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Journal

SLEEP, 47(2)

Authors

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Publication Date

2024-02-08

DOI

10.1093/sleep/zsad100

Peer reviewed

SLEEP, 2024, 47, 1–12
https://doi.org/10.1093/sleep/zsad100
Advance access publication 5 April 2023
Original Article

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Exposure to indoor light at night in relation to multiple dimensions of sleep health: findings from the Sister Study

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Abstract

Study Objective: To examine the association between light at night (LAN) and multiple sleep health dimensions

Methods: Among 47 765 Sister Study participants, indoor LAN (TV on in the room, light(s) on in room, light from outside the room, nightlight, no light) and sleep dimensions were self-reported at baseline (2003–2009). We used Poisson regression with robust variance to estimate adjusted prevalence ratios (PR) and 95% confidence intervals (CI) for the cross-sectional associations between LAN and short sleep duration (<7 hours/night), insomnia symptoms (difficulty falling or staying asleep), frequent napping (≥3 naps/week), inconsistent sleep/wake time (differed day-to-day and week-to-week), sleep debt (≥2 hours between longest and shortest duration), recent sleep medication use, and a cumulative poor sleep score (≥3 poor sleep dimensions). Population-attributable risks (PARs) were determined for any light exposure vs. none by race/ethnicity.

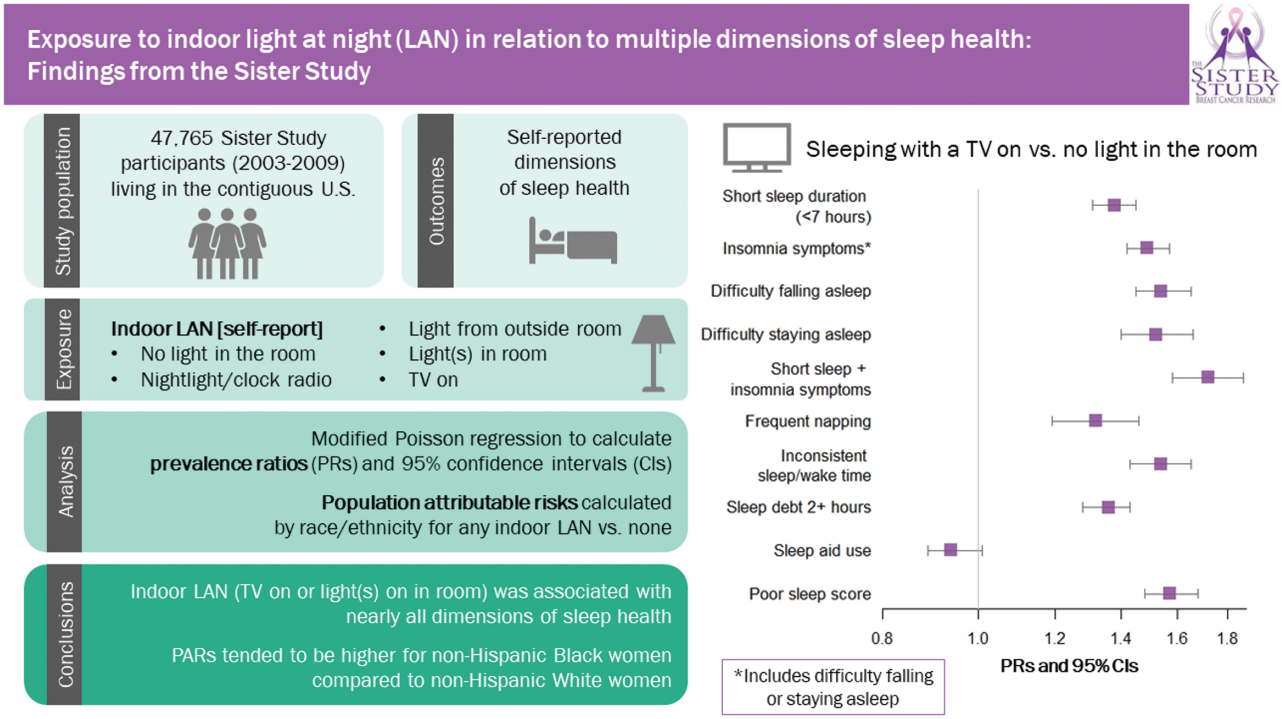
Results: Compared to sleeping with no light in the bedroom, sleeping with a TV on was associated with a higher prevalence of most dimensions of poor sleep (e.g. short sleep duration: PR = 1.38, 95% CI: 1.32 to 1.45; inconsistent sleep/wake time: PR = 1.55, 95% CI: 1.44 to 1.66; sleep debt: PR = 1.36, 95% CI: 1.29 to 1.44; poor sleep score: PR = 1.58, 95% CI: 1.48-1.68). PARs tended to be higher for non-Hispanic black women compared to non-Hispanic white women.

Conclusions: Sleeping with a TV on was associated with poor sleep health among US women, and non-Hispanic black women may be disproportionately burdened.

Key words: Epidemiology; sleep health; environmental health; light at night

Submitted for publication: November 1, 2022; **Revised:** February 23, 2023

Graphical Abstract



Statement of Significance

Exposure to light at night (LAN) can disrupt circadian rhythms and suppress melatonin production. Sleep regulation is driven partly by circadian rhythms and is disrupted by melatonin suppression. Epidemiologic studies of LAN and sleep are limited, and no studies, to date, have investigated potential racial/ethnic differences in the association between LAN and sleep health despite differences in environmental conditions. In our analysis of indoor LAN and multiple sleep health dimensions in a large cohort of US women, we found that sources of indoor LAN, specifically sleeping with a TV on, were associated with poorer sleep. Our population-attributable risk analysis demonstrates that non-Hispanic black women may be disproportionately burdened by exposure to indoor LAN.

Introduction

Sleep is considered critical for human mental and physical health, although the purpose or specific functions of sleep are still being investigated and debated [1]. Shorter sleep duration has been associated with an increased risk of obesity, hypertension, type 2 diabetes, and cardiovascular disease [2–5]. Adequate sleep duration was recently added to the American Heart Association's recommended list of health behaviors and factors ("Life's Essential 8") that are important for optimal cardiovascular health [6]. Frequent napping, which may be an indicator of consistently short sleep duration or poor quality nighttime sleep, has been associated with, for instance, type 2 diabetes risk [7, 8] and metabolic syndrome [9]. Inconsistent sleep or wake times and inconsistent sleep durations (also referred to as "sleep debt") throughout the week may be associated with an elevated prevalence of metabolic abnormalities [9] and risk of cardiovascular disease [10]. Insomnia, generally defined as consistently experiencing difficulty falling or staying asleep despite having an opportunity to sleep, is associated with increased risks of cardiovascular disease [11], metabolic syndrome [9, 12], and worse daytime functioning [13]. Poor sleep is common among US adults with more than a third of US women reporting short sleep duration, defined as an average of <7 hours per day [14], and approximately one-fifth of US adults experiencing symptoms of insomnia [15–17].

Sleep is driven both by circadian processes—approximately 24-hour cycles of body temperature and hormones such as melatonin—and homeostatic drive—the increasingly heightened biological need for sleep with increasingly long periods without sleep [18]. The human brain's suprachiasmatic nucleus, the primary regulator of human circadian rhythms, is sensitive to the light–dark cycle [19], which has led to concerns that exposure to artificial light at night (LAN; night defined as the period between dusk and dawn [weather.gov/glossary/]) likely causes circadian disruption. Lending support to this hypothesis is evidence from several experimental studies, which demonstrated that late-night exposure to blue or violet light was associated with a temporary reduction in melatonin [20]. Both experimental and observational studies have suggested that exposure to bright light or electronic devices within several hours before falling asleep are associated with a delay in the melatonin peak, as well as poorer sleep in adults [21]. Less is known about exposure to LAN during the sleeping period, and a recent experimental study found no differences in the timing of melatonin onset or total plasma melatonin

among those exposed to room-level lighting during sleep compared to those exposed only to dim light [22].

Large-scale, population studies of sleep duration, and quality in relation to light exposure during the sleeping period are limited. A previous analysis of indoor LAN and obesity in the Sister Study population observed that a higher proportion of women who reported sleeping with either a TV or at least one light on in the bedroom reported experiencing multiple dimensions of poor sleep compared to women who slept with no light, but multivariable-adjusted associations were not explored [23]. A few cross-sectional studies have suggested that exposure to higher levels of indoor LAN is associated with shorter sleep and poorer sleep quality [24–26]. However, these studies have been limited in their ability to address effect measure modification by age or race/ethnicity. A study of indoor LAN and sleep conducted in a population of older Japanese adults observed greater odds of insomnia for those exposed to the highest level of indoor LAN (OR = 1.61, 95% CI: 1.05 to 2.45) [24]. A US-based study found that sleeping with a light on was associated with higher odds of sleeping <6 hours per night (OR = 1.46, 95% CI: 1.19 to 1.79) [25] but did not describe the racial/ethnic distribution of the study participants or stratify their results by race/ethnicity. Sleep duration, quality, and timing are altered in older adults [27] and differ by race/ethnicity in the United States [28].

We examined cross-sectional associations between indoor LAN exposure during the sleeping period and multiple dimensions of poor sleep in a large cohort of US women. We also evaluated indoor LAN-sleep health associations stratified by age and race/ethnicity.

Methods

The Sister Study cohort

We used data from the Sister Study (Data Release 9.1) prospective cohort of 50 884 women enrolled between 2003 and 2009. The cohort was designed to assess environmental risk factors for breast cancer and is described in more detail elsewhere [29]. Briefly, women were eligible for participation if they were ages 35 to 74 years, resided in the US States including Puerto Rico, were free of breast cancer at baseline data collection, and had a full or half-sister with breast cancer. At study entry, participants completed mailed questionnaires and computer-assisted telephone interviews to assess demographics, lifestyle factors, residential history and current address, and environmental and occupational risk factors. A home visit was conducted at baseline, during which trained examiners collected anthropometric data. Brief questionnaires are completed annually with detailed follow-ups completed every 2–3 years. The Institutional Review Board of the National Institutes of Health approved the Sister Study, and all participants provided written informed consent. The current analysis was reviewed by the University of North Carolina Institutional Review Board and determined to be non-human subject research.

Study population

From the original cohort of 50 884 study participants, women were excluded from the analytic sample population if they withdrew from the study (n = 5), were blind (n = 6), worked at night (due to our interest in non-occupational LAN exposure) (n = 1497), worked on a flight crew (flight attendants/pilots; n = 22), or reported daylight as the only light source in the bedroom while sleeping (n = 202; excluded because daylight is not an artificial source or light). Women were also excluded for missing (n = 280) or improbable (n = 91) values for sleep health dimensions (i.e. sleep duration <3 hours per night, waking up >20 times per night), missing indoor LAN (n = 11), or missing covariates (n = 1005). The final analytic sample included 47 765 women.

Assessment of light at night

Indoor LAN was self-reported on the baseline questionnaire completed at enrollment. Women reported sleep mask usage as well as the sources of light present in the bedroom while sleeping: daylight, one or more lights on in the room, light from a television on in the room for most or all of the night, light from other rooms, light from outside shining in, and light from a small nightlight or clock radio (select all that apply). For this analysis, women who reported daylight as the sole light source were excluded, as indicated above. The remaining light sources were analyzed as five categories, reflecting highest to lowest level of assigned exposure: (1) a TV on in the room, (2) one or more lights, (3) light from outside the room (either from other rooms or through the windows), (4) light from a small nightlight or clock radio, and (5) none. Sleep mask use was assumed to block out all light, and women who reported using sleep masks were classified as "(5) none" regardless of the light sources they reported. Women who reported multiple sources were classified based on the highest reported level.

Assessment of multiple dimensions of sleep health

Information on sleep health dimensions was ascertained at baseline (complete questionnaire available at sisterstudystars.org). On the baseline questionnaire, women reported their typical sleep duration and quality during the prior 6 weeks. Participants were asked "About how many hours and/or minutes of sleep per night do you get on average?," which we dichotomized as <7 hours (short sleep duration) or ≥7 hours per night, based on the National Sleep Foundation criteria [30]. Difficulty falling asleep was determined based on the question "About how long does it take you to fall asleep on average?" which excluded time spent in bed reading or watching television. Participants could select from four choices (less than 15 minutes, 15 minutes to half an hour, more than half an hour but less than 1 hour, 1 hour or more) and our variable was categorized as ≤30 minutes (no) and >30 minutes (yes) [8, 9, 31, 32]. Two questions ("When you are asleep, how often do you wake up for any reason?" and "On those nights, how many times do you wake up each night?") were used to determine difficulty staying asleep, which we categorized as waking up ≥3 times per night ≥3 nights per week (yes) and waking up <3 times per night [8, 9, 31, 32]. The presence of insomnia symptoms was categorized as reporting either difficulty falling asleep or difficulty staying asleep. Short sleep plus insomnia symptoms was defined as having a short sleep duration and reporting insomnia symptoms. To determine frequent napping, participants were asked "How often do you take naps?" with six response options (every day or most days, 3 or 4 days a week, 1 or 2 days a week, 1 to 3 days per month, less than once a month, never). We collapsed the options into two categories: ≥3 times per week (yes) and <3 times per week (no) [8, 9, 31–33]. Participants were asked to report their sleep patterns over the 6 weeks prior ("Which of the following best describes your pattern for waking up during the past 6 weeks?" and "Which of the following best describes your pattern for going to sleep during the past 6 weeks?"), with four choices: about the same time/within 1 hour, same time on work days with different time for days off, consistent pattern week-to-week but not day-to-day, or

no consistent pattern. Participants who answered "yes" for "no consistent pattern" for either their wake time or sleep time were classified as having inconsistent sleep/wake time [9]. Sleep debt was determined by subtracting the shortest reported duration from the longest reported duration and was dichotomized as sleep debt ≥2 hours (yes) or <2 hours (no). Recent sleep medication use was determined based on the question "Have you taken prescription or over-the-counter medication in the past 6 weeks to help you fall asleep?"; herbal teas, milk, liquor, or acupuncture were not included [9]. A cumulative poor sleep score was created by allotting one point per sleep dimension (short sleep duration, difficulty falling asleep, difficulty staying asleep, frequent napping, inconsistent sleep/wake time, sleep debt, and sleep medication use) that was reported, with a maximum possible score of 7. Having a score of ≥3 was considered a high poor sleep score. A similar approach has been used previously in the Sister Study [8, 9, 33].

Assessment of covariates

Women reported their year of birth, race (American Indian/Alaska Native, Asian, black/African American, Native Hawaiian/Pacific Islander, and white; with the option to select multiple), ethnicity (Hispanic/Latina, with the option to provide country/region of origin), marital status, educational attainment, annual household income, history of depression, alcohol consumption, smoking status, and primary residential address on the baseline questionnaire. Race/ethnicity is associated both with differences in sleep health dimensions [3] and, due to systematic discriminatory practices such as redlining [34], with location of residence and neighborhood characteristics. Multiple imputations by fully conditional specification [35] were used to impute annual household income for the 1995 women who were missing that information. During the baseline home visit, trained examiners measured height and weight, which was used to calculate body mass index (BMI; kg/m^2).

Residential and neighborhood covariates were determined using geocoded primary residential addresses at baseline. Census tract level population density was determined for the year 2000 using publicly available data from the US Census Bureau (http://www.census.gov) by dividing the tract population size by the tract area in square miles (N/miles [2]). Area Deprivation Index (ADI) is a weighted Census block group-level measurement of neighborhood disadvantage based on 17 US Census indicators of poverty, education, housing, and employment from the 2000 long-form Census and ranges from 1 (low deprivation; e.g. most of Manhattan, NY) to 100 (high deprivation; e.g. most of Detroit, MI) [36, 37]. Latitude of primary residence at baseline was classified as either Northern (≥37°N) or Southern (<37°N) to account for differences in length of night associated with latitude and because sleep duration may vary by latitude [38].

Statistical analysis

Frequencies and proportions were determined for categorical variables and means and standard deviations for continuous variables. Descriptive statistics are presented for all participants and by level of indoor LAN.

We used Poisson regression with robust variance to estimate prevalence ratios (PRs) and 95% confidence intervals (CIs) for the association between indoor LAN with the different sleep health dimensions. Poisson regression with robust variance has been demonstrated to be a valid approach to directly estimating the PRs in cross-sectional analyses with binary outcomes [39]. Adjustment for multiple comparisons of the main outcome models was evaluated using the False Discovery Rate (FDR) approach [40]. To assess the absolute impact of LAN on sleep health, percent prevalence differences (PPDs) and 95% CIs were estimated.

Confounders were selected a priori using a directed acyclic graph [41]. Indoor LAN models of all sleep health dimensions were adjusted for age (continuous), self-identified race/ethnicity [non-Hispanic white, non-Hispanic black/African American, Hispanic/Latina, "other" (collapsed due to small numbers; includes women who self-identified as Asian, Native Hawaiian/Pacific Islander, or American Indian/Alaska Native)], educational attainment (high school diploma or equivalent, some college or a technical degree, Bachelor's degree or higher), annual household income (<$50 000, $50 000–$99 999, $100 000–$200 000, >$200 000), ADI (continuous), population density (continuous, persons/square-mile), latitude (<37°N, ≥37°N), and prevalent self-reported diagnosis of depression (yes/no).

We assessed effect measure modification of the association between indoor LAN and baseline sleep health dimensions by race/ethnicity (non-Hispanic white, non-Hispanic black, Hispanic/Latina, "other"), ADI (< national 75th percentile, ≥national 75th percentile), depression at baseline (yes, no), age (<45 years, 45–<65 years, ≥65 years), and BMI (≥18.5–<25.0 kg/m^2, 25.0–<30.0 kg/m^2, ≥30.0 kg/m^2). A total of 527 underweight women (BMI<18.5 kg/m^2) and 17 women with missing BMI were excluded from the BMI-stratified analysis. Poorer sleep outcomes have been reported for historically marginalized individuals [28], those living in lower socioeconomic status neighborhoods [42], and depressed [43], older [27], and obese [44] individuals. Interaction was assessed using multiplicative interaction terms, and significance was determined using the Wald chi-square for the interaction term at the $p < 0.05$ significance level. Stratified PRs and 95% CIs are presented for all stratified analyses. For race/ethnicity stratified analyses, Poisson regression models [45] were used to calculate the population attributable risk (PAR) for any indoor LAN exposure compared to none by contrasting the observed prevalence of each sleep dimension in the total population with the model-predicted prevalence of the sleep dimension under no exposure (i.e. no light), expressed as a percent of the observed prevalence of the sleep dimension. The PAR combines both the effect size and exposure prevalence and contrasts health outcomes under the observed scenario (i.e. the "factual" exposure) with the counterfactual (i.e. "counter to fact") scenario in which the exposure has been removed from the entire population [46].

Statistical significance was determined using two-sided tests with *P*-values of 0.05. All analyses were conducted using SAS statistical software version 9.4 (SAS Institute, Cary, NC).

Results

Of 47 765 eligible participants, the majority were non-Hispanic white (85%), college educated with a bachelor's degree or higher (51%), had an annual household income between $50 000 and $200 000 (68%), and lived in the northern half of the United States (66%) (Table 1). The average age of study participants was 56 years. Short sleep duration (<7 hours/night; 28%), insomnia symptoms (27%), sleep debt of ≥2 hours (25%), and recent use of sleep medications (24%) were the most commonly reported poor sleep dimensions. Women who reported sleeping with a TV on were more likely to be non-Hispanic black (31% vs. 9%) and live in the Southern half of the United States (42% vs. 34%) compared to women who reported sleeping with no light in the bedroom.

Table 1. Baseline Sociodemographic Characteristics, Sleep Health Dimensions, Residential/Environmental Characteristics, Health Behaviors, and Clinical Characteristics of Sister Study Participants (*N* = 47 765) Overall and by Indoor LAN Exposure

	Total population	No light *n* = 8650	Small nightlight *n* = 18 782	Light from outside the room *n* = 14 621	Light(s) on in the room *n* = 1204	TV on most/all of night *n* = 4508
Sociodemographic characteristics						
Age at baseline, years (mean ± SD)	55.7 ± 9.0	56.2 ± 8.9	55.8 ± 8.9	55.9 ± 9.2	56.3 ± 9.3	54.0 ± 8.6
Race/ethnicity						
Non-Hispanic white	40 790 (85)	7354 (85)	16 844 (90)	12 836 (88)	939 (78)	2817 (62)
Non-Hispanic black	4160 (9)	754 (9)	983 (5)	902 (6)	146 (12)	1375 (31)
Hispanic/Latina	1562 (3)	315 (4)	516 (3)	469 (3)	72 (6)	190 (4)
"Other"[1]	1253 (3)	227 (3)	439 (2)	414 (3)	47 (4)	126 (3)
Married/living as married, yes[2]	35 924 (75)	6401 (74)	14 900 (79)	10 794 (74)	919 (76)	2910 (65)
Educational attainment						
HS or less	7252 (15)	1172 (14)	2712 (14)	2297 (16)	189 (16)	882 (20)
Some college/technical	16 114 (34)	2812 (33)	6187 (33)	4779 (33)	407 (34)	1929 (43)
Bachelor's or higher	24 399 (51)	4666 (54)	9883 (53)	7545 (52)	608 (50)	1697 (38)
Annual household income						
<$50 000	11 802 (25)	2061 (24)	4017 (21)	3932 (27)	311 (26)	1481 (33)
$50 000–$99 999	19 707 (41)	3450 (40)	7802 (42)	6126 (42)	501 (42)	1828 (41)
$100 000–$200 000	12 784 (27)	2377 (27)	5449 (29)	3676 (25)	303 (25)	979 (22)
>$200 000	3472 (7)	762 (9)	1514 (8)	887 (6)	89 (7)	220 (5)
Sleep health characteristics						
Short sleep duration, yes	13 479 (28)	2332 (27)	4736 (25)	3980 (27)	388 (32)	2043 (45)
Insomnia symptoms, yes	12 833 (27)	2131 (25)	4545 (24)	3972 (27)	340 (28)	1845 (41)
Difficulty falling asleep, yes	8388 (18)	1451 (17)	2829 (15)	2473 (17)	217 (18)	1418 (31)
Difficulty staying asleep, yes	6511 (14)	1011 (12)	2398 (13)	2119 (14)	180 (15)	803 (18)
Short sleep + insomnia symptoms, yes	5527 (12)	943 (11)	1774 (9)	1584 (11)	149 (12)	1077 (24)
Frequent napping, yes	5019 (11)	841 (10)	1802 (10)	1584 (11)	165 (14)	627 (14)
Inconsistent sleep/wake time, yes	6904 (14)	1268 (15)	2223 (12)	2041 (14)	224 (19)	1148 (25)
Sleep debt ≥2 hours, yes	11807 (25)	2030 (23)	4187 (22)	3568 (24)	350 (29)	1672 (37)
Recent use of sleep medications, yes	11547 (24)	2194 (25)	4564 (24)	3495 (24)	264 (22)	1030 (23)
Cumulative poor sleep score ≥3, yes	8732 (18)	1519 (18)	2882 (15)	2595 (18)	259 (22)	1477 (33)
Residential characteristics						
Census tract population density, per square-mile (mean ± SD)	3372.5 ± 9209.2	3702.0 ± 10399.4	2856.8 ± 8389.4	3664.0 ± 9601.2	3615.7 ± 9309.3	3876.9 ± 8598.8
ADI (2000) (mean ± SD)	34.2 ± 24.5	32.7 ± 24.6	32.1 ± 23.2	35.6 ± 25.0	35.1 ± 24.6	41.2 ± 26.1
Latitude						
<37° N	16373 (34)	2951 (34)	6092 (32)	4951 (34)	469 (39)	1911 (42)
≥37° N	31392 (66)	5699 (66)	12690 (68)	9670 (66)	736 (61)	2597 (58)
Health behaviors						
Alcohol consumption status[3]						
Never	1660 (3)	321 (4)	623 (3)	531 (4)	42 (3)	143 (3)
Past	7124 (15)	1283 (15)	2464 (13)	2269 (16)	246 (20)	862 (19)
Current	38 917 (82)	7028 (81)	15 671 (84)	11 806 (81)	915 (76)	3497 (78)
Smoking status[4]						
Never	26 642 (56)	4775 (55)	10 735 (57)	8426 (58)	643 (53)	2083 (46)
Past	17 250 (36)	3212 (37)	6812 (36)	5134 (35)	443 (37)	1649 (37)
Current	3871 (8)	683 (8)	1235 (7)	1059 (7)	118 (10)	776 (17)
Clinical characteristics						
BMI[5], kg/m^2						
<25	18 425 (39)	3640 (42)	7809 (42)	5428 (37)	410 (34)	1138 (25)
25–<30	15 142 (32)	2705 (31)	5980 (32)	4677 (32)	376 (31)	1404 (31)
≥30	14 181 (30)	2300 (27)	4989 (27)	4511 (31)	417 (35)	1964 (44)
Depression at baseline, yes	10 120 (21)	1726 (20)	3674 (20)	3360 (23)	295 (25)	1065 (24)

SD, standard deviation; HS, high school; LAN, light at night; ADI, Area Deprivation Index; BMI, body mass index
[1]"Other" category includes women who self-identified as Asian, Native Hawaiian/Pacific Islander, or American Indian/Alaska Native
[2]*n* = 5 women were missing marital status
[3]*n* = 64 women were missing alcohol consumption at enrollment
[4]*n* = 2 women were missing smoking status at enrollment
[5]*n* = 17 women were missing BMI at enrollment

Table 2. Prevalence Ratios and 95% Confidence Intervals for Baseline Sleep Health Dimensions Associated With Indoor Light at Night Among Women in the Sister Study (*n* = 47 765)

	Short sleep duration	Insomnia symptoms	Difficulty falling asleep	Difficulty staying asleep	Short sleep + insomnia symptoms
PR (95% CI)					
Indoor LAN[1]					
No light	1.0 (ref)	1.0 (ref)	1.0 (ref)	1.0 (ref)	1.0 (ref)
Small nightlight	0.97 (0.93, 1.01)	1.00 (0.95, 1.04)	0.93 (0.87, 0.98)	**1.09 (1.02, 1.17)**[2]	**0.90 (0.83, 0.97)**[2]
Outside room	1.02 (0.98, 1.06)	**1.08 (1.03, 1.13)**[2]	0.99 (0.93, 1.05)	**1.21 (1.13, 1.30)**[2]	0.98 (0.91, 1.06)
Light(s) on in room	**1.14 (1.05, 1.25)**[2]	1.09 (0.99, 1.20)	0.99 (0.87, 1.13)	**1.25 (1.08, 1.44)**[2]	1.05 (0.90, 1.24)
TV	**1.38 (1.32, 1.45)**[2]	**1.50 (1.42, 1.58)**[2]	**1.56 (1.46, 1.66)**[2]	**1.52 (1.39, 1.66)**[2]	**1.73 (1.59, 1.88)**[2]
	Frequent napping	**Inconsistent sleep/wake time**	**Sleep debt ≥2 hours**	**Sleep medication use**	**Poor sleep score**
PR (95% CI)					
Indoor LAN[1]					
No light	1.0 (ref)	1.0 (ref)	1.0 (ref)	1.0 (ref)	1.0 (ref)
Small nightlight	1.03 (0.95, 1.11)	**0.84 (0.78, 0.89)**[2]	0.96 (0.92, 1.00)	0.95 (0.91, 1.00)	**0.90 (0.85, 0.95)**[2]
Outside room	**1.09 (1.01, 1.18)**[2]	**0.93 (0.87, 0.99)**[2]	1.02 (0.97, 1.07)	**0.92 (0.88, 0.97)**[2]	0.99 (0.93, 1.04)
Light(s) on in room	**1.31 (1.13, 1.52)**[2]	**1.19 (1.05, 1.34)**[2]	**1.18 (1.08, 1.30)**[2]	**0.84 (0.75, 0.94)**[2]	**1.13 (1.01, 1.27)**[2]
TV on in room	**1.33 (1.20, 1.46)**[2]	**1.55 (1.44, 1.66)**[2]	**1.36 (1.29, 1.44)**[2]	0.95 (0.89, 1.01)	**1.58 (1.48, 1.68)**[2]

Statistically significant results are bolded.
IQR, interquartile range; LAN, light at night; PR, prevalence ratio; CI, confidence interval; ADI, Area Deprivation Index
[1]Adjusted for age, race/ethnicity, educational attainment, household income, ADI, latitude, population density, and depression
[2]False discovery rate-corrected *P*-value was statistically significant at the 0.05 level

The prevalence of nearly all poor sleep health dimensions was higher among women who reported sleeping with a TV on relative to women who slept with no light in the bedroom (Table 2). Sleeping with a TV on was statistically significantly associated with short sleep plus insomnia symptoms (PR = 1.73, 95% CI: 1.59, 1.88); a higher poor sleep score (PR = 1.58, 95% CI: 1.48, 1.68); inconsistent sleep/wake time (PR = 1.55, 95% CI: 1.44, 1.66); difficulty falling asleep (PR = 1.56, 95% CI: 1.46, 1.66); difficulty staying asleep (PR = 1.52, 95% CI: 1.39, 1.66); insomnia symptoms (PR = 1.50, 95% CI: 1.42, 1.58); short sleep (PR = 1.38, 95% CI: 1.32, 1.45); having a sleep debt of ≥2 hours (PR = 1.36, 95% CI: 1.29,1.44); and frequent napping (PR = 1.33, 95% CI: 1.20, 1.46) compared to women who slept with no light in the bedroom. After accounting for the FDR, these associations remained statistically significant. Absolute comparisons suggested that sleeping with a TV on versus sleeping with no light in the bedroom was associated with 13 excess cases of insomnia symptoms per 100 women (PPD = 13.09, 95% CI: 11.36, 14.82) and 12 excess cases of short sleep duration per 100 women (PPD = 12.45, 95% CI: 10.68, 14.21; Table 3).

Sleeping with one or more lights on in the room was associated with a higher relative prevalence of frequent napping (PR = 1.31, 95% CI: 1.13,1.52); difficulty staying asleep (PR = 1.25, 95% CI: 1.08, 1.44); inconsistent sleep/wake time (PR = 1.19, 95% CI: 1.05, 1.34); having a sleep debt of ≥2 hours (PR = 1.18, 95% CI: 1.08, 1.30); short sleep (PR = 1.14, 95% CI: 1.05, 1.25); and a higher poor sleep score (PR = 1.13, 95% CI: 1.01, 1.27) compared to sleeping with no light (Table 2). Recent sleep medication use was less prevalent among women who slept with at least one light on, compared to women who slept with no light in the bedroom (PR = 0.84, 95% CI: 0.75, 0.94). All associations remained statistically significant after accounting for the FDR adjustment.

In stratified analyses of indoor LAN and dimensions of sleep health, estimates for non-Hispanic black women tended to be lower than those for the other racial/ethnic groups. For example, sleeping with a TV on was associated with a smaller relative increase in the prevalence of short sleep for non-Hispanic black women (vs. no light: PR = 1.16, 95% CI: 1.07, 1.26) than for non-Hispanic white women (vs. no light: PR = 1.50, 95% CI: 1.41, 1.59; *p*-interaction <0.0001; Figure 1A). However, the prevalence of sleeping with a TV on for most or all of the night was higher among non-Hispanic black women (33% of all black women; Supplementary Figure S1) than among non-Hispanic white women (7% of all white women). Furthermore, most of the unfavorable dimensions of sleep health were more common among non-Hispanic black women than women of other races/ethnicities but most notably compared to non-Hispanic white women (Figure 2A). Among non-Hispanic white women, sleeping with a TV on was not associated with recent use of sleep medication, while among non-Hispanic black women, sleeping with a TV on was associated with a lower prevalence of recent sleep medication use. The PARs were generally lowest for non-Hispanic white women compared to black, Hispanic/Latina, and "other" women (Figure 2B). For example, eliminating all indoor light exposure would eliminate 1.4% of the prevalent cases of poor sleep (based on the cumulative score ≥3) among non-Hispanic white women, 5.0% of the prevalent cases among non-Hispanic black women, 9.7% of the prevalent cases among Hispanic/Latina women, and 8.0% of the prevalent cases among women of other racial/ethnic groups.

PRs for the association between sleeping with a TV on and short sleep and difficulty staying asleep were higher among those reporting diagnosed depression than among those without depression (Figure 1B). However, women who were depressed had a lower PR for frequent napping (TV vs. no light: PR = 1.15, 95% CI: 0.97, 1.36) than women who were not depressed (TV vs. no light: PR = 1.42, 95% CI: 1.26, 1.60), although the interaction was not statistically significant (*p*-interaction = 0.09). The inverse association observed between sleeping with a TV on and recent sleep medication use in the overall study population was not observed for depressed women (vs. no light: PR = 1.01, 95% CI: 0.92, 1.12).

There were no statistically significant differences across the three age categories (Supplementary Figure S1A), all categories of

Table 3. Prevalence Differences and 95% Confidence Intervals for Sleep Health Dimensions Associated With Indoor Light at Night Among Women in the Sister Study

	Sleeping with a TV on vs. no light[1]	Sleeping with light(s) on vs. no light[1]
	PPD (95% CI)	
Short sleep duration	**12.45 (10.68, 14.21)**	**4.14 (1.37, 6.91)**
Insomnia symptoms	**13.09 (11.36, 14.82)**	1.33 (–1.23, 3.90)
Difficulty falling asleep	**11.02 (9.45, 12.59)**	–0.80 (–2.88, 1.28)
Difficulty staying asleep	**5.33 (4.05, 6.62)**	**2.22 (0.22, 4.21)**
Short sleep + insomnia symptoms	**9.74 (8.34, 11.14)**	0.52 (–1.33, 2.37)
Frequent napping	**2.42 (1.31, 3.54)**	**2.19 (0.40, 3.99)**
Inconsistent sleep/wake time	**8.65 (7.21, 10.10)**	**2.58 (0.40, 4.77)**
Sleep debt ≥2 hours	**9.57 (7.88, 11.27)**	**4.12 (1.45, 6.78)**
Use of sleep medications	**–1.83 (–3.34, –0.32)**	**–4.83 (–7.11, –2.55)**
Poor sleep score	**11.47 (9.90, 13.04)**	2.14 (–0.18, 4.47)

Statistically significant results are bolded.
PPD, percent prevalence difference (per 100 women); LAN, light at night; CI, confidence interval; ADI, Area Deprivation Index
[1]Adjusted for age, race/ethnicity, educational attainment, household income, ADI, latitude, population density, and depression.

BMI (Supplementary Figure S1B), or among women living in either low/moderate or high deprivation neighborhoods (Supplementary Figure S1C).

Discussion

In our large cohort of women from across the United States, participants who slept with either a TV or light(s) on in the bedroom reported a higher prevalence of multiple dimensions of poor sleep than women who slept with no lights on in the bedroom, including several dimensions that have not been previously evaluated in relation to this exposure (frequent napping, inconsistent sleep/wake time, sleep debt ≥2 hours, and cumulative poor sleep score). Sleeping with a small nightlight or with light entering the room from outside or from another room were not associated with most sleep health dimensions.

Melatonin is a sleep-promoting hormone that is lowest during the day and peaks in the middle of the night [47]. In addition to other biological functions, melatonin synchronizes the body's master clock with peripheral clocks in other tissues [48, 49] and helps regulate various biological processes that follow a circadian pattern, such as body temperature [50]. LAN exposure is proposed to negatively impact sleep by reducing melatonin production, and both experimental and observational evidence suggests that light exposure prior to sleep support this hypothesis [21, 47]. Our finding of an association between exposure to indoor LAN and difficulty falling asleep (also referred to as long sleep onset latency) is consistent with studies that found exposure to LAN prior to sleep delays melatonin onset. Long sleep latency could lead to an increase in short sleep duration, especially during the work week, when wake times may be less flexible. Another potential consequence of difficulty falling asleep is a greater sleep debt, in which individuals sleep fewer hours during the work week and "catch up" on sleep hours during their off days.

The indoor LAN and sleep results of our large, nationwide analysis of US women are consistent with earlier studies of indoor LAN and sleep health dimensions. Among older adults in the Chicago Healthy Aging Study, exposure to actigraphy-measured light while sleeping was associated with greater wake after sleep onset (i.e. more episodes of waking up during the night after falling asleep), less time in bed, less total sleep time, and reduced sleep efficiency, also measured via actigraph [26]. In a population of older Japanese adults, individuals exposed to the highest level of indoor LAN had 1.61 times the odds of self-reported insomnia (95% CI: 1.05, 2.45) compared to those exposed to the lowest level [24]. We also observed a higher prevalence of insomnia among women who reported the highest level of indoor LAN. Analyses investigating the relationship between sleeping with a TV on and dimensions of sleep health are limited. A study of adults who reported using various forms of media as sleep aids found that the odds of poor quality sleep as determined by the Pittsburgh Sleep Quality Index were higher among individuals who reported using a TV as a sleep aid at least some of the time compared to never users [51]. An association between sleeping with a light on and getting <6 hours of sleep per night was suggested in a study of US adults when indoor LAN was included as a covariate in their model of outdoor LAN and short sleep duration [25].

Women in our study population who slept with at least one light on were less likely to report recently using sleep medications, either prescription or over-the-counter. This inverse association could be due to women who use sleep medications having a higher "health literacy" (e.g. a greater awareness of sleep hygiene), including knowledge about the potentially disruptive impact of LAN on sleep. When stratified by race/ethnicity, sleeping with a TV on was associated with a lower prevalence of sleep medication use only for non-Hispanic black women. We also observed that non-Hispanic black women were less likely to report recent use of sleep medications compared to women of other race/ethnicity groups. Racial differences in sleep medication use were also observed in the Johnson County Osteoarthritis Project population [52], which the authors suggest could be related to several factors, including differences in income, prescription drug insurance that can influence out-of-pocket medication costs, or patient preferences or willingness to use a particular drug treatment.

Both the exposure (sleeping with a TV on) and the outcome (poor sleep dimensions) were more common among non-Hispanic black women than among non-Hispanic white women. We also observed higher PARs for any light compared to no light for non-Hispanic black women than for non-Hispanic white women for several dimensions of sleep health. PARs were also higher for

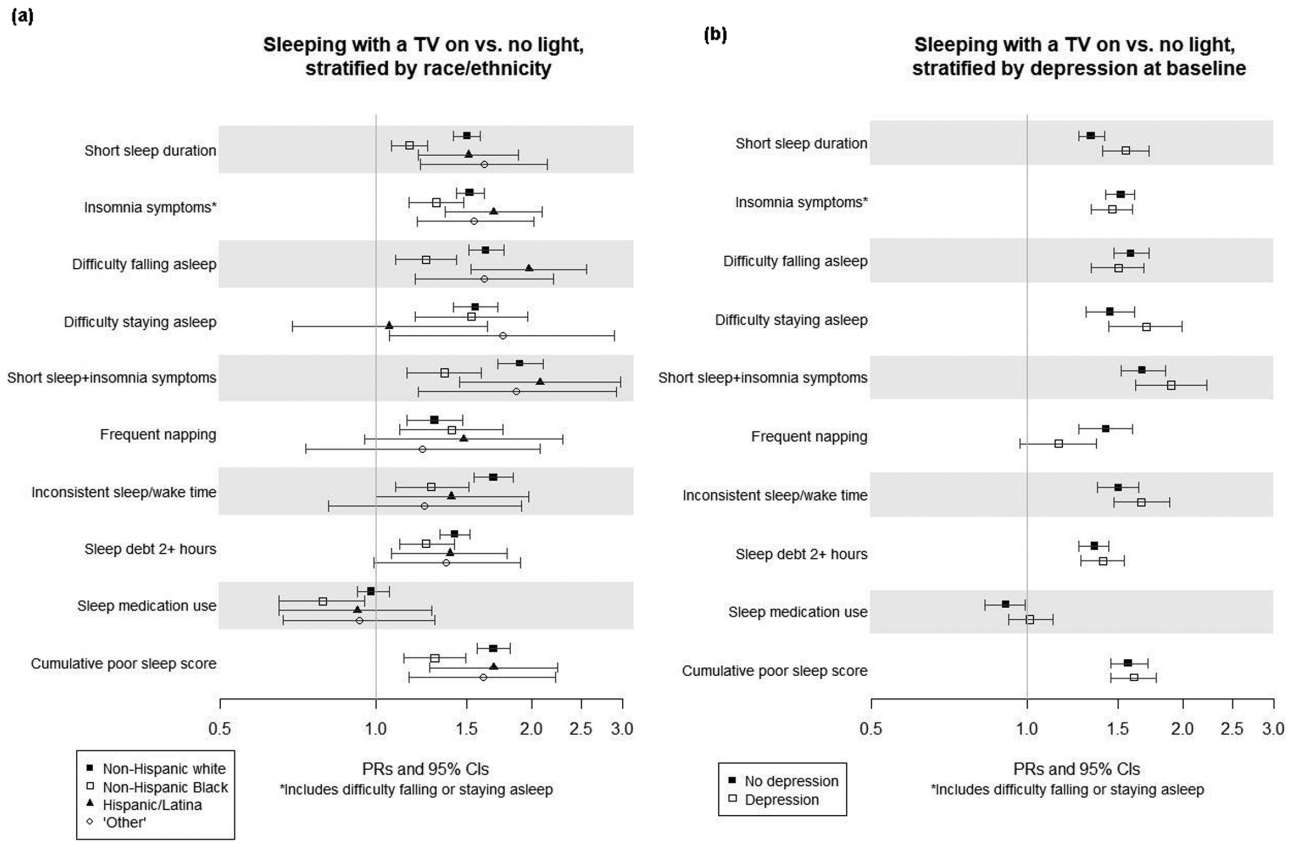


Figure 1. Prevalence ratios (PRs) and 95% confidence intervals (CIs) for the association between sleeping with a TV on (compared to sleeping with no light) and multiple dimensions of sleep health, stratified by race/ethnicity (A) and depression (B). All models adjusted for age, race/ethnicity (except a), educational attainment, household income, ADI, latitude, population density, and depression (except b). Note: ADI, Area Deprivation Index; "Other" race/ethnicity category includes women who self-identified as Asian, Native Hawaiian/Pacific Islander, or American Indian/Alaska Native.

Hispanic/Latina and "other" women, although the estimates were based on small sample sizes (N = 1562 and 1253, respectively). With relevance to public health impact and disparities in exposure burden, this finding suggests that eliminating this adverse exposure may have a greater benefit on sleep health for non-Hispanic black women (and possibly for Hispanic women) than for non-Hispanic white women, which was not evident from the stratified ratios of prevalence estimates with their racial counterparts as a comparison. Therefore, future studies should include both absolute and relative measures of association and explore associations among Hispanic, Asian, and other race/ethnicity women.

Our study has several limitations. For instance, this analysis was cross-sectional, and, as such, temporality cannot be determined. Reverse causality could explain, at least in part, the observed associations between indoor LAN and sleep health dimensions. It is possible that women chose to sleep with a TV on because they already slept poorly. It is also possible that women who knew that they would wake up in the middle of the night for a health reason (e.g. nocturia) were more likely to leave a light on. Experimental studies in which usual TV sleepers refrain from sleeping with the TV on or non-TV sleepers start sleeping with the TV on could better address this issue.

Indoor LAN was self-reported by study participants at baseline. Although we did not ask about the use of black-out curtains, participants could report that no light was present in the bedroom, which would include women who used curtains to block light from outdoors. The baseline questionnaire also did not include questions about the brightness level, the types of bulbs used, or the use of handheld electronic devices, such as mobile phones, prior to falling asleep. In ordering our indoor LAN exposure categories, we assumed that certain light sources were generally brighter than others. For example, sleeping with a light on in the room is likely to result in more exposure than if a light was on in an adjacent room, which in turn would result in more exposure than the use of a nightlight alone. However, without information on objective brightness levels, some women may have been misclassified as being exposed to either more or less light than was actually the case. Additionally, the types of bulbs used in the household have changed since the Sister Study participants were enrolled, with many individuals switching to light-emitting diode bulbs, which emit blue light [53], instead of incandescent bulbs. Blue light is wavelength that is most disruptive to circadian rhythms [54]. Our observed associations for sleeping with one or more lights on in the bedroom may therefore underestimate the associations that would be observed were the study conducted today. Use of light meters, which can provide objective measures of indoor light exposure, were infeasible in our large epidemiologic study and are still subject to misclassification, as light meters require participants to correctly use the light meter and placement of the meter needs to be consistent for all participants. Our findings for self-reported indoor LAN and insomnia were, however, consistent with the results of a prior study of objectively measured light that was conducted between 2010 and 2013 [24], suggesting that any misclassification or underestimation of exposure is likely to be minimal.

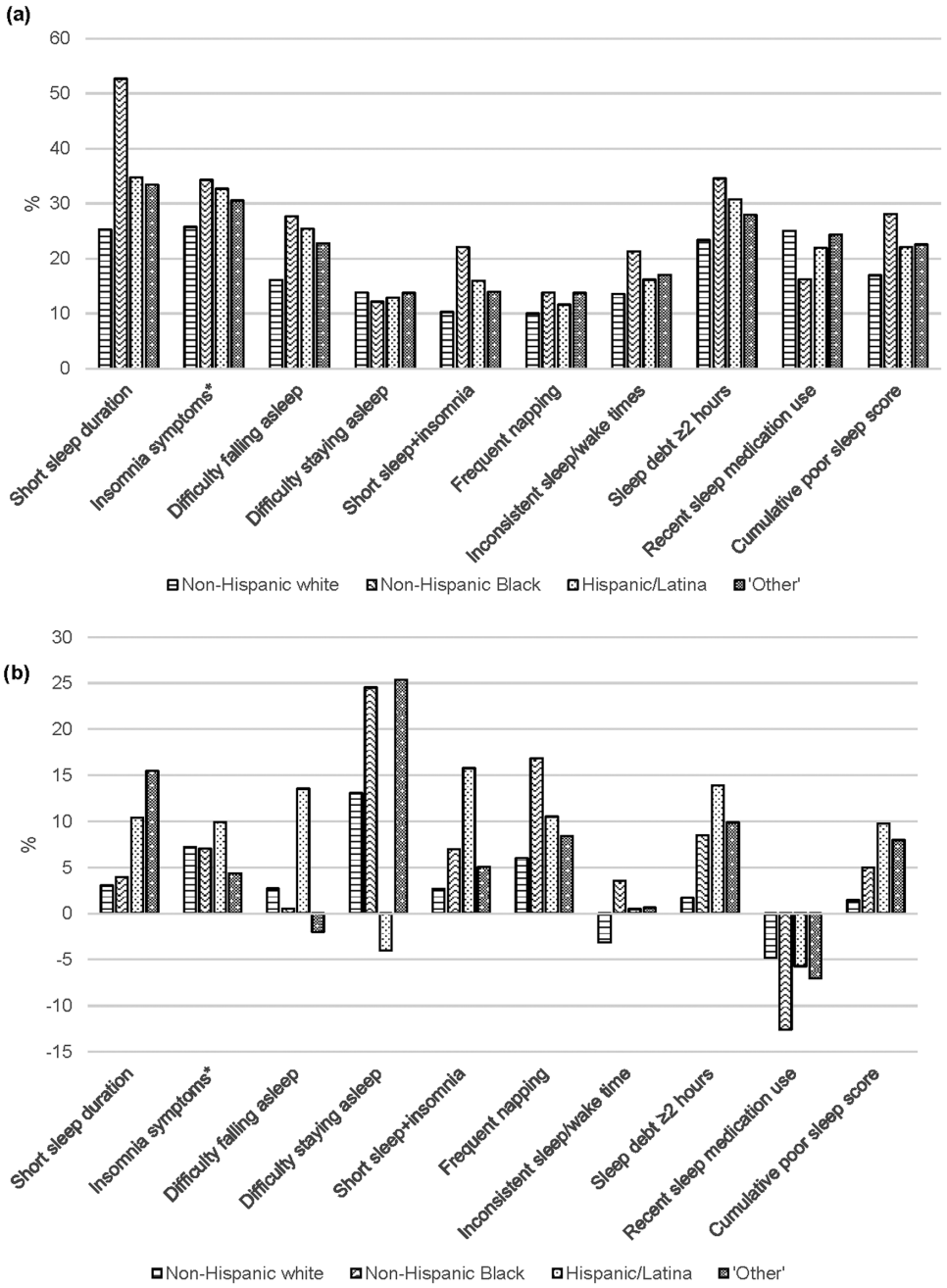


Figure 2. (A) Unadjusted prevalence of dimensions of sleep health by race/ethnicity. Percentages are determined within each category of race/ethnicity and do not sum across race/ethnicity categories. (B) Model-based population attributable risk for any indoor light exposure vs. none by race/ethnicity. Note: Insomnia symptoms includes difficulty falling asleep or difficulty staying asleep; "Other" race/ethnicity category includes women who self-identified as Asian, Native Hawaiian/Pacific Islander, or American Indian/Alaska Native.

Sleep dimensions were self-reported, and can, therefore, be subject to measurement error or misclassification. Evidence from validation studies suggests that sleep duration is commonly over-reported [55, 56], although the amount and direction of the bias that could result depends on the extent of the misclassification and whether it was differential by exposure status. For example, if women who slept with a TV on were more likely than women who slept with no light to over-report duration, we would expect our observed association to be an underestimate of the true association. We would expect an overestimate of the true association if the no-light women were more likely to over-report their sleep duration. Nonetheless, we observed associations between indoor LAN and multiple dimensions of sleep health, including a composite poor sleep score, beyond sleep duration alone. The Sister Study baseline questionnaire included 21 items, and this wealth of data allowed us to create a cumulative poor sleep score, which incorporated duration, quality, and sleep disorders. While self-reported sleep may differ from objectively measured dimensions, perceived sleep quality has been associated with several health outcomes [7–9]. There is also evidence that when participants are told that they had better sleep, they reported better daytime functioning and performed better on cognitive tests [57].

Although we had data on a large number of sleep dimensions, we did not have data on sleep apnea at baseline. There

is some evidence that occurrences of sleep apnea follow a circadian pattern [58], indicating that it warrants investigation in future studies of indoor LAN. Furthermore, participants were asked about sleeping with a TV on for at least some of the night, but we did not have information about the TV volume. Although the sound is one explanation for the elevated associations [59], another possible explanation is the frequently changing light intensity produced by TVs. We observed a higher prevalence of several sleep health dimensions when sleeping with at least one light on in the bedroom, supporting the hypothesis that consistently bright light may negatively impact sleep. Intermittent bright light exposure prior to sleep has been demonstrated to delay melatonin onset [60], increase alertness, and decrease total sleep time and sleep efficiency [61]. Intermittent light exposure during sleep, as from a TV, could plausibly have a similar impact on sleep.

Our study population, while more racially and ethnically diverse than several other large US cohorts, is still predominantly non-Hispanic white. Additionally, participants tended to have higher annual household incomes and higher educational attainment than the general US population. Therefore, our results may not be generalizable to the US population.

An important strength of our analysis is the use of a large study sample that includes women from all 48 of the contiguous United States. In addition to being able to conduct multiple stratified analyses, we had the ability to evaluate sleeping with a TV on as well as a number of sleep health dimensions not included in previous studies. Our PAR analysis enabled us to evaluate the absolute impact of sleeping with indoor LAN on sleep health among different racial and ethnic groups, which is useful for translation.

In this large, US cohort of women, indoor LAN was associated with a higher prevalence of most dimensions of poor sleep. Although we cannot establish a causal relationship between indoor LAN and sleep from this analysis alone, it is important to note that indoor LAN is modifiable. If our findings are further replicated by studies addressing our study limitations, women who experience poor sleep may consider reducing their indoor LAN by, for instance, turning off lights, using black-out curtains, or wearing a mask as part of a larger effort to improve sleep health. We also encourage continued exploration of disparities in this relationship. Ultimately, optimal lighting may serve as an important prevention and intervention tool.

Supplementary Material

Supplementary material is available at *SLEEP* online.

Funding

This work was funded, in part, by the Intramural Program at the NIH, National Institute of Environmental Health Sciences [Z1AES103325 (C.L.J.); Z01ES044005 (D.P.S.); Z1AES103332 (A.J.W.)], and by the Intramural Research Program of the NIH, National Institute on Minority Health and Health Disparities. Additional funding was provided by the Extramural Program at the NIH, National Institute of Environmental Health Sciences [F31ES033062 (M.R.S.); T32ES007018 (M.R.S.)].

Disclosure Statement

None declared

Data Availability

The data used in this article will be shared on reasonable request through the Sister Study data tracking system (STaRS: https://www.sisterstudystars.org).

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