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Characteristics of objectively-measured naturalistic light exposure patterns in U.S. adults: A cross-sectional analysis of two cohorts

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2025.178839.

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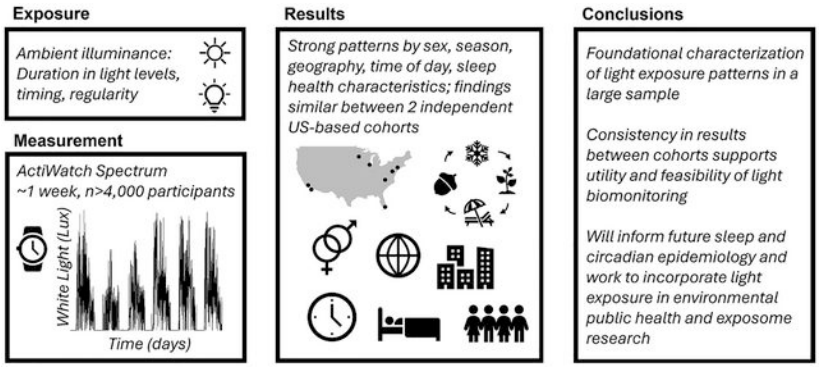
Abstract

Light is an environmental feature important for human physiology. Investigation of how light affects population health requires exposure assessment and personal biomonitoring efforts. Here, we derived measures of amount, duration, regularity, and timing from objective personal light (lux) measurement in >4000 participants across two United States (US)-based cohort studies, the Multi-Ethnic Study of Atherosclerosis (MESA) and the Hispanic Community Health Study / Study of Latinos (HCHS/SOL), encompassing eight geographic regions. Objective light and actigraphy data were collected over a week using wrist-worn devices (Actiwatch Spectrum). Cohort-stratified light exposure metrics were analyzed in relation to sex, season, time-of-day, location, and demographic and sleep health characteristics using Spearman correlation and linear and logistic regressions (separately by cohort) adjusted for age, sex (where applicable), and exam site. Light exposure showed sex-specific patterns and had seasonal, diurnal, geographic, and demographic and sleep health-related correlates. Results between independent cohorts were strongly consistent, supporting the utility and feasibility of light biomonitoring. These findings provide a fundamental first characterization of light exposure patterns in a large US sample and will inform future work to incorporate light as a biologically relevant exposure in environmental public health and key component of the human exposome.

Graphical Abstract



Keywords

Illumination; Seasonality; Chronobiology; Circadian; Sleep disorders; Photoperiod

1. Introduction

Light is a vital component of our environment, yet its relevance to human health is only beginning to be recognized. As life on Earth evolved, the ability to track and anticipate light cycles as a temporal marker was a biological advantage (Ouyang et al., 1998; Woelfle et al., 2004) out of which arose the circadian system, a molecular and physiological organization of internal “clocks”. While humans evolved in a natural setting of daylight, starlight, and moonlight, extensive development and engineering efforts over the past 100 years have led to widespread electrification and major changes in the modern light milieu. It is presumed that the availability of inexpensive electric lighting, coupled with lifestyle shifts that favor greater time indoors (Klepeis et al., 2001; Webler et al., 2019), have altered population-wide light exposure patterns.

Light is important for many aspects of health beyond vision. Light can exert health effects through pathways such as inducing synthesis of Vitamin D or through phototransduction, the process by which light (photons) elicits a conformational change in light-sensitive opsin proteins to convert light to a bioelectric signal (Bellingham and Foster, 2002; Shichida and Matsuyama, 2009). Once light enters the eye and interacts with retinal opsins, it causes a signaling cascade that leads to altered membrane potential of retinal neurons and downstream signaling (Berson et al., 2002; Shichida and Matsuyama, 2009). In addition to the classic photoreceptors (rods and cones), intrinsically photosensitive retinal ganglion cells (ipRGCs) represent a third class of photoreceptors that contribute to non-image forming vision (Provencio et al., 2000; Hattar et al., 2002). The dendrites of these ipRGCs create a “photoreceptive net” (Provencio et al., 2002) in the retina and project to the suprachiasmatic nucleus (SCN), a cluster of hypothalamic neurons adjacent to the optic chiasm that constitute the central clock, or pacemaker, for the body’s biological timing system (Gooley et al., 2001; Berson et al., 2002). A light stimulus is then relayed from the eye to the SCN, which can cause a phase shift in the timing of the central clock (Khalsa et al., 2003). In addition to the SCN, ipRGC subtypes are diverse and project to other brain regions related to outcomes such as mood, sleep, and learning (Aranda and Schmidt, 2021). Thus, light exposure is relevant to both visual and non-visual health.

The electric light environment differs in duration, amount, timing, and spectral distribution compared to the pre-electric light environment (Knoop et al., 2020). Electric illumination can provide a photoperiod, or daily ratio of light to dark exposure, that is longer than the one provided by the sun, effectively prolonging the “biological” day; similarly, exposure to dim indoor electric light can also prolong the “biological” night. Compared to the bright, full spectrum of light from the sun, indoor electric lighting is dimmer and can differ in spectral signature, emitting higher or lower amounts of energy at specific wavelengths, which may affect chronotype and behavior rhythms (Wright et al., 2013). Daylight, which refers to direct and indirect light from the sun, is also dynamic, with spectra changing over the course of the day (Knoop et al., 2020). Each of these dimensions (e.g., duration, amount, timing, wavelength, exposure history) of light exposure may influence human health, such as through entrainment of the circadian system or through other, non-circadian, mechanisms (Dumont and Beaulieu, 2007; Stephenson et al., 2012; Blume et al., 2019; Münch et al., 2020; Vetter et al., 2021). Continued work to understand the human health impacts of

daylight may seek to investigate current gaps in knowledge, such as the use of daylight as a therapeutic treatment or countermeasure (Münch et al., 2020; Figueiro et al., 2021; Amdisen et al., 2022). However, despite the relevance of daylight and electric light to human health, light exposure patterns in the general population are relatively unknown.

The human circadian system is also responsive to seasonal changes in light exposure (Stothard et al., 2017), but it is unclear whether seasonality affects modern light exposure patterns due to indoor living habits. For example, the reliance on electric lighting may lead to less dynamic light patterns that are dimmer during the day and brighter during the night, with little or no seasonal variation (Khodasevich et al., 2021). Another study compared light levels of adults living in San Diego, California ($n = 30$) and Rochester, Minnesota ($n = 24$) and reported significant seasonal variation (greater variation in Minnesota) in duration of time spent at different light intensities between the two locations (Cole et al., 1995). This finding may be expected, as photoperiod varies by season and latitude. Photoperiod alone has also been shown to alter melatonin production and duration, with shorter photoperiods (such as during winter when days are shorter and nights are longer) extending melatonin production (Wehr, 1991). Changing spectral distribution and light patterning (e.g., abrupt vs. gradual transitions from light to dark) have also been shown to affect the circadian system in mammals (Daan, 2000; Danilenko et al., 2000; Boulos et al., 2002; Dkhissi-Benyahya et al., 2007; Lall et al., 2010; Stefani et al., 2021). Temperature is another component that can influence light measurement or exposure through behavioral adaptations (e.g. wearing long-sleeved clothing that could obscure wrist-measured light or impacting the choice to spend time outdoors vs. indoors) and is also related to daylength and geographic characteristics. Sleep patterns may also be influenced by light exposure (Wams et al., 2017) (or vice versa). Light exposure can differ by age, sex, and occupation, or other characteristics (Heil and Mathis, 2002; Dumont and Beaulieu, 2007; Lee et al., 2020; Wallace, 2024); for example, the availability of natural lighting in a workspace (e.g., outdoors vs. indoors; proximity or availability of windows) (Hubalek et al., 2010; Figueiro and Rea, 2016; Figueiro et al., 2017, 2019; Peeters et al., 2021) and timing of work (e.g., day shift vs. night shift) can be occupational components that affect light exposure among working people (Boubekri et al., 2014; Vested et al., 2019). However, these factors have not been evaluated as a comprehensive whole.

Ambient light exposure is an important component of the exposome (Vermeulen et al., 2020), and investigating the characteristics and exposure patterns of light in “real world” settings would advance chronobiology, sleep, and environmental public health research. Prior field studies have described characteristics of light exposure in naturalistic settings and associations with health outcomes (Böhmer et al., 2021), but the majority of light-related studies are either experimental or rely on satellite-measured light exposures (such as satellite-measured light at night (LAN)). Measurement of “real-world” light exposure in community-based or population-based studies is feasible but requires dedicated exposure assessment and personal biomonitoring efforts (Hartmeyer and Andersen, 2024). To advance this effort and future integration of light as a fundamental component of the lived environment, we characterized light exposure patterns using objective, individual-level data in two large, prospective United States (US) cohorts that encompassed a range of ages and geographic locations. We hypothesized that dimensions of amount, timing, and

duration would be correlated with each other and with seasonal, diurnal, geographic, demographic, anthropomorphic, and sleep health-related correlates. We discuss patterns within and between these independent cohorts, limitations, and considerations for future research.

2. Methods

2.1. Study populations

This analysis utilized data from the Hispanic Community Health Study/Study of Latinos (HCHS/SOL) and the Multi-Ethnic Study of Atherosclerosis (MESA). HCHS/SOL is an ongoing community-based cohort study of 16,415 self-identified Hispanic or Latino adults designed to evaluate risk and protective factors associated with cardiovascular and respiratory health, as previously described (Lavange et al., 2010; Sorlie et al., 2010). Briefly, participants aged 18–74 years were recruited from households across four sites in the US (San Diego, California; Miami, Florida; Chicago, Illinois; and Bronx, New York) from 2008 to 2011, as shown in Supplemental Fig. 1. From 2009 to 2013, the HCHS/SOL Sueño Ancillary Study recruited 2252 HCHS/SOL participants aged 18–64 years old to collect 1 week of wrist-worn actigraphy (Loredo et al., 2019). Previous comparison of all HCHS/SOL participants to those in the Sueño sub-sample reported similar characteristics (Cespedes et al., 2016).

The prospective MESA study design and sample characteristics have been previously described (Bild et al., 2002); briefly, the cohort study was designed to measure risk factors that predict progression from subclinical to clinically overt cardiovascular disease in a diverse, population-based sample (Bild et al., 2002). The initial study sample (Baseline Exam) included 6814 people without clinical cardiovascular disease of multiple ethnicities aged 45–84 years old recruited by six field centers across the US (Los Angeles, California; Chicago, Illinois; Baltimore, Maryland; St. Paul, Minnesota; New York City, New York; and Forsyth County, North Carolina; Supplemental Figs. 1) from 2000 to 2002. Following Exam 5, the MESA Sleep Ancillary Study took place from 2010 to 2013 and recruited 2237 participants for 1 week of wrist-worn actigraphy measurement (Chen et al., 2015). Among those eligible, participants in the Sleep Ancillary Study were more likely to be non-smokers, younger, without existing hypertensive or chronic obstructive pulmonary disease, and report Black or African-American, Chinese-American, or Hispanic race or ethnicicty compared to non-participants, as previously described (Chen et al., 2015).

This analysis included participants with at least 6 valid days (day defined as a full 24-h period from midnight to midnight) of actigraphy measurement (Tworoger et al., 2005; Knutson et al., 2007) to capture a weekend day and to maximize the number of participants in the analysis. An invalid day was defined as >6 h missing light or activity data. Data from the first 6 valid days of measurement were used in deriving all light and actigraphy-based measures. As an additional quality assurance step, each participant's light data was plotted and visually inspected; visual inspection of each participant's data provided the opportunity to examine within-individual patterns and identify data that were potentially spurious if: (1) minimum light values (e.g., stretches of time across measurement periods when light levels are at their lowest) shifted or degraded over time or (2) minimum light values were greater

than approximately ~2 lx (i.e., $\log_{10}$(lux+1) value >0.5). This ~2 lx threshold is specific to the data and was chosen as a clear visual demarcation point. Participants with incorrect epoch lengths (e.g., 15 s rather than 30 s) were also excluded (Supplemental Fig. 1). The HCHS/SOL and MESA studies were approved by the Institutional Review Boards at each participating institution and written informed consent was obtained from all participants.

2.2. Light and rest-activity measurement

Actigraphy and light data were measured similarly for both studies. White light data (lux) and activity data (triaxial movement sum as measured by a piezo-electric accelerometer device) were continuously collected in 30-s epochs over a week during the HCHS/SOL Sueño Ancillary Study (following the baseline Exam) and the MESA Sleep Ancillary Study using wrist-worn Actiwatch Spectrum devices (Phillips Respironics). Actiwatch Spectrum devices were worn on the wrist, with the watch face in the same plane as the top of the hand. In both cohorts, new Actiwatch devices were purchased from the manufacturer and deployed following factory calibration; specific calibration details are unavailable and there was no further recalibration of the devices before use. According to the manufacturer's specifications, this device measures light in the 400–700 nm range and at amounts ranging from approximately 0.1–35,000+ lux (Stothard et al., 2017; Shneor et al., 2023); however, actual measured values can range from 0 to approximately 100,000 lx.

2.3. Demographic, anthropometric, and sleep health-related measures

Demographic, anthropometric, and sleep health-related measures included age (in years) at time of actigraphy measurement, body mass index (BMI), information on shift work, and sleep characteristics. Sleep and chronotype measures were collected using identical questionnaires including the Women's Health Initiative Insomnia Rating Scale (WHIIRS) (Levine et al., 2003) to report insomnia symptoms, the Epworth Sleepiness Scale (ESS) (Johns, 1991) to report daytime sleepiness symptoms, and a modified version of the Horne-Östberg Morningness-Eveningness Questionnaire (MEQ) (Horne and Ostberg, 1976; Huang and Redline, 2019) to report chronotype. Sleep duration was calculated from scored sleep-wake data (Supplemental Table 1). Participants who indicated their usual work schedule as: "Afternoon shift", "Night shift", "Split shift", "Irregular or on-call", or "Rotating shifts" were considered shift workers.

Non-parametric measures of rest-activity rhythms (RAR) including interdaily stability (IS), intradaily variability (IV), relative amplitude (RA), and amount and timing of the 10 h of greatest (M10) and 5 h of lowest (L5) activity were calculated for activity using the R "nparACT" package (Blume et al., 2016). For the RAR measures, missing data was imputed with each participant's average triaxial activity value for that clock time. Following this step, any remaining missing activity values were imputed by linear interpolation.

2.4. Definition of season

In analyses where month was used to test seasonality, months were treated as numeric values from 1 to 12, corresponding to January–December, and later converted to radians, as described in the statistical analysis. For seasonal categories, groups were based on solstice and equinox dates (Clarkson-Townsend et al., 2020) to derive the following categories:

"Winter" defined as November to January, "Spring" defined as February to April, "Summer" as May to July and "Fall" as August to October (specific to the Northern hemisphere). While approximate daylength or photoperiod was also derived for each participant (as described below), the range in latitudes between study sites resulted in site-specific ranges for photoperiod; for example, the Minnesota site had a lower range in photoperiod than the Florida site.

2.5. Outdoor temperature derivation

Daily temperature maximum data (degrees Celsius, ~4 km gridded resolution) for the United States were obtained from the PRISM all-networks daily values dataset (https://prism.oregonstate.edu/) (Spangler et al., 2019). Maximum daily temperature values were matched to participant data by approximate latitudes and longitudes of study sites (Supplemental Table 2) and dates of actigraphy measurement and averaged across days.

2.6. Light variable derivation

Summary light and activity measures (average and standard deviation (SD)) were calculated across days; circular mean and SD were calculated for time variables (Klerman et al., 2017). Where applicable for metrics based on light amount, average illuminance was calculated with or without first $\log_{10}$-transforming the lux values; log-transformation was performed after first adding 1 to the lux value ($\log_{10}$(lux value+1)) (Burgess and Eastman, 2006; Emens et al., 2009; Crowley et al., 2015). The $\log_{10}$-transform is often used in analyses of light data because responses of the circadian system to light tend to follow a semi-logarithmic response (Nelson and Takahashi, 1991; Cajochen et al., 2000; Zeitzer et al., 2000; Thapan et al., 2001; Wang et al., 2003; Hut et al., 2008). However, because results will differ depending on whether $\log_{10}$-transformation is performed prior to or after calculation of summary metrics (Hartmeyer and Andersen, 2024), where appropriate we also provide measures without prior $\log_{10}$-transformation. Metrics where lux values were first $\log_{10}$-transformed prior to calculating summary measures are denoted with "log" in the variable name or otherwise indicated in table or figure annotation. Duration of time above light thresholds (TALT) (Cole et al., 1995) were calculated for specified thresholds (e.g. 1–10, 10–100, 100–1000, 1000+ lux), as visualized in Fig. 1. These thresholds are commonly used to demarcate dark/dim, dim/low, moderate, and bright light environments, respectively, and were chosen to align with prior community-based observational studies of environmental light exposure (Ostrin, 2017; Dautovich et al., 2019). Light exposure above 1000 lx generally represents daylight exposure (Ostrin, 2017; Shneor et al., 2023), whereas lower thresholds (e.g., <1000 lx) generally characterize indoor, electric light exposure or outdoor evening exposure (Stevens and Rea, 2001); 1000 lx is a commonly used threshold to characterize indoor versus outdoor exposure (Ostrin, 2017; Dautovich et al., 2019), but light exposure while indoors can sometimes exceed 1000 lx (such as in close proximity to windows due to daylight). Average light exposure ($\log_{10}$-lux) during sleep or during wake was also calculated from the scored sleep-wake data. Duration of time in ≥1 ($LEDS_{TALT1}$) and ≥ 3 lx during sleep ($LEDS_{TALT3}$) were calculated as metrics of LAN; the 1 and 3 lx thresholds were chosen in relation to prior work of melatonin suppression (Glickman et al., 2002; Gooley et al., 2011; Lucas et al., 2014; Phillips et al., 2019). First time (FTL) and last time of light (LTL) exposure at thresholds were calculated as the first and last daily time

when there were 3 consecutive epochs (equivalent to 1.5 min) of light exposure at or above a particular threshold (≥10, 100, or 1000 lx). Individual photoperiod (IP) was then calculated as the duration of time between FTL and LTL at the particular threshold (≥10, 100, or 1000 lx). Mean light timing revised (MLiTR) was derived as the MLiT (Reid et al., 2014) measure developed by Reid et al. and calculated as the circular (i.e., vectorized) mean time of timestamps when light exposure was at or above 10, 100, or 1000 lx, with the revision that 3 or more timestamps were required for the mean calculation (Fig. 1, Supplemental Table 1). Approximate daylength for each participant at the time of actigraphy measurement was calculated from the sunrise and sunset times (adjusted for daylight savings) derived from the latitudes and longitudes of the cohort site and the first date of actigraphy measurement using the R "suncalc" package (Thieurmel, 2019). Light exposure in the 2 h before ("2hrP") or 2 h after ("2hrF") sunrise and sunset, as well as between sunrise and sunset times, were also derived. Average and SD metrics of light (log_{10}-transformed) in 2-h increments were calculated. Because there is no objective indicator of light sensor occlusion, two separate experimental variables were also created to flag "possible occlusion" or obstruction of the light sensor by clothing or bedding: (1) duration of time when white light was <5 lx during the active period (i.e., during awake epochs from the scored sleep-wake data), and (2) duration of time when white light was <3 lx during the active period (i.e., during awake epochs from the scored sleep-wake data) between sunrise and sunset. However, these possible occlusion metrics may be conservative (Scheuermaier et al., 2010) and/or have some degree of error and should be regarded as exploratory. For all time-related (circular) variables, timestamps were converted into hours and circular mean and circular SD calculated. In correlational and seasonal analyses, time-related variables were analyzed in the same way as linear variables; L5 start time was re-centered before analysis by adding 24 to L5 start times occurring before noon.

For the above light metrics, if light data within a valid day was missing for a particular 30-s epoch, it was marked as missing ("NA") and metrics derived using the available non-missing data (e.g., complete case analysis of data from valid days). A sensitivity analysis was also performed to impute missing white light data using the participant's median white light value for that specific 30-s epoch from valid days where data at that epoch was not missing. Following this step, any remaining missing light values were imputed by linear interpolation (this interpolation step occurred for $n = 2$ participants in MESA and $n = 0$ participants in HCHS/SOL). The light metrics were re-derived for the imputed data and results presented in the Supplemental Materials.

2.7. Statistical analyses

Descriptive statistics (mean, SD) for demographic, anthropometric, sleep health-related, and light variables (Supplemental Table 1) were calculated and compared between cohorts using chi-square tests and/or 2-way analysis of variance (ANOVA). For continuous summary measures (Supplemental Figs. 2–3), Spearman correlation coefficients were calculated. Where appropriate, 95 % confidence intervals (95 % CI) are provided. The associations of sex with average illuminance and average duration in bright light were tested in linear regression models adjusted for age, site, and season. Light metrics were also summarized by seasonal category. To evaluate seasonality of light and sleep-related variables, linear

regression models adjusted for age, sex, and site and with or without cos and sin terms for month-radians were compared using likelihood ratio tests (LRT). Month-radians were calculated by converting month of measurement (1–12) to radians (month number / 12 * 2π). The *p*-values of the seasonality analysis thus refer to the results of the LRTs comparing models with and without cos and sin terms.

To evaluate whether patterns in seasonality and correlates were affected by shift work or possible device occlusion, sensitivity analyses additionally adjusted for the primary metric of possible device occlusion (average duration of time spent in lux <5 during active interval, continuous) and/or shift work (binary, yes/no), excluded participants who reported shift work, or excluded participants who had ≥5.5 h average of possible device occlusion (white light <5 lx during active interval; the 5.5 h threshold was chosen as the approximate mean value in both cohorts). Sex differences in shift work prevalence were tested with chi-squared tests. For descriptive statistics of the primary possible occlusion variable (<5 lx during active interval), means and SD and estimates from separate univariate linear regression models for sex, shift work, season, and location were calculated. Forest plots to illustrate estimates with or without the inclusion of covariates were also generated. Where relevant, false discovery rate (FDR) multiple testing correction was applied using the Benjamini and Hochberg (BH) method (Benjamini and Hochberg, 1995) and resulting q-values provided. All statistical analyses were performed in R version 4.4.0 and results considered significant if $p < 0.05$ or $q < 0.05$ (where calculated).

3. Results

The analysis included 2147 HCHS/SOL and 1910 MESA participants (Supplemental Fig. 1). Of the HCHS/SOL participants, the average age was 47 ± 11.6 years old (age range: 19–68 years), most participants were female (65 %), and 21 % reported shift work. Of the MESA participants, the average age was 70 ± 9.2 years old (age range: 54–95 years), most participants were female (54 %), and 12 % reported shift work (Table 1). MESA study sites tended to be in more northern latitudes relative to HCHS/SOL sites (Supplemental Fig. 4, Supplemental Table 2). Compared to those with actigraphy data who were included in the analysis, excluded HCHS/SOL and MESA participants slightly differed by race and ethnicity, BMI, study site, and income (Supplemental Table 3). Missingness due to non-wear or off-wrist was low, with an average 3.4 min of missing light or activity data per valid day in HCHS/SOL and 11.4 min of missing light or activity data per valid day in MESA (Table 1, Supplemental Fig. 5). The average light exposure was 0.97 $\log_{10}$-lux (95%CI: 0.96, 0.98) and 0.94 $\log_{10}$-lux (95%CI: 0.93, 0.95) (or 831 lx (95%CI: 790, 871) and 700 lx (95%CI: 661, 739) without $\log_{10}$-transformation) and average time spent in bright light ($TALT_{1000}$) was 1.5 (95%CI: 1.5, 1.6) and 1.2 h (95%CI: 1.2, 1.3) in HCHS/SOL and MESA, respectively (Supplemental Table 4).

3.1. Sex differences in light exposure

In both cohorts, males had greater average illumination and greater time spent in bright light across age compared to females (Fig. 2). In HCHS/SOL and MESA, the average illuminance for females was 0.94 $\log_{10}$-lux (95%CI: 0.93, 0.96 $\log_{10}$-lux) and 0.93 $\log_{10}$-lux (95%CI:

0.91, 0.94 log_{10}-lux), compared to 1.02 log_{10}-lux (95%CI: 0.99, 1.04 log_{10}-lux) and 0.96 (95%CI: 0.94, 0.98 log_{10}-lux) for males. Similarly, the average time spent in bright light for females was 1.2 (95%CI 1.19, 1.29) and 1 (95%CI: 0.95, 1.06) hours per day, compared to 2 (95%CI: 1.90, 2.15) and 1.4 (95%CI: 1.35, 1.53) hours per day for males, an increase for males of approximately 67 % and 40 % in HCHS/SOL and MESA. These sex differences remained after adjusting for age, site, and season, with males having approximately 0.07 log_{10}-lux (HCHS/SOL 95%CI: 0.05, 0.09 log_{10}-lux) and 0.03 log_{10}-lux (MESA 95%CI: 0.01, 0.05 log_{10}-lux) greater average illuminance than females in HCHS/SOL and MESA, respectively ($q < 0.05$; Supplemental Table 5). On average, males also spent 46 (HCHS/SOL 95%CI: 0.67, 0.87) and 26 more minutes per day (MESA 95%CI: 0.35, 0.53 h) in bright light in HCHS/SOL and MESA than females ($q < 0.05$; Supplemental Table 5). Males had greater possible occlusion, with approximately 24 (HCHS/SOL 95 % CI: 0.17, 0.63 h) and 39 (MESA 95 % CI: 0.39, 0.90 h) more minutes per day compared to females (Supplemental Table 6). Prevalence of shift work did not differ by sex in either cohort (approximately 13 % females and 16 % males in HCHS/SOL, 11 % females and 14 % males in MESA; $p \geq 0.05$). The sensitivity analyses adjusting for possible occlusion and shift work and excluding participants with >5.5 h of possible device occlusion or who reported shift work did not alter these findings (Supplemental Figs. 5–6, Supplemental Table 5).

3.2. Seasonal differences in sleep health-related measures and light exposure

Some sleep-related variables showed a seasonal pattern. For example, in MESA, sleep duration, IV, L5, and L5 start time were seasonally rhythmic, with longest sleep duration in the winter. In contrast, in HCHS/SOL variability in sleep midpoint was the only seasonal sleep health-related variable, with winter having the highest variability and spring having the lowest variability (Table 2). There was no evidence for seasonal patterns in insomnia symptoms, daytime sleepiness, or chronotype.

In both cohorts, many of the light exposure measures showed seasonal patterns. Average amount and duration of time spent in bright light were seasonally rhythmic, higher around the summer solstice (May–July; longest photoperiod) and lower around the winter solstice (November–January; shortest photoperiod; difference between winter vs. summer was −0.35 log_{10}-lux in HCHS/SOL and −0.44 log_{10}-lux in MESA, $q < 0.05$) (Fig. 3, Table 2, Supplemental Table 7). Average light exposure during daylight hours (sunrise to sunset) was also higher in the summer, whereas average light exposure during nighttime hours (sunset to sunrise) was higher in the fall and winter. Time spent in brighter environments ($TALT_{100–1000}$, $TALT_{1000}$, IP_{1000}) was also higher during the summer and fall. Summer also had the earlier first daily exposure and latest last daily exposure to bright light. Seasonal patterns in light timing were also apparent in plots of light averaged by season, with light exposure decreasing around 4 PM in the winter, 6 PM in the fall and spring, and 8 PM in the summer (Fig. 3).

While possible device occlusion variables also showed seasonal patterns (Supplemental Fig. 6; Supplemental Table 6), possible device occlusion did not appear to be responsible for driving seasonal trends in light exposure. Sensitivity analyses adjusting or excluding for possible occlusion or excluding shift workers showed similar patterns in seasonality,

although some were attenuated (Supplemental Tables 7–8; Supplemental Fig. 7). Adjusting for or excluding possible device occlusion mostly affected seasonal patterns of light 2 h after sunset and dim or moderate light exposure, such as IP_{10}, FTL_{10}, or LTL_{10}, FTL_{100}, $TALT_{100–1000}$ and $TALT_{1–10}$. Adjusting for possible occlusion also attenuated the magnitude of the effect for Miami, FL and San Diego, CA study site locations in HCHS/SOL, as well as the spring and winter seasons in both cohorts when modeled in linear regression models with average illuminance, average log_{10}-illuminance, or average $TALT_{1000}$ as outcomes; in these same models, adjusting for shift work did not meaningfully affect estimates (Supplemental Fig. 7).

3.3. Dimensions of light exposure

Light variables showed very similar correlation patterns in HCHS/SOL and MESA (Fig. 4). Greater average log_{10}-transformed illuminance was positively correlated with daylength (rho = 0.44 and rho = 0.56 in HCHS/SOL and MESA, $p < 0.05$), temperature (rho = 0.62 and rho = 0.60 in HCHS/SOL and MESA, $p < 0.05$), and time spent in bright ($TALT_{1000}$ rho = 0.84, 0.80 in HCHS/SOL and MESA, $p < 0.05$) and moderate light ($TALT_{100–1000}$ rho = 0.79, 0.80 in HCHS/SOL and MESA, $p < 0.05$) but negatively correlated with time spent in dim light ($TALT_{1–10}$ rho = −0.44, −0.30 in HCHS/SOL and MESA, $p < 0.05$). Median illuminance had similar correlation patterns to average log_{10}-transformed illuminance. With respect to timing of exposure, greater average log_{10}-transformed illuminance was correlated with earlier first timing of bright (FTL_{1000} rho = −0.62, −0.53 in HCHS/SOL and MESA, $p < 0.05$) and moderate light (FTL_{100} rho = −0.59, −0.49 in HCHS/SOL and MESA, $p < 0.05$) and later last timing of bright (LTL_{1000} rho = 0.67, 0.67 in HCHS/SOL and MESA, $p < 0.05$) and moderate light (LTL_{100} rho = 0.59, 0.54 in HCHS/SOL and MESA, $p < 0.05$). Similarly, greater average illuminance was positively associated with longer individual photoperiods in moderate or bright light (Fig. 4). Greater light exposure during sleep ($LEDS_{TALT3}$) was correlated with longer daylength (rho = 0.16, 0.24 in HCHS/SOL and MESA, $p < 0.05$), greater time spent in low light ($TALT_{1–10}$ rho = 0.22, 0.17 in HCHS/SOL and MESA, $p < 0.05$), longer individual photoperiod in low light (IP_{10} rho = 0.36, 0.39 in HCHS/SOL and MESA, $p < 0.05$), and earlier first timing of exposure to low light (FTL_{10} rho = −0.37, −0.35 in HCHS/SOL and MESA, $p < 0.05$). In line with the occurrence of greater possible occlusion during the winter and less possible occlusion during the summer (Supplemental Table 6), possible occlusion variables were negatively correlated with longer days, greater average illuminance, and greater duration in bright and moderate light and positively correlated with lower median light value, decreased temperature, and decreased time spent in moderate (≥ 100 lx) or bright (≥ 1000 lx) light environments (Fig. 4).

Light variable correlation patterns were similar in sensitivity analyses with imputed missing light values (Supplemental Fig. 8) and in sensitivity analyses excluding shift workers (Supplemental Fig. 9). Correlations for the sensitivity analysis excluding people with possible device occlusion showed fewer correlations, with attenuated correlations for some dim light and SD variables (Supplemental Fig. 10).

3.4. Time-of-day patterns

When summarized in 2-h clock time intervals, measures of illuminance (average and SD) displayed time-of-day correlations (Fig. 5). Average and SD measures of $\log_{10}$-transformed illuminance were strongly positively correlated with an adjacent preceding or subsequent time block. The average-average and SD-SD correlations were greatest during daylight hours (approximately 10 AM-8 PM). Negative average-average correlations occurred between late night hours (12 AM–4 AM in HCHS/SOL, 10 PM-2 AM in MESA) and daylight hours (6 AM-6 PM in HCHS/SOL, 6 AM-12 PM in MESA; HCHS/SOL rho = −0.02 to −0.28, all $p < 0.05$; MESA rho = −0.02 to −0.1, all $p < 0.05$). Strong correlations also existed between average-SD within the same time block, particularly during late evening hours (10 PM-2 AM) and approximate sunrise and sunset times (6–8 AM and 6–8 PM). When analyzed in 2-h increments of clock time, hourly patterns in light exposure mean and SD were correlated with light-related (Supplemental Fig. 11) and sleep health-related variables (Supplemental Fig. 12). For example, greater duration in bright light ($TALT_{1000}$) was most strongly correlated with illuminance around midday (2 PM–4 PM rho = 0.84, 0.82 in HCHS/SOL and MESA, $p < 0.05$; Supplemental Fig. 11). Among the sleep health-related variables, greater variability in sleep midpoint was correlated with greater illuminance around midnight (midnight-2 AM rho = 0.38, 0.30 in HCHS/SOL and MESA, $p < 0.05$), greater morningness in chronotype was correlated with greater average illuminance in the morning (6–8 AM rho = 0.30, 0.34 in HCHS/SOL and MESA, $p < 0.05$), and greater interdaily stability correlated with less illuminance around midnight (midnight-2 AM rho = −0.33, −0.30 in HCHS/SOL and MESA, $p < 0.05$; Supplemental Fig. 12).

3.5. Differences in light exposure by location

Average light exposure and bright light exposure differed by study site (a proxy for latitude). Both average light exposure and $TALT_{1000}$ showed trends of increasing light exposure moving from northern to southern study sites (Supplemental Fig. 13). In HCHS/SOL, Miami, FL had the greatest and the Bronx, NY site had the lowest average illuminance (mean difference between San Diego and the Bronx: 0.34 $\log_{10}$-lux; Supplemental Table 9). In MESA, Forsyth County, NC had the greatest and the New York City, NY site had the lowest average illuminance (mean difference between Forsyth County and New York City: 0.17 $\log_{10}$-lux, $p < 0.05$; Supplemental Table 9). When compared by season, in the winter the average $TALT_{1000}$ was approximately 10 min in the Bronx or in New York City, 14 min in Chicago, 22 min in St. Paul, 32 min in Baltimore, 44 min in Forsyth County, 61 min in Los Angeles, 69 min in San Diego, and 108 min in Miami (Supplemental Table 10).

In sensitivity analyses adjusting for possible occlusion (<5 lx while active, continuous), location differences were attenuated. The largest attenuations were seen for the Miami, FL vs. Bronx, NY comparison and the Miami, FL vs. Chicago, IL comparison for HCHS/SOL; in MESA, the largest attenuations were seen in the New York City, NY vs. Baltimore, MD comparison, the St. Paul, MN vs. Baltimore, MD comparison, and the Forsyth County vs. Chicago, IL comparison (Supplemental Table 9).

3.6. Sleep health-related correlates of light exposure

Correlations between sleep health measures and light exposure variables were similar between cohorts. Of note, the insomnia and daytime sleepiness measures showed less correlation with light variables compared to other sleep health measures (Fig. 6). The sleep health-related measures with the greatest correlation with light metrics were sleep midpoint SD, chronotype, and RAR variables. Overall, measures of light timing (MLiTR, FTL, LTL) had stronger correlation patterns with sleep health metrics than measures of amount and duration in different light levels. Greater M10, a measure of physical activity, was weakly correlated with greater duration in bright ($TALT_{1000}$ rho = 0.13, 0.20 in HCHS/SOL and MESA, $p < 0.05$) and moderate ($TALT_{100–1000}$ rho = 0.21, 0.16 in HCHS/SOL and MESA, $p < 0.05$) light and decreased light exposure during sleep ($LEDS_{TALT3}$ rho = −0.10, −0.29 in HCHS/SOL and MESA, $p < 0.05$). Interdaily stability (IS), a measure of regularity in behavioral activity, was negatively correlated with variability in first timing of moderate light exposure ($FTL_{100}SD$ rho = −0.37, −0.34 in HCHS/SOL and MESA, $p < 0.05$). Intradaily variability (IV) was weakly correlated with light variables, with general directionality opposite that of IS, and was positively correlated with time spent in dim light ($TALT_{1–10}$ rho = 0.17, 0.12 in HCHS/SOL and MESA, $p < 0.05$). Relative amplitude showed similar correlation patterns to IS and was positively correlated with later first timing of low light (FTL_{10} rho = 0.36, 0.33 in HCHS/SOL and MESA, $p < 0.05$) and negatively correlated with individual photoperiod in low light (IP_{10} rho = −0.32, −0.28 in HCHS/SOL and MESA, $p < 0.05$) and light during sleep ($LEDS_{TALT3}$ rho = −0.28, −0.26 in HCHS/SOL and MESA, $p < 0.05$). Results were similar in a sensitivity analysis excluding shift workers (Supplemental Fig. 14).

4. Discussion

Light exposure patterns may be especially relevant for public health and future work will seek to evaluate the effects of light exposure across the lifespan. Using two large US cohort studies, we described characteristics of light exposure measured using wrist-worn actigraphy, considering demographics, season, time of day, place, and sleep health indicators. Light exposure patterns showed high agreement and consistency between cohort studies, as well as credible exposure characteristics; for example, overall exposure patterns aligned with expected light levels in daylight and indoor light, such that bright light exposure gradually grew from sunrise, peaked in midday, and dropped off at sunset, while light exposure before sunrise and after sunset became dimmer and more characteristic of indoor environments. While there are measurement limitations, these qualities, in addition to the low amount of missingness due to non-wear, support the reliability of the measured light data. The results support the cross-sectional association of both season and daylength (photoperiod) as important factors in the amount, duration, and timing of light exposure in the modern light milieu. Additionally, we observed correlations between dimensions of light exposure and sleep health-related measures, particularly with variability in sleep midpoint, chronotype, and RAR. Overall, these findings confirm the relevance of season, temporality, and location when assessing light exposure and support further research in investigating “real-world” light exposure in population health research.

There were striking sex differences in light exposure in both cohorts, with males having greater average illumination and greater time spent in bright (≥1000 lx) light. These results align with prior community-based (Jean-Louis et al., 2000) and population-based studies (Wallace, 2024). For example, an analysis of data representative of the non-institutionalized US population showed that males spent approximately 60 % more time in bright light compared to females ages 18–80 + (Wallace, 2024). While more research is needed to disentangle the causes and consequences of this sex difference in light exposure, sex differences in time spent indoors vs. outdoors may play a role; it may also be a possible contributing factor to sex differences in sleep and circadian health (Lok et al., 2024). While age-related patterns should be interpreted with caution due to between-cohort differences in age range and measurement location, there were also interesting patterns by sex and age; in HCHS/SOL, sex differences in light exposure became more apparent in older age, whereas the opposite pattern occurred in MESA (the cohort with an older age range). Generational effects (e.g., due to occupational trends, behavioral trends) and/or changes related to aging may be interacting with sex and playing a role in these patterns. However, to examine why these differences exist and whether they influence downstream sex-differences in health outcomes, such as for sleep or vulnerability to adverse effects of LAN, future follow-up work is needed.

Our results show that light exposure and some sleep-related measures exhibit distinct seasonal patterns, similar to prior studies (Thorne et al., 2009; Crowley et al., 2015; Nioi et al., 2017; Dunster et al., 2023), accounting for age, sex, and study site location. Amount and duration were greater during the summer and fall (characterized by longer days and/or warmer weather) and individuals spent more time in dim or dark environments during the winter (when days are shortest). These seasonal differences primarily stemmed from extended duration in afternoon/evening bright light in the summer, similar to results from smaller studies of seasonal light exposure in the United Kingdom ($n = 34$) (Thorne et al., 2009) and office workers in the US ($n = 14$; $n = 6$ with repeated measures) (Crowley et al., 2015). Our seasonal light findings contradict a smaller study which reported no substantial differences in individual light exposure ($n = 23$ participants) across seasons (Khodasevich et al., 2021); however, similar to our findings, they report light exposure being most consistent during the afternoon hours (Khodasevich et al., 2021). The majority of participants from this prior study (Khodasevich et al., 2021) were living in New York City, which had the lowest average light exposure in our study; however, our results still supported seasonality in light exposure in New York sites. Therefore, the small sample size, different light sensor used, and aspects of behavior and the built environment (such as building density) that limit sunlight exposure may have contributed to these differences in findings. These findings also imply that personal light exposure may differ by features of the built environment, urban or rural location, or climate indicators such as temperature; future work is needed to investigate the reasons for these differences and whether they contribute to relevant downstream health effects.

In addition to quantifying time in low light, we attempted to capture possible device occlusion using exploratory metrics. Device occlusion, a form of measurement error, could cause measured light levels to be dimmer than actual exposure (exposure misclassification), although whether this measurement error could bias the direction and magnitude of results

would be study-specific and depend on factors such as whether measurement error differed by group of interest (differential misclassification of exposure). While this study was largely descriptive in nature, this is an important issue that should be considered in future studies, particularly those testing the association of light exposure with health outcomes. As may be expected, some results related to seasonal rhythmicity and correlation patterns of dim and low light metrics were attenuated in sensitivity analyses for possible occlusion. For example, possible occlusion was highest in the winter, so adjusting for possible occlusion led to the largest attenuation for winter-related light exposure metrics. However, attenuation by site was highest for Miami and San Diego, the two southern-most (and warmest) sites. Time of day plots of possible occlusion also indicate a "bump" in the late afternoon that occurs later with season, appearing to coincide with approximate sunset times. Taken together, these findings suggest that the possible occlusion metric may lack sensitivity. Possible occlusion could be overestimated if valid epochs are incorrectly flagged – e.g., epochs where dim light is due to environmental conditions and not due to covering (false positive). In such cases, adjusting for possible occlusion could introduce bias. While future studies should consider how occlusion or covering of a device could influence results, a more satisfactory approach would be to objectively measure occlusion, such as with an active infrared sensor, in tandem with light measurement. Importantly, however, the results of this analysis align with prior findings and are largely robust after accounting for possible occlusion.

The average amount of daily bright light exposure (a proxy for sunlight) in HCHS/SOL, the cohort with younger participants and two southern latitude sites, was approximately 1.5 h a day, compared to the 1.2 h a day in MESA, the cohort with older participants and five northern latitude sites. These averages and site-specific seasonal patterns are similar to those from a longitudinal study approximately 30 years prior that compared seasonal light exposure between participants in Rochester, Minnesota (n = 31, average $TALT_{1000}$ = 1.3 h) and San Diego, California (n = 50, average $TALT_{1000}$ = 1.8 h) (Cole et al., 1995) and a smaller study in San Diego, California (n = 10, average $TALT_{2000}$ = 1.5 h) (Savides et al., 1986). Notably, neither the average duration in bright light in the present study nor in prior studies is close to that of the natural (outdoor daylight) photoperiod (Savides et al., 1986). Society has shifted to spending more time indoors (Klepeis et al., 2001), and prior studies of naturalistic light exposure based in the U.S. and Canada suggest people spend approximately 60–90 % of their time in light dimmer than 100 lx (Savides et al., 1986; Kawinska et al., 2005; Scheuermaier et al., 2010; Reid et al., 2014), similar to our findings. A prior comparison of different age groups also reported that younger (n = 22, average age 23 years old) participants spent >25 % and older (n = 22, average age 66 years old) participants spent >20 % of their waking day in dim (<10 lx) light (Scheuermaier et al., 2010). Prior studies of older adults (n = 16 aged 72–99 years old) have also reported summer-winter differences in light exposure, but low light exposure overall (Nioi et al., 2017); because sleep disorders become more prevalent with age (Miner and Kryger, 2017), light exposure may be important to support healthy sleep with aging. For example, due to age-related changes, such as yellowing of the lens, older adults may need 3 times as much light intensity as younger adults to entrain to the 24-h day (Turner and Mainster, 2008). Increasing bright daytime light, either through greater outdoor time or electric lighting, may improve sleep-related morbidity (Van Someren et al., 1997), although greater research is needed. Future multi-site

studies of light exposure should consider site, latitude, and age differences in study design and analyses. Studies of light exposure should also collect and provide information on season and evaluate seasonality in measures (Schöllhorn et al., 2023).

Light exposure also showed temporal time-of-day correlation patterns. Light exposure was highest in the late morning and early afternoon hours when sunlight is brightest and when a behavioral overlap may exist among individuals with varying habits and rest-wake activity patterns, such that people who have early or late rise times are both likely to be out and about. These results highlight underlying temporal dynamics in light (and sleep) patterns that should be considered if modeling light at a particular clock time as an exposure (e.g., if light exposure at 9 AM correlated with light exposure at 3 PM). These dynamics pose a challenge in data analysis as light exposure history may influence the effects of future light exposure. Future research should aim to incorporate modeling techniques that account for time-varying exposures and/or include markers of light exposure history in analyses.

Variability in sleep midpoint, chronotype, and RAR variables showed some of the stronger correlation patterns among sleep-related measures with light exposure. Insomnia and daytime sleepiness measures showed some weak correlations with light exposure metrics. For example, being more of a morning person was positively correlated with light exposure just prior to and after sunrise, as well as earlier timing of bright light exposure. Among RAR metrics, longer duration in bright light ($TALT_{1000}$), a proxy for sunlight exposure, was correlated with higher RA, IS, and M10, possibly reflecting the influence of bright light and/or outdoor physical activity on circadian entrainment. RAR markers of rest and activity timing were also correlated with light exposure timing variables.

4.1. Strengths and limitations

This study has several strengths and limitations. We analyzed objective personal measures of light data (rather than outdoor or satellite measures, which may be poorly correlated with personal light exposure (Rea et al., 2011; Huss et al., 2019)) from two independent, large U.S.-based cohorts and compared findings by sex, season, study site, and cohort. Light exposure in both cohorts followed expected patterns and showed high concordance, supporting the reliability of the data. Overall, data missingness in both cohorts was low. Participants in the HCHS/SOL and MESA studies were not provided specific instructions regarding covering of the device or procedures to ensure that the device remained uncovered, which could contribute to exposure misclassification (Wallace, 2023). Although recorded light values can be 0 or higher than 35,000 lx, the range of the Actiwatch Spectrum as listed by the manufacturer (Phillips Respironics) is 0.1–35,000 lx; therefore, light values at the extremes of this range may be less accurate and may have benefited from calibration prior to use. Light readings may also deviate from those provided by a photometer. Light exposure measured from a wrist-worn device may not be as accurate as that captured by a head-mounted or head-proximal device (Stampfli et al., 2023). Because the light data presented here were collected using a wrist-worn device, they reflect environmental light exposure to the wrist rather than the eyes, which house the photoreceptors responsible for entrainment of the core circadian pacemaker, and may not accurately capture light input to the circadian system (Price et al., 2012). Light measured using a head-worn device

would be expected to provide a stronger signal to noise ratio for associations with health, suggesting that the correlations between light exposure measured using a wrist-worn device and sleep metrics (for example) presented in this analysis may be conservative estimates of the true relationships due to attenuation towards the null. Indeed, measurement differences between wrist vs. head sensors may be inconsistent under different scenarios (Stampfli et al., 2023; Aarts et al., 2017). Prior work examining light measurement error for wrist-worn vs. head-worn devices has not subsequently examined the direction and magnitude of this error on associations with health outcomes. Future work could jointly examine sensor placement and the effects of measurement error on epidemiological associations for different outcomes under different scenarios. The device used in this study is also no longer available from the manufacturer (Phillips Respironics). Due to the limited spectral resolution of the Actiwatch, we did not derive measures such as the Melanopic Equivalent Daylight Illuminance (m-EDI) (Lucas et al., 2014; Brown, 2020), a standard adopted by the International Commission on Illumination (CIE)(CIE, 2018); we also did not consider results in relation to other standards, such as the WELL Building lighting standards (International Well Building Institute, 2020) and Underwriters Laboratories Design Guideline for Promoting Circadian Entrainment with Light for Day-Active People (DG 24480) (Rea and Figueiro, 2016; Underwriters Laboratories, 2019; Rea, 2022). However, we aim to collect and report such measures in future research where appropriate data is available. Likewise, while we derived metrics using lux thresholds utilized in prior research, future studies investigating light exposure and health could consider exploring additional light levels (Peeters et al., 2022). Outdoor temperatures were also derived from approximate study site location, rather than based on a participant's real-time location, and may not accurately reflect an individual's actual temperature exposure. Another limitation is the treatment of time-related (circular) variables as linear variables. We also did not examine causality or biological mechanisms in this analysis, which were outside the purpose of this study.

4.2. Considerations for future research

To realize the goal of incorporating light dosimetry and measurement in studies of human health, accurate and reliable measurement of light is necessary. This complex issue has been explicitly discussed in prior work (Aarts et al., 2017; Mason et al., 2018; Brown et al., 2022; Spitschan et al., 2022; Hartmeyer and Andersen, 2024) and is not trivial, as light exposure can be highly dynamic and mediated by behavior, the built and natural environment, and physiology (Webler et al., 2019). In the field, light is commonly measured using wrist-worn devices (Spitschan et al., 2022), which may be less cumbersome and easier to use than head-worn devices (Jardim et al., 2011). Light measured at the wrist vs. at the eye level are well-correlated (Okudaira et al., 1983; Cole et al., 1990), but there are measurement differences, with greater variability for light measured at the wrist compared to at the chest or eye level (Figueiro et al., 2013; Aarts et al., 2017); additionally, these comparison studies were performed in small samples of participants (n ~ 10 to 12) and may not be generalizable across devices or populations (Hartmeyer and Andersen, 2024). The degree of measurement error could also differ by light level or dynamic properties of the environment, such as greater difference in head vs. wrist measurements in brighter (>5000 lx) light or outdoors (Jardim et al., 2011; Aarts et al., 2017). Occlusion may also be less of a concern for head-based devices, although evidence is needed to support this. Light source, geometry

of a space, movement, body placement of an individual within a space, and even facial structure can also influence incoming light to the eye (Spitschan et al., 2022). After light enters the eye, there are additional layers of complexity, such as inter-individual differences in physiology and processing of a light stimulus; for example, lens clarity (Lerman and Borkman, 1976; Turner and Mainster, 2008), retinal circuitry and functional integrity of retinal cells (Jean-Louis et al., 2008; Jimura et al., 2023), or use of medications or other substances (Lee et al., 2022) could influence how a light stimulus is ultimately perceived. Thus, measuring light "dose" is complicated.

From a data analysis perspective, the design of light-sensing devices could be improved to include features for sensing occlusion and on/off-body placement. To date, few devices include capacitance sensors or other tools to objectively indicate whether the device is being worn. Likewise, light-sensing devices do not currently offer objective measurement of occlusion or obstruction, but possibly could with the inclusion of an active infrared sensor or other tool. The use of "nearable" devices for environmental light measurement may represent an additional way to supplement light measures from wearable devices.

5. Conclusion

Light is an elemental component of our environment, but it has been largely overlooked in public health research. Light exposure has changed drastically over the past 100 years with the advent of electric lighting, and it is relevant to environmental health research as well as to health more broadly, such as sleep and chronobiology. However, light exposure has not been widely characterized in the general population. Here, we analyze objective light data from 4067 participants from two large US cohorts to investigate the importance of demographic factors, season, time of day, place, and sleep health-related measures in environmental light exposure patterns. Light was measured using a wrist-worn device and thus represents light exposure at the wrist, rather than at the eye level; thus, compared to estimates from eye-measured light, associations may be conservative. When evaluating an experimental measure of possible occlusion, some results related to seasonality and location were attenuated, but overall patterns remained. Light exposure patterns and high concordance between independent cohorts support the reliability of the light data. These findings underscore the importance of considering demographics, place, seasonality, and temporal dynamics of light exposure in analyses of light data. The findings from this largely descriptive analysis will inform future, focused research investigating specific outcomes and research development, with the overarching goal of advancing the inclusion of light as a basic environmental exposure in public health research.

There are a few factors that could help this vision come to fruition. For example, sharing previously collected light data through accessible databases would enhance the richness and diversity of existing light data. While wearable light sensors exist, another important factor is the current need for scalable device options that have been validated, are low-cost, are open-source, are unobtrusive and easy-to-use, have sufficient battery life, have on/off-body detection (for evaluation of missingness), objectively measure occlusion, and are able to measure light in a wide range of spectra and intensities (such as for α-opic measures and dim LAN exposure). Wearable devices that can accurately capture an individual's

light exposure and be deployed on a large scale would enable longitudinal research and biomonitoring studies. Scientific interest in light exposure is not new, but it is hoped that technological advancements amidst a growing appreciation for the fundamentality of light to human biology will catalyze efforts to more fully understand the impacts of light for human health.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Declaration of competing interest

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Data availability

Actigraphy data and data from HCHS/SOL and MESA are available after completing the appropriate data use agreements from the NHLBI-funded National Sleep Research Resource (NSRR) at: https://sleepdata.org/ and from the HCHS/SOL and MESA study data coordinating centers at: https://www.mesa-nhlbi.org/ and https://sites.cscc.unc.edu/hchs/.

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HIGHLIGHTS

- Objective light measurements in >4000 adults show patterns by sex, season, time of day, geography, and health
- Light exposure patterns are consistent between two independent US-based cohorts
- Results support the utility and feasibility of light measurement for future biomonitoring and personal exposure assessment

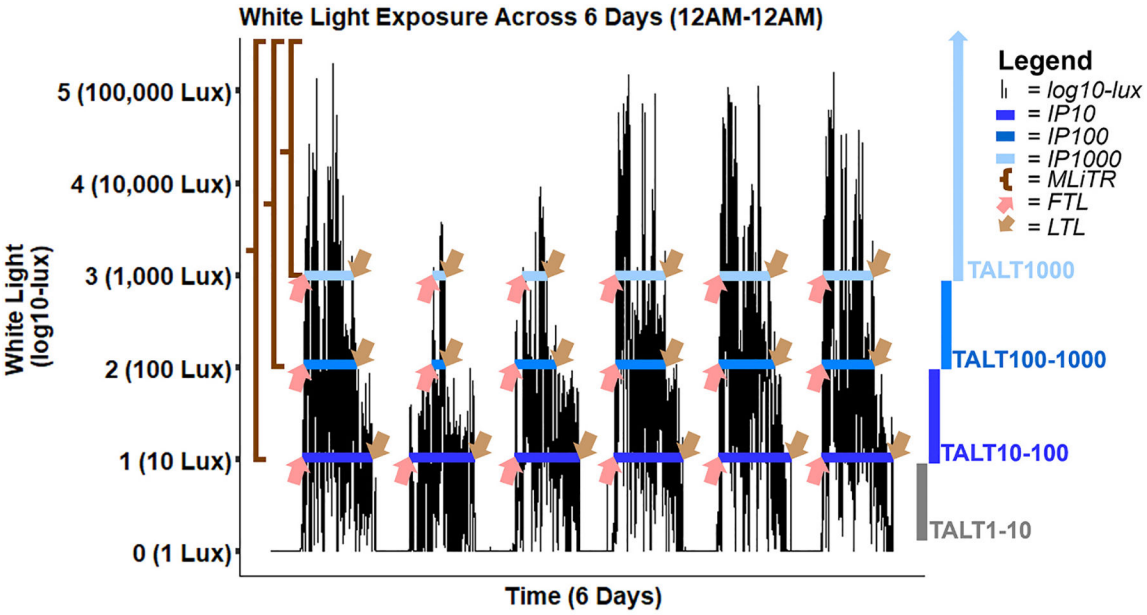

Fig. 1.

Example of white light exposure for one participant across 6 days (12 AM–12 AM) and derived light variables. Black lines represent log10-transformed white light illuminance (lux+1) values. Horizontal blue bars represent illuminance thresholds (≥10, ≥100, and ≥ 1000 lx) for calculating time above light thresholds (TALT). The span of each horizontal blue bar represents the daily individual photoperiod (IP) at the specified illuminance threshold (IP_{10}, IP_{100}, IP_{1000}), the downward salmon arrows and upward tan arrows represent the first (FTL) and last timing (LTL) of light exposure at that threshold, respectively. The brown curly brackets represent the data used for the timestamps in calculating the mean light timing revised (MLiTR) at the corresponding illuminance threshold (≥10, ≥100, and ≥ 1000 lx).

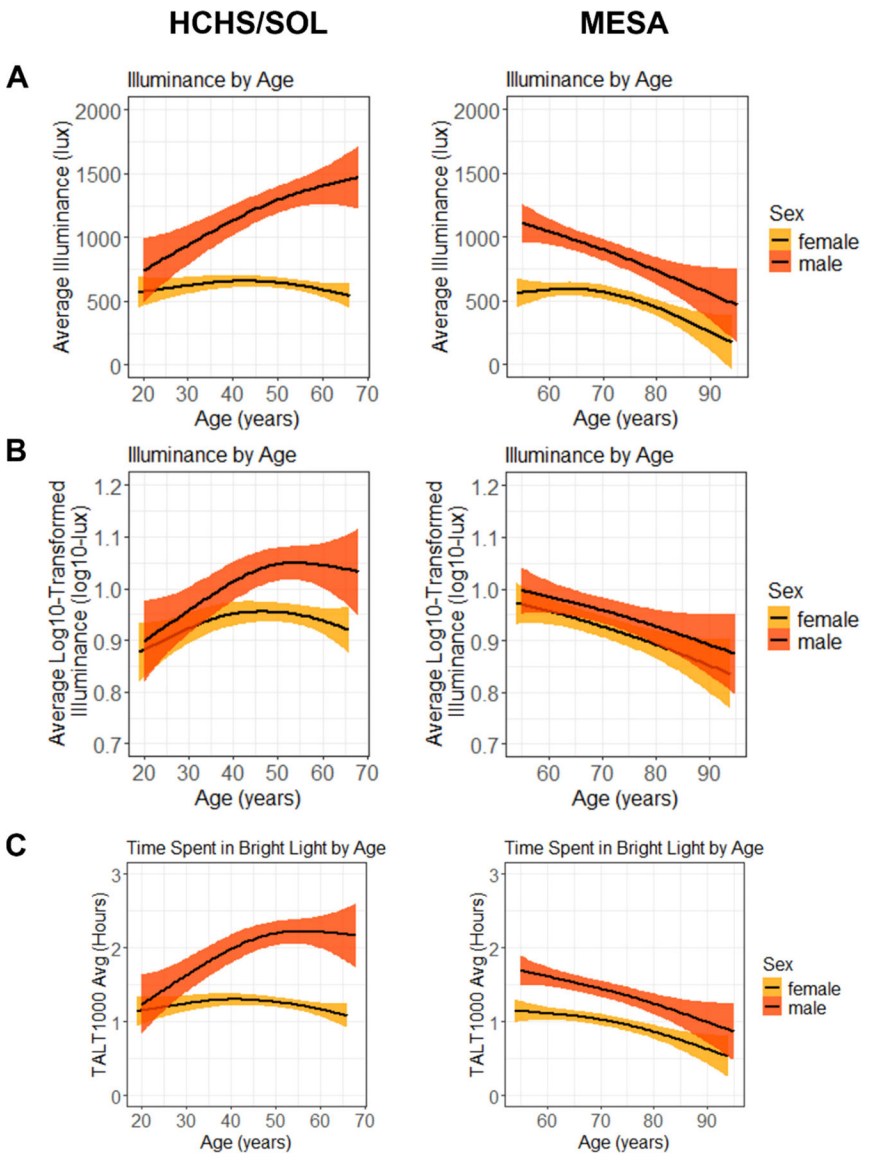

Fig. 2.

Plots showing differences in light exposure by sex across age in HCHS/SOL and MESA. Males (dark orange) had higher levels of both average illuminance calculated (**A**) without and (**B**) with prior $\log_{10}$-transformation and (**C**) duration spent in bright light (≥1000 lx, $TALT_{1000}$) compared to females (light orange) across different ages. The shaded bands indicate 95 % confidence intervals.

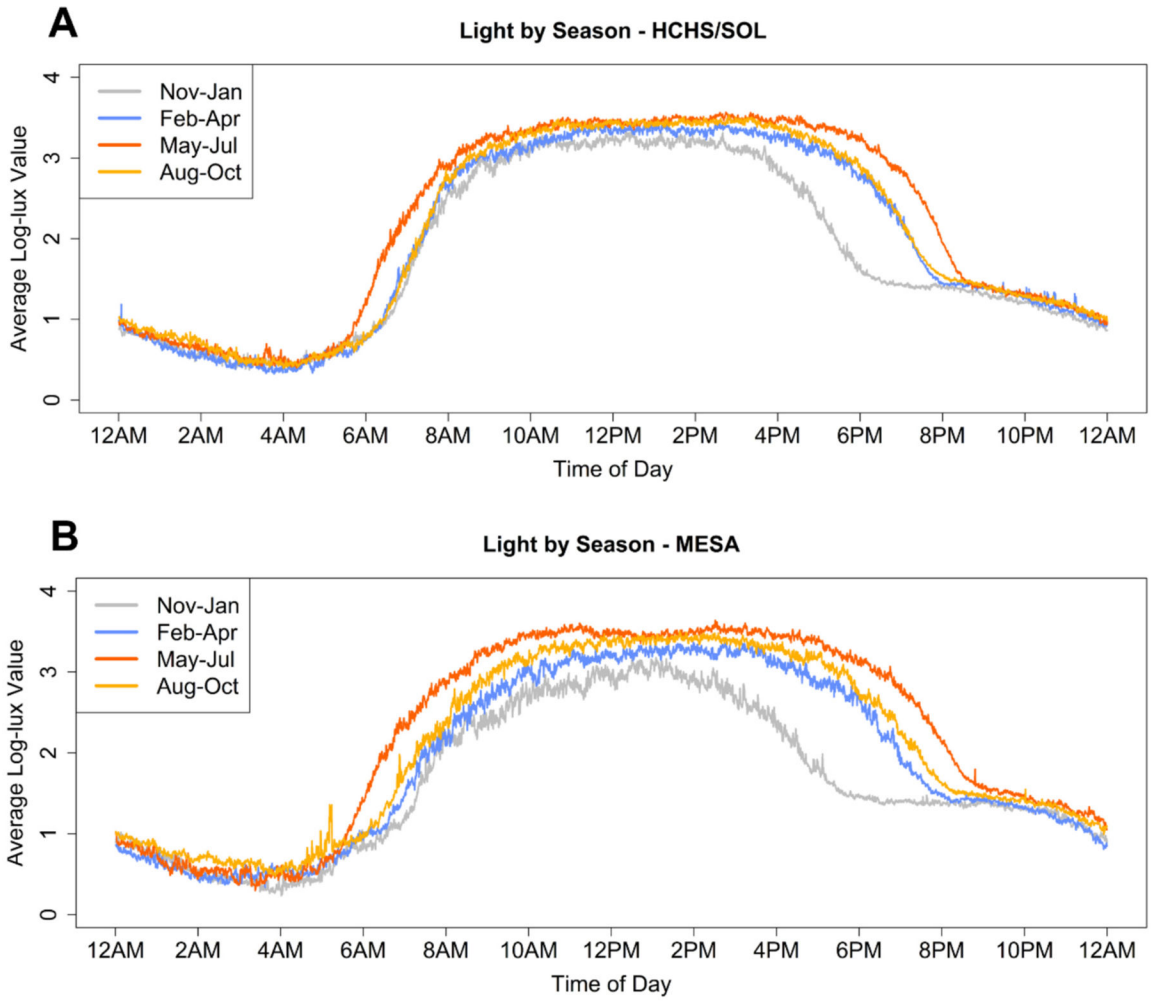

Fig. 3.

Average log10-lux illuminance values in (**A**) HCHS/SOL and (**B**) MESA and by time of day, grouped by season of measurement. Grey line represents average light exposure during the winter season (November – January), blue line represents the spring season (February–April), the dark orange line represents the summer season (May–July), and the light orange line represents the fall season (August–October).

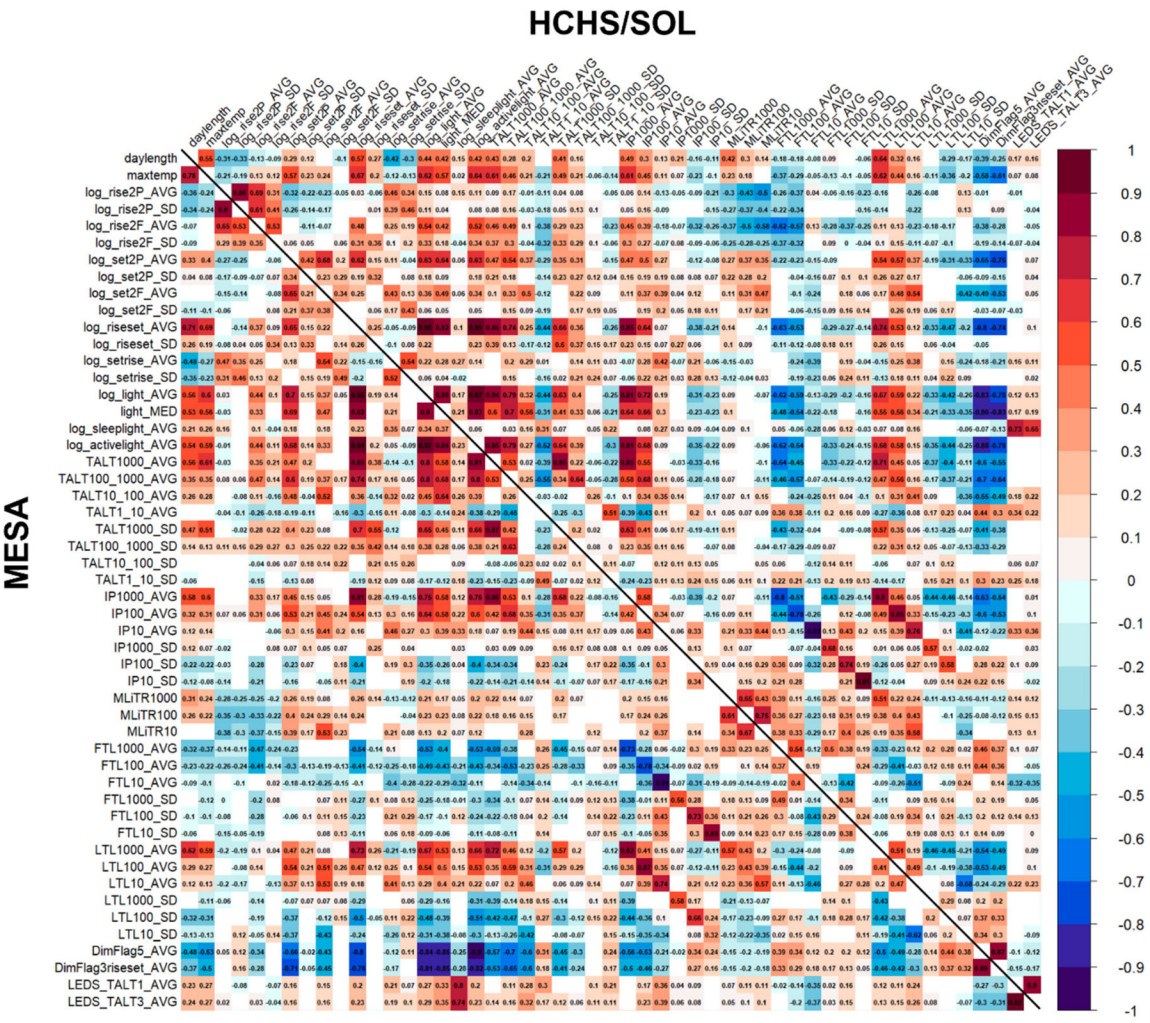

Fig. 4.

Heatmap plotting the Spearman correlations ($p < 0.05$) between light variables in HCHS/SOL (upper right triangle, $n = 1931$ with complete data) and MESA (lower left triangle, $n = 1693$ with complete data); diagonal black line indicates cohort-stratified correlations are within, not between, cohorts). Variables with a “log” prefix indicate that lux values were log10-transformed prior to metric calculation. Correlations with $p > 0.05$ are left blank. Blue color indicates positive correlation and red color indicates negative correlation. Abbreviations: FTL = first timing of light; HCHS/SOL = Hispanic Community Health Study / Study of Latinos; IP = individual photoperiod; LEDS = light exposure during sleep; LTL = Last timing of light; maxtemp = maximum daily temperature (degrees Celsius); MESA = Multi-Ethnic Study of Atherosclerosis; MLiTR = mean light timing revised; SD = standard deviation; TALT = time above light threshold.

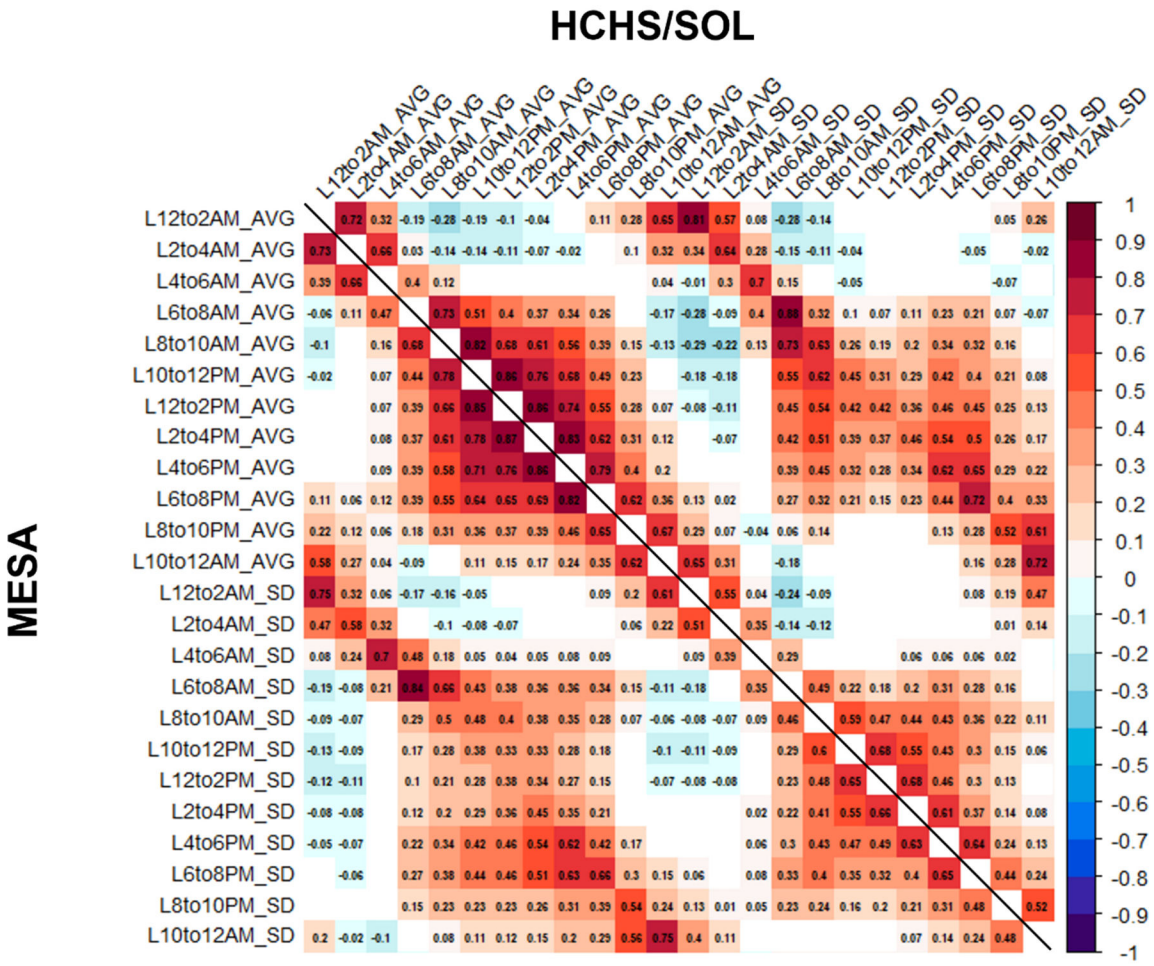

Fig. 5.

Heatmap plotting the Spearman correlations ($p < 0.05$) with average and SD of log10-transformed illuminance in 2-h time windows in HCHS/SOL (upper right triangle) and MESA (lower left triangle; diagonal black line indicates cohort-stratified correlations are within, not between, cohorts). Correlations with $p > 0.05$ are left blank. Blue color indicates positive correlation and red color indicates negative correlation.

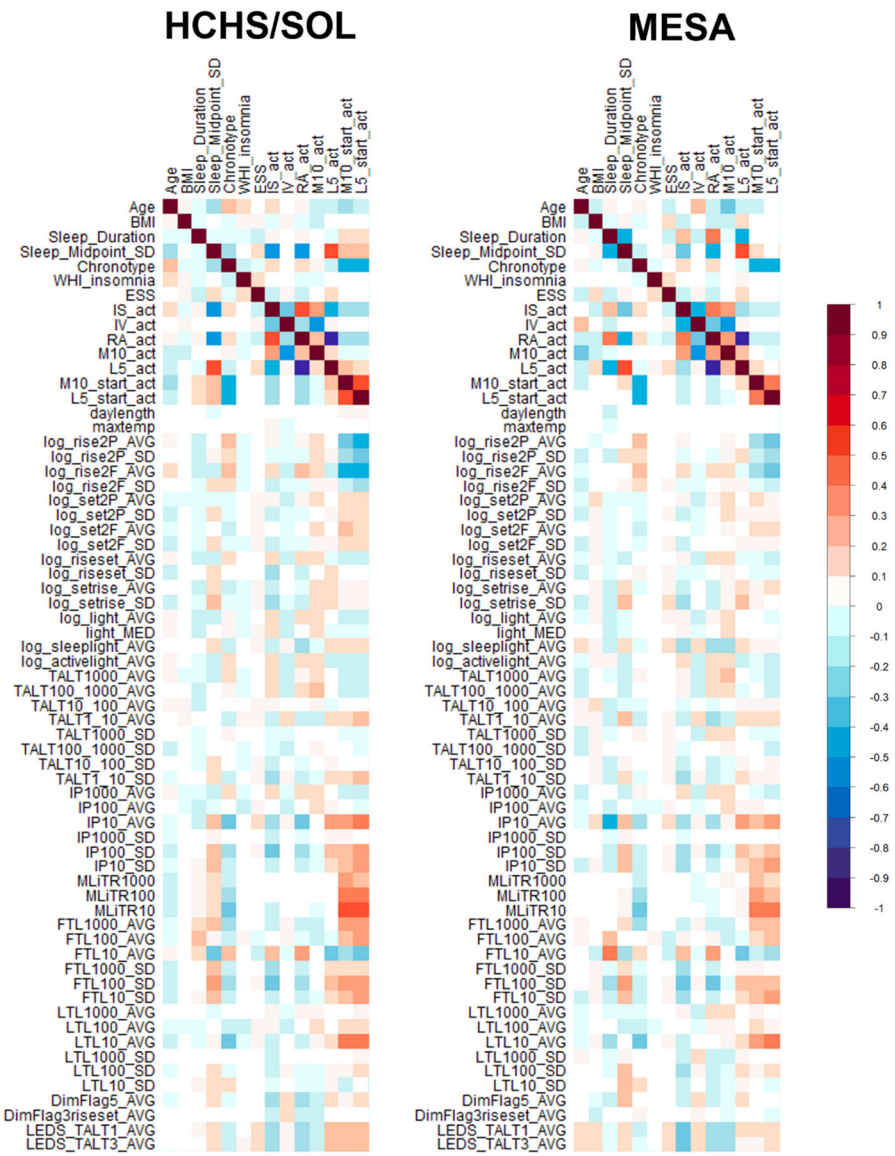

Fig. 6.

Heatmap plotting the Spearman correlations ($p < 0.05$) between age, BMI, sleep-related and light variables in HCHS/SOL and MESA (cohort-stratified; correlations are within, not between, cohorts). Variables with a "log" prefix indicate that lux values were log10-transformed prior to metric calculation. Correlations with $p > 0.05$ are left blank. Blue color indicates positive correlation and red color indicates negative correlation. Abbreviations: BMI = body mass index; ESS = Epworth Sleepiness Scale; FTL = first timing of light; HCHS/SOL = Hispanic Community Health Study / Study of Latinos; IP = individual photoperiod; IS = interdaily stability; IV = intradaily variability; L5 = activity during the 5 h of lowest activity; L5 start = start time of the 5 hours of lowest activity; LEDS = light exposure during sleep; LTL = last timing of light; M10 = activity during the 10 h of highest activity; M10 start = start time of the 10 hours of highest activity; MESA = Multi-Ethnic Study of Atherosclerosis; MEQ = Morningness-Eveningness questionnaire; MLiTR = mean

light timing revised; RA = relative amplitude; SD = standard deviation; TALT = time above light threshold; WHIIRS = Women's Health Initiative Insomnia Rating Scale.

Table 1

Demographic and sleep health-related characteristics of each cohort.

	HCHS/SOL (*n* = 2147)	MESA (*n* = 1910)
Age, years (mean (SD))	46.94 (11.59)	69.57 (9.17)
Sex, male (n (%))	751 (35.0)	881 (46.1)
Race and ethnicity (n (%))	462 (21.5) *Central or South American* 385 (17.9) *Cuban* 258 (12.0) *Dominican* 586 (27.3) *Mexican* 16 (0.7) *More than one/Other heritage* 439 (20.5) *Puerto Rican*	536 (28.1) *Black/African-American* 205 (10.7) *Chinese-American* 426 (22.3) *Hispanic* 743 (38.9) *White*
BMI (mean (SD))	30.18 (6.35)	28.82 (5.68)
WHIIRS score (mean (SD))	7.44 (5.24)	7.45 (4.49)
ESS score (mean (SD))	5.72 (4.55)	6.03 (4.15)
MEQ score (mean (SD))	16.95 (3.73)	17.21 (3.63)
Average sleep duration, hours (mean (SD))	7.91 (1.39)	7.12 (1.43)
Shift work, yes (n (%))	443 (20.6)	233 (12.3)
Study site (n (%))	351 (16.3) *San Diego, CA* 664 (30.9) *Miami, FL* 582 (27.1) *Chicago, IL* 550 (25.6) *Bronx, NY*	249 (13.0) *Los Angeles, CA* 356 (18.6) *Chicago, IL* 298 (15.6) *Baltimore, MD* 354 (18.5) *St. Paul, MN* 320 (16.8) *Forsyth County, NC* 333 (17.4) *New York City, NY*
Average missingness per valid day, minutes (mean (SD))	3.4 (10.9)	11.4 (19.8)

Abbreviations: BMI = Body mass index; ESS = Epworth Sleepiness Scale; HCHS/SOL = Hispanic Community Health Study / Study of Latinos; MESA = Multi-Ethnic Study of Atherosclerosis; MEQ = Morningness-Eveningness questionnaire; WHIIRS = Women's Health Initiative Insomnia Rating Scale.

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Table 2

Summary measures (mean (SD)) of light and sleep health-related measures by season and cohort.[†]

Variable, mean (SD)	Winter (Nov-Jan)		Spring (Feb-Apr)		Summer (May-Jul)		Fall (Aug-Oct)		p-val*	p-val*	q-val	q-val
	HCHS/SOL *n* = 514	MESA *n* = 430	HCHS/SOL *n* = 530	MESA *n* = 492	HCHS/SOL n = 514	MESA *n* = 502	HCHS/SOL *n* = 589	MESA *n* = 486	HCHS/SOL	MESA	HCHS/SOL	MESA
MEQ (chronotype)	17.03 (3.77)	17.17 (3.75)	17.1 (3.8)	17.27 (3.64)	16.9 (3.62)	17.33 (3.61)	16.79 (3.74)	17.06 (3.55)	3.99E-01	2.82E-01	4.3E-01	3.1E-01
WHIIRS (insomnia)	7.26 (5.24)	7.45 (4.75)	7.41 (5.21)	7.73 (4.57)	7.3 (5.23)	7.2 (4.32)	7.74 (5.27)	7.43 (4.36)	7.64E-01	6.20E-01	7.8E-01	6.5E-01
ESS (sleepiness)	5.61 (4.58)	5.95 (3.94)	5.7 (4.44)	5.96 (4.29)	5.77 (4.65)	6.09 (4.24)	5.77 (4.54)	6.1 (4.09)	9.86E-01	4.43E-01	9.9E-01	4.7E-01
Sleep duration (hours)	8.01 (1.37)	7.4 (1.31)	7.91 (1.39)	6.88 (1.54)	7.93 (1.39)	6.97 (1.42)	7.8 (1.41)	7.27 (1.37)	2.02E-01	4.28E-10	2.3E-01	7.2E-10
Sleep midpoint SD (hours)	1.31 (1.08)	1.43 (1.94)	1.08 (0.72)	1.43 (1.77)	1.14 (0.79)	1.19 (1.33)	1.13 (0.86)	1.49 (1.83)	4.10E-03	2.22E-01	5.6E-03	2.5E-01
IS (activity)	0.56 (0.14)	0.57 (0.12)	0.58 (0.13)	0.56 (0.12)	0.57 (0.12)	0.56 (0.12)	0.56 (0.13)	0.56 (0.12)	2.80E-01	7.47E-01	3.1E-01	7.7E-01
IV (activity)	0.68 (0.19)	0.84 (0.23)	0.69 (0.2)	0.84 (0.24)	0.69 (0.2)	0.85 (0.23)	0.69 (0.19)	0.8 (0.22)	6.12E-01	3.69E-02	6.4E-01	4.6E-02
RA (activity)	0.86 (0.12)	0.86 (0.1)	0.88 (0.1)	0.87 (0.1)	0.86 (0.11)	0.87 (0.1)	0.87 (0.11)	0.86 (0.11)	7.45E-02	9.65E-02	8.9E-02	1.1E-01
M10 (activity)	179.32 (58.04)	123.48 (43.3)	178.35 (60.33)	127.18 (44.46)	179.79 (60.63)	124.07 (46.99)	177.82 (55.02)	130.16 (45.43)	7.26E-01	1.52E-01	7.5E-01	1.8E-01
L5 (activity)	13.43 (14.7)	9.04 (7.59)	11.26 (10.85)	8.63 (7.31)	13.71 (13.59)	8.47 (6.83)	12.89 (14.1)	9.93 (9.95)	5.19E-02	2.12E-02	6.4E-02	2.7E-02
M10 start time (activity)	09:15 (2.49)	08:33 (1.92)	09:22 (2.28)	08:31 (2)	09:30 (2.56)	08:29 (2.02)	09:31 (2.41)	08:42 (1.98)	2.40E-01	4.93E-01	2.7E-01	5.2E-01
L5 start time (activity)	01:09 (1.82)	00:48 (1.54)	01:02 (1.59)	00:34 (1.52)	01:16 (1.66)	00:32 (1.28)	01:11 (1.65)	00:44 (1.57)	1.78E-01	2.35E-02	2.0E-01	3.0E-02
Daylength (hours)	10.12 (0.58)	9.72 (0.46)	12.05 (0.97)	12.04 (1.14)	14.31 (0.64)	14.65 (0.46)	12.32 (0.95)	12.42 (1.17)	0.00E+00	0.00E+00	0.0E+00	0.0E+00
Max daily temperature (Celsius)	15.81 (9.09)	9.74 (7.1)	16.7 (8.44)	13.46 (7.34)	26.9 (4.24)	26.39 (4.74)	25.78 (5.3)	22.89 (5.64)	0.00E+00	0.00E+00	0.0E+00	0.0E+00
Log_{10}light 2 h prior sunrise (2hrP)	0.68 (0.53)	0.75 (0.52)	0.59 (0.59)	0.53 (0.44)	0.35 (0.45)	0.4 (0.49)	0.48 (0.61)	0.51 (0.49)	2.03E-29	1.24E-53	6.8E-29	5.4E-53
Log_{10}light 2 h after sunrise (2hrF)	1.21 (0.66)	1.19 (0.53)	1.18 (0.69)	1.14 (0.52)	1.01 (0.71)	1.13 (0.66)	1.17 (0.72)	1.18 (0.57)	2.97E-05	2.93E-02	4.2E-05	3.7E-02
Log_{10}light 2 h prior sunset (2hrP)	0.92 (0.46)	0.81 (0.37)	1.07 (0.53)	0.96 (0.41)	1.25 (0.49)	1.17 (0.46)	1.28 (0.52)	1.16 (0.47)	6.93E-59	3.17E-74	3.4E-58	1.7E-73

Variable, mean (SD)	Winter (Nov-Jan)		Spring (Feb-Apr)		Summer (May-Jul)		Fall (Aug-Oct)		p-val*	p-val*	q-val	q-val
	HCHS/SOL *n* = 514	MESA *n* = 430	HCHS/SOL *n* = 530	MESA *n* = 492	HCHS/SOL n = 514	MESA *n* = 502	HCHS/SOL *n* = 589	MESA *n* = 486	HCHS/SOL	MESA	HCHS/SOL	MESA
Log_{10}light 2 h after sunset (2hrF)	0.75 (0.32)	0.73 (0.33)	0.75 (0.36)	0.72 (0.37)	0.73 (0.33)	0.71 (0.39)	0.81 (0.34)	0.81 (0.38)	6.11E-02	4.42E-07	7.4E-02	6.9E-07
Log_{10}light between sunrise and sunset	1.26 (0.54)	1.12 (0.41)	1.41 (0.5)	1.29 (0.43)	1.62 (0.46)	1.64 (0.42)	1.6 (0.48)	1.52 (0.43)	5.94E-237	4.61E-312	1.1E-235	1.17E-310
Log_{10}light between sunset and sunrise	0.44 (0.16)	0.44 (0.17)	0.41 (0.17)	0.38 (0.16)	0.39 (0.19)	0.37 (0.19)	0.43 (0.18)	0.43 (0.19)	1.41E-74	6.08E-106	8.1E-74	4.5E-105
Average log_{10}illuminance	0.79 (0.29)	0.72 (0.24)	0.92 (0.29)	0.85 (0.25)	1.12 (0.28)	1.16 (0.28)	1.03 (0.28)	1.01 (0.28)	2.32E-139	9.58E-181	2.1E-138	1.1E-179
Median illuminance	3.14 (4.7)	2.19 (3.85)	4.89 (6.15)	3.45 (5.48)	9.04 (9.62)	12.71 (19.68)	6.85 (6.91)	7.15 (8.47)	4.85E-60	3.34E-53	2.5E-59	1.4E-52
Average log_{10}light during sleep period	0.13 (0.11)	0.15 (0.12)	0.13 (0.11)	0.15 (0.12)	0.17 (0.14)	0.23 (0.18)	0.14 (0.13)	0.21 (0.18)	4.14E-10	3.49E-24	7.0E-10	1.1E-23
Average log_{10}light during active period	1.14 (0.42)	1.03 (0.34)	1.32 (0.42)	1.2 (0.37)	1.58 (0.38)	1.63 (0.39)	1.49 (0.4)	1.43 (0.39)	8.69E-135	6.47E-176	7.4E-134	6.8E-175
TALT $_{1000}$	0.9 (1.12)	0.49 (0.56)	1.3 (1.29)	0.9 (0.92)	2.08 (1.41)	1.95 (1.39)	1.76 (1.4)	1.38 (1.11)	3.14E-94	1.78E-140	2.1E-93	1.7E-139
TALT $_{100–1000}$	2.06 (1.48)	2.09 (1.44)	2.54 (1.51)	2.55 (1.47)	3.04 (1.6)	3.42 (1.62)	2.82 (1.54)	2.97 (1.55)	3.11E-41	4.36E-53	1.2E-40	1.8E-52
TALT $_{10–100}$	4.67 (1.64)	4.58 (1.76)	5.04 (1.61)	4.83 (1.6)	5.38 (1.62)	5.71 (1.69)	5.21 (1.52)	5.47 (1.81)	4.58E-15	2.94E-39	8.9E-15	1.0E-38
TALT $_{1–10}$	4.56 (2.3)	4.11 (1.91)	4.18 (2.21)	4.11 (2.18)	4.42 (2.35)	3.85 (1.98)	4.43 (2.21)	4.14 (2.06)	1.82E-02	2.19E-02	2.4E-02	2.8E-02
IP $_{1000}$	3.76 (2.76)	2.85 (1.99)	5.38 (2.99)	4.47 (2.74)	7.69 (2.73)	7.55 (3.02)	6.28 (2.76)	5.69 (2.69)	8.87E-187	7.66E-208	1.1E-185	1.2E-206
IP $_{100}$	9.39 (4.01)	10.22 (4.33)	10.64 (3.67)	11.36 (3.51)	11.97 (3.23)	13.27 (3.05)	11.18 (3.36)	12.29 (3.59)	6.14E-57	4.19E-49	2.8E-56	1.7E-48
IP $_{10}$	17.34 (2.97)	16.98 (3.33)	17.63 (2.91)	17.04 (2.72)	18.27 (2.89)	17.89 (2.68)	17.98 (2.87)	17.79 (2.94)	8.74E-08	4.10E-12	1.4E-07	7.3E-12
MLiTR $_{1000}$	12:35 (1.19)	12:35 (1.42)	13:26 (1.43)	13:21 (1.33)	14:04 (1.31)	13:40 (1.46)	13:36 (1.19)	13:33 (1.26)	3.16E-82	8.96E-35	1.9E-81	3.1E-34
MLiTR $_{100}$	13:08 (1.61)	13:00 (1.62)	13:39 (1.49)	13:27 (1.33)	14:03 (1.34)	13:44 (1.31)	13:47 (1.32)	13:40 (1.40)	3.57E-26	2.22E-15	1.2E-25	4.5E-15
MLiTR $_{10}$	14:11 (1.82)	14:03 (1.72)	14:24 (1.48)	14:09 (1.43)	14:35 (1.34)	14:14 (1.14)	14:28 (1.37)	14:16 (1.36)	9.58E-06	8.36E-02	1.4E-05	9.9E-02
FTL $_{1000}$	10:41 (1.86)	11:01 (1.67)	10:32 (1.98)	10:57 (1.81)	09:53 (2.09)	09:39 (1.95)	10:17 (1.86)	10:29 (1.81)	1.94E-20	1.83E-40	5.9E-20	6.7E-40

Variable, mean (SD)	Winter (Nov-Jan)		Spring (Feb-Apr)		Summer (May-Jul)		Fall (Aug-Oct)		p-val*	p-val*	q-val	q-val
	HCHS/SOL *n* = 514	MESA *n* = 430	HCHS/SOL *n* = 530	MESA *n* = 492	HCHS/SOL n = 514	MESA *n* = 502	HCHS/SOL *n* = 589	MESA *n* = 486	HCHS/SOL	MESA	HCHS/SOL	MESA
FTL $_{100}$	08:45 (2.44)	08:15 (2.39)	08:25 (2.18)	08:00 (1.85)	08:00 (2.24)	07:14 (1.86)	08:19 (2.22)	07:41 (2.13)	2.72E-13	3.29E-16	5.2E-13	6.9E-16
FTL $_{10}$	04:57 (2.54)	05:15 (2.53)	04:53 (2.48)	05:21 (2.24)	04:30 (2.56)	04:52 (2.28)	04:41 (2.49)	04:49 (2.42)	2.71E-03	6.21E-06	3.7E-03	9.3E-06
LTL $_{1000}$	14:34 (1.78)	13:58 (1.79)	16:10 (1.99)	15:38 (1.97)	17:50 (1.36)	17:33 (1.87)	16:46 (1.56)	16:26 (1.83)	1.45E-271	1.57E-195	3.1E-270	2.2E-194
LTL $_{100}$	18:14 (2.6)	18:40 (2.91)	19:09 (2.19)	19:31 (2.25)	20:00 (1.62)	20:32 (1.76)	19:29 (1.91)	20:01 (2.05)	1.31E-67	6.97E-47	6.9E-67	2.7E-46
LTL $_{10}$	22:20 (1.15)	22:18 (1.4)	22:31 (1.05)	22:22 (1.1)	22:45 (0.94)	22:41 (0.87)	22:39 (0.97)	22:34 (1.06)	9.22E-11	2.59E-12	1.6E-10	4.7E-12
Dim flag for possible occlusion, lux < 5 during active interval (hours)	6.74 (2.83)	7.18 (2.76)	5.67 (2.62)	6.53 (2.69)	4.29 (2.06)	3.84 (2.11)	4.68 (2.23)	4.84 (2.53)	8.78E-97	1.16E-130	6.2E-96	9.2E-130
Dim flag for possible occlusion, lux < 3 during active interval between sunrise and sunset (hours)	2.78 (1.71)	3.28 (1.7)	2.74 (1.8)	3.33 (1.86)	1.86 (1.42)	1.88 (1.46)	1.81 (1.35)	2.19 (1.57)	4.58E-57	1.96E-82	2.2E-56	1.2E-81
LEDS$_{TALT1}$(hours)	0.64 (1.11)	0.69 (1.04)	0.69 (1.23)	0.78 (1.31)	0.98 (1.46)	1.22 (1.45)	0.81 (1.36)	1.13 (1.44)	1.59E-06	9.56E-14	2.4E-06	1.8E-13
LEDS$_{TALT3}$(hours)	0.31 (0.46)	0.44 (0.65)	0.33 (0.47)	0.43 (0.73)	0.5 (0.64)	0.81 (0.94)	0.41 (0.61)	0.73 (0.97)	3.95E-09	1.14E-20	6.5E-09	3.5E-20

Note: “TALT” refers to duration of time spent at, above, or within a particular light threshold, respectively; “IP” refers to individual photoperiod; “MLiTR” refers to mean light timing revised at a particular threshold; “FTL” and “LTL” refer to first or last time of light exposure at a particular threshold; the dim flag for “possible occlusion” variables are exploratory metrics indicating possible device occlusion; and the “LEDS” variable indicates light exposure ≥1 or ≥ 3 lx during the sleep period.

*p-values from likelihood ratio test comparing a model with age, sex, and site with a model with additional cos and sin terms for month of measurement (1–12) as the predictor.

†Time-based (circular) outcomes were analyzed the same way as the linear outcomes; L5 start-time was re-centered.