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Original article

History of COVID-19 and Circadian Light Hygiene in Young Adults

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Abstract: Background — The COVID-19 pandemic disrupted sleep and circadian rhythms, but the specific effects of prior infection on the body's response to light for circadian regulation remain unclear. This study builds on previous research examining COVID-19 status and susceptibility to daylight by investigating seasonal variations in light hygiene and sleep parameters among young adults.

Methods — We enrolled 187 medical students (mean age, 19.03±1.63 years; 132 females) from Tyumen, Russia. Participants wore *ActTrust2* actigraphy devices with RGB light sensors for 1 week in spring (April-May; $n=95$) or autumn (October-November; $n=92$). We quantified circadian light hygiene using parametric and nonparametric measures, along with the normalized circadian amplitude of blue light exposure (NA BLE). Participants were grouped by COVID-19 infection history. We analyzed data with multiple linear regression and two-way ANOVA.

Results — COVID-19-negative individuals had significantly higher daytime light exposure than COVID-19-positive individuals. Season and NA BLE were significant predictors of sleep parameters, with spring associated with shorter sleep duration and earlier bedtime compared with autumn. Higher NA BLE correlated with longer sleep duration, earlier bedtime, and greater relative amplitude of activity. Two-way ANOVA showed significant interactions between COVID-19 status and NA BLE for bedtime ($p=0.021$) and total sleep duration ($p=0.019$). These results indicate that prior COVID-19 infection modulates the association between light hygiene and sleep timing.

Conclusions — Prior COVID-19 infection is linked to reduced daylight exposure and alters circadian sensitivity to light, affecting sleep timing and quality in young adults. These findings support considering COVID-19 history when developing light-based circadian interventions.

Keywords: COVID-19, circadian rhythms, light exposure, sleep duration, bedtime, young adults, actigraphy, blue light, seasonal effects.

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Introduction

The COVID-19 pandemic profoundly disrupted human physiology, including sleep, circadian rhythms, and light exposure patterns. Emerging evidence connects individual circadian differences to SARS-CoV-2 infection susceptibility and complications [1-6]. Sleep disorders often persist after recovery, raising long COVID risks, and circadian misalignment worsens these outcomes [6-9]. Light exposure – particularly blue light for circadian regulation and UVB for vitamin D synthesis and antiviral immunity – plays a crucial role in health [10-15]. Circadian light hygiene, which involves optimizing 24-hour light dynamics to align with natural sleep-wake cycles, is undermined by evening or nighttime overexposure, insufficient daylight, or irregular patterns. Such disruptions impair rhythms and immunity [13-14, 16-17]. In contrast, strong rhythms foster longevity and infection resistance

[18-19], whereas misalignment from shift work, chronotype, or social jetlag (>2 hours) heightens viral risks [20-21]. Daytime outdoor light exposure improves sleep and well-being while potentially lowering infection risks and boosting antibody responses to vaccination [1, 22-23]. Vaccination efficacy also varies by circadian phase, enhanced by adequate sleep but reduced by deprivation, which may compromise long COVID protection [24]. Actigraphy objectively measures activity, sleep, circadian robustness, and light exposure [14, 25]. Recent advances include the normalized amplitude of blue light exposure (NA BLE) as a standardized metric for circadian light hygiene. This measure accounts for interindividual variability in absolute values, facilitating comparisons and serving as a potential biomarker for circadian health. NA BLE associates with sleep parameters such as duration, bedtime, wake time, and activity rhythm amplitude,

influenced by health status. For example, COVID-19-positive individuals show greater vulnerability [15], with lower NA BLE tied to delayed sleep, reduced activity amplitude, and weaker circadian robustness-effects less pronounced in COVID-19-negative individuals [6]. This study used week-long actigraphy in Tyumen residents (57°N, 65°E) to evaluate NA BLE's predictive value for sleep and circadian parameters in young adults across two seasons, adjusting for COVID-19 history, sex, age, and body mass index (BMI).

Material and Methods

This cross-sectional study followed the Declaration of Helsinki and received approval from the Ethics Committee of Tyumen State Medical University (*protocol no. 115, June 30, 2023*). All participants provided written informed consent.

Participants and Data Collection

We recruited 187 young adults (mean age, 19.03±1.63 years; 132 females) for this observational study. Most were medical students from Tyumen with no history of acute or severe chronic mental or somatic diseases. Data collection occurred in two periods: May ($n=95$; 66 females) and November ($n=92$; 66 females). Participants wore *ActTrust2* actigraphy devices with red-green-blue (RGB) light sensors for one week to measure circadian light hygiene and sleep parameters [13-14, 25]. We grouped participants by COVID-19 history: 100 with prior infection (COVID-19-positive; diagnosed ≥2 months before enrollment; all recovered and employed) and 87 without (COVID-19-negative). The groups did not differ significantly in sex, BMI, or vaccination status. We collected data during nonacademic periods to reduce influences from schedules and exams. The similar mean age and sex distribution between COVID-19-positive and -negative groups, both overall and by season, minimized the potential for season-specific factors (*e.g.*, social jetlag) to differentially affect circadian rhythm variations.

Actigraphy Measurements

Participants wore the *ActTrust2* monitor (*Condor Instruments*; São Paulo, Brazil) on their nondominant wrist for seven consecutive days in either autumn (October–November) or spring (April–May). The device recorded light exposure (LE; in lx) and blue light exposure (BLE; in $\mu\text{W}/\text{cm}^2$) at 1-minute intervals. For LE, BLE, and physical activity (PA), we calculated circadian parameters (MESOR, 24-hour amplitude, acrophase) and nonparametric indices, including M10 (most active 10-hour period), M10 onset, L5 (least active 5-hour period), L5 onset, and relative amplitude ($\text{RA}=[\text{M10} - \text{L5}]/[\text{M10} + \text{L5}]$). To evaluate circadian light hygiene, we computed the normalized amplitude (24-hour amplitude relative to MESOR) [13-14] for BLE, which outperformed the amplitude of log-transformed BLE, as reported elsewhere [1].

Statistical Analysis

We used linear regression to assess associations between COVID-19 status and actigraphy variables, adjusting for sex, age, and BMI. Significant predictors entered multiple regression models. Analyses were performed with *LibreOffice Calc*, *STATISTICA 6*, and *SPSS version 23.0*. We assessed normality with the Shapiro–Wilk test; for normally distributed data, we applied ANOVA, and for nonnormal data, Mann–Whitney *U* or Kruskal–

Wallis tests. Significance was set at $p < 0.05$, and Benjamini–Hochberg false discovery rate (FDR) correction ($\text{FDR} \geq 0.1$) was applied for multiple comparisons. We compared correlation strengths statistically using the *cocor* package in R [26] to evaluate differences between coefficients, whether variables overlapped or not.

Results

Circadian Light Exposure by COVID-19 Status

Comparisons of circadian light exposure metrics between COVID-19-positive and -negative groups showed significant differences in several parameters ([Table 1](#)). COVID-19-negative individuals had higher LE amplitude (83.74 ± 69.33 lx vs. 60.37 ± 60.70 lx; $p=0.001$) and LE MESOR (63.41 ± 45.28 lx vs. 48.13 ± 38.19 lx; $p=0.002$) than COVID-19-positive individuals. Similarly, BLE amplitude (13.33 ± 12.10 vs. 9.41 ± 10.15 $\mu\text{W}/\text{cm}^2$; $p=0.002$), BLE M10 (18.63 ± 15.44 vs. 13.74 ± 13.06 $\mu\text{W}/\text{cm}^2$; $p=0.005$), and BLE MESOR (9.09 ± 7.60 vs. 6.91 ± 6.39 $\mu\text{W}/\text{cm}^2$; $p=0.009$) were higher in the COVID-19-negative group. No significant differences were found in BLE M10 onset, NA BLE, BLE L5, LE acrophase, BLE L5 onset, or BLE relative amplitude. These results suggest that COVID-19-negative participants experienced greater daytime light intensity, particularly blue light. Significant differences were observed in both men and women, with no significant interaction between COVID-19 status and sex (two-way ANOVA; all $p>0.05$).

Associations of the Normalized Amplitude of Blue Light Exposure (NA BLE) With Sleep Parameters

The normalized circadian amplitude of blue light exposure (NA BLE) showed differential associations with sleep parameters by COVID-19 status. In COVID-19-positive participants, higher NA BLE correlated with earlier bedtime ($r=-0.476$; $p<0.001$), but no association was seen in COVID-19-negative individuals ($r=0.019$; $p=0.866$); the difference in correlation coefficients was significant (Fisher $z=-3.602$; $p=0.0003$). For relative amplitude of physical activity (RA), a measure of circadian robustness, NA BLE correlated positively in COVID-19-positive participants ($r=0.222$; $p=0.026$) but not in COVID-19-negative individuals ($r=-0.090$; $p=0.411$); the coefficients differed significantly (Fisher $z=2.212$; $p=0.034$). Total sleep time (TST) also varied with NA BLE by COVID-19 status, with a significant difference in correlation strength (Fisher $z=2.294$; $p=0.022$). No significant difference by COVID-19 status was found for the correlation between wake time and NA BLE. [Figure 1](#) illustrates key relationships between light exposure metrics, sleep parameters, and COVID-19 status, as described above.

Multiple Regression Analyses of Sleep and Circadian Parameters

Multiple linear regression models identified key predictors of sleep parameters, showing that relationships between light hygiene, sleep, and circadian metrics varied significantly by COVID-19 status ([Table 2](#)). Total sleep duration (TST) was shorter in spring than autumn for both COVID-19-positive ($\beta=-0.486$; $p<0.001$; $\eta^2=0.222$) and -negative ($\beta=-0.398$; $p<0.001$; $\eta^2=0.147$) groups. TST was longer in COVID-19-positive individuals with higher NA BLE ($\beta=0.286$; $p=0.003$; $\eta^2=0.090$), an effect not seen in the negative group. Sex, age, and BMI had minimal influence. Higher NA BLE

was associated with earlier bedtime only in the COVID-19-positive group ($\beta=-0.401$; $p<0.001$; $\eta^2=0.170$). Spring linked to earlier bedtimes in both groups (COVID-19-positive: $\beta=-0.271$; $p=0.008$; $\eta^2=0.085$; COVID-19-negative: $\beta=-0.242$; $p=0.026$; $\eta^2=0.062$). Men in the COVID-19-negative group had later bedtimes ($\beta=0.302$; $p=0.006$; $\eta^2=0.092$). Wake time was influenced primarily by season, occurring earlier in spring than autumn in both groups, with no significant NA BLE effect. Relative amplitude (RA) of physical activity (PA) was negatively associated with season in both COVID-19-positive ($\beta=-0.450$; $p<0.001$; $\eta^2=0.194$) and -negative ($\beta=-0.518$; $p<0.001$; $\eta^2=0.224$) groups, with smaller amplitudes in

spring than autumn. In the COVID-19-positive group only, higher RA was coupled with higher NA BLE ($\beta=0.366$; $p<0.001$; $\eta^2=0.138$).

Interaction Effects

Two-way ANOVA revealed significant interactions between COVID-19 status (positive vs. negative) and NA BLE status (large >1 vs. small <1) on bedtime ($F=5.547$; $p=0.021$) and total sleep duration ($F=5.645$; $p=0.019$), indicating that COVID-19 history moderates the relationship between light hygiene and these sleep outcomes.

Table 1. Comparison of circadian light exposure measures between COVID-19-positive and -negative groups

Variable	COVID-Positive Mean (SD)	COVID-Negative Mean (SD)	Z-value	p-value (Mann-Whitney U Test)
LE Amplitude (lx)	60.37 (60.70)	83.74 (69.33)	3.31	0.001
LE MESOR (lx)	48.13 (38.19)	63.41 (45.28)	3.12	0.002
BLE Amplitude ($\mu W/cm^2$)	9.41 (10.15)	13.33 (12.10)	3.04	0.002
BLE M10 ($\mu W/cm^2$)	13.74 (13.06)	18.63 (15.44)	2.83	0.005
BLE MESOR ($\mu W/cm^2$)	6.91 (6.39)	9.09 (7.60)	2.60	0.009
BLE M10 Onset (hours:minutes)	8:24 (1:12)	8:10 (1:26)	1.94	0.053
NA BLE	1.25 (0.38)	1.34 (0.30)	1.57	0.116
BLE L5 ($\mu W/cm^2$)	0.18 (0.26)	0.27 (0.39)	1.49	0.137
LE acrophase (hours:minutes)	13:12 (2:53)	13:41 (1:55)	0.89	0.375
BLE acrophase (hours:minutes)	13:12 (2:10)	13:26 (1:12)	0.79	0.430
BLE L5 Onset (hours:minutes)	3:07 (2:38)	3:07 (2:10)	0.59	0.552
BLE Relative Amplitude	0.96 (0.05)	0.97 (0.04)	0.03	0.977

Variables are ordered by z-value. LE, Light Exposure, lx; BLE, Blue Light Exposure, $\mu W/cm^2$. M10, the 10-hour period of maximum exposure; M10 onset, the onset time of the 10-hour period of maximum exposure; L5, the least 5-hour exposure period; L5 onset, the onset time of the least 5-hour exposure period. MESOR, Midline Estimating Statistic of Rhythm. Significant differences ($p<0.05$) from the Mann-Whitney U test, confirmed after Benjamini-Hochberg false discovery rate (FDR) correction for multiple testing at $FDR=0.1$, are marked in **bold**.

Table 2. Multiple linear regression results for predictors of sleep parameters (total sleep duration, bedtime, wake time, and relative amplitude of physical activity)

Variable	COVID-Positive Group			COVID-Negative Group		
	β (95% CI)	p-value	η^2	β (95% CI)	p-value	η^2
Total Sleep Duration						
SEASON (SPR)	-0.486 (-0.673, -0.299)	<0.001	0.222	-0.398 (-0.613, -0.182)	<0.001	0.147
NA BLE	0.286 (0.100, 0.472)	0.003	0.090	-0.084 (-0.300, 0.132)	0.442	0.008
Sex (m)	0.150 (-0.026, 0.326)	0.094	0.030	-0.090 (-0.301, 0.122)	0.401	0.009
Age	0.106 (-0.075, 0.148)	0.247	0.014	0.013 (-0.200, 0.226)	0.903	0.001
BMI	-0.027 (-0.202, 0.148)	0.759	0.001	0.031 (-0.174, 0.236)	0.763	0.001
Bedtime						
NA BLE	-0.401 (-0.585, -0.218)	<0.001	0.170	-0.028 (-0.232, 0.177)	0.988	<0.001
SEASON (SPR)	-0.271 (-0.456, -0.087)	0.008	0.085	-0.242 (-0.458, -0.026)	0.026	0.062
BMI	0.141 (-0.032, 0.313)	0.108	0.028	0.081 (-0.136, 0.298)	0.200	0.021
Sex (m)	0.056 (-0.117, 0.230)	0.517	0.005	0.302 (0.088, 0.516)	0.006	0.092
Age	0.002 (-0.176, 0.179)	0.986	0.001	0.052 (-0.179, 0.283)	0.939	<0.001
Wake Time						
SEASON (SPR)	-0.618 (-0.784, -0.452)	<0.001	0.372	-0.518 (-0.711, -0.324)	<0.001	0.264
BMI	0.090 (-0.066, 0.247)	0.254	0.014	0.131 (-0.052, 0.314)	0.158	0.025
Sex (m)	0.055 (-0.102, 0.212)	0.491	0.005	0.087 (-0.101, 0.276)	0.359	0.011
NA BLE	-0.054 (-0.220, 0.112)	0.523	0.004	-0.165 (-0.360, 0.030)	0.095	0.035
Age	0.077 (-0.083, 0.238)	0.339	0.001	0.001 (-0.189, 0.191)	0.993	<0.001
Relative Amplitude of Physical Activity						
SEASON (SPR)	-0.450 (-0.638, -0.263)	<0.001	0.194	-0.518 (-0.723, -0.314)	<0.001	0.224
NA BLE	0.366 (0.179, 0.552)	<0.001	0.138	0.138 (-0.056, 0.331)	0.162	0.022
Sex (m)	0.091 (-0.068, 0.249)	0.259	0.021	-0.175 (-0.363, 0.013)	0.067	0.038
BMI	-0.066 (-0.233, 0.101)	0.436	0.021	-0.050 (-0.254, 0.155)	0.629	0.003
Age	0.167 (-0.011, 0.345)	0.066	0.003	-0.101 (-0.319, 0.116)	0.357	0.010

The table presents regression coefficients (β), their 95% confidence intervals (CI), p-values, and effect sizes, estimated by partial eta-squared (η^2). Spring relates to shorter total sleep duration, earlier bedtime, wake time, and smaller relative amplitude of physical activity in both COVID-19-positive and COVID-19-negative groups. Later bedtime in male COVID-19-negative participants is evident. Exclusively in the COVID-19-positive group, a larger NA BLE is associated with a larger relative amplitude of physical activity and longer total sleep duration due to earlier bedtime. However, there is no association with wake time.

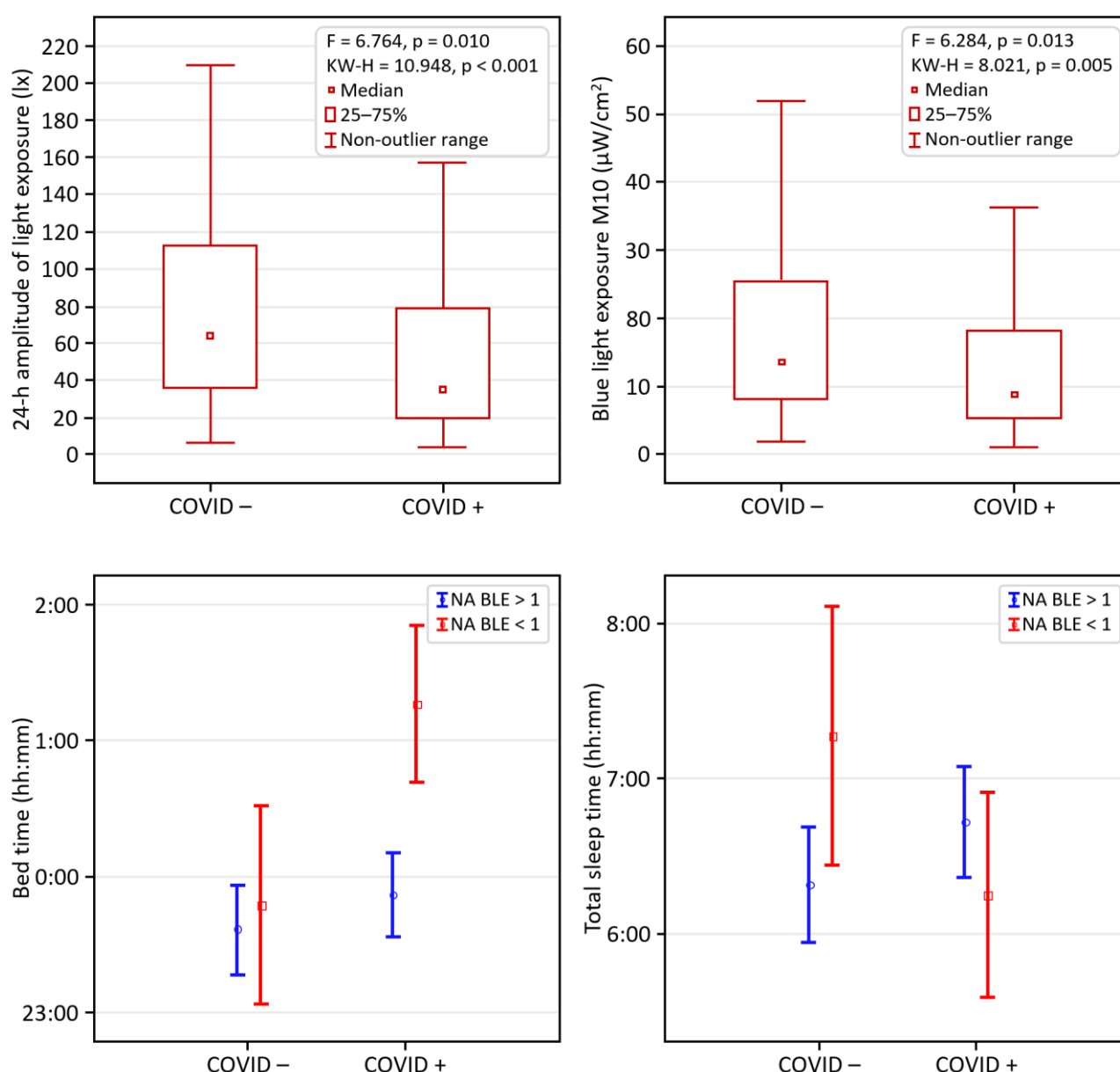


Figure 1. Associations of Light Exposure Metrics and Sleep Parameters With COVID-19 Status.

Upper Row: Larger 24-hour light exposure amplitude (left) and greater M10 of blue light exposure (BLE) (right) are associated with a COVID-19-free status. Lower Row: Means and 95% confidence intervals are depicted. A normalized amplitude of BLE (NA BLE) below 1 is associated with later bedtime in individuals who tested positive for COVID-19 (COVID-19-positive), $p < 0.0001$, but not in the COVID-19-free population, $p = 0.276$ (left). Total Sleep Time significantly interacts with NA BLE and COVID-19 status ($F = 5.645$, $p = 0.019$) (right).

Discussion

This study further elucidates the complex interplay between circadian light hygiene, seasonality, and COVID-19 history on sleep and circadian parameters. The normalized amplitude of blue light exposure (NA BLE) emerged as a key predictor of sleep timing and circadian robustness, especially in individuals with prior SARS-CoV-2 infection. Higher NA BLE linked to earlier bedtime and greater relative amplitude of activity rhythm in COVID-19-positive participants, associations absent in COVID-19-negative individuals. This differential susceptibility underscores COVID-19's moderating effect on circadian regulation and light sensitivity. Seasonality independently influenced sleep patterns, with spring associated

with shorter total sleep duration and earlier bedtime and wake time, reflecting natural photoperiod changes and social schedules. NA BLE retained predictive value beyond seasonal effects, emphasizing the importance of personalized circadian light hygiene irrespective of ambient conditions.

The observed interaction between COVID-19 status and NA BLE suggests that individuals recovering from COVID-19 may be more vulnerable to circadian disruptions from suboptimal light exposure. This finding aligns with prior reports of delayed circadian phase and reduced amplitude in COVID-19-positive individuals with poor light hygiene [6]. Our results extend these to a larger, seasonally diverse cohort. Mechanistically, robust

circadian rhythms support immune balance and epithelial barrier integrity, reducing susceptibility to viral infections, including COVID-19 [27-29]. Daylight exposure promotes circadian alignment and physical activity rhythms, while UVB radiation in sunlight inactivates viruses and boosts vitamin D synthesis for antiviral immunity [30-31]. Conversely, disrupted circadian rhythms and poor light hygiene impair melatonin production, immune function, and psychological well-being, heightening vulnerability to infection and post-COVID complications [6, 32–33].

Our data show that COVID-19-positive individuals with better circadian light hygiene (higher NA BLE) exhibit greater circadian robustness, earlier sleep timing, and stronger activity rhythms, suggesting benefits of optimized light exposure in this population. The heightened photosensitivity and altered visual processing reported in COVID-19 survivors may underlie their increased sensitivity to light hygiene [34-35]. The association between time since COVID-19 diagnosis and poorer circadian light hygiene raises questions about causality: whether preexisting poor light hygiene predisposes to infection or results from postinfection behavioral or physiological changes. Only COVID-19-positive individuals with low NA BLE showed related circadian and sleep alterations, indicating heterogeneity in susceptibility. Sex, age, and BMI had minimal effects on sleep parameters in this young, relatively homogeneous cohort, suggesting that light hygiene and COVID-19 history are stronger determinants of circadian health here. The significant moderation of light hygiene's impact by COVID-19 status points to potential disruptions in molecular pathways of circadian regulation. Light detected by retinal melanopsin (OPN4) and neuropsin (OPN5) signals to the suprachiasmatic nucleus (SCN), suppressing melatonin and entraining circadian rhythms [36]. Interindividual variability in this system [37] likely explains why season and NA BLE predict sleep parameters (e.g., longer sleep and higher circadian robustness with higher NA BLE). Light also affects metabolism [38-39] and immunity via the retina-SCN-brown adipose tissue axis [40], modulated by genetics [36]. Prior COVID-19 infection may compromise these pathways sensitivity [41]. Understanding these molecular alterations is crucial for developing targeted light-based interventions for post-COVID sleep disturbances. The NA BLE threshold of >1, validated in prior research [6, 14, 39] and supported by our critical, yet unpublished findings, serves as a clinically relevant indicator of favorable circadian, sleep, and metabolic profiles, including differences in COVID-19-positive individuals.

Strengths of this study include reliance on actigraphy for light exposure monitoring within specific seasons and geographic locations, minimizing confounding from environmental light variability.

Limitations include the observational, cross-sectional design, limiting causal inference; a relatively small sample limited to young adults; and lack of control for confounders such as preexisting conditions, medication use, diet, and stress. Additionally, COVID-19-positive status was self-reported, potentially introducing bias. The interplay with chronotype was not addressed here. Although chronotype has a genetic basis, studies (e.g., Leocadio-Miguel et al., 2021 [42]) report moderate heritability (0.28-0.37), highlighting exogenous factors. Environmental light, especially at dawn and dusk, drives sleep phase and chronotype shifts [43-46]. While subjective chronotype data were collected, analysis of its intricate relationship with environmental influences and sleep

patterns requires a dedicated future analysis in a separate publication.

Conclusion

This study underscores the pivotal role of circadian light hygiene, as quantified by Normalized Amplitude of Blue Light Exposure, in regulating sleep timing and circadian robustness in young adults. NA BLE's impact on sleep is modulated by COVID-19 history, with COVID-19-positive individuals showing reduced daylight exposure but heightened sensitivity to light patterns. Seasonal variation influences sleep but does not diminish the need for optimal light hygiene. These findings advocate for personalized circadian interventions, especially for those vulnerable to circadian disruption after SARS-CoV-2 infection. Promoting adequate daytime light exposure, particularly in the morning, may improve sleep health and overall circadian function postpandemic.

Conflict of Interest

The authors declare no conflicts of interest.

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Ethical Approval

All procedures performed in studies involving human participants complied with the ethical standards of the institutional or national research committee and with the 1964 Helsinki Declaration and its later amendments or comparable ethical standards.

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