Atherosclerosis (MESA) 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 static 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.[25] However, the above-mentioned studies employed cross-sectional study designs which cannot establish temporality nor causality. 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 new study designs and statistical analyses.[35]

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.[36,37] We hypothesized that adverse built environments and high crime rates in residential areas are negatively associated with sleep health, and that the relationships between built environments and sleep health are mediated by physical activity.

3.2 Methods

Data

The PHRESH Zzz is a sub-cohort of an original study of Pittsburgh Hill/Homewood Research on Eating, Shopping, and Health (PHRESH). The participants were randomly recruited based on households in two low-income, predominantly African American neighborhoods in Pittsburgh, Pennsylvania.[38] From 2013, there has been significant neighborhood revitalization projects in one neighborhood (the Hill District) compared to the other neighborhood (Homewood). The urban revitalization covered housing and greenspace improvements and retail and business developments. The PHRESH Zzz was designed to examine the impact of changes in neighborhood characteristics 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, and in 2016 the number of participants were 828, and in 2018 it was 820, resulting in 22% attrition rate which is similar with other longitudinal actigraphy studies.[39,40] Participants who had less than 4 nights of actigraphy data (n = 224) and/or who were missing sociodemographic covariates (n = 16) were dropped from the analysis. 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.[41] In addition, for the mediation analysis, a total of 570 participants who completed the three waves of data collection was included in the analysis to estimate random intercept and random slope.

The PHRESH Zzz study incorporated micro-level street audit data collection on social and built environments in the two low-income neighborhoods. This objective assessment utilized a wide-range of items based on validated audit tools, including Systematic Pedestrian and Cycling Environmental Scan,[42] St. Louis Analytic Audit Tool and Checklist,[43] and Systematic Social

Observation protocol.[44] The PHRESH Zzz street audit tools emphasized on neighborhood-level features that have bearings on physical activity, sleep, and obesogenic behaviors.[45] 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 recorded status of various social and physical features including urban design, walking environments, and neighborhood disorder. The majority of audit items indicated more than good reliability based on Krippendorff's alpha (KA) test (KA > 0.4),[46] as well as percentage inter-observer (PO) agreement (PO > 75%) across waves.[47,48] The KA is an index that indicates whether the agreement exceeded chance levels, and KA > 0.75 is regarded as excellent agreement, KA between 0.4 and .75 indicates intermediate to good agreement, and KA < 0.4 indicates poor agreement based on previous research.[49] As KA is sensitive to prevalence rate, percentage inter-observer agreement was also tested, and PO > 90% indicates excellent agreement, PO between 75% and 90% indicates good agreement, and PO < 75% is regarded as moderate and fair to poor agreement.[50,51] Recorded neighborhood conditions from the street audit tools were spatially joined to participants' address as average scores of street segments within or intersecting with 1/4-mile network buffers. Details on the street audit tools and data collection methods are described elsewhere.[45]

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.[52-54] Participants were asked to wear the wrist-watch device for 7 consecutive days. Sleep and wake rhythms were calculated based on Cole-Kripke algorithm resulting in total sleep time, sleep efficiency, and wake-after sleep onset (WASO). The sleep health measures were averaged across all nights,[55] 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.[56]

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 420 minutes (7 hours) was categorized as insufficient sleep,[57] 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 visual inspection of actigraphy data. Higher values of sleep efficiency mean better sleep continuity.

Physical Activity

A validated score that evaluates the level of physical activity (PA) was derived from International Physical Activity Questionnaire (IPAQ) Short Form.[58] Three questions on times spending on vigorous, moderate, and walking PAs 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).[58] The IPAQ was measured during the office visit of 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.

Of note, previous sleep could have contributed to both physical activity and subsequent sleep measures, representing a major source of confounding.

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 designed based on the previous literature that evaluates human scale street characteristics associated with physical activity and walking.[59] 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%).[45] The urban design index ranges from 0 to 3, and higher score indicates better urban design features on the street segments.

Walkability

Similar to the urban design index, the walkability index was derived from the audit data based on ¼-mile street network buffer of residential locations. The items to evaluate walkability covers 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.[60] Each item showed good to excellent agreement (KA > 0.4; PO >75%).[46] For each street segment, the scores of all items were summed, and the average across the street segments within or interesting 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 physical disorder

Physical characteristics that may indicates neighborhood disorder was derived from the street audit data. The pairs of 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.[61] 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 based on 1/4-mile street network buffer of each participant's address. 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 of participants address was summed for each year. The 1/4-mile distance was selected, as a previous studies on walkability employed 1/4-mile for "walking distance".[62,63]

Covariates

Several individual-level sociodemographic factors were examined as a priori potential confounders. The selected covariates included age, gender, per capita annual household income (in $1,000), education (less than high school [referent], 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 a car 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. 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.[64] 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,…,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 social environments at prior time can consistently affect the sleep health.[65,66] When Y is a dichotomized outcome (e.g. insufficient sleep), the SNMM fits the causal risk ratio.[67] Percentile-based 95% confidence intervals for each parameter were calculated based on 500 bootstrapping samples.

The mediating roles of physical activity 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. physical activity). Under this notation, the direct effect is the effect A → Y, not through M, and the indirect effect is the effect A → M → Y. The conditional natural direct/indirect effects are defined as $E(Y_{ij}^{a,M_{ij}^{a^*}} - Y_{ij}^{a^*,M_{ij}^{a^*}} \mid C_{ij} = c)$, and $E(Y_{ij}^{a,M_{ij}^{a}} - Y_{ij}^{a,M_{ij}^{a^*}} \mid C_{ij} = c)$, 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.[68] The models for the mediator have subject-specific random intercepts and random exposure slopes for each participant (Equation 1). The outcome models have random intercepts and random slopes for the exposure, and the mediator (Equation 2).

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

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

where *i* corresponds to each participant and *j* to each visit; β_0 and γ_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 physical activity, and $Y_{i,j}$ corresponds to sleep health outcomes. β_{NBHD}NBHD and γ_{NBHD}NBHD correspond to neighborhood characteristics, and $\gamma_M M_{i,j}$ corresponds to physical activity in the mediator-outcome association. $\varepsilon_{i,j}$ and $\eta_{i,j}$ are the within-subject, within-visit error terms.

In the equations, γ_{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,[68] 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 and mediator; and b) an association between mediator and outcome.[69] 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, the last assumption, C4, might be violated. Some covariates, especially indicators of socioeconomic status, might be affected by previous neighborhood social environments at prior timepoint, and sleep health outcomes at one visit may potentially affect physical activity 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).[69,70] We tested the association between prior sleep health and subsequent physical activity from Equation 3, but the other sources still remain as potential confounders.

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

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

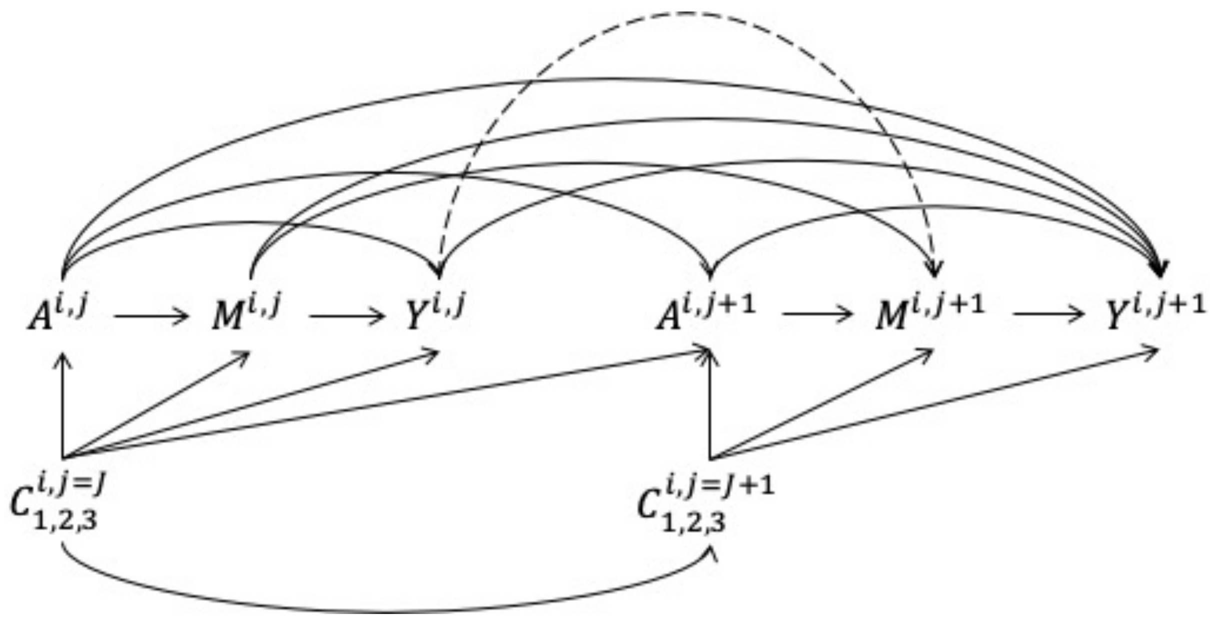


Figure 1. Directed acyclic graph (DAG) for mediation analysis. $A_{i,j}$ represents neighborhood characteristics for *i*th subject at *j*th visit; $M_{i,j}$ represents psychological distress for *i*th subject at jth visit; $Y_{i,j}$ represents sleep health outcomes for *i*th subject at jth visit. $C^{1,2,3}{}_{i,j}$ represents exposure outcome confounders (C_1), exposure mediator confounders (C_2), and mediator outcome confounders (C_3).

3.3 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 minutes in 2013, 334 minutes in 2016, and 327 minutes in 2018. The average WASO were 89, 111, and 123 minutes in each data waves.

Overall association between neighborhood 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% confidence interval [-4.31, -0.33]) (Table 2). Neighborhood walkability was not associated with sleep outcomes in the analysis. Neighborhood disorder was negatively associated with sleep efficiency (RD: -0.46 percent point, 95% CI [-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, 95% CI [1.01, 1.10]), increased WASO (RD: 3.62 minutes, 95% CI [0.16, 5.89]), and decreased sleep efficiency (RD: -0.54 percent point, 95% CI [-0.93, -0.08]).

Mediation Analysis

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 physical activity, the mediator. Physical activity (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.

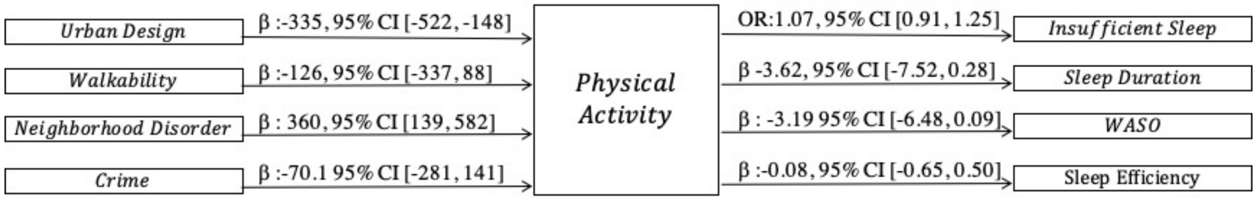
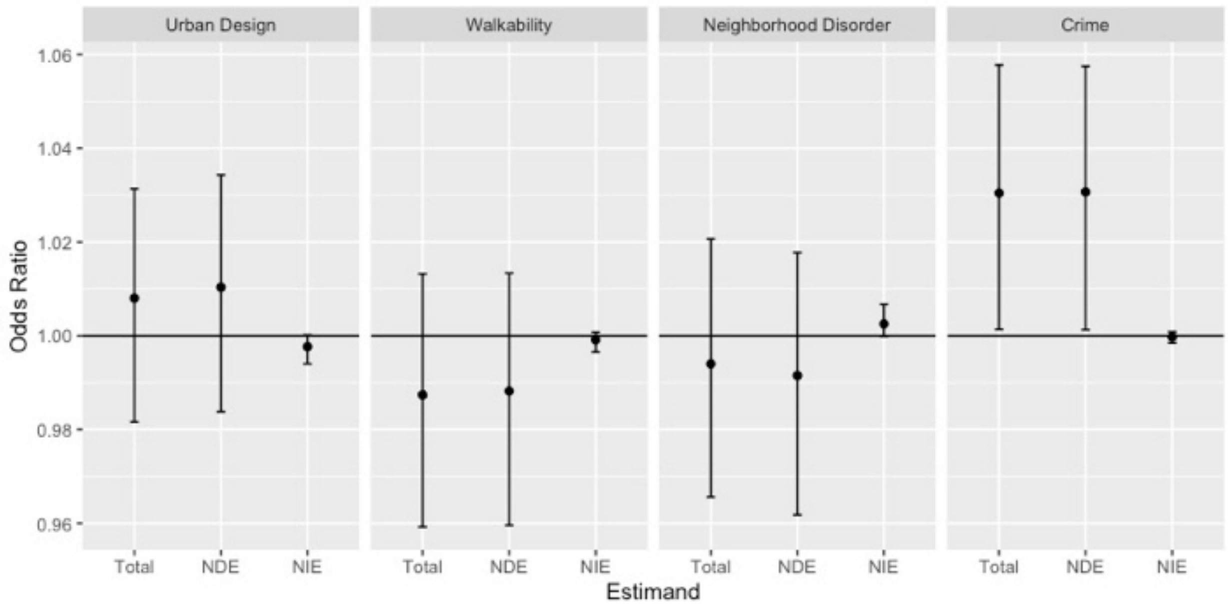


Figure 2. Exposure-mediator and mediator-outcome associations. Each mixed-effect regression models were adjusted for age, sex, income, education, employment, marital status, family structure, and number of years in current neighborhood.

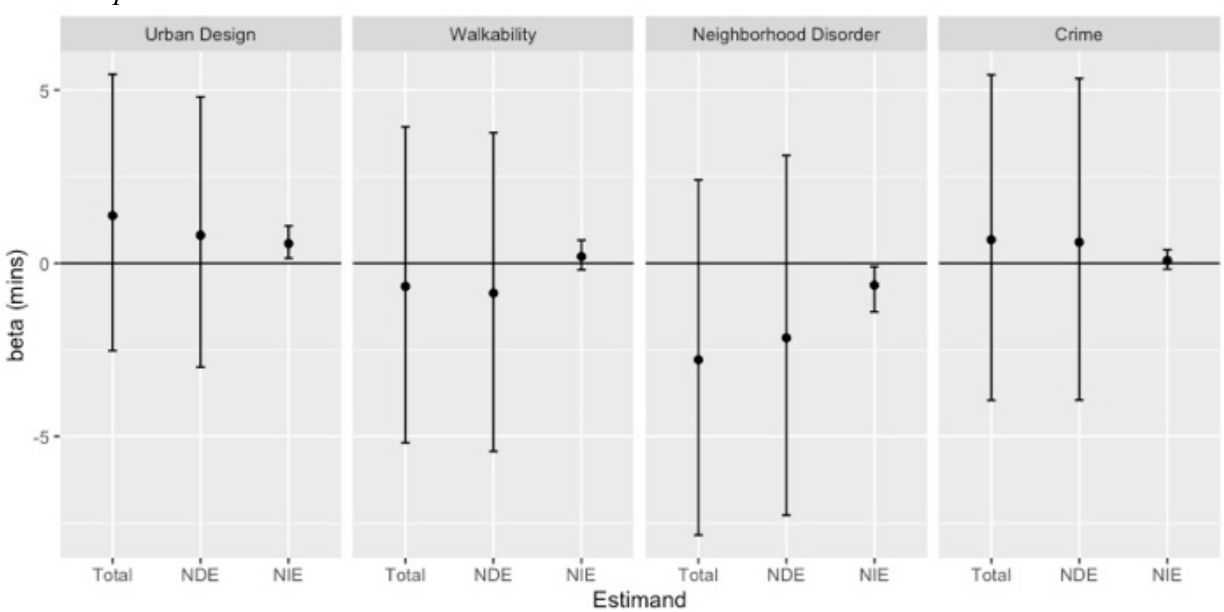
The additional analysis results to support the longitudinal mediation analysis from equation 3 were provided in the supplemental table 1 (Table S1). The post-exposure confounding for the M-Y association (dotted arrow in Figure 1) due to previous sleep measures was tested using multivariable mixed-effect models with lagged variable for physical activity, and physical activity levels at subsequent visits did not show associations with previous sleep health outcomes. However, other time-varying confounders, specifically covariates for socioeconomic status, still remain as potential sources of bias.

Table 3 shows the natural direct and indirect effects between neighborhood characteristics and sleep health as well as proportion mediated by physical activity. The natural direct/indirect effects were also presented in Figure 3. The association between urban design and sleep duration was mediated by physical activity (β: 0.57, 95% CI [0.14, 1.08]), however, the total effect and direct effect were not significant (Figure 3-b). The relationship between urban design and WASO was partially mediated by physical activity (β: 0.37, 95% CI [0.06, 0.78]), but the direction of mediating effect was opposite to the direct effect (β: -2.90, 95% CI [-5.99, -0.68]) (Figure 3-c). Despite the weak total effects of neighborhood disorder on sleep duration (β: -2.79, 95% CI [-7.84, 2.4]), physical activity played small mediating roles between the associations (β: -0.63, 95% CI [-1.40, -0.10]) (Figure 3-b).

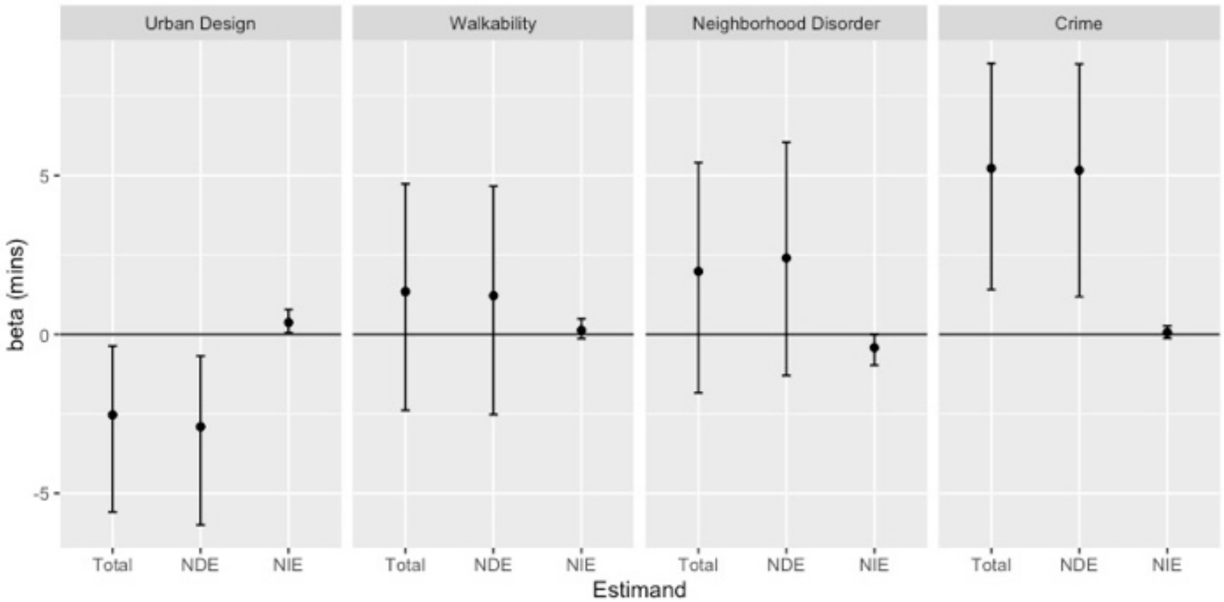
3-a. Insufficient Sleep



3-b. Sleep Duration



3- c. WASO



3-d. Sleep Efficiency

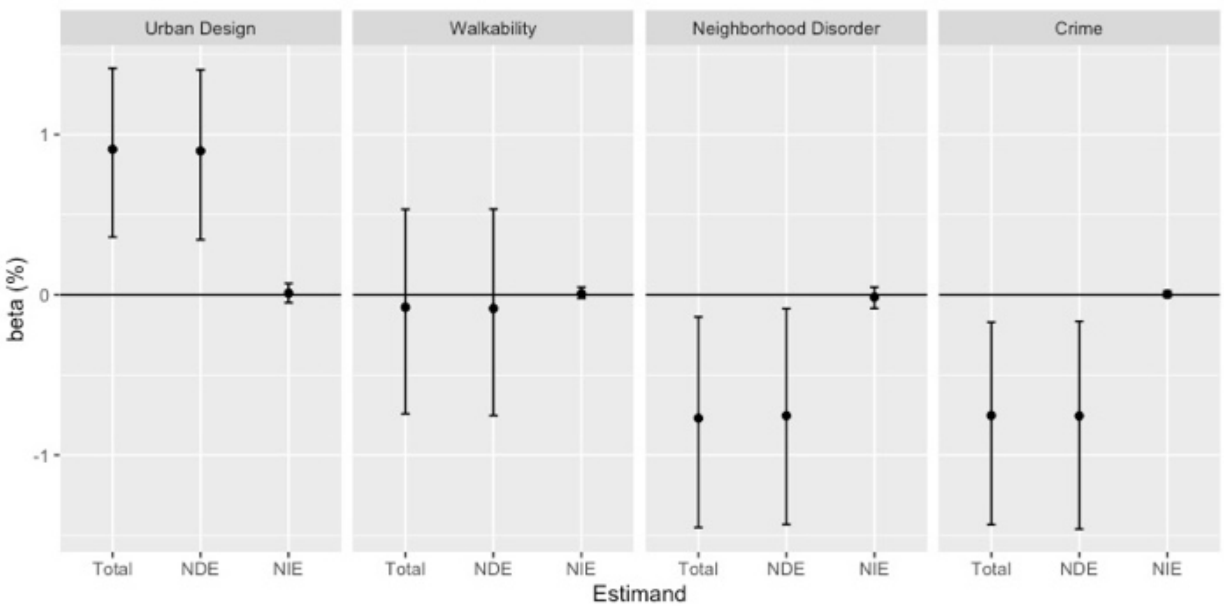


Figure 3. Mediation analysis results. Figure 3-a is for insufficient sleep, 3-b for sleep duration, 3-c for WASO, and 4-d for sleep efficiency outcomes. Each plot represents the four built environment characteristics. Total: total effect, NDE: natural direct effect, NID: natural indirect effect

3.4 Discussion

Prior studies have demonstrated that adverse physical conditions in a neighborhood are associated with poor sleep health,[10-13] and despite the small magnitudes, our analyses showed consistent associations of neighborhood urban design with decreased WASO, and neighborhood physical disorder with decreased sleep efficiency. Previous studies on built environments and sleep health found positive associations between neighborhood walkability and sleep duration,[10-12] however, we did not find these same 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. That is, the walkability index measured street connectivity and land use mix which may be related to increased traffic and ambient noise and nocturnal light. We also hypothesized that physical activity may mediate the associations between neighborhood built environments and sleep health, yet the mediating role of physical activity was found to be weak or not significant. The majority of study participants was female, and the mean age at the third wave was 60. The average level of physical activity was significantly less than the recommended levels of moderate intensity activity,[71] which is consistent with other population-based studies among older females in the U.S.[72,73] Due to the significantly low level of physical activity from the baseline, our physical activity measures may not have had enough variation to examine the mediating role among the study participants.

Adverse built environments are more salient risk factors of multiple health outcomes and behaviors especially in low-income and racial/ethnic minority communities,[74,75] 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.[76] Built environments of neighborhood are essentially associated with social characteristics of the neighborhood, as social and built environment can effect changes in each other. Previous literature examined social environments, such as neighborhood trust and social cohesion, as important determinants of various health outcomes,[77-79] however, intervening on the social characteristics are cumbersome and not tangible in terms of actual interventions. Neighborhood built environments, on the other hand, 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.[80] 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.[81,82]

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.[83-85] 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 simple analysis focusing on one neighborhood characteristic may not fully reflect the complex relationships between neighborhood features and sleep health. In addition, the longitudinal nature of the data, may also introduce a post-exposure confounding on the association between physical activity and sleep health, which is a violation of an assumption for the causal mediation analysis. We assumed that physical characteristics of neighborhood may have direct impact on physical activity, but it is also possible that other determinants of sleep health, such as stress and psychological well-being, may act as a potential post-treatment confounder. In this analysis, the baseline sleep outcomes and psychological distress measures were not measured nor included as covariates, which may result biased estimates. However, baseline adjustment with potential measurement errors can also cause additional biases.[86]

The exposure variables, neighborhood characteristics, were derived based on participants' residential address. Such static residential boundary cannot capture diverse neighborhood experiences from daily mobility.[87] For example, individuals travel multiple (e.g. residential, work, socializing) neighborhood environments 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.[88] In addition, two neighborhoods in the study, Hill District and Homewood in Pittsburgh, are small communities with little geographic variations, which unlikely represent various neighborhood factors across 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. Lastly, despite the strength in measuring sleep health objectively, actigraphy data have limitations, such as dropping out participants with less than 4 night. Due to the exclusion, the present analysis may not fully represent the characteristics of the PHRESH Zzz data.

To summarize, we found that built environments of a neighborhood 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 and social environmental, including via urban design, which are easy to intervene compared to other individual-level characteristics, such as income. Furthermore, enhancing such physical and social 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]

3.5 Tables

Table 1. PHRESH Zzz Study Characteristics

	PHRESH Zzz					
	2012 (n=1,051)		2016 (n=828)		2018 (n=820)	
	Mean or count	SD or %	Mean or count	SD or %	Mean or count	SD or %
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 or 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	0.81	0.37	0.39	0.32	0.77	0.22
Walkability score	7.74	2.13	8.74	1.87	8.24	1.92
Neighborhood disorder score (in ¼-mile buffer)	4.66	1.21	4.82	1.10	4.54	1.0
Total Crime (in ¼-mile buffer)	23.1	18.1	23.7	17.5	23.9	21.0

Table 2. Joint causal effects of neighborhood built environments on sleep health

Exposure	Outcome	Risk Ratio (or Risk Difference)	95% Confidence Interval
Urban Design	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)
Walkability	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)
Neighborhood Disorder	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)*
Crime	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)*

*:p-value<0.05, 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 Results (complete case analysis)

	Insufficient Sleep		Sleep Duration		WASO		Efficiency	
	ORs	95% CI	β	95% CI	β	95% CI	β	95% CI
Urban Design								
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)
Walkability								
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)
Neighborhood Disorder								
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)
Crime								
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)

NDE: Natural Direct Effect, NIE: Natural Indirect Effect, *:p-value<0.05
All models were adjusted for age, sex, education, marital status, family structure, vehicle availability, and number of years in current neighborhood.

Table S1. Associations of sleep health outcomes with psychological distress at the subsequent visit (t + 1)

Neighborhood Characteristic	Sleep at t	Physical Activity at t+1	95% CI
Urban Design	Insufficient Sleep	1.44	(-363.31, 651.15)
	Sleep Duration	-0.78	(-3.69, 2.13)
	WASO	-3.43	(-7.2, 0.34)
	Sleep Efficiency	15.46	(-4.9, 35.83)
Walkability	Insufficient Sleep	135.10	(-372.55, 642.69)
	Sleep Duration	-0.87	(-3.78, 2.04)
	WASO	-3.26	(-7.03, 0.5)
	Sleep Efficiency	14.15	(-6.18, 34.48)
Neighborhood Disorder	Insufficient Sleep	135.60	(-371.06, 642.17)
	Sleep Duration	-0.73	(-3.63, 2.17)
	WASO	-3.45	(-7.21, 0.31)
	Sleep Efficiency	15.94	(-4.4, 36.28)
Crime	Insufficient Sleep	87.49	(-412.18, 587.16)
	Sleep Duration	-1.00	(-3.89, 1.89)
	WASO	-3.36	(-7.08, 0.35)
	Sleep Efficiency	14.15	(-5.88, 34.18)

Table S2. PHRESH Zzz Study Characteristics – Complete Case Only

	PHRESH Zzz (n=570)					
	2012		2016		2018	
	Mean or count	SD or %	Mean or count	SD or %	Mean or count	SD or %
Age	55.8	14.2	58.9	14.1	61.6	14.2
Race						
African-American	536	94%	536	94%	536	94%
Non African-American	34	6%	34	6%	34	6%
Female	463	81.2%	463	81.2%	463	81.2%
Per capita annual household income (in 1,000)	14.1	14.3	14.6	13.6	15.2	15.1
Education						
Less than high school	71	12.5%	71	12.5%	63	11.1%
High school	242	42.5%	242	42.5%	219	38.4%
Some college	180	31.6%	180	31.6%	212	37.2%
College	77	13.5%	77	13.5%	76	13.3%
Marital status						
Married or living with partner	110	19.3%	91	16.0%	84	14.7%
Never married	234	41.1%	241	42.3%	238	41.8%
Widowed, divorced or separated	226	39.6%	238	41.8%	248	43.5%
Household with child(ren)	140	24.6%	119	20.9%	98	17.2%
Employment						
Full-time	137	24.0%	124	21.8%	127	22.3%
Part-time	81	14.2%	84	14.7%	76	13.3%
Not employed	352	61.8%	362	63.5%	367	64.4%
Car owner or access to a car	315	55.3%	347	60.9%	365	64.0%
Years in current neighborhood	32.5	22.4	29.4	21.9	33.2	23.1
Sleep health						
Mean minutes sleep duration	342	80.5	334	74.5	327	82.4
Insufficient sleep (<6hr)	130	22.80%	143	25.10%	167	29.30%
Mean minutes of WASO	88	55.9	112	64.1	123	73.5
Mean sleep efficiency (%)	78.3	10.8	73	11.8	71.1	12.3
Physical activity (MET-min/week)	3,330	3,845	3,639	3,989	2.421	3,336
Urban design score	0.82	0.38	0.41	0.33	0.77	0.21
Walkability score	7.90	2.12	8.74	1.94	8.30	1.98
Neighborhood disorder score (in ¼-mile buffer)	4.57	1.23	4.75	1.11	4.49	1.0
Total Crime (in ¼-mile buffer)	23.2	17.7	24.1	18.0	23.8	21.4

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