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A systematic review of the amount and timing of light in association with objective and subjective sleep outcomes in community-dwelling adults

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ABSTRACT

Light is considered the dominant environmental cue, or zeitgeber, influencing the sleep-wake cycle. Despite recognizing the importance of light for our well-being, less is known about the specific conditions under which light is optimally associated with better sleep. Therefore, a systematic review was conducted to examine the association between the amount and timing of light exposure in relation to sleep outcomes in healthy, community-dwelling adults. A systematic search was conducted of four databases from database inception to June 2016. In total, 45 studies met the review eligibility criteria with generally high study quality excepting for the specification of eligibility criteria and the justification of sample size. The majority of studies involved experimental manipulation of light ($n = 32$) vs observational designs ($n = 13$). Broad trends emerged suggesting that (1) bright light (>1000 lux) has positive implications for objectively assessed sleep outcomes compared to dim (<100 lux) and moderate light (100-1000 lux) and (2) bright light (>1000 lux) has positive implications for subjectively assessed sleep outcomes compared to moderate light (100-1000 lux). Effects due to the amount of light are moderated by the timing of light exposure such that, for objectively assessed sleep outcomes, brighter morning and evening light exposure are consistent with a shift in the timing of the sleep period to earlier and later in the day, respectively. For subjectively assessed sleep outcomes, brighter light delivered in the morning was associated with self-reported sleep improvements and brighter evening light exposure was associated with worse self-reported sleep.

Introduction

Light is considered the dominant environmental cue, or zeitgeber, influencing the sleep-wake cycle.[1] Light input enters the retina; passes through the retinohypothalamic tract; and entrains the central circadian pacemaker, the suprachiasmatic nucleus, to a daily cycle.[2] Under natural conditions, the suprachiasmatic nucleus is reset daily by exposure to light. However, with advances in technology, exposure to light has become desynchronized from the natural light-dark cycle. As research on jet lag and the effects of shift work illustrates, this desynchronization can have a detrimental impact on sleep and overall well-being.[3–5] Despite recognizing the importance of light for our well-being, less is known about the specific conditions under which light is optimally associated with healthy sleep. Although the specific components of light in association with sleep have been examined in reviews focused on light interventions for

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specific disorders,[6,7] no systematic review to date has examined the role of light in relation to the sleep of healthy individuals.[8] As such, the objective of this review is to increase understanding of the association between light exposure and sleep outcomes in healthy community-dwelling adults.

As light is a multifaceted construct, multiple characteristics of light are important for the entrainment of the sleep-wake cycle. For example, facets of light exposure such as amount, timing, duration, rate of change, prior history, and spectrum have the potential to influence sleep outcomes.[9,19] Specifically, light exposure of insufficient amount or duration can result in unstable circadian rhythms that are desynchronized from the light-dark cycle.[10,11] Light exposure in the beginning of the night can induce a delay in the timing of the sleep period, whereas light exposure at the end of the night can induce a shift in the opposite direction, resulting in earlier timing of the sleep period.[12,13] The nature of the appearance of light (eg, more gradual vs sudden onset) can differentially affect sleep outcomes, and the impact of light can depend on prior light exposure history.[14] Lastly, the spectral composition of light has important implications for sleep, with light enriched in blue wavelengths being more impactful than wavelengths outside of this range.[15,16]

The current review will focus on 2 specific components of light exposure: amount and timing. These 2 components of light exposure are selected for specific focus given that they are salient to individuals and, consequently, are amenable to modification within a home environment. As such, any conclusions drawn from the review of these 2 characteristics of light have the potential to be tested and applied within the daily lives of community-dwelling adults. Conversely, the average individual is less likely to be aware of other components of light exposure such as the rate of change or spectrum of light. Furthermore, the amount and timing of light have a longer history of being examined or manipulated in studies of light exposure and sleep compared to the other characteristics of light which have been investigated only more recently. Unfortunately, a comprehensive review of the literature examining multiple characteristics of light in association with sleep is prohibited by the lack of studies including multiple characteristics of light.

The *amount of light exposure*, or illuminance level, is defined as the amount of light measured in a specified area. Light can be quantified in "lux" units (equivalent to a 0.0929 foot-candle), with lux levels approximately corresponding to the illumination of objects and surfaces by the following indoor and outdoor light sources: >100,000 lux = sunlight, ~1000 lux = overcast day, ~500 lux = indoor office, ~300 lux = living area within a home, and ~10 lux = twilight.[17,18] The amount of light required to entrain the sleep-wake cycle depends on a complex combination of the above-mentioned characteristics of light. To organize the literature and enable comparison across multiple levels of light, for the purpose of this review, the amount of light will be compared across 3 broad categories: dim (<100 lux), moderate (100- 1000 lux), and bright light (>1000 lux). These categories are selected based on their face validity such that natural outdoor daylight is visually distinguishable from indoor lighting to the naked eye.[20] Consequently, any conclusions drawn from the review will have ecological validity within natural environments with individuals able to discern whether they are being exposed to dim, moderate, or bright light (eg, 1000 lux is considered a reliable level for differentiating between artificial and natural light).[20] As a result, any summary conclusions based on the review could have real-world applicability for individuals interested in how the amount of light affects their sleep. Furthermore, these categories are congruent with many clinical recommendations for light exposure (eg, limit exposure to even dim light at night).[21] As such, the use of these categories can facilitate communication between providers and clients/patients Lastly, this categorization schema will be adopted to facilitate abstraction across studies, as the vast majority of the reviewed articles used some combination of these categories (31 of 45 studies).

Timing of light exposure is categorized as broadly occurring during the morning, afternoon, evening, or across the full 24-hour day of the solar day. The time of day that individuals are exposed to light is an important factor to examine in association with sleep outcomes, as the proximity of light exposure to the sleep period has the potential to shift the timing of sleep period. Light presented early in the night is associated with shifts in timing to a later hour (delay), and light presented in the late night or early morning is associated with shifts in timing to an earlier hour (advance).[22] Furthermore, light exposure during the day also shows potential to shift sleep timing.[22]

In sum, given the theoretical and empirical research linking light exposure to sleep outcomes, there is a need to systematically summarize the existing body of literature in this area. Furthermore, there is a need to collate literature on this topic within healthy, community-dwelling adults. Therefore, this systematic review has the following aims:

1 To describe the association between the amount of light exposure and objective and subjective sleep outcomes in healthy, community-dwelling adults. Specifically, to assess whether dim (<100 lux), moderate (100-1000 lux), or bright (>1000 lux) light is differentially associated with objective and subjective sleep outcomes in experimental and observational designs.
2 To describe the association between the timing of light exposure and objective and subjective sleep outcomes in healthy, community-dwelling adults. Specifically, to assess whether the time of day of light exposure (eg, morning, evening, or night) is differentially associated with sleep outcomes within experimental and observational studies.

Methods

This systematic review was conducted according to the guidelines presented by the Preferred Reporting Items for Systematic Review guiding document.[23]

Eligibility criteria

Studies were selected for inclusion in the review based on the following study and review eligibility criteria: (1) published or translated into English; (2) participants are human; (3) participants are 18 years of age or older; (4) contains original research; (5) measures of light amount and timing and sleep are included; (6) quantitative (vs solely qualitative) data are presented; (7) light and sleep are not assessed solely in the context of treatments for clinically diagnosed disorders (eg, disordered sleep, dementia, mood disorders); (8) participants are not blind or visually impaired; (9) participants are not engaging in shift work; (10) disordered sleep is not the only sleep outcome; and (11) participants are community-dwelling individuals (vs inhabiting institutionalized settings such as assisted living, inpatient, or hospital environments).

Information sources and search strategy

A systematic search (from database inception to June 2016) was conducted across 4 databases: PubMed, PsycINFO, Cumulative Index to Nursing and Allied Health Literature, and Scopus. Search terms were decided a priori and piloted by the research team and health information specialists with systematic review experience (JC and NB). Search terms varied depending on the database used and consisted of controlled vocabulary and keywords referencing measures of light (light, photoperiod, phototherapy, lighting, sunlight, lux, LAN, artificial dawn, illumination, photic, light*, photo*, lumin*) and sleep (sleep, REM, NREM, sleep stages, sleep onset, sleep wake cycle, wakefulness, polysomnography, actiwatch). An example search using the PubMed database is presented below:

Sample search strategy for PubMed/MEDLINE.

1. "Light, Photoperiod, Phototherapy, Lighting"[Mesh] OR "Sunlight"[Mesh].
2. Light*[tiab] OR "Illumination"[tiab] OR Photic*[tiab] OR Photo* [tiab] OR Lumin*[tiab] OR "Sunlight"[tiab] OR "Lux"[tiab] OR "LAN"[tiab] OR "Artificial Dawn"[tiab].
3. #1 OR #2.
4. "Sleep"[Mesh] OR "Sleep, REM"[Mesh] OR "Sleep Stages"[Mesh] OR "Polysomnography"[Mesh].
5. Sleep*[tiab] OR "Polysomnography"[tiab] OR "REM"[tiab] OR Actiwatch*[tiab].
6. #4 OR #5.
7. #3 OR #6.

Data management, selection, and collection process

Search results were exported to reference management software where any duplicates were removed (see Fig. 1). The title and abstract of each of the nonduplicate records were screened by 2 reviewers (ND, DS, JI, KS, CT, AL, or CO) for inclusion based on the eligibility criteria. Two reviewers then screened the full text of each paper for inclusion in the review (ND, DS, JI, KS, or CT). Across both stages of the screening, reviewer discrepancies were resolved by a third reviewer and discussed with the review team until consensus was reached. Study quality was assessed according to criteria selected from the Methods Guide for Effectiveness and Comparative Effectiveness Reviews that was developed by the Agency for Healthcare Research and Quality.[24] Quality ratings were conducted by one reviewer (ND or DS), with 25% overlap of the records rated by both reviewers. Items for data extraction were selected based on recommendations from the STROBE statement regarding data extraction.[25] Data extractions were performed by one reviewer with verification of a random sample of 25% of extractions by an additional reviewer (ND or DS).

Results

Search results

Systematic searches resulted in 10,779 unique articles to screen after duplicates were removed. After title and abstract screening for the eligibility criteria, 342 articles were retained for the full-text screening. Based on the full-text review, 45 articles met full eligibility criteria for inclusion in the review. Please see Fig. 1 for a flowchart of the screening process.

Study characteristics

Characteristics of the included studies are summarized in Table 1. In terms of the amount of light, 4 studies compared dim to moderate light, 4 studies compared moderate to bright light, and 23 studies compared dim to bright light. Studies assessed light exposure at multiple points of the day: 30% morning, 43% evening/night, 23% full day of light, and .04% afternoon light. The duration of light exposure ranged from 5 minutes to 24 hours. The 24-hour duration of exposure occurred in studies using actigraphy to record daily light. When the 24-hour actigraphy studies are excluded from totals, the mean duration was 3.01 hours (SD = 3.21, range 5 minutes to 16 hours). The spectrum of light was not reported in the majority of articles (58%). Of those articles that did report spectrum levels, 19 used the full spectrum of visible light, and 2 specified lux of a specific wavelength. Only 62% of articles recorded participants' light history.

Study design

Included articles were published between 1986 through 2016. The majority of studies implemented an experimental design (n = 30), with light amount or timing experimentally manipulated in comparison to a control condition (eg, dim light) or another time period (eg, morning vs evening exposure). The remaining studies (n = 15) used an observational design with light amount or timing assessed in association with sleep outcomes in naturalistic settings.

Sample characteristics

Based on the reported data, samples consisted primarily of younger adults (60%, ages 18-39), followed by older adults (22%, age 60+), middle-aged adults (14%, ages 40-60), and adults spanning the adult lifespan (4%). The majority of research was conducted with samples from North America (38.64%), followed by Asia (31.82%), Europe (25%), Australia (2.27%), and South America (2.27%). The majority of participants were male (53.71%), and the sample size of studies ranged from 5 to 15,863. Only 2 of the included studies reported race and ethnicity information for the sample. The samples for these 2 studies were 90%[26] and 72%[27] White/non-Hispanic.

Light and sleep measures

Light was delivered or assessed through both objective (93%) and subjective (7%) methods. Specifically, the majority (67.39%) of studies manipulated light using a calibrated device such as a light box, overhead lighting, visor, or dawn stimulation. Other objective devices or measures included actigraphy with a light sensor (21.74%), hobo light pendant (2.17%), or an eReader device (2.17%). A minority (6.52%) of studies used subjective methods such as a retrospective survey of light exposure. Sleep outcomes were also assessed using objective (59.37%) and subjective methods (40.63%). Polysomnography was the primary measure used (32.81%), followed by self-reported retrospective logs or measures (28.31%), actigraphy (25%), self-reported daily diaries (12.50%), and an under mattress monitoring system (1.56%).

Quality assessment

A summary of the assessment of study quality criteria is presented in Fig. 2. Each study was evaluated to determine whether the following criteria were met: (1) a priori aim and/or hypothesis; (2) sample size was justified through power analysis or based on effect sizes from previous studies; (3) specification of relevant eligibility criteria; (4) validated and direct measures of light; (5) validated measures of nocturnal sleep; and (6) interpretation of the results and the conclusions are believable considering the study limitations. Overall, the majority of reviewed studies (>73%) met 5 of the specified quality criteria. However, the majority of studies (95.35%) did not justify the sample size for their proposed aims and analyses.

Primary results

In total, 45 studies were included in the review. Of this total, the majority involved experimental manipulation of light (n = 32) compared to observational designs (n = 13). The majority of the experimental designs manipulated light amount (n = 30) but not timing (n = 2). The results are grouped by sleep outcome (objective vs subjective) with the results within each sleep outcome organized into 5 different sections based on lux levels (dim vs moderate, dim vs bright,

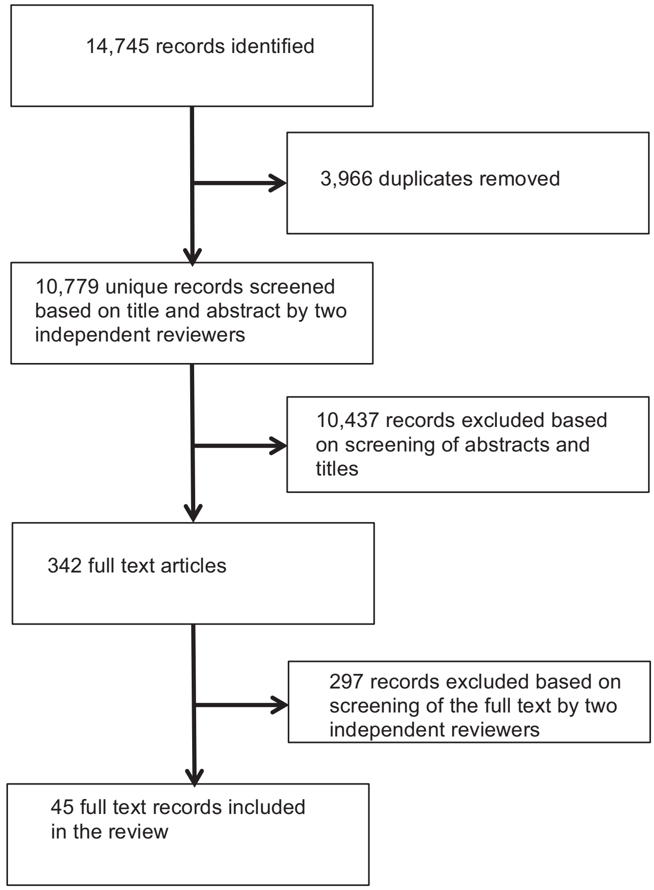

Fig. 1. Flowchart of studies illustrating the screening process.

moderate vs bright, light exposure with no specific lux identified, and light exposure with lux specified but no comparisons across lux levels).

Objectively assessed sleep outcomes

Of the 45 reviewed studies, 36 included objectively assessed sleep outcomes. Lux was compared across multiple levels with the majority of studies comparing sleep outcomes between dim vs bright light (19 studies). The proportion of studies with significant findings differed across lux comparison levels: 0% (dim vs moderate light), 100% (moderate vs bright light), and 68% (dim vs bright light). Furthermore, when light was analyzed as a continuous variable, light variables were associated with objective sleep outcomes in 73% of studies. Finally, light was associated with objective sleep outcomes in 33% of studies that did not involve comparisons across the specified lux categories.

Although the timing of light exposure was not manipulated in the majority of studies, light was delivered or assessed at various time points across studies (eg, morning, afternoon, evening, and full day exposure). The most consistent findings across reviewed studies involved an interaction between time of day of light presentation and lux levels. Overall, compared to dim light, brighter morning light was associated with an advance of the sleep period (eg, shorter sleep onset latency and earlier wake time). Conversely, compared to moderate and dim light, brighter evening light was associated with sleep changes consistent with a delay of the sleep period (eg, longer sleep onset latency and later wake time). Bright morning light was associated with mixed outcomes for other components of sleep such as fewer awakenings, greater wake after sleep onset, more fragmented sleep, and lower sleep efficiency. Findings from studies examining light as a continuous variable without specifying lux also showed an interaction between the time of day of light presentation and light levels such that greater average lux exposure in the morning was associated with sleep changes consistent with an advance and greater average lux exposure in the evening was associated with sleep changes consistent with a delay. Furthermore, overall lower levels of lux exposure during the day were associated with sleep characteristics consistent with a delay.

Dim vs moderate light. Light exposure less than 100 lux was compared to light exposure between 100 and 1000 lux in 2 experimental designs assessing the effects of exposure to light boxes during the morning[28] and evening.[29] No differences were observed for objective sleep outcomes assessed via polysomnography[29] or actigraphy (motor activity during sleep)[28] between the 2 quantities of light. The Santhi et al (2012) study examined illuminance differences (~146 lux vs ~773 lux) while controlling for light spectrum, and the Kohsaka et al (1999) study compared illuminance of 1000 lux to a control condition (indoor lighting without light box).

Moderate vs bright light. The effects of illuminance levels on objectively assessed sleep were assessed by one study comparing 300 lux of light emitted from a desk lamp to light ranging from 3800 to 6000 lux emitted from light racks during the evening.[30] The higher lux condition resulted in significantly longer sleep latency and delayed sleep onset time as recorded by polysomnography compared to the lower lux condition.

Dim vs bright light. Nineteen studies compared the effects on objective sleep outcomes from illuminance levels less than 100 lux to those greater than 1000 lux.[31–49] Significant associations between light exposure and objective sleep outcomes were observed in 13 of the 19

Table 1
Summary of study characteristics

Citation	Study design	Sample: N, sex (% female), age (M [SD], range), race/ethnicity, country	Light measures	Sleep measures	Covariates	Association between light and sleep outcomes
Boubekri et al, 2014	Obs: compared work environments with windows to those without. Light history not specified.	49, 61%, 19-60+ y, 90% White/non-Hispanic, 4% Black/African American, 2% American Indian/Alaskan Native, 2% Latino/Hispanic, 2% other, United States	Daylight deprivation survey (amount of exposure to daylight [never to always], hours of outdoor activities, duration of light exposure); actigraphy at the wrist (average 8.4 d) assessing light, activity, and sleep, spectrum not specified.	PSQI; actigraphy (~11 d): sleep onset time, sleep onset latency, sleep efficiency, wake after sleep onset, sleep time, sleep fragmentation.	No	Workers without windows reported poorer overall PSQI global sleep quality and significant PSQI sleep disturbance. Workers with windows slept 46 min longer during workweek nights and 117 min longer on free days compared to windowless workers according to actigraphy. More light exposure measured by actigraphy during work hours was significantly correlated with actigraphically measured longer sleep time during work nights.
Bunnell et al, 1992	Exp: adaptation night, counterbalanced bright light night followed by dim light night, repeated following week in reverse order. Light history: Subjects arrived at lab each day 3 h before bedtime.	5, 0%, ages 20-28 y, United States	Color monitor: video tapes on color monitor (<100) lux vs full-spectrum fluorescent lights (>2500) lux for 2 h before bed, photometrically measured at eye level.	Polysomnography: duration of stages 1-4, REM, wake after sleep onset, movement, sleep latency, REM latency, slow wave sleep.	No	Greater REM latency and NREM duration in bright light condition.
Burgess et al, 2001	Exp: 6 d: adaptation night, dim light night, counterbalanced bright light night and bright light + melatonin (5 mg) night. Light history: participants light exposure was self-selected while outside the lab.	16, 50%, $M = 21.3$ (2.7), Australia	Light box: <10 lux vs >3000 lux; 30 min duration, 1.5 before to 2.5 h after melatonin onset, spectrum not specified.	Polysomnography: sleep onset latency to stage 1 (SOL1) or stage 2 (SOL2) sleep.	No	Greater latency to stages 1 and 2 sleep in bright light vs dim light and bright light + melatonin conditions.
Burgess et al, 2003	Exp: between-subjects design (3 groups: continuous light, intermittent light, dim light administered for 3 d), baseline sleep period followed by fixed sleep schedule. Light history: full night's sleep ($M = 7.6 \pm 0.5$ h.) before morning light treatments.	28, 50%, $M = 27.7$ (5), 22-43 y, United States	Light box: 3.5 h continuous bright light exposure, intermittent bright light for 3.5 h (.5 h on, .5 h off), or dim ordinary light at <60 lux for 3.5 h), bright light was ~3000-11,000 lux depending on angle of gaze, measured at eye level, full spectrum, all light lux completed in morning.	Daily sleep log (bedtime, sleep onset time, wake time, final morning awakening, naps); actigraphy (total sleep time, movement time, sleep onset latency, sleep efficiency).	No	Sleep diary sleep onset latency lengthened during treatment in both continuous and dim light groups but not the intermittent group, actigraphic movement time decreased across treatment for all 3 groups.
Cajochen et al, 1998	Exp: placebo controlled 4-wk crossover design with randomization (bright light exposure (5000 lux) or no bright light (<10 lux). Light history: participants wore sunglasses in the morning before reporting to the lab at 1000 hours, remained in <150 lux room, procedure at 1400 hours	10, 0%, $M = 27$ (5), Switzerland	Light box: 3 h bright light (5000 lux at eye level) exposure or no bright light (<10 lux) exposure from 2100 to 2400 hours, spectrum not specified.	Leed's Sleep Evaluation questionnaire completed 10 min after awakening (sleep quality, sleep latency, awakening process); polysomnography (total sleep time, sleep efficiency, sleep latency, REM sleep latency, stage 1, stage 2, slow wave sleep, REM sleep arousal).	No	During treatment, bright light increased sleep latency (objective and subjective). Superficial sleep (objective stage 1 and arousal within sleep) increased after bright light tx. During posttreatment night - objective sleep onset delayed after bright light treatment.
Cajochen et al, 2008	Exp: balanced crossover design with intrasubject	8, 0%, $M = 26.6$ (6.5), Switzerland	Light box: initial 6-h light deprivation	Polysomnography: total sleep time, sleep	Preintervention expectations, caffeine,	No difference in sleep outcomes by light

(continued on next page)

Table 1 *(continued)*

Citation	Study design	Sample: N, sex (% female), age (M [SD], range), race/ethnicity, country	Light measures	Sleep measures	Covariates	Association between light and sleep outcomes
	comparisons, 3 light conditions (left side bright light, right side bright light, no light). Light history: participants were requested to avoid direct exposure to sunshine before reporting at 10:00 AM to the lab		episode (8 lux, polychromatic, at eye level; polychromatic white light) followed by Bright Light Box: 2 h of 1500 lux, full daylight spectrum, from the left side or right side in 15-min bursts with 5-min rests from 2000 to 2200 hours	efficiency, sleep onset latency, REM sleep onset latency, waking after sleep onset, stage 1-4, slow-wave sleep, REM sleep.	alcohol, sleep time, medical history	condition.
Campbell et al, 1992	Exp: within-subjects design, baseline night, 3 consecutive days morning bright light Light history: after 8 h of sleep in the lab, participants were exposed to bright light between 0715 hours and 1115 hours.	7, 86%, $M = 21.9$ (1.9), United States	Light boxes: ~4000 lux at eye level, full spectrum, 4 h (0715-1115 hours).	Polysomnography: sleep onset latency, wake after sleep onset, sleep efficiency, sleep stage percentages, stage changes, REM latency.	No	Treatment associated with significantly shorter sleep onset latencies, greater wake after sleep onset, lower sleep efficiency, and more fragmented sleep illustrated by higher number of stage changes.
Carrier et al, 1995	Exp: between-subjects design, 17 d: first 6 spent at home, 2 adaptation nights, 1 sleep eval day, 3 baseline days, 3 d bright light exposure, 2 d posttreatment sleep and eval, 3 d additional eval. (morning group, afternoon [control] group, evening group). Light history: ambient light exposure <100 lux while at lab.	23, 28%, $M = 22.8$ (0.9), Canada	Light panels: 5 h, 6000-13,000 lux at eye level; Morning group: 0830-1330 hours; Afternoon group: 1330-1830 hours; Evening group: 1830-2330 hours, spectrum not specified.	Polysomnography: sleep latency, wake in first 90 min of night, wake in last 90 min of night, sleep efficiency, number of stage transitions, %stage 2, slow wave sleep, slow wave sleep latency, % REM, REM latency from lights off and sleep onset.	No	Sleep onset latency was increased by evening bright light, decreased by morning bright light, and was not affected by afternoon bright light. Evening group was different from morning and afternoon but morning did not differ from afternoon. Amount of wakefulness in first 90 min was lower for morning light, increased for evening light, and no change for afternoon light. Evening group differed from morning and afternoon but morning did not differ from afternoon.
Ceolim et al, 2000	Obs: 23 consecutive days of actigraphy with healthy elderly subjects who exercised daily. Light history not specified.	23, 65%, $M = 70.17$ (3.55), 65-76 y, Brazil	Actigraphy: >3000 lux, measured at wrist, was considered bright light, spectrum not specified.	Daily sleep log; Actigraphy; sleep onset latency, sleep termination, sleep duration, sleep efficiency, total 24 h sleep time, naps per day (onset, offset, duration).	No	Duration of bright light exposure showed positive correlation with subjective sleep quality.
Chang et al, 2015	Exp: randomized crossover design with adaptation night followed by 2 conditions presented for 5e nights each with 1 night between conditions; light-emitting ebook compared to print book. Light history not specified.	12, 50%, $M = 24.92$ (2.87), United States	Light-emitting eReader vs printed book held by participants; both conditions read in very dim light, 4 h before bed, spectrum not specified.	Polysomnography: sleep onset latency, total sleep time, sleep efficiency, time spent in each sleep stage.	No	In the light-emitting eReader condition, sleep onset latency was longer (10 min), there was less REM sleep (12 min) and no difference in total sleep time or other sleep stages.
Cho et al, 2016	Exp: randomized design with 2 conditions 5 lux vs 10 lux; 3 nights (adaptation night, night without light, and night with light condition). Light history: lights on at 0700 and off at 2300 hours	23, 0%, $M = 22.26$ (2.65), 19-29 y, South Korea	LED dim light box (general color rendering index: 90) placed opposite participant's head emitting either 5 or 10 lux, measured at eye level, from 2300 to 0700 hours.	Polysomnography: time in bed, total sleep time, sleep efficiency, wake after sleep onset, sleep onset latency, stage N1, stage N2, stage N3, stage R, Stage R latency, REM density, total arousal time, spontaneous arousal	Total sleep time	Significant sleep differences between nights with light vs no light but no significant differences between lux groups. Nights with light were associated with worse wake after sleep onset, increased stage N1, decreased

Table 1 *(continued)*

Citation	Study design	Sample: N, sex (% female), age (M [SD], range), race/ethnicity, country	Light measures	Sleep measures	Covariates	Association between light and sleep outcomes
				time.		stage N2, increased stage R.
Cooke et al, 1998	Exp: within-person design, 3 phases (pre/post [7 d] and treatment [14 d]). Light history not specified.	10, 100%, $M = 79.4$ (6.7), 67-87 y, United States	Light visor worn on participant's head for 30 min each evening that emitted 2000 lux at the eyes, spectrum not specified.	Home monitoring system (pressure-sensitive pad under sheet or mattress pad) and sleep logs: time in bed, sleep onset latency, sleep, total 24 h sleep, sleep period, longest sustained sleep period, wake after sleep onset, number of awakenings, sleep efficiency.	No	Decreased sleep onset latency and increased sleep (time spent asleep excluding arousals) during light treatment weeks and maintained during posttreatment week.
Dijk et al, 1989	Exp: balanced crossover design with 2 light conditions (dim vs bright light), 3 consecutive days (evening dim light, then sleep, then morning bright or dim light), 4th day sleep until refreshed. Light history: 1900-2200 hours at 1 lux, 2200-0600 hours at 0 lux, dim/bright condition from 0600 to 0900 hours	8, 0%, $M = 23.1$ (2.5), Netherlands	Dim light: 3 h at 1 lux, Bright light: 3 h light screen - white fluorescent lamps 2000 lux measured at eye level; delivered 0600-0900 hours	Polysomnography: stage 2-4, sleep onset, sleep duration, REM/non-REM power densities; Groningen Sleep Complaints Scale.	No	Bright light advanced time of sleep termination, sleep onset held constant, reduction in sleep duration was at expense of REM sleep.
Dijk et al, 1991	Exp: balanced crossover design with 2 light conditions (dim vs bright light), 3 consecutive days (adaptation night, second night either bright or dim light, third night dim or bright light [opposite of second night]). Light history: participants arrived at lab at 1930 hours and were exposed to dim/bright conditions from 2100-0000 hours.	7, 0%, 23-32 y, Switzerland	Light box: dim light (1 h at 6 lux), bright light (1 h at 2500 lux, full spectrum, measured at eye level), delivered 2100-0000 hours.	Polysomnography: stage 1-4, REM, sleep onset, sleep duration.	No	Bright light significantly increased sleep onset latency.
Drennan et al, 1989	Exp: counterbalanced crossover design with 2 groups, 2 light conditions (bright vs dim light), 2 instances of 3 consecutive days (3 evenings bright or dim light exposure, 5 d recuperation, 3 evenings reversed light condition). Light history: light exposure between 0800 and 1800 hours not experimentally controlled, but randomized between bright-light and dim-light conditions.	9, 0%, 18-30 y, United States	Dim light: desk lamp, 300 lux at eye level. Bright light: two full spectrum white fluorescent light racks, 3800-6000 lux. Both conditions: 1st night - 3 h, 1800-2100 hours. 2nd/3rd nights - 5 h, 1800-2300 hours.	Polysomnography: stage 2-4, REM, sleep onset latency, REM onset latency, total sleep time.	No	Bright light increased sleep latency and delayed sleep onset time.
Fukushige et al, 2014	Exp: between-person, 4 groups: (Poor*Dim, Poor*Bright, Rich*Dim, Rich*Bright), lasting 5 d and 4 nights, either tryptophan-poor or	33, 0%, $M = 22$ (3.1), Japan	Dim light: <50 lux; Bright light: natural light/lighting device <5000 lux; both conditions: between 730-1800 hours,	Actigraphy: sleep efficiency, sleep latency; Oguri-Shirakawa-Azumi (OSA) sleep inventory.	Food intake	No significant differences or interactions in sleep efficiency and latency as assessed from actigraphs. No

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Table 1 *(continued)*

Citation	Study design	Sample: N, sex (% female), age (M [SD], range), race/ethnicity, country	Light measures	Sleep measures	Covariates	Association between light and sleep outcomes
	-rich breakfast in the morning, dim or bright light during the daytime. Light history not specified.		measured at eye level, spectrum not specified.			significant group differences on the OSA.
Gimenez et al, 2010	Exp: 2 studies, each a within subject design study 1: light from wake-up light varied every 2 wk (control [0 lux], medium [50 lux], high [250 lux]) study 2: artificial dawn wake up light, participants chose the amount of light (ranged from 20-400 lux), randomized to use self-selected amounts for 2 wk (dawn condition) or 0 lux (control condition). Light history not specified.	Study 1 and 2 combined: 46, 54%, *M* = 30 (11), the Netherlands	Artificial dawn wake-up light used during waking for 30 min duration, Study 1: control (0 lux), medium (50 lux), high (250 lux) in morning, Study 2: control (0 lux) or self-selected amount (range from 20 to 400 lux), full-spectrum light.	Daily sleep diaries: bedtime, sleep onset, alarm time, sleep offset, get-up time.	No	Bedtime and sleep offset not significantly different across conditions for study 1 and 2. In study 2, sleep offset was earlier in artificial dawn condition vs control.
Gordijn et al, 1999	Exp: counterbalanced crossover, 4 consecutive days a week for 4 wk. 1st wk: 3 d dim light and then sleep. 4th day, dim light and sleep until refreshed. 2nd wk: same with bright light instead, 2 groups - morning light and evening light. 4th wk, conditions reversed from 2nd wk Light exposure controlled within the lab environment.	12, 50%, *M* = 39.3 (12.1), 23.6-56.7 y, Netherlands	Dim light: <10 lux, Bright light: 2500 lux, (group 1: 0600-0900 hours; group 2: 1800-2100 hours). Bright light: full spectrum fluorescent light tubes in a light box placed vertically at an eye distance of 60 cm; ultraviolet light (<400 nm) was filtered out.	Polysomnography: sleep latency, sleep termination, tendency for sleep termination, movement time, REM latency, duration of first REM episode.	No	Average time of sleep termination after morning light condition was significantly earlier than sleep termination after evening light condition. In morning light condition, duration of first REMS episode was longer than evening light.
Higuchi et al, 2005	Exp: randomized crossover design with adaptation night followed by experimental night of exposure to bright vs dark light video display terminal. Light history not specified.	7, 0%, *M* = 24.7 (5.6), Japan	Color display: bright light (45 lux) and dim light (15 lux) at eye level, delivered between 2300 and 0145 hours, spectrum not specified.	Polysomnography: sleep onset latency, total REM sleep, total sleep time, REM latency, sleep efficiency, movement time, wake and total time of stage 1, 2, and slow wave sleep, slow wave activity.	No	No significant group differences between bright and dark light variables for all sleep variables.
Ishibashi et al, 2010	Exp: participants blinded, crossover, counterbalanced design, acclimation night followed by experimental nights in each condition separated by 1 wk. Light history: participants reported to the lab at 20.00, and remained in 650 lux until 00:00 when light conditions commenced	10, 0%, *M* = 23.9 (1.3), 19-32 y, Japan	White fluorescent lamps delivered 30 vs 5000 lux (approximate illuminance levels at ~17 and 1700 at eye level) from 2130 to 0000 hours.	Actigraphy: sleep onset latency.	No	No significant differences between 2 light conditions in terms of sleep onset latency.
Kobayashi et al, 1999	Exp: between-subjects design (bright light, control), protocol = 5 d of light + sleep monitoring starting on night 4. Light history not specified.	10, 100%, *M* = 61.7 (2.3), 50-72 y, Japan	Light box: bright light condition = 8000 lux for 1 h in the morning for 5 consecutive days (control = sit in front of device without light), spectrum not specified.	Polysomnography: time in bed, sleep period time, total sleep time, sleep efficiency, number of awakenings, sleep latency, REM sleep latency, proportion of each sleep stage to sleep period time;	No	No significant differences for polysomnography-measured sleep except for proportion of awakening time in first 1/3 of sleep decreased and proportion in last 1/3 of sleep increased in

Table 1 *(continued)*

Citation	Study design	Sample: N, sex (% female), age (M [SD], range), race/ethnicity, country	Light measures	Sleep measures	Covariates	Association between light and sleep outcomes
				Subjective sleep evaluated with Oguri-Shirakawa-Azumi (OSA) sleep inventory: sleepiness, sleep maintenance, anxiety, integrated sleep, sleep initiation.		bright light compared to control condition. Sleep maintenance in the OSA was higher in the bright light vs control condition.
Kohsaka et al, 1998	Exp: balanced crossover design, bright light (6000 lux) and control conditions. Light history not specified.	7, 0%, 61-78 y, Japan	Desktop lighting device: (bright light - 6000 lux or control), sat in front of device for 30 min in the morning for 6 d, spectrum not specified.	Actigraphy for 6 d; Oguri-Shirakawa-Azumi (OSA) subjective sleep feelings/quality for 6 d; polysomnography for one night (6th night).	No	Actigraphic counts of motor activity during sleep were significantly reduced in light condition vs control.
Kohsaka et al, 1999	Exp: counterbalanced crossover design, examined under moderately bright light (1000 lux at eye level) and control condition. Light history not specified.	8, 100%, $M = 67.4$, 56-72 y, Japan	Light box: bright light (1000 lux at eye level) or control, sat looking directly at light source for 1 h in the AM for 1 wk, spectrum not specified.	Oguri-Shirakawa-Azumi (OSA): subjective sleep feelings/quality measured by sleep maintenance, sleep initiation, anxiety, integrated sleep, sleepiness; Actigraphy.	No	Sleep maintenance, integrated sleep significantly increased on 4th day of bright light condition, motor activity measured via actigraph was not different by condition.
Kohsaka et al, 2000	Exp: bright light vs control light for 6 d. Light history not specified.	5, 0%, $M = 69.0$ (3), 66-72 y, Japan	Light box: bright light (6000 lux) or control light (no light) for 30 min each morning, spectrum not specified.	Polysomnography on 6th night: time in bed, sleep period time, total sleep time, sleep latency, REM latency, sleep efficiency, waking time, number of awakenings, sleep stage percentage, REM sleep fragmentation by stage 1 or stage W.	No	Bright light exposure was associated with shorter time in bed, fewer awakenings, and decreased time to stage 1 sleep from REM (measured by polysomnography).
Komada et al, 2000	Exp: within-person, bright light vs dim light, counterbalanced, crossover design, 1 night adaptation, 1 night exposure to condition, 5-d break, 1 night adaptation, 1 night exposure to condition. Light history not specified.	7, 42%, $M = 22.7$ (0.76), 22-24 y, Japan	Light box: Bright or dim light for 40 min before bed (2500 lux vs no lux) measured at eye level, spectrum not specified.	Polysomnography: stage α: a train of ≥50% alpha activity; stage d: suppressed waves; stage θ: low-voltage theta waves; stage v: vertex sharp waves; stage s: at least 1 well-defined spindle.	No	Prolonged sleep onset process (longer latency of appearance of theta waves) following bright light exposure.
Kripke et al, 2004	Obs: prospective crosssectional design, actiwatch worn up to 1 wk. Light history: reported through actigraphy.	416-450, 100%, $M = 67.7$ (7.9), 72.2% European American, 13. % Hispanic American, 9.4% African American, 4.0% Asian-Pacific American, 0.7% Native-Aleut America, United States	Actigraphy wrist monitor with light lux variables of mesor $\log_{10}$ [lux] and acrophase of light, spectrum not specified.	Actigraphy sleep duration; daily sleep diary sleep duration; 10-item retrospective sleep questionnaire (poorer sleep quality, trouble falling asleep, waking up several times a night, waking up earlier than planned, trouble falling back asleep).	Age, ethnicity	Lower average light amounts associated with higher actigraphic sleep duration and later bed and wake times; lower light amounts were also associated with self-reported poorer sleep quality, trouble falling asleep, waking up several times a night, waking up earlier than planned, trouble falling back asleep.
Kubota et al, 1998	Obs: dim light (wk 1) or bright light (wk 2) in the evening for 5 d. Light history: participants arrived at lab at 17.30 h, exposed to light conditions from 1900 to 2130 hours.	6, 0%, $M = 26$ 21-35 y, Japan	Light box: dim light,150 lux; bright light, 3000 lux; 2.5 h (1900-2130 hours) at eye level, spectrum not specified.	Self-report questionnaire.	No	Sleep initiation and sleep quality were aggravated significantly by evening bright light exposure.

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Table 1 *(continued)*

Citation	Study design	Sample: N, sex (% female), age (M [SD], range), race/ethnicity, country	Light measures	Sleep measures	Covariates	Association between light and sleep outcomes
Lee and Kimble, 2009	Obs: cross sectional and descriptive exploratory design (48 h). Light history: reported through actigraphy.	20, 100%, $M = 23.6$ (5.5), United States	Actigraphy worn for 48 h, spectrum not specified.	General Sleep Disturbance Scale (GSDS), Actigraphy (total sleep time, wake time after sleep onset).	No	Greater average daytime light exposure associated with less subjectively reported sleep disturbances, less actigraphically assessed total sleep time, and earlier wake time according to actigraphy.
Leppamaki et al 2003	Community-Based Exp: 2 d of adaptation, followed by 8-wk period, dawn simulators used for 2 wk at a time, each subject served as their own control (ABAB design). Light history not specified.	77, 61%, $M = 35.3$, 18-70 y, Finland	Dawn simulation: adaptation = max level for 2 d, followed by 200 lux for first day, 100 lux or 300 lux for day 2, instructed to keep the simulator to their preferred setting (ie, 100, 200, 300 lux, measured by dawn simulator settings) for remainder of study. Simulators activated 30 min prior to waking Spectrum: "Colored Sunrise Simulation."	14-item Quality of sleep daily diary scale (Groningen Sleep Quality Scale [GSQS]).	Light amounts, age, sex, season, seasonality, morningness-eveningness, pre-intervention expectations	No significant treatment effect, but quality of sleep improved consistently during the daily administration of simulated dawn (treatment × time effect).
Martinez-Nicolas et al, 2011	Obs: cross sectional (1 wk) Light history: reported by data logger pendant.	88, 59%, 18-23 y, Spain	Hobo Pendant: worn on lanyard close to eyes for 1 wk. Light variables: mean amount over 24 h; mean amount in morning (08:00-15:50), evening (16:00-23:50), and night (00:00-7:50); light quality index, light interdaily stability, intradaily variability, light relative amplitude, spectrum not specified.	Sleep diary: sleep onset, offset, sleep time.	No	Greater daily stability, mean amount, relative day to night exposure, morning, evening, and quality of light amount was associated with better sleep diary sleep outcomes (more stable sleep across days). More within-day variability in light amount was associated with worse sleep diary sleep outcomes (less stable sleep across days).
Obayashi et al, 2014	Obs: two 48-h assessments were conducted 4 mo apart. Light history: reported through actigraphy.	192, 50%, $M = 69.9$, 63.6-76.2 y, Japan	Actigraphy worn on the wrist: average light amounts 4 h before bedtime; Sensor above bed: average light amounts 2 h after bedtime, spectrum not specified.	Actigraphy: sleep onset latency.	Age, sex, daytime physical activity, in-bed time, day length, amount of night time exposure	Brighter evening and nighttime light amounts were associated with longer sleep onset latency.
Ohayon et al, 2016	Obs: cross-sectional telephone study using self-report questionnaires. Light history not specified.	15,863 adults (no sex/gender provided), 18 y and older (no mean/range), United States	Self-report measurement of (a) sleeping with the light on (always/often to never), (b) self-report if bedroom light is too bright, and (c) self-report of watching TV in bed (at least 4/5 times/wk), spectrum not specified.	Self-report using the sleep-EVAl system: bedtime, sleep latency, nighttime sleep duration, wake-up time.	Sex, age, children in the house, occupation, population density, nighttime radiance, sleeping place, noise level	Sleeping with light on was associated with an increased likelihood of sleeping less than 6 h per night, later bedtime and later wake-up time. Watching TV in bed was associated with sleeping less than 6 h per night.
Park et al, 2007	Obs: across at least 6 d. Light history: reported through actigraphy	384, 100%, $M = 67.9$ (7.7), United States	Actigraphy: acrophase (h), mesor, amplitude. Illumination measured by actigraphy at both the wrist and the lapel, then on the forehead at night. Spectrum not specified.	Actigraphy: sleep latency, sleep onset time, time in bed, sleep period time, total sleep time, total wake time, wake-up time after sleep onset, sleep efficiency, sleep percent. Self-report sleep diary: sleep latency, sleep onset time, time in bed, sleep period time. WHI Insomnia Rating Scale.	Use of hypertensives, age, systolic blood pressure, BMI, diastolic blood pressure, anxiety symptoms, depressive symptoms, hot flashes, daily wrist activity, offset time of aMT6s, onset time of aMT6s acrophase of wrist activity, acrophase of sleep, sleep offset time, sleep onset time	Greater amounts of daily light exposure was associated with shorter self-reported sleep onset latency.

Table 1 *(continued)*

Citation	Study design	Sample: N, sex (% female), age (M [SD], range), race/ethnicity, country	Light measures	Sleep measures	Covariates	Association between light and sleep outcomes
Reid et al, 2014	Obs: assessed for 7 d. Light history: reported through actigraphy.	54, 50%, $M = 30.6$ (11.7), United States	Actigraphy: light exposure in a 24-h period (time above threshold, mean light timing above threshold, and standard deviation of mean light timing above threshold), measured at the wrist, spectrum not specified.	Daily sleep diary and actigraphy: sleep start, sleep end, sleep duration, sleep midpoint.	No	Later timing of mean of light exposure >500 lux was associated with a later midpoint of sleep according to actigraphy.
Rosenthal et al, 1987	Exp: balanced randomization control trial to bright light or dim light condition, 2 wk of baseline questionnaires (sleep, mood), 1 wk of light tx, 1 wk of questionnaires after light tx, took place in participants' homes. Light history not specified.	22, 91%, $M = 35.45$ (10.25), United States	Light box - (2500 lux, 300 lux), 2 h from 630 to 930 hours for 7 d, full-spectrum light.	Daily sleep diary (4 wk, began 2 wk before light treatment): total sleep time.	No	No overall treatment effect. Participants slept less during bright and dim light treatment week than during baseline week. There was a significant difference in the mean duration of sleep lost per day during bright light treatment and dim light treatment compared to baseline sleep duration.
Saletu et al, 1986	Exp: 2 adaptation d, 3 24-h periods (baseline, intervention, recovery) with biologically active light (BL) tx and partial sleep deprivation (PSD). Light history not specified.	10, 100%, $M = 24.2$, 21-29 y, Austria	Tungsram daylight 55 florescent tubes (4500 lux at ceiling level, 2800 lux at eye level, 1700 lux at floor level), bright light exposure from 1700 to 2100 hours and 0600 to 0900 hours, spectrum: simulated daylight.	Polysomnography: sleep latency, awakenings, total sleep time, sleep onset, light sleep stage, S1, S2, S3, S4, REM; subjective sleep questionnaire.	No	Bright light treatment significantly reduced PSG awakenings and increased total sleep time in the "recovery night," there was a significant augmentation of deep sleep stages 3, 4, and REM in bright light during the recovery night, there was a significant improvement in subjective sleep quality and awakening quality in the intervention nights after bright light.
Santhi et al, 2011	Exp: within-person, counterbalanced, crossover design, 1 night adaptation, followed by 6 experimental nights. Light history: participants reported to the lab between 1600 and 1630 hours.	22, 30%, $M = 23.14$, 18-34 y, United Kingdom	Light box: 4 h before sleep 5 spectrum conditions: near darkness (<1 lux), blue-depleted (~239 lux), blue-intermediate (~127 lux), blue-enhanced (~146 lux), bright blue-enriched (~773 lux), measured at angle of gaze.	Polysomnography: latency to persistent sleep; sleep onset latency; slow-wave sleep latency; rapid eye movement sleep latency; total sleep time; wake after sleep onset; slow-wave sleep; rapid eye movement; sleep efficiency.	Randomization sequence	No significant difference in sleep outcomes between the bright vs nonbright levels of blue-enriched light.
Takasu et al, 2006	Exp: within-person, 15 d, participants followed daily schedule of 8-h sleeping and 16-h waking. Participants exposed to dim light for first 6 d and bright light for next 7 d Light history: controlled in living facility, 0.01 lux for 8 h at night, bright or dim conditions for 16 h during the day.	8, 0%, 20-29 y, Japan	Light box: dim light (~10 lux) and bright light (~5000 lux) measured at eye level, during 16-h waking period, spectrum: fluorescent light.	Polysomnography: time in bed, sleep latency, stage 1, stage 2, stage 3, stage 4, REM sleep, REM latency, wake after final awakening, sleep period time, wake after sleep onset, wake time during sleep period, time from final awakening to time of getting up, time from sleep onset to sleep end, movement time, total sleep time, sleep efficiency.	No	Dim light differed from baseline with less time in stage 2, less time in stage 1 + 2, smaller % stage 2, smaller % stage 1 + 2. Bright light differed from baseline with shorter sleep period time, shorter REM latency, less time in stage 2, less time in stage 1 + 2, smaller % stage 2, smaller % stage 1 + 2. Bright light differed from dim light with shorter sleep period time.

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Table 1 *(continued)*

Citation	Study design	Sample: N, sex (% female), age (M [SD], range), race/ethnicity, country	Light measures	Sleep measures	Covariates	Association between light and sleep outcomes
Takeuchi et al, 2001	Obs: cross-sectional design using surveys. Light history not specified.	381, 63%, 18-28 y, Japan	Self-report retrospective survey assessing light conditions and curtain type, spectrum not specified.	Morningness-Eveningness Questionnaire (M-E): sleep onset time, wake-up time, sleep latency.	No	Light source use was not associated with significantly different sleep-onset time or wake-up time; brighter light use was associated with earlier bedtime on night before work compared to small light or no light use. Black-out curtain use was associated with significantly longer sleep onset latency compared to usual curtain use on nights before weekdays and holidays.
Thompson et al, 2014	Exp: counterbalanced trials, adaptation night, 2 experimental nights (intervention and control), trials separated by 5-9 d Light history: participants arrived to lab 2 h prior to sleep, light in the lab standardized at 300 lux, light conditions applied after 7.5 h of sleep.	8, 50%, $M = 24$ (9), United Kingdom	Dawn simulation device: 30 min prior to waking simulation started at .001 lux and rose to 300 lux measured at eye level, spectrum: simulated daylight.	Actigraphy: sleep latency, sleep efficiency, actual sleep time; Subjective sleep quality upon awakening using visual analogue scale.	No	Perceived sleep quality on visual analogue scale was higher for dawn simulation group compared to control group. No statistical differences in objective sleep quality measured via actigraphy (efficiency, latency, total sleep time).
Wakamura & Tokura, 2000	Exp: within-subjects design, 4 d in experimental chamber during daytime and evening. First 42 h = adaptation to protocol, only last 2 d used for analysis, Randomization of dim and bright light conditions during the day, no light exposure at night. Light history: controlled within lab environment.	7, 100%, $M = 20$ (2), Japan	Florescent light source: bright (>4000 lux) or dim (200 lux) light during the daytime, measured at eye level, spectrum: "Cool White" fluorescent.	Oguri-Shirakawa-Azumi (OSA): sleep maintenance, sleep initiation, integrated sleep, sleepiness.	No	OSA Sleeping Inventory showed that the participants had a better 'integrated sleep feeling' during bright exposure than during dim.
Wallace-Guy et al, 2002	Obs: cross-sectional design across 7 d using actigraphy. Light history: reported through actigraphy.	154, 100%, $M = 66.7$, 51-81 y, United States	Actigraphy (worn on wrist): average illumination across 4 h before bed, average 24-h illumination, spectrum not specified.	Actigraphy: sleep latency, sleep efficiency, total sleep time, sleep timing.	Age, season	Illumination before bed was not associated with sleep outcomes; greater 24-h illumination was correlated with shorter sleep latencies and reduced wake within sleep.
Yetish et al, 2015	Obs: 3 pre-industrial societies, measured for 6-28 d with actigraphy. Light history: reported through actigraphy.	did not specify	Actigraphy: worn on wrist for 6-28 d, spectrum not specified.	Actigraphy: sleep onset, offset.	No	Neither sleep onset or offset were linked to light levels.
Youngstedt et al, 2004	Obs: 4 wk of retrospective sleep assessment, 5-7 consecutive days of wearing Actilume monitors (light exposure). Light history: reported through actigraphy.	459 females, $M = 67.7$ (.4), 50-81 y, United States	Actigraphy (worn on wrist): mesor (mean of 24-h cosine-fitted lux); mean of lux during first 4 h after awakening; acrophase (peak time of 24-h fitted cosine), spectrum not specified.	4-wk recall questionnaire of sleep habits (trouble falling asleep, waking up often during the night, awakening earlier than planned, daytime napping, sleep quality, total sleep time on a 'typical' night); Actigraphy and sleep diary: bedtime, wake time, sleep latency, total sleep time, sleep efficiency.	No	Morning light was positively correlated with 4-wk recall, actigraphic, and sleep diary total sleep time; actigraphic final time of awakening, 4-wk recall sleep quality. Morning light was negatively correlated with actigraphic and diary sleep onset latency, 4-wk recall of trouble falling asleep, waking

Table 1 *(continued)*

Citation	Study design	Sample: N, sex (% female), age (M [SD], range), race/ethnicity, country	Light measures	Sleep measures	Covariates	Association between light and sleep outcomes
						up often, and waking up earlier than planned. Mean light was positively correlated with 4-wk recall sleep quality and negatively correlated with 4-wk recall of trouble falling asleep, actigraphic and diary sleep latency, 4-wk recall and actigraphic wakefulness during night, and 4-wk recall of waking up earlier than planned. Acrophase was positively correlated with actigraphic final time of awakening.
Zeitzer et al, 2014	Exp: two conditions - exposure to darkness or light flash sequence**.** Light history: participants stayed in the laboratory for a 35-h protocol starting 7 h after habitual wake time. In the lab, subjects exposed to <10 lux during scheduled wake and < 0.05 lux during sleep.	13, 54%, $M = 26.9$ (4.8), United States	Light device: two conditions delivered 2-3 h after bedtime: 60 min of darkness or flash sequence of ~2995 lux at eye level, 2-ms flash of white light delivered every 30 s, spectrum: white light.	Polysomnography: change in wake, stage N1, stage N2, stage N3, REM, number of state transitions, predefined spectral bands.	No	No significant difference in sleep between the two light conditions.

studies. Light was delivered in the morning, evening, and across the day (morning, afternoon, and evening). *Morning* bright light exposure (>1000 lux) was associated with a significantly greater advance of the sleep period and changes in sleep architecture and activity compared to morning dim light exposure (<100 lux). Specifically, as assessed by polysomnography, bright light exposure in the morning was associated with shorter sleep onset latency,[31] decreased awakenings during first third of sleep and increased awakenings during last third of sleep,[32] fewer overall awakenings,[33] greater wake after sleep onset,[31] lower sleep efficiency,[31] more fragmented sleep,[31] advanced time of sleep termination,[34] and shorter sleep duration[33,34] compared to dim light. Additionally, actigraphic counts of motor activity were significantly reduced in the bright light vs dim light condition.[35]

Conversely, *evening* bright light exposure (>1000 lux) compared to dim light exposure (<100 lux) resulted in a delay of the sleep period according to polysomnography with a greater delay to stages 1 and 2 sleep[36,37] and REM sleep[36] as well as greater sleep onset latency.[38–40] Additionally, bright evening light was associated with more superficial sleep using polysomnography including more time spent in stage 1 and more arousals compared to dim light.[38] Two studies, however, reported on the positive impact of evening light

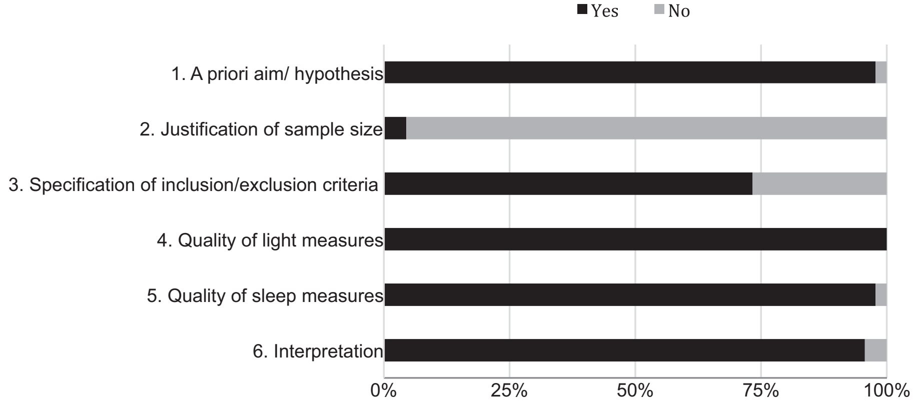

Fig. 2. Summary of study quality assessement criteria across the 45 included studies. The black bar indicates percent of studies that met criteria.

on sleep assessed by polysomnography[36] and a sleep home monitoring system.[41] Bright evening light was associated with greater overall NREM duration[36,41] and decreased sleep onset latency[41] compared to dim evening light.

In contrast to studies focusing exclusively on morning or evening light, one study compared bright light (>1000 lux) delivered in the *morning* vs *evening*.[42] A pattern of results similar to the above-mentioned sleep period advances and delays was observed with the average time of sleep termination after morning light condition occurring significantly earlier than after exposure to the evening light condition.[42] Additionally, in the morning light condition, the duration of first REMS episode was longer than evening light condition.[42]

Finally, 2 studies compared the effects of bright (>1000 lux) vs dim (<100 lux) light delivered across multiple times of the day. The first presented light across the *full day (morning, afternoon, and evening)* and found that bright light was associated with a shorter sleep period compared to dim light.[43] The second compared bright to dim light that was presented in the morning and evening.[44] Compared to dim light, the bright light treatment significantly reduced awakenings; increased total sleep time; and augmented deep sleep stages 3, 4, and REM during the "recovery night" following the 24-hour period with the light intervention.[44]

Light exposure with no specific lux levels identified. Eleven observational studies examined the association between light exposure and objective sleep outcomes without identifying the specific lux levels of light.[14,26,27,50–57] The studies in this section did not provide specific estimates of lux, prohibiting comparisons across lux levels. Eight of these studies found a significant association between light exposure and sleep outcomes. Greater amount of light exposure (eg, higher average lux levels as assessed by actigraphy across multiple hours to days) was associated with positive actigraphic sleep outcomes in 2 studies such as longer total sleep time,[26] shorter sleep latencies,[55] and reduced wake after sleep onset.[55] Conversely, 3 studies observed an association between greater average amount of light exposure and the negative actigraphic sleep outcome of shorter total sleep time.[27,50,57] Greater average light exposure was also associated with the timing of the sleep period with lower average light associated with a delayed sleep period.[27,50] In addition to examining the effect of overall light exposure, several observational studies examined time of day effects of light exposure on actigraphic sleep outcomes. Longer sleep onset latency[14,51] and shorter REM sleep (as assessed by polysomnography)[14] were associated with higher evening light exposure, and longer total sleep time and shorter sleep onset latency were associated with brighter morning light exposure.[57] Furthermore, the average timing of light exposure was linearly associated with the timing of the actigraphic sleep period, with later timing of the mean of light exposure >500 lux associated with later sleep midpoint[53] and later acrophase (peak time of the 24-hour fitted cosine) associated with later final wake-time.[57]

Light exposure with lux specified but no comparisons across lux levels. Three studies examined the effects of lux on objectively assessed sleep but did not fit the above designated comparison categories.[58–60] Two studies compared 2 levels of dim light (5 vs 10 lux[58] and 15 vs 45 lux[59]) and found no significant differences in terms of sleep outcomes between exposure to the 2 dim light levels. A third study compared bright light (6000 to 13,000 lux) delivered in the morning, afternoon, and evening.[60] Similar to the above-mentioned findings regarding the sleep period advancing and delaying properties of morning vs evening light, sleep onset latency was increased by evening bright light, decreased by morning bright light, and was not affected by afternoon bright light. Additionally, the amount of wakefulness in first 90 minutes was lower for morning light, increased for evening light, and did not change for afternoon light.

Subjectively assessed sleep outcomes

Of the 45 reviewed studies, 23 included subjectively assessed sleep outcomes. Lux was compared across multiple levels with the majority of studies comparing sleep outcomes between dim vs bright light (5 studies). The proportion of studies with significant findings differed across lux comparison levels: 50% (dim vs moderate light), 67% (moderate vs bright light), and 40% (dim vs bright light). When light was analyzed as a continuous variable, light was associated with objective sleep outcomes in 90% of studies. Finally, light was associated with objective sleep outcomes in 67% of studies that did not involve comparisons across the specified lux categories.

Light was assessed at various time points across studies (eg, morning, afternoon, evening, and full day exposure). Brighter morning light exposure uniformly predicted better self-reported sleep outcomes except for the lack of an association when moderate morning light was compared to bright morning light. Conversely, brighter evening light was primarily associated with negative self-reported sleep outcomes except for 2 studies which reported a positive correlation between evening light levels and subjective sleep outcomes. Light exposure assessed across the full day was uniformly positively associated with sleep outcomes such that higher levels of light across the day were associated with better sleep outcomes.

Dim vs moderate light. Dim light (<100 lux) was compared to moderate light (100-1000 lux) in 2 studies assessing the effects of morning light.[28,61] An artificial dawn wake-up light was not associated with changes in sleep reported via sleep diaries across dim vs moderate light conditions.[61] The presentation of morning light of 1000 lux via a light box was associated with sleep improvements according to a retrospective sleep questionnaire including better sleep maintenance and more integrated sleep compared to a control condition.[28]

Moderate vs bright light. Morning, evening, and full-day bright light (>1000 lux) was compared to moderate light (100-1000 lux) in 3 studies using light boxes.[62–64] Bright light exposure during the full day was associated with reports of more integrated sleep using a retrospective inventory compared to moderate light exposure.[64] Bright light in the evening was associated with worse self-reported sleep according to a retrospective questionnaire including longer sleep initiation and poorer sleep quality compared to moderate evening light exposure.[62] Lastly, no treatment differences were observed between bright and moderate light delivered during the morning hours.[63]

Dim vs bright light. Five studies compared dim light (<100 lux) to bright light (>1000 lux) using subjective sleep measures.[32,35,38,45,47] Two of the 5 studies found a significant association between light and sleep, with bright light in the evening associated with longer self-reported sleep onset latency[38] and bright light in the morning associated with better self-reported sleep maintenance compared to dim light conditions.[32] Both studies presented light via a light box and used retrospective sleep questionnaires.

Light exposure with no specific lux levels identified. Ten studies examined light exposure in association with subjective sleep outcomes without specification of lux levels.[20,26,27,50,52–54,57,65,66] Nine of the 10 studies reported significant associations.

Five of the 10 studies used actigraphy to assess light exposure and found that higher levels of light exposure across 24 hours (eg, greater mean lux) and higher levels of morning light exposure were associated with better self-reported sleep outcomes. Specifically, using sleep diaries, higher overall mean lux predicted shorter sleep onset latency,[52,57] whereas higher mean lux during the morning predicted longer total sleep time and shorter sleep onset latency.[57] Actigraphically assessed light was also positively associated with sleep outcomes reported using retrospective questionnaires. Lower average lux was associated with self-reported poorer sleep quality,[27,57] trouble falling asleep,[27,57] waking up several times a night,[27,57] waking up earlier than planned,[27,57] trouble falling back asleep,[27] and higher sleep disturbance.[50] Higher average morning light was positively correlated with retrospectively reported sleep quality and negatively correlated with reported trouble falling asleep and waking up often.[57]

Three of the 10 studies used self-report measures of both light exposure and sleep outcomes. Specifically, a survey of daylight deprivation found that workers without windows reported poorer sleep quality and greater sleep disturbance compared to workers with windows using retrospective sleep questionnaires.[26] Two studies assessed lighting in the bedroom via questionnaires and found that sleeping with a light on was associated with an increased risk of sleeping less than 6 hours per night, a later bedtime, and a later wake-up time,[65] whereas bright light before bed was associated with an earlier bedtime on work nights.[66]

One of the 10 studies objectively assessed light using Hobo Light Pendants and examined self-reported sleep diary data.[20] Multiple characteristics of light exposure were examined, and the researchers found that greater daily stability, mean amount, relative day-to-night exposure, morning, evening, and quality of light were associated with more stable sleep across days. More within-day variability in light amount was associated with less stable sleep across days.

Light exposure with lux specified but no comparisons across lux levels. Three studies examined the association between light and subjective sleep outcomes without comparing across levels of lux.[44,67,68] Two of the 3 studies found a significant association, with longer exposure to bright light (>3000 lux) as assessed by actigraphy associated with better sleep quality ratings on a daily sleep log[67] and bright light (> 1000 lux) administered in morning and evening associated with improved sleep quality and awakening quality using a sleep questionnaire.[44]

Discussion

Summary of findings

To our knowledge, this is the first systematic review of light amount and timing in association with sleep outcomes in healthy, community-dwelling adults. After a systematic search and screening of the literature, 45 of an initial 10,779 studies met the review eligibility criteria. The majority of studies used an experimental design (n = 30), permitting the study of causal associations between light and sleep. The remaining studies (n = 15) used observational methods to assess correlational associations between light and sleep. The mixed methodological approaches limit generalizations across studies and preclude broad generalizations about causation. However, the mixed methods do reflect research that was high in both internal and external validity and, consequently, can inform understanding of the association between light and sleep in both controlled and ecologically valid settings.

Overall, the study samples were diverse in terms of age, geographical location, and sex of participants. Females and males, across the adult lifespan who inhabited 5 continents, were represented in the results. However, little information was provided about the race or ethnicity of the samples, which undermines our ability to generalize conclusions to specific races and ethnicities. There was large variability in the sample sizes of the studies, reflecting the diverse methodological approaches. Light and sleep were assessed or manipulated primarily using objective methods such as actigraphy, light delivery devices, or polysomnography. However, subjective methods such as daily diaries and retrospective questionnaires were also represented. The light measures were disproportionately objective (93%) compared to the sleep measures (59.37%), which often resulted in designs assessing associations between objective light measures and subjective sleep measures. The study quality assessment indicated an overall high quality of the included studies, with more than 73% of the studies meeting 5 of the 6 quality expectations. However, there were weaknesses such as less specification of study eligibility criteria (missed by 26.67% of studies) and lack of justification for sample size in 95.35% of studies. These methodological weaknesses have negative implications for validity and for the significance of findings. Specifically, potential confounds may not have been controlled for by study eligibility criteria, and studies may have been over- or underpowered to detect a significant association.

Nonetheless, despite diverse methodological approaches and some weaknesses in study design, several consistent associations emerged across the reviewed studies. However, the observed associations do not account for all aspects of light, which limits the strength of our conclusions. First, an amount by timing interaction occurred such that the effects of light level on objectively measured sleep differed depending on the time of day the light was presented. Bright light was more strongly associated with objective sleep compared to moderate and dim light, and the pattern of findings suggested a delay or advance of the sleep period depending on time of day of light exposure. Specifically, bright evening light was associated with a delay of the sleep period evidenced by polysomnographic longer sleep onset latency[30,38–40] and delayed sleep onset[30,36,37] compared to both dim and moderate light. An inverse and expected pattern of findings emerged for bright morning light suggesting an advance of the sleep period. In particular, bright morning light was associated with polysomnographic shorter sleep onset latency[31] and advanced time of sleep termination compared to dim light.[34] One study reported results incongruent with this pattern of findings, with shorter sleep onset latency associated with bright evening light compared to dim light.[41] However, participants in this study were older adults experiencing a normal age-related phase advance of their sleep period. As such, delaying the onset of sleep in a population experiencing a phase advance could be expected to result in a condensed sleep onset period.[69,70] The association between time of day of light exposure and the timing of the sleep period is illustrated by the Gordijn et al (1999) study which found that the average time of sleep termination occurred significantly earlier for the morning bright light vs evening bright light condition. Overall, this pattern of results is consistent with theoretical and empirical evidence underlining the importance of time of day of light exposure for delaying or advancing the sleep cycle.[12,13] Importantly, the effects of light on the timing of the sleep period may occur directly (eg, suppressing melatonin or having an alerting effect) and are not necessarily indicative of a shift of the underlying circadian phase that would result in an indirect and enduring effect on sleep timing.[71]

In contrast to the consistent pattern of findings suggesting an amount by timing interaction for the effects of light on objectively assessed sleep, results were less consistent regarding other aspects of objectively assessed sleep outcomes. According to polysomnography, brighter light during the morning was associated with fewer awakenings,[33] greater wake after sleep onset,[31] more fragmented sleep,[31] and lower sleep efficiency.[31] One possible explanation to help reconcile these discrepant findings is that the "poorer" sleep outcomes (greater wake time, more fragmented sleep, and lower sleep efficiency) were seen in a sample of young adults, whereas the "better" sleep outcomes emerged in studies examining older adults. In the Campbell et al (1992) study of young adults, the authors used bright light to create a phase advance of core body temperature of 97 minutes while holding the timing of the sleep period constant. Consequently, the timing of the sleep period was misaligned with participants' core temperature rhythm such that they were sleeping when they had a decreased capacity to maintain sleep as a result of rising core temperatures.[31] Therefore, the "poorer" sleep observed in response to bright light is likely due in large part to the misaligned circadian rhythms rather than due to directly to the bright light. Another set of mixed findings involved research assessing light exposure as a continuous variable. Although most studies in this category found exposure to higher average levels of lux to be associated with more positive sleep outcomes, 3 studies observed a negative association between higher average lux and shorter total sleep time.[27,50,57] These 3 studies assessed sleep in postmenopausal[27,57] and postpartum[50] women, and the authors suggest explanations for the shorter sleep duration findings other than bright light exposure. Specifically, shorter sleepers were less likely to be depressed and experienced better overall sleep suggesting a confound of mood,[27] shorter sleepers showed less sleep debt indicating the shorter sleep may not be a poor sleep outcome,[50] and the shorter sleep associated with greater overall light exposure was due to more out of bed time by shorter sleepers and hence more light exposure.[57] Consequently, although mixed findings emerged in the association between bright light and sleep outcomes outside of the timing of the sleep period, unique circumstances specific to each study appear to explain these discrepancies.

In terms of subjective sleep outcomes, bright light was more strongly associated with subjective sleep outcomes compared to moderate light for the majority of studies. Although for a portion of the reviewed studies bright light differed significantly from dim light and moderate light differed significant from dim light, the majority of studies in these 2 lux comparison categories found no significant difference in light levels. Overall, for all studies that did find a significant difference between light levels, the brighter light resulted in significantly different sleep outcomes compared to the dimmer light, and the direction of these associations was consistent across light levels (eg, brighter light associated with better sleep outcomes). Similar to the objectively assessed sleep outcomes, the amount of light appeared to interact with the timing of light exposure. Brighter light in the morning was associated with self-reported sleep improvements on retrospective questionnaires (better sleep maintenance and more integrated sleep[32]) compared to dimmer light levels. Brighter evening light exposure was associated with worse self-reported sleep on retrospective questionnaires (eg, longer sleep initiation[38,62] and poorer sleep quality[62]) compared to dimmer light levels. Two studies found that evening light exposure was associated with positive sleep outcomes (an earlier bedtime[66] and subjective reports of better sleep quality and awakening quality).[20] These results, however, are worth commenting on. For the first study, brighter evening light was associated with an earlier bedtime before a full day's work, not necessarily earlier sleep onset.[66] This study examined light use and sleep in Japanese college students. It is possible that students reporting using the brighter evening light (described as fluorescent overhead lighting) may select to go to bed earlier knowing they have to work the next day. Hence, bright light may not be driving the decision to go to bed earlier. For the second study, both morning bright light and evening bright light were administered, so we cannot determine if the positive sleep outcomes were due to the evening, morning, or a combination of both types of light exposure.[44] Lastly, brighter light across the full day was also associated with reports of more integrated sleep based on retrospective questionnaires compared to dimmer light.[64] In research that analyzed light as a continuous variable, higher levels of light exposure across 24 hours and higher levels of morning light exposure were associated with better sleep outcomes as assessed by sleep diaries[20,52,57] and retrospective questionnaires.[27,50,57]

Overall, the results for both objective and subjective sleep outcomes are consistent with theoretical and empirical evidence underlining the importance of sufficient light exposure during the day for a healthy sleep-wake cycle.[10,11] Importantly, many of the sleep outcomes in each study were not associated with light, despite the presence of some significant associations. However, given the multifaceted nature of sleep and the multiple valid approaches to measurement, discrepancies across sleep outcomes are to be expected.

Limitations

There are several limitations that affect the generalizability of conclusions from this systematic review. First, given the variability in methodological approaches and the small number of studies examining amount of light at different times of the day, we were unable to conduct meta-analyses on the strength of the observed associations. Second, the majority of studies did not systematically examine the "dose-response" rate of light amount in relation to sleep. Rather, bright light was typically compared to a control condition consisting of dim light. As a result, we cannot specify the relative importance of differing intensities of bright light beyond its absence or presence. Third, operationalization of the "brightness" of light was arbitrarily implemented for the purpose of organizing the results of the review. Consequently, although there were consistent broad trends across these categories, these associations may differ depending on the use of different parameters. The nomenclature *dim*, *moderate*, and *bright* was arbitrarily applied to facilitate readability and does not reflect the innate illuminance of these categories of light. Fourth, individual factors moderating the association between light and sleep were not reported or statistically examined in the majority of studies. For example, only 2 studies reported on the race or ethnicity of the sample, and other aspects of identify, such as age, were not examined as moderators in analyses. Finally, this review focused on 2 aspects of light exposure—amount and timing—in association with sleep. Other important facets of light exposure such as spectrum, prior light history, rate of change, and duration were not typically assessed, reported, or controlled for in the present studies. Consequently, the significant effects of light amount and timing may be conflated with other important components of light.

Future directions

Although a large amount of work has investigated the role of the amount and timing of light exposure in relation to sleep, the conclusions that can be drawn are broad and lack specificity. Future work is needed to compare relative intensities of light within the same study design to specify optimum intensities. Furthermore, the effects of light amount and timing on sleep likely differ according to individual characteristics such as age. Consequently, the examination of these associations is warranted across the adult lifespan, within the same study design. Relatedly, little is known about the relative importance of light amount and duration in racially and ethnically diverse samples. Recruitment of diverse samples and reporting of sample demographics will increase the generalizability of results. Finally, other important facets of light exposure such as spectrum, prior light history, rate of change, and duration should be included and clearly reported in subsequent research to facilitate future reviews in these important topics.

Conclusions

Light is considered the dominant environmental cue influencing our sleep-wake cycle.[1] Consistent with this perspective, the amount and timing of light exposure emerged as significant predictors of both subjective and objective sleep outcomes in a systematic review of the literature focused on healthy, community-dwelling adults. Despite the heterogeneity of study designs, broad trends emerged suggesting that (1) bright light has positive implications for objectively assessed sleep outcomes compared to dim and moderate light and (2) bright light has positive implications for subjectively assessed sleep outcomes compared to moderate light. Furthermore, the amount of light appears to interact with the timing of light exposure such that, for objectively assessed sleep outcomes, brighter morning and evening light exposure is consistent with an advance and delay of the sleep timing period, respectively. For subjectively assessed sleep outcomes, brighter light delivered in the morning was associated with self-reported sleep improvements, and brighter evening light exposure was associated with worse self-reported sleep. Greater specificity of these associations can be obtained by examining different intensities, delivered at different time points, within the same study protocol, and in diverse samples.

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