

Light Exposure Profiles and Depressive Symptoms in a Nationally Representative Sample: Sleep Regularity as a Mediating Pathway

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Abstract

Light exposure and sleep regularity influence mood, but their interrelationships at the population level remain poorly understood. Actigraphy from 5,757 adults in the 2011–2014 National Health and Nutrition Examination Survey captured light exposure profiles and sleep regularity. Mediation models assessed the links between multiple dimensions of light exposure (illuminance, duration, timing, and rhythmicity) and depressive symptoms (PHQ-9), and tested whether sleep regularity mediated these associations, accounting for chronotype as an upstream mediator and adjusting for sociodemographic confounders. Higher PHQ-9 scores were associated with lower daytime illuminance (IRR = 0.87, P_{adj} = .01), higher late-night illuminance (IRR = 1.19, P_{adj} = .03), and lower light IS (IRR = 0.91, P_{adj} = .01). Sequential mediation through chronotype and SRI revealed that daytime illuminance operated predominantly directly (46% mediated by SRI), whereas late-night illuminance and IS operated through SRI (62% and 73% mediated; direct effects of both non-significant). Clustering the population based on light exposure patterns revealed that only minority of our sample (n = 219) were characterized by high late-night illuminance, the remainder were split either between groups with high daytime illuminance and IS (n = 2,900) or low daytime and night illuminance (n = 2,638). These findings challenge the focus on nighttime light as an independent risk factor and instead position sleep regularity and light exposure regularity, alongside bright daytime exposure, as actionable targets for population-level mood and mental health interventions.

1. Background

Major depressive disorder (MDD) is among the leading contributors to global disability,^{1,2} yet its etiology remains incompletely understood and effective preventive strategies are limited.^{3–5} Identifying modifiable environmental and behavioral factors with biological relevance is, therefore, a priority.^{6–8} Light exposure is a compelling candidate^{9,10} because it plays a central role in circadian and sleep regulation,^{11,12} systems closely linked to mood.^{13–15} Retinal light input influences mood-related brain regions through both suprachiasmatic nucleus (SCN)-dependent and SCN-independent pathways, providing a neurobiological basis for effects of light on emotional regulation, both via sleep–circadian mechanisms and through direct non-circadian neural pathways.^{16–18}

Mood-relevant effects of light are jointly determined by its level (e.g., illuminance), spectral composition, timing, and duration, properties that interact such that the circadian impact of any given light exposure cannot be reduced to a single characteristic.^{19,20} No single metric fully captures the light environment relevant to circadian entrainment and mood, yet most epidemiologic investigations have examined light exposure using one or a few parameters in isolation,^{21–24} providing an incomplete picture of how the broader temporal and rhythmic organization of daily light environments relates to depression.

To our knowledge, only one large population-based analysis has examined the rhythmic properties of light exposure in relation to depressive symptoms.²⁵ Using actigraphy data from the National Health and

Nutrition Examination Survey (NHANES), prior work demonstrated that disruptions in metrics characterizing rhythms (i.e., interdaily stability, intradaily variability, and relative amplitude) of both rest–activity and light exposure are associated with greater depressive symptoms. While these findings highlight the potential relevance of light-related rhythmicity, the analysis was limited to a small set of summary rhythm parameters and did not investigate other clinically meaningful dimensions of light exposure, such as the timing, illuminance, and duration across day and night periods. Moreover, this study did not examine behavioral mechanisms through which alterations in light rhythms may influence mood.

In this context, sleep regularity (i.e., the stability of sleep timing and duration across days) has emerged as a biologically plausible marker of circadian disruption or misalignment.^{26–28} Preliminary evidence suggests that sleep regularity may mediate or modify light–mood associations, but existing studies face important methodological limitations: Bonatto et al.²² leveraged detailed, multidimensional characterizations of light exposure in a convenience sample relying on subjective assessment of light exposure, whereas Wallace et al.^{29,30} examined sleep stability as an effect modifier in two large, community-representative samples but characterized only nighttime light exposure.

2. Objective

To address these gaps, we objectively characterized light exposure across multiple interrelated dimensions (illuminance, duration, timing, and temporal organization across daytime and nighttime periods) in a nationally representative NHANES sample.³¹ We examined independent associations with depressive symptoms using multivariable models accounting for the intercorrelated structure of light parameters. Then, we tested sleep regularity as a mediating behavioral mechanism linking each dimension of light exposure to depressive symptoms. Finally, we applied unsupervised clustering to identify ecologically valid light exposure profiles. This integrated approach provides the most comprehensive characterization to date of how multiple dimensions of the daily light environment relate to depressive symptoms, and whether chronotype and sleep regularity – as a fundamental behavioral mechanism – accounts for these associations.

3. Methods

3.1. Ethics statement

NHANES protocols were approved by the National Center for Health Statistics Research Ethics Review Board, and all participants provided written informed consent.³¹ The present study involved secondary analysis of deidentified, publicly available data.

3.2. Study design and participants

We included participants from the 2011–2012 and 2013–2014 NHANES survey cycles, cycles in which wrist actigraphy was collected. The analytic sample was restricted to adults aged 18 years or older. Participants were excluded if data were missing for variables or covariates of interest.

3.3. Actigraphy data collection and processing

Participants wore the ActiGraph GT3X+ device (ActiGraph, Pensacola, Florida) on the non-dominant wrist for 7 consecutive days and nights. Initial preprocessing and data quality control were conducted by the NHANES research team.³¹ Minutes of data where a quality flag was marked by NHANES pre-processing procedures; non-wear, or unknown status were treated as invalid, and days with >6 hours of missing/invalid data were excluded. Participants with fewer than 7 valid days were excluded. The remaining missing data were imputed based on the recommendations of Comiran Tonon et al.³², using participant-specific mean values at each timepoint across the 7-day recording period, with consistently missing timepoints imputed using the mean of the surrounding 30-minute window.

3.4. Definition of parameters

Light Exposure Metrics

Raw values of light illuminance (in lux) were log10-transformed. Time series were then smoothed using local regression (LOESS),¹² applied over an average span of 21 minutes per day (**Supplementary Figure 1**). A mean 24-h light exposure waveform was generated by computing the minute-by-minute average across all valid days and all participants, and was used to identify the periods of lowest and highest overall light exposure (**Supplementary Figure 2**). Based on its inspection, 04:00 was defined as the midpoint of the darkest portion of the day. All metrics were therefore calculated using 24-h windows anchored from 04:00 to 04:00.

Within each 24-h cycle, predefined nighttime (early, 20:00–00:00; late 00:00–04:00) and daytime (07:00–17:00) intervals were established. For each, we calculated 1) the total duration of exposure above a predefined lux threshold (daytime >1,000 lux; nighttime >10 lux)³³ and 2) the mean illuminance. In addition, we extracted the onset of exposure exceeding 1000 lux, and the latest time of exposure above 10 lux. Parameters calculated from the daily windows were averaged within subjects for all days. Finally, using the 7-day time series aggregated at the hour level, we derived interdaily stability (IS) and intradaily variability (IV), reflecting day-to-day regularity and within-day fragmentation of light exposure patterns, respectively.

Chronotype and Sleep Regularity

Chronotype was estimated using the method described by Juda et al.³⁴, defined as the sleep-corrected mid-sleep on free days (MSFsc): the average sleep midpoint corrected for oversleep on non-work days.

Sleep Regularity Index (SRI) was calculated using the definition by Phillips et al^{35,36} and reflects the probability of being in the same sleep or wake state at the same clock time on consecutive days, averaged across the recording period. For the calculation of SRI, we used the minute-level sleep–wake classification provided by NHANES pre-processing, and applied a 30-minute rolling filter such that windows with ≥ 1 sleep were classified as sleep; otherwise, as wake.

Depressive Symptoms

Depressive symptoms were assessed using the Patient Health Questionnaire–9 (PHQ-9).³⁷ In NHANES, the PHQ-9 was administered on the day of the MEC examination, prior to the initiation of actigraphy monitoring.

Covariates

Covariates included age, sex, body mass index, ethnicity, educational attainment, employment, and season (November–April vs May–October).

3.5. Statistical Analysis

Statistical analyses were performed in *R* version 4.4.1, according to the NHANES analytical guidelines, by incorporating survey weights, strata, and primary sampling units in model variance estimations.³¹ Continuous predictors were standardized (z-scored) prior to analysis. *P* values were adjusted for multiple comparisons using the Benjamini-Hochberg procedure (False Discovery Rate).

To characterize the structure of light exposure parameters, we constructed a Pearson correlation matrix across all light exposure metrics. To quantify the independent associations between light metrics, sleep regularity, and depressive symptoms, we fitted survey-weighted generalized linear models (GLMs) with negative binomial distribution. Given substantial intercorrelations among parameters (particularly between daytime illuminance, amplitude and duration, $r > 0.7$), and high variance inflation factors (VIF), we modelled duration and illuminance parameters separately. Two sequential models were specified for each. First model regressed PHQ-9 on all light exposure parameters simultaneously, adjusting for covariates. The second model added SRI as a main effect to the first model.

To further investigate the role of SRI within the associations of light exposure and PHQ-9, counterfactual mediation analysis was performed using g-computation. Given that chronotype reflects an individual's circadian phenotype and is shaped by habitual light exposure, we modeled chronotype as an upstream mediator preceding sleep regularity. This ordering is supported by evidence that late chronotypes are disproportionately exposed to misalignment between biological circadian timing and socially imposed schedules, resulting in greater irregularity in sleep–wake patterns³⁸. This allowed us to decompose the total effect of light into pathways operating through circadian preference, sleep regularity, or both, and to isolate the contribution of sleep regularity independent of chronotype. Mediation was tested for light

parameters that showed significant association with PHQ-9 in the multivariate models, after correcting for multiple comparisons. Four effects were estimated: the natural direct effect (NDE) between light exposure and PHQ-9 ($X \rightarrow Y$); the natural indirect effect (NIE) via chronotype ($X \rightarrow M_1 \rightarrow Y$); the NIE via SRI ($X \rightarrow M_2 \rightarrow Y$); and the sequential NIE via both chronotype and SRI ($X \rightarrow M_1 \rightarrow M_2 \rightarrow Y$). Effects were estimated using a survey-weighted bootstrap replicate design (using 1000 replicates). Percentile confidence intervals and two-sided P values were derived from the bootstrap distribution.

Finally, to evaluate whether light exposure parameters aggregate into ecologically meaningful real-world profiles, we performed k-means clustering across light exposure variables selected for mediation models³⁹. According to the majority rule, 10 *NbClust* indices revealed three as the optimal number of clusters. Cluster-wise stability was evaluated using Jaccard coefficients, where values >0.75 are considered indicative of stable clusters. Across clusters, group-level differences in continuous variables were tested using design-based Kruskal-Wallis tests, and Pearson chi-squared tests with a design-based Rao & Scott adjustment for categorical variables. Pairwise differences in chronotype, PHQ-9 scores and SRI values were determined with a survey-weighted Wilcoxon Rank test, and differences in the prevalence of clinical significant depressive symptoms ($\text{PHQ-9} \geq 10$) were determined by examining standardized residuals of the survey-weighted Chi-squared test, with standard residual ≥ 1.96 as the significance threshold.

4. Results

4.1 Sample description

19,931 participants have data available from the 2011-2012 and 2013-2014 NHANES survey cycles. After excluding those below the age of 18 ($n = 7,954$), pregnant or unsure if they were ($n = 201$), had incomplete actigraphy data for sleep and light regularity parameters ($n = 9,423$) and incomplete PHQ-9 or covariate data ($n = 2,353$), 5,757 participants were included in the final analysis (**Supplementary Figure 3**). Summary statistics of the demographic variables, as well as the sleep and light metrics, are shown in **Table 1**, and distributions are shown in **Supplementary Figure 4**.

4.2. Independent Associations Between Light and Depressive Symptoms

Figure 1 shows the correlation matrix of parameters. Daytime and early-night illuminance and duration metrics were strongly and positively intercorrelated.

In multivariable models adjusting for covariates (**Figure 2**), lower daytime illuminance was significantly associated with higher PHQ-9 scores ($P_{\text{adj}} = .01$), while higher late night illuminance was significantly associated with higher PHQ-9 scores ($P_{\text{adj}} = .03$). Among the duration parameter model, lower IS was significantly associated with higher PHQ-9 scores ($P_{\text{adj}} = .01$). Upon addition of SRI, daytime illuminance

remained the only parameter significantly associated with PHQ-9 scores ($P_{\text{adj}} = .03$). Model coefficients and model fit comparisons are described in **Supplementary Table 1** and **Supplementary Table 2**.

Daytime illuminance, late-night illuminance, and light IS showed significant mediation by SRI (**Figure 3**), with proportions mediated of 46%, 62%, and 73%, respectively. Chronotype showed significant mediation for these variables, with proportions mediated of 4.8%, 15% and 5.8%, respectively. The sequential path (chronotype, then SRI) was also significant, with proportions mediated of 4.5%, 15% and 4.9%, respectively. Direct, non-mediated effects were significant for daytime illuminance (NDE = 0.94, 95% CI: 0.91 to 0.97, $P < .001$).

4.3. Light Exposure Clustering Analysis

The three clusters are visualized in **Supplementary Figure 5** and their demographic, sleep, and light exposure characteristics are presented in **Table 2**. All three clusters exceeded the threshold for cluster stability (Jaccard coefficients: 0.81, 0.93, and 0.90, respectively).

Cluster 1 ($n = 2,900$) was characterized by high daytime illuminance, high IS, and low late-night illuminance. This cluster had the earliest chronotype (3.14 hours, IQR – 2.26 to 4.17), the lowest proportion of clinically significant depressive symptoms (PHQ-9 ≥ 10 : 6.7%), and the highest sleep regularity (SRI = 87, IQR – 83 to 90). Cluster 2 ($n = 2,638$) was characterized by low daytime illuminance, low late-night illuminance, and intermediate IS. This cluster had an early-intermediate chronotype (3.70 hours, IQR – 2.50 to 5.22), 12% prevalence of clinically significant depressive symptoms (PHQ-9 ≥ 10), and intermediate sleep regularity (SRI = 82, IQR – 76 to 87). Cluster 3 ($n = 219$) was characterized by high late-night illuminance, low daytime illuminance, and intermediate IS. This cluster had the latest median chronotype of all three groups (5.69 hours, IQR – 3.85 to 7.40), the highest proportion of PHQ-9 ≥ 10 (13%), and the lowest sleep regularity (SRI = 78, IQR – 73 to 85). Pairwise differences for PHQ-9 scores, chronotype and SRI values are presented in **Supplementary Table 3**. Examination of the standardized residuals of the prevalence of PHQ-9 ≥ 10 across clusters showed that the association was driven by a significantly lower frequency in Cluster 1 and a higher frequency in Cluster 2. These results are presented in **Supplementary Table 4**.

5. Discussion

In a nationally representative sample, multiple dimensions of objectively measured light exposure were independently associated with depressive symptom severity. Lower daytime illuminance showed a direct association with higher depressive symptoms independently of sleep regularity, while the associations of higher late-night light exposure and lower light rhythm stability with depressive symptoms were largely accounted for by sleep regularity. These findings indicate that the relevance of nighttime light for mood is contingent on the regularity of sleep–wake behavior, whereas daytime light relates to depressive symptoms through mechanisms that extend beyond sleep timing and regularity.

This study moves beyond prior work^{24,29,40,41} by jointly characterizing multiple dimensions of the daily light environment, including illuminance, timing, and rhythmic organization, rather than examining single parameters in isolation. Although a previous NHANES analysis reported associations between depressive symptoms and canonical rhythm metrics (i.e., IS, IV and RA),²⁵ the present study demonstrates that these associations are not independent of one another, and that when parameters are examined simultaneously and sleep regularity is accounted for, daytime illuminance emerges as the most robust independent correlate of depressive symptoms. The associations of light rhythm stability and late-night illuminance with depressive symptoms were largely explained by sleep regularity, suggesting that previously reported links between rhythmic light disruption and mood may reflect shared variance with sleep–wake regularity rather than independent effects of the light environment itself.

A key novel finding is that sleep regularity plays a central role in these associations. Although chronotype (reflecting an individual's biological circadian phase) was modeled as an upstream mediator, sleep regularity emerged as the more proximal and behaviorally relevant pathway: it accounted for the majority of associations involving late-night illuminance and IS (62% and 73%, respectively), with direct effects becoming non-significant for both, while chronotype alone explained little of the total effect. In contrast, daytime illuminance retained a direct association with depressive symptoms, with sleep regularity accounting for less than half of its total effect (46%). This pattern suggests that circadian misalignment – reflected in irregular sleep–wake timing rather than circadian phase *per se* – may be the primary mechanism through which nighttime and unstable rhythms of light exposure influences mood,^{42,43} whereas daytime light exerts both indirect^{44,45} and direct effects.⁴⁶ These findings are consistent with neurobiological models in which light influences mood through circadian regulation as well as through pathways independent of sleep–wake timing.^{16–18,47,48}

The clustering analysis provided convergent ecological validation of the parameter-level findings from multivariable models. Profiles characterized by high daytime light, low nighttime light, and stable light rhythms (Cluster 1) showed the lowest prevalence of clinically significant depressive symptoms, whereas profiles with low daytime light and/or high nighttime light showed substantially higher prevalence. Cluster 3, defined by high nighttime illuminance, low daytime illuminance, and low IS, had the latest chronotype, the lowest sleep regularity, and a higher prevalence of PHQ-9 ≥ 10 (13%) compared to Cluster 1 (6.7%). This profile is consistent with later chronotypes in which late and irregular light exposure disrupts sleep–wake regularity, representing individuals who are particularly prone to circadian disruption and unable to maintain stable sleep–wake schedules.^{49,50} Concordant with mediation analyses showing that SRI accounts for 99% of the association between late-night illuminance and PHQ-9, the elevated depressive symptom burden in this cluster may operate through mechanisms of circadian disruption. Cluster 2 did not exhibit the high daytime illuminance and light stability that characterized Cluster 1, and showed comparably elevated depressive symptom prevalence to Cluster 3, suggesting that the favorable depressive symptom profile observed in Cluster 1 may be specifically tied to robust daytime light exposure rather than to nighttime light avoidance alone.

Strengths of this study include the use of a large, population-representative sample and objective, high-resolution measures of light exposure across multiple dimensions in real-world settings. Significant disparities in ethnicity, sex, and employment status were found across clustering analyses, suggesting the influence of social structures in environmental light exposure and presenting an important line for further inquiry.^{11,51,52} Limitations include light exposure and sleep were assessed over a limited observation window and may not reflect long-term or seasonal patterns. Moreover, cross-sectional data collection does not allow for causality assertions. Finally, SRI captures the behavioral regularity of sleep–wake timing, and it is suggested as a proxy for circadian disruption.⁵³ However, it does not directly index endogenous circadian phase or amplitude; whether the observed associations reflect underlying circadian disruption beyond sleep behavior cannot be determined from these data.

In summary, daytime illuminance is directly and independently associated with depressive symptoms, while the associations of nighttime light exposure and light rhythm instability with depressive symptoms are largely accounted for by sleep regularity. These results suggest that nighttime light represents an environmental risk factor for depressive symptoms and this association primarily represents a marker of irregular sleep–wake behavior. This study unveils a reframing with direct implications for how prior findings in this area may be interpreted. Future epidemiological studies examining light exposure and depression would be strengthened by accounting for behavioural components like sleep regularity to avoid misattributing its explanatory role to light parameters. These findings position daytime light exposure and sleep regularity as independent and complementary targets through which the light environment and sleep behaviour impact mental health, and support a reorientation of research and public health efforts toward promoting sufficient daytime light alongside stable sleep rhythms.

Declarations

6. Data Availability

The data that support the findings of this study are publicly available from the National Health and Nutrition Examination Survey (NHANES), maintained by the National Center for Health Statistics (NCHS), and can be accessed at <https://www.cdc.gov/nchs/nhanes>.

7. Code Availability

All code used for analysis is available upon request.

8. Acknowledgments

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9. Author contributions

Authors A.C.T. and F.Q. contributed equally in all aspects of this study and share first authorship. A.N, D.B.C. M.P.H and. L.K.P. contributed to developing and defining the light exposure metrics, as well as advising on the analytical framework. J.R. contributed to conducting the cluster analysis. A.N. and R.U. contributed to the development and revision of the statistical methods. B.N.F. contributed to the conceptual development and refinement of the study. All authors reviewed the manuscript and provided helpful comments.

10. Competing Interests

The authors report no conflicts of interest.

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Tables

Table 1. Sample Demographics, Sleep and Light Metrics.	
Characteristic	N = 5,757
Age (Years)	53 [37, 66]
Gender	
Female	2,920 (51%)
Male	2,837 (49%)
Ethnicity	
Mexican-American	651 (11%)
Non-Hispanic Asian	583 (10%)
Non-Hispanic Black	1,370 (24%)
Non-Hispanic White	2,459 (43%)
Other Hispanic	532 (9.2%)
Other Race - Including Multiracial	162 (2.8%)
Education Level	
Less Than 9th Grade	463 (8.0%)
9-11th Grade	768 (13%)
High School Equivalent	1,290 (22%)
Some College or AA Degree	1,763 (31%)
College Graduate or Above	1,473 (26%)
Employment Status	
Not Employed	2,774 (48%)
Currently Employed	2,983 (52%)
Lifetime Concern of Ever Having Sleeping Trouble	
No	4,235 (74%)
Yes	1,521 (26%)
BMI (kg/m2)	28 [24, 33]
Season	
May to October	2,950 (51%)
November to April	2,807 (49%)

MSFsc (Chronotype, Hour of Day)	3.49 [2.41, 4.86]
PHQ-9 Total Score	2.0 [0.0, 4.0]
PHQ-9 ≥ 10	
No	5,220 (91%)
Yes	537 (9.3%)
Sleep Regularity Index	84 [78, 88]
Daytime Duration of Light Exposure over 1000 Lx (Minutes)	27 [10, 56]
Early Night Duration of Light Exposure over 0 Lx (Minutes)	24 [8, 54]
Late Night Duration of Light Exposure over 0 Lx (Minutes)	0 [0, 5]
Daytime illuminance of Light Exposure ($\log(Lx + 1)$)	1.21 [0.85, 1.56]
Early Night illuminance of Light Exposure ($\log(Lx + 1)$)	0.28 [0.13, 0.51]
Late Night illuminance of Light Exposure ($\log(Lx + 1)$)	0.02 [0.00, 0.07]
Onset of Exposure > 1000 Lx (Hour of Day)	11:25 [10:13, 12:44]
Last Exposure > 10 Lx (Hour of Day)	21:54 [20:21, 23:21]
Lx IS	0.64 [0.52, 0.74]
Lx IV	0.52 [0.40, 0.67]
Continuous variables are represented as median [IQR]. Categorical variables are represented as number of observations and (% of the total). Due to problems with collinearity, the levels of the Ethnicity group were collapsed such that participants reporting their ethnicity as "Non-Hispanic Asian" were grouped together with those reporting "Other Race - Including Multiracial." IS: interdaily stability; IV: intradaily variability; Lx: lux; MSFsc: Mid-Sleep on Free days, Sleep-Corrected, proxy of chronotype; PHQ-9: Patient Health Questionnaire-9.	

Table 2. Summary Demographics, by Cluster					
Characteristic	1, N = 2900	2, N = 2638	3, N = 219	<i>P</i>	<i>P_{adj}</i>
Age (Years)	51 [39, 63]	50 [34, 64]	50 [31, 61]	0.008	0.017
Gender				<0.001	<0.001
Female	1,385 (48%)	1,434 (54%)	101 (46%)		
Male	1,515 (52%)	1,204 (46%)	118 (54%)		
Ethnicity				<0.001	<0.001
Mexican-American	365 (13%)	267 (10%)	19 (8.7%)		
Non-Hispanic Black	556 (19%)	741 (28%)	73 (33%)		
Non-Hispanic White	1,380 (48%)	994 (38%)	85 (39%)		
Other Hispanic	268 (9.2%)	251 (9.5%)	13 (5.9%)		
Other Race - Including Multiracial	331 (11%)	385 (15%)	29 (13%)		
Education Level				0.4	0.4
9-11th Grade	385 (13%)	356 (13%)	27 (12%)		
College Graduate or Above	759 (26%)	653 (25%)	61 (28%)		
High School Equivalent	672 (23%)	568 (22%)	50 (23%)		
Less Than 9th Grade	251 (8.7%)	203 (7.7%)	9 (4.1%)		
Some College or AA Degree	833 (29%)	858 (33%)	72 (33%)		
Employment Status				<0.001	<0.001
No	1,258 (43%)	1,433 (54%)	83 (38%)		
Yes	1,642 (57%)	1,205 (46%)	136 (62%)		
Lifetime Concern of Sleeping Trouble				0.003	0.004
No	2,215 (76%)	1,860 (71%)	160 (73%)		
Yes	685 (24%)	777 (29%)	59 (27%)		
BMI	28 [25, 32]	28 [24, 33]	29 [25, 34]	0.2	0.4

Quasi-Season				<0.001	<0.001
May to October	1,626 (56%)	1,207 (46%)	117 (53%)		
November to April	1,274 (44%)	1,431 (54%)	102 (47%)		
MSFsc (Chronotype, Hour of Day)	3.14 [2.26, 4.17]	3.70 [2.50, 5.22]	5.69 [3.85, 7.40]	<0.001	<0.001
PHQ 9 Total Score	1.0 [0.0, 3.0]	2.0 [0.0, 5.0]	2.0 [0.0, 6.0]	<0.001	<0.001
PHQ 9 $\geq$ 10				<0.001	<0.001
No	2,706 (93%)	2,324 (88%)	190 (87%)		
Yes	194 (6.7%)	314 (12%)	29 (13%)		
Sleep Regularity Index	87 [83, 90]	82 [76, 87]	78 [73, 85]	<0.001	<0.001
Daytime Duration of Light Exposure over 1000 Lx	49 [26, 91]	13 [5, 28]	31 [9, 54]	<0.001	<0.001
Early Night Duration of Light Exposure over 0 Lx (Minutes)	32 [13, 62]	18 [6, 42]	93 [55, 155]	<0.001	<0.001
Late Night Duration of Light Exposure over 0 Lx (Minutes)	0 [0, 3]	0 [0, 5]	70 [55, 100]	<0.001	<0.001
Daytime Illuminance of Light Exposure ^a	1.57 [1.36, 1.82]	0.84 [0.63, 1.04]	1.16 [0.91, 1.46]	<0.001	<0.001
Early Night Illuminance of Light Exposure (log(Lx + 1))	0.34 [0.18, 0.56]	0.23 [0.11, 0.42]	0.80 [0.53, 1.22]	<0.001	<0.001
Late Night Illuminance of Light Exposure (log(Lx + 1)) ^a	0.01 [0.00, 0.04]	0.02 [0.00, 0.07]	0.60 [0.49, 0.82]	<0.001	<0.001
Onset of Exposure > 1000 Lx (Hour of Day)	10.86 [9.77, 11.92]	12.22 [11.07, 13.41]	12.16 [10.63, 13.39]	<0.001	<0.001
Last Exposure > 10 Lx (Hour of Day)	-1.96 [-3.16, -0.94]	-2.35 [-4.10, -0.79]	2.08 [1.47, 3.26]	<0.001	<0.001
Lx IS ^a	0.74 [0.68, 0.80]	0.52 [0.44, 0.59]	0.50 [0.36, 0.62]	<0.001	<0.001
Lx IV	0.42 [0.34, 0.51]	0.65 [0.52, 0.80]	0.59 [0.48, 0.74]	<0.001	<0.001

Continuous variables are represented as median [IQR]. Categorical variables are represented as the number of observations and (% of the total). *P* values were calculated using the Kruskal-Wallis test for

continuous variables, and a Pearson's Chi-Squared test with the Rao & Scott adjustment for categorical variables. *P* values were corrected for the false discovery rate. IS: interdaily stability; IV: intradaily variability; Lx: lux; MSFsc: Mid-Sleep on Free days, Sleep-Corrected, proxy of chronotype; PHQ-9: Patient Health Questionnaire-9.

^a Variables used to cluster study participants.

Figures

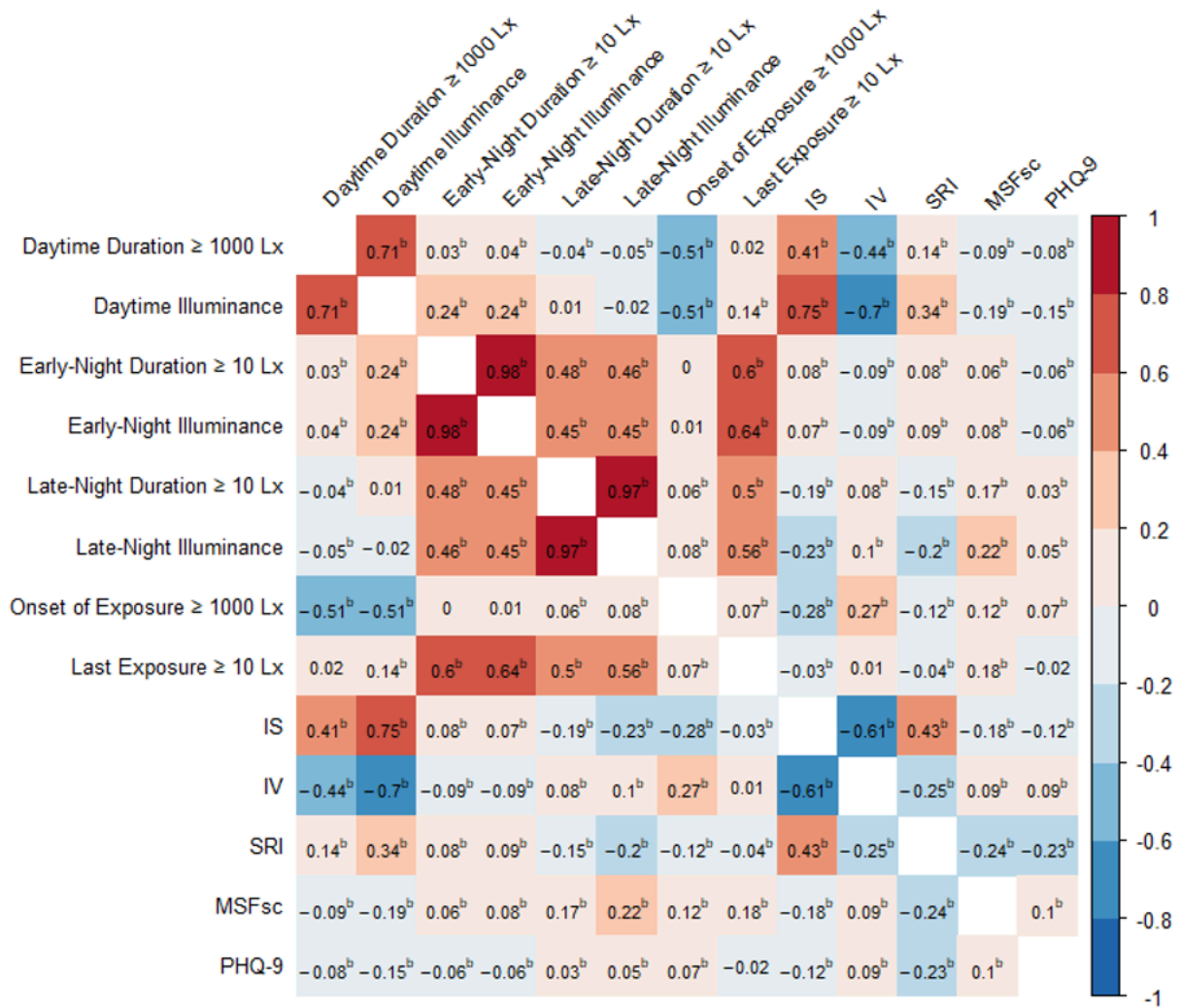


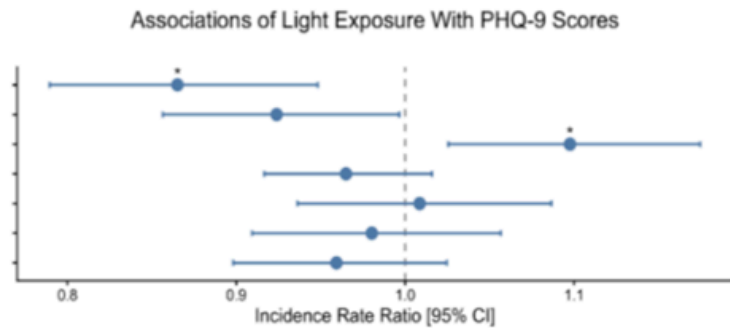
Figure 1

Correlation matrix of light exposure metrics. IS: interdaily stability; IV: intradaily variability; Lx: lux; MSFsc: Mid-Sleep on Free days, Sleep-Corrected, proxy of chronotype; PHQ-9: Patient Health Questionnaire-9; SRI: Sleep Regularity Index. *P* < .05 is denoted by ^a, and *P*_{adj} < .05 by ^b.

A

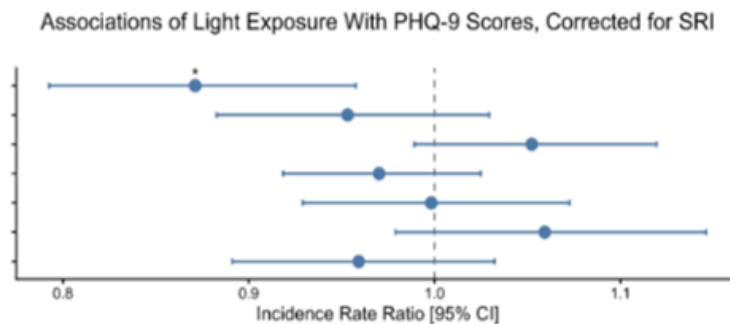
Light Variable	IRR	Confidence Interval	P (Adjusted)
Daytime Illuminance	0.87	0.79, 0.95	0.01
Early-Night Illuminance	0.92	0.86, 1.00	0.09
Late-Night Illuminance	1.10	1.03, 1.17	0.03
Onset of Exposure ≥ 1000 Lx	0.97	0.92, 1.02	0.30
Last Exposure ≥ 10 Lx	1.01	0.94, 1.09	0.82
Lx IS	0.98	0.91, 1.06	0.70
Lx IV	0.96	0.90, 1.02	0.30

P Values Adjusted for the False Discovery Rate



Light Variable	IRR	Confidence Interval	P (Adjusted)
Daytime Illuminance	0.87	0.79, 0.96	0.03
Early-Night Illuminance	0.95	0.88, 1.03	0.33
Late-Night Illuminance	1.05	0.99, 1.12	0.33
Onset of Exposure ≥ 1000 Lx	0.97	0.92, 1.02	0.33
Last Exposure ≥ 10 Lx	1.00	0.93, 1.07	0.96
Lx IS	1.06	0.98, 1.15	0.33
Lx IV	0.96	0.89, 1.03	0.33

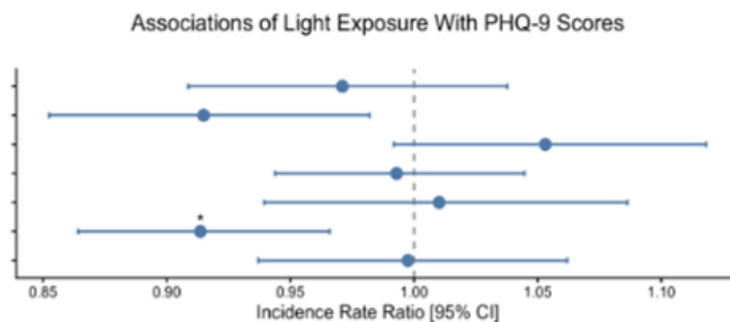
P Values Adjusted for the False Discovery Rate



B

Light Variable	IRR	Confidence Interval	P (Adjusted)
Daytime Duration ≥ 1000 Lx	0.97	0.91, 1.04	0.68
Early-Night Duration ≥ 10 Lx	0.91	0.85, 0.98	0.05
Late-Night Duration ≥ 10 Lx	1.05	0.99, 1.12	0.21
Onset of Exposure ≥ 1000 Lx	0.99	0.94, 1.04	0.92
Last Exposure ≥ 10 Lx	1.01	0.94, 1.09	0.92
Lx IS	0.91	0.86, 0.97	0.01
Lx IV	1.00	0.94, 1.06	0.94

P Values Adjusted for the False Discovery Rate



Light Variable	IRR	Confidence Interval	P (Adjusted)
Daytime Duration ≥ 1000 Lx	0.97	0.90, 1.04	0.94
Early-Night Duration ≥ 10 Lx	0.94	0.88, 1.01	0.53
Late-Night Duration ≥ 10 Lx	1.02	0.97, 1.09	0.94
Onset of Exposure ≥ 1000 Lx	1.00	0.94, 1.05	0.94
Last Exposure ≥ 10 Lx	1.00	0.93, 1.07	0.94
Lx IS	1.00	0.94, 1.06	0.94
Lx IV	0.99	0.93, 1.06	0.94

P Values Adjusted for the False Discovery Rate

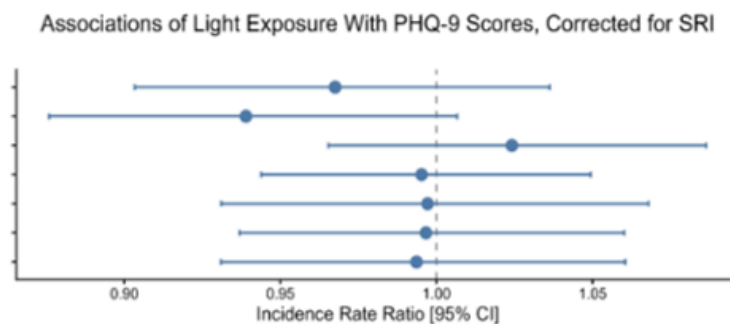


Figure 2

Multivariable models of light variables and PHQ-9 scores, with and without accounting for SRI. Coefficients are expressed in Incidence Rate Ratios (IRR), which are obtained from exponentiating the raw coefficients from the negative binomial models. A 1 SD change in light parameter is associated with a multiplicative change of the IRR on PHQ-9 scores. **A.** Shows the multivariable model including measures of illuminance, timing and regularity. **B.** Shows the multivariable model including measures of light exposure duration, timing and regularity. P-values were adjusted for the False Discovery Rate. IS:

interdaily stability; IV: intradaily variability; Lx: lux; RA: relative amplitude. All models were fully adjusted for all covariates.

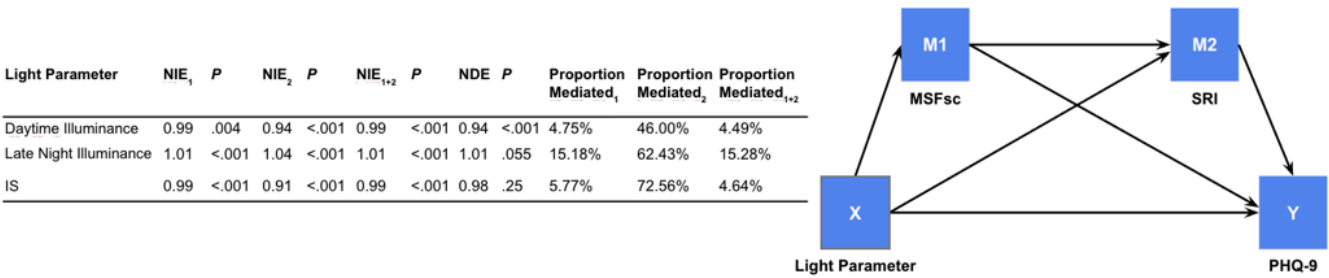


Figure 3

Mediation models. IS: Interdaily Stability; NDE: natural direct effect; NIE₁: natural indirect effect via chronotype; NIE₂: natural indirect effect via SRI; NIE₁₊₂: natural indirect effect via chronotype, then SRI. MSFsc: Mid-Sleep on Free days, Sleep-Corrected, proxy of chronotype; PHQ-9: Patient Health Questionnaire; SRI: Sleep Regularity Index.

Supplementary Files

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