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The Influence of Intensity and Timing of Daily Light Exposure on Subjective and Objective Sleep in Adolescents with an Evening Circadian Preference

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Abstract

Study Objectives: The aim of the present study is to examine the relationship between light and sleep, in adolescents with an evening circadian preference.

Methods: For a period of seven days, ninety-nine adolescents wore a wrist actigraph to assess light exposure and objective sleep and completed a sleep diary to assess subjective sleep.

Results: Lower average light intensity across the preceding 24 hours was associated with a later sleep onset (p<.01) and a later next-day sleep offset (p<.05). A later time of last exposure to more than 10 lux was associated with a later sleep onset (p<.001) and a shorter objective total sleep time (p<.001), as well as a later bedtime (p<.001) and a shorter subjective total sleep time (p<.001). Furthermore, exploratory analyses found that lower average early morning light exposure (between 4–9AM) was associated with later sleep onset (p<.05), a later next-day sleep offset (p<.05), and a later next-day waketime, (p<.01), lower average afternoon light exposure (between 2–7PM) was associated with an later next-day sleep offset (p<.05), and lower average evening light exposure (between 7PM-12AM) was associated with longer subjective total sleep time (p<.001).

Conclusion: This study highlights the importance of light exposure, particularly the timing of light exposure, for establishing healthy patterns of sleep among adolescents with a propensity for a delayed bedtime and waketime. These findings provide additional evidence for targeting light exposure when designing interventions to improve adolescent sleep.

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Keywords

adolescence; circadian preference; light; actigraphy; sleep diary

1. INTRODUCTION

Adolescence is a period characterized by a myriad of changes. The onset and progression of puberty is associated with a shift towards an evening circadian preference, characterized by a desire to go to bed later and wake later (Gradisar et al., 2011; Hagenauer et al., 2009). Unfortunately, an evening circadian preference can conflict with early wake-times for school, contributing to insufficient sleep (Crowley et al., 2007). Perhaps not surprisingly, there is an association between an evening circadian preference, insufficient sleep, and mental health (Giannotti et al., 2002; Li et al., 2018). Therefore, there is a need to identify modifiable factors associated with an evening circadian preference. One potential target is light exposure.

Light is one of the strongest cues used by the human body to align internal circadian rhythms to the external world (Czeisler et al., 1999). The gold standard measure of circadian rhythms, dim light melatonin onset (DLMO), is derived by measuring melatonin secretion under dim light conditions in the hours before bedtime (Lewy & Sack, 1989). As DLMO requires dim light conditions, it is not surprising that nighttime light exposure can delay DLMO and suppress nighttime melatonin production (Zeitzer et al., 2000). Hence, light exposure influences how our circadian rhythms align with the external world.

The intensity and timing of light exposure is associated with both sleep timing and circadian preference. Specifically, exposure to sunlight (>100,000 lux) is associated with an earlier bedtime and a morning circadian preference (Harada et al., 2002; Roenneberg et al., 2003), while exposure to indoor light (~300–500 lux) is associated with an evening circadian preference (Martin et al., 2012; Van der Maren et al., 2018; Wams et al., 2017). Moreover, morning light can advance the circadian rhythms, while evening light can delay the circadian rhythms, suppression of melatonin production, and increased nighttime alertness (Cajochen et al., 2011; Crowley & Eastman, 2017; Khalsa et al., 2003; Zeitzer et al., 2000). Interestingly, the widespread use of electronic devices, especially during adolescence, can delay the timing of light later into the evening, likely contributing to later bedtimes and phase delays (Cain & Gradisar, 2010; Chang et al., 2013; Chinoy et al., 2018). Therefore, it is important to consider both the intensity and the timing of light exposure when examining how light exposure influences sleep and circadian preference.

Naturalistic studies continuously measure light to clarify the habitual pattern of light exposure and the relationship between light and sleep in daily life (Auger et al., 2011; Martin et al., 2012). A consistent finding that has emerged across these studies is that individuals with an evening circadian preference or delayed sleep phase disorder, the extreme end of the evening circadian preference, are more likely to be exposed to lower intensity light during the day and to a later timing of light in the evening (Auger et al., 2011; Harada et al., 2002; Martin et al., 2012). Additionally, lower intensity light during the day has been associated with worse sleep outcomes including a later sleep onset time

and shorter total sleep time (Auger et al., 2011). However, previous naturalistic studies have often averaged data across the week and utilized subjective measures. The present study extends the existing literature by examining daily patterns of light and both objective and subjective measures of sleep.

Our goal is to examine how the intensity and timing of light exposure relates to daily sleep in a sample of adolescents with an evening circadian preference. The first aim was to evaluate the relationship between light and objective sleep, as measured by actigraphy. We hypothesized that lower intensity light exposure across the preceding 24 hour day and a later timing of first and last exposure to more than 10 lux would be associated with later sleep onset, later sleep offset the next morning, and a shorter total sleep time. The second aim was to evaluate the relationship between light and subjective sleep, as measured by sleep diary. We hypothesized that lower intensity of light exposure across the preceding 24 hour day and a later timing of first and last exposure to more than 10 lux would be associated with later bedtime, a later waketime, and a shorter total sleep time.

2. MATERIALS AND METHODS

2.1 Participants

Participants were recruited between March 2013 and March 2016 for an NICHD-funded randomized controlled trial (RCT; NCT01828320). The goal of the larger RCT (Harvey et al., 2018) was to modify the psychosocial, behavioral and cognitive processes that contribute to sleep problems and circadian dysfunction via the Transdiagnostic Sleep and Circadian Intervention for Youth (TranS-C; Harvey & Buysse, 2017). Adolescents with an evening circadian preference who were at risk in at least one of five health domains were recruited. The rationale for this focus is that an evening circadian preference is common during adolescence (Carskadon et al., 1997; Gradisar et al., 2011) and is associated with adverse outcomes across health domains (Gau et al., 2007). The current study uses data collected during the pre-treatment period. A total of 398 participants were assessed for eligibility and 220 (55.6%) were excluded for not meeting inclusion criteria (n=154) or refusing to participate (n=66). A total of 176 participants were enrolled in the larger RCT (Harvey et al., 2018). Ninety-nine participants (female, n = 59; male, n = 40, and mean age = 14.76 years) were included in the current study. The remaining participants (n = 80) were excluded due to an accidental manual overwrite of the actigraphy database resulting in loss of data. Excluded participants did not differ on demographics or basic clinical data relative to included participants.

Individuals were included if they were (a) between 10 and 18 years old, living with a parent or guardian, and had a regularly scheduled activity (e.g. school or work) starting no later than 9am at least 3 days/week; (b) fluent in English; (c) able and willing to give informed assent; and (d) reported an evening circadian preference by scoring within the lowest quartile of the Children's Morningness-Eveningness Preference Scale (CMEP; 27 or lower) (Dagys et al., 2012), had a 7-day sleep diary (Carney et al., 2012) showing a sleep onset time of 10:40pm or later for 10–13 year olds, 11pm or later for 14–16 year olds, and 11:20pm or later for 17–18 year olds at least 3 nights per week, and reported a pattern of late bedtimes for the last three months. These age-group cutoffs are derived from Giannotti and

Cortesi (2002) and reflect developmental changes in sleep patterns and durations across this phase of development (Maslowsky & Ozer, 2014). Participants also needed to be 'at risk' in at least one of five health domains (Emotional, Behavioral, Social, Cognitive, or Physical) as defined elsewhere (Harvey et al., 2018).

Individuals were excluded if they had (a) an active, progressive physical illness or neurological degenerative disease directly related to the onset and course of their sleep (b) evidence of obstructive sleep apnea, restless leg syndrome, or periodic limb movement disorder assessed using the Duke Structured Interview for Sleep Disorders (Edinger et al., 2004); (c) intellectual disability, autism spectrum disorder, or other significantly impairing pervasive developmental disorder; (d) bipolar disorder, schizophrenia, or another current Axis I disorder if there was a risk of harm if treatment was curtailed. Individuals who had taken medications that altered sleep (e.g., hypnotics) within the past 4 weeks (2 weeks for melatonin) were excluded. Finally, individuals were excluded if they had a history of substance dependence in the past six months or current suicide risk sufficient to preclude treatment on an outpatient basis. All study procedures were approved by the University of California, Berkeley Institutional Review Board. Parents or guardians of all participants provided informed consent and participants provided informed assent.

Treatments for the RCT commenced after the pre-treatment assessment period. Data from the pre-treatment assessment period are the focus of the present study. To the best of our knowledge, no participant was undergoing other treatments or procedures that could have influenced their sleep or exposure to light.

2.2 Procedures and Materials

2.2.1 Actigraphy.—The Actiwatch Spectrum (Philips Respironics) is a small, wrist-worn device containing an accelerometer to sample physical motion. Actigraphy is a widely used objective method for estimating sleep/wake patterns using algorithms to quantify activity and has been validated against the gold standard objective measure, polysomnography, in adolescents (Quante et al., 2018; Sadeh, 2011). A minimum of five days of actigraphy is required to achieve a reliable measurement of sleep patterns in adolescents (Acebo et al., 1999). For the present study, participants were instructed to wear an actiwatch on the non-dominant wrist for seven days, to remove the actiwatch only when showering, and to press the event maker button on the side of the actiwatch at bedtime and wake time. Activity data were logged in 30 second epochs and analyzed using the Actiware software v.6 (Philips Respironics, Bend, OR, USA). The scoring algorithm's sensitivity for wake/sleep detection was set to medium. The Actiwatch Spectrum detects when and for how long the actiwatch is removed and data from off-wrist periods were classified as missing. For the present study, light and objective sleep data were extracted from the actiwatch.

The main rest window was the longest period of inactivity identified by the scoring algorithm within a 24-hour window. The rest window was adjusted using visual inspection and a concurrently collected sleep diary. First, the rest windows were visually inspected and adjusted to begin with a visible decrease in activity and to end with a visible increase in activity. Next, when available, data from a concurrently collected sleep diary was used to confirm and adjust the rest window (Boyne et al., 2013; Matthews et al., 2018). The

rest window was adjusted to match the sleep diary when bedtime and waketime values fell within 30 minutes of the onset/offset time set by the algorithm and visual inspection of the rest window. If the sleep diary values were greater than 30 minutes or the sleep diary was unavailable, only the scoring algorithm and visual inspection were used to confirm the rest window. Sometimes the scoring software will divide the night of sleep into multiple rest windows. If two or more rest windows fell during the main rest window reported on sleep diary, the windows were combined to create one rest window. Participants rarely pushed event markers as instructed. Therefore, data from event markers was not available and could not be used to adjust the rest window.

2.2.1.1 Light Data.: The *intensity* of light was operationalized as the average intensity of light exposure across the 24 hour period preceding the night of interest and was measured in lux. The *timing* of light was operationalized with two variables: (1) the time of first light exposure greater than 10 lux and (2) the time of last light exposure greater than 10 lux. Light values of less than 10 lux are commonly classified as dim light and 10 lux is a recommended threshold for measuring dim light melatonin onset (Pandi-Perumal et al., 2007). Moreover, exposure to light levels of 15 lux has been shown to suppress melatonin in adolescents (Crowley et al., 2015). In the present study and consistent with prior research (Wams et al., 2017), a threshold of 10 lux was selected to represent the transition from dim light to brighter light.

Light data processing procedures were derived from published methods utilizing actigraphically measured light data (Wams et al., 2017). Light data was parsed into epochs beginning at the sleep onset time on the preceding night and ending at the sleep onset time of the night of interest. Therefore, light data included approximately 24 hours of light exposure preceding the main sleep window of interest. Any values below the device sensitivity threshold were set to 1 lux and light data was $\log_{10}$ transformed. Data was smoothed using a local polynomial regression procedure (LOESS, span of 72 minutes) (Cleveland et al., 1992). The first time and the last time the smoothed (LOESS) data crossed 1 $\log_{10}$(lux) threshold each day were used to determine times of first and last exposure to more than 10 lux respectively. Average light intensity was calculated from the nonsmoothed $\log_{10}$-transformed data.

2.2.1.2 Objective Sleep Data.: Objective sleep variables included sleep onset, sleep offset, and total sleep time, which is the interval from sleep onset to sleep offset minus wake after sleep onset.

2.2.1.3 Circadian Disruption.: Interdaily stability (IS), a non-parametric circadian variable, was calculated from the raw epoch by epoch activity data from actigraphy (Mitchell et al., 2017; Quante et al., 2019). IS measures the stability of the 24 hour rest-activity pattern. (i.e. how closely it follows the light-dark cycle) and is a value from 0 to 1, with higher values reflecting synchronization to light and other zeitgebers. IS was calculated as the ratio between the variance for the average 24 h pattern around the mean and the overall variance.

2.2.2 Sleep Diary.—The consensus sleep diary (Carney et al., 2012) was collected by phone every morning for a period of 7 days by a trained research assistant. In addition to self-reported sleep information, participants also reported how they woke up in the morning (i.e. alarm clock/radio, another person, noises, awoke naturally). The sleep diary data was collected concurrently with actigraphy. Subjective sleep included bedtime ("What time did you try to fall asleep?"), waketime ("What time was your final awakening?"), and total sleep time, which is the interval from bedtime to waketime minus sleep onset latency and wake after sleep onset.

2.2.3 Dim light melatonin onset (DLMO).—Salivary melatonin was collected during an overnight assessment conducted in the lab. A total of 13 saliva samples were collected in dim light (<50 lux) every 30 minutes for a period beginning 5.5 hours before the participant's average weeknight bedtime and extending to 30 minutes after the participant's average weeknight bedtime as determined by the previous week's sleep diary. Participants rinsed their mouth following ingestion of any food or drink and were not allowed to ingest caffeine, fruit, chocolate, nonsteroidal anti-inflammatory drugs, or alcohol. The method of DLMO collection and storage was described in more detail elsewhere (Dolsen & Harvey, 2018; Harvey et al., 2018). Circadian alignment was assessed by calculating phase angle, which is duration of time between DLMO and average bedtime as recorded by sleep diary and between DLMO and average sleep onset as recorded by actigraphy (Crowley et al., 2014).

2.2.4 Children's Morningness-Eveningness Preference Scale.—This self-report measure has 10 questions regarding preferred timing of activities during the day and night (Carskadon et al., 1993). The maximum score is 42 (maximum morning preference) and the minimum score is 10 (maximum evening preference).

2.3 Statistical Analysis

Data analysis was performed in R (R Development Core Team, 2018). Instead of averaging across the week, daily data for light and both objective and subjective sleep was included. Hierarchical linear models (HLM) with restricted maximum likelihood estimation and unstandardized regression coefficients were used for all analyses (Bates et al., 2015). All HLM analyses included a random intercept for participant. The first aim included light exposure (average light intensity across the 24 hour period preceding the night of interest, time of first exposure, and time of last exposure) as the predictors and objective sleep (sleep onset, sleep offset, total sleep time) as the outcomes. The second aim included the same predictors and subjective sleep (bedtime, waketime, and total sleep time) as the outcomes. Statistical models also included age and a dummy variable for weekend (0 or 1). Sex was also initially included as a covariate but was not significant for any models and was therefore discarded. Time of first exposure to more than 10 lux, time of last exposure to more than 10 lux, sleep onset, sleep offset, bedtime, and waketime were set to decimal hours (e.g. 11:00 PM = 23.00) and times occurring after midnight were converted by adding 24.00 to the decimal hour value (e.g. 1:05 AM = 25.08). Rest interval duration and total sleep time were entered into the model as hours (e.g. 7 hours and 24 minutes = 7.4 hours). A critical *p*-value of 0.05 was maintained for all analyses and significance was tested using the 'lmerTest'

package (Kuznetsova et al., 2017). The ‘anova’ command from the ‘lmerTest’ package (Kuznetsova et al., 2017) was used to compare a model without the predictor variable to a model with the predictor variable to test whether including the predictor variable improved model fit. The results from this likelihood ratio test (χ^2) are reported for all models in the appropriate tables. Outliers were removed for all variables when the value was 3 standard deviations above or below the mean and accounted for less than 2% of the total data collected.

3. RESULTS

Demographic information and descriptive statistics for objective and subjective sleep variables are presented in Table 1. Pearson’s correlations for the objective and subjective sleep variables are presented in Supplemental Table 1. Descriptive statistics for light exposure variables are presented in Table 2.

3.1 Aim 1: Light Exposure and Objective Sleep

The association between light exposure and objective sleep, as measured by actigraphy, was examined first (Table 3). Average light intensity across the 24 hour period preceding the night of interest was negatively associated with sleep onset (Figure 1A). Time of last exposure to more than 10 lux was positively associated with sleep onset (Figure 1B). Time of first exposure to more than 10 lux was not significantly associated with sleep onset.

Average light intensity across the 24 hour period preceding the night of interest was negatively associated with next-day sleep offset (Figure 1C). Time of first exposure to more than 10 lux and time of last exposure to more than 10 lux were not significantly associated with next-day sleep offset.

Time of last exposure to more than 10 lux was negatively associated with total sleep time (Figure 1D). Average light exposure across the 24 hour period and time of first exposure to more than 10 lux were not significantly associated with total sleep time.

3.2 Aim 2: Light Exposure and Subjective Sleep

The association between light exposure and subjective sleep, as measured by sleep diary, was examined next (Table 4). Time of last exposure to more than 10 lux was positively associated with bedtime (Figure 2A). Average light intensity across the 24 hour period preceding the night of interest and time of first exposure to more than 10 lux were not significantly associated with bedtime.

Average light intensity across the 24 hour period preceding the night of interest, time of first exposure to more than 10, and time of last exposure to more than 10 lux were not significantly associated with next-day waketime.

Time of last exposure to more than 10 lux was negatively associated with total sleep time (Figure 2B). Average light exposure across the 24 hour period, and time of first exposure to more than 10 lux were not significantly associated with total sleep time.

3.3 Exploratory Analysis

Given the finding that evening light exposure and average light exposure across the 24h day were influencing sleep in this sample, an additional exploratory analysis was conducted to examine whether smaller light bins (4–9AM, 9AM-2PM, 2PM-7PM, 7PM-midnight) would be associated with any of the sleep outcomes (see Supplemental Table 2). In brief, higher average light between 4–9AM was associated with an earlier sleep onset the next evening as well as both an earlier sleep offset and an earlier waketime the next morning, lower average light between 2–7PM was associated with a later sleep offset the next morning, and lower average light between 7PM-midnight was associated with a longer total sleep time. There was no association between light exposure between 9AM-2PM and any of the subjective or objective sleep outcomes. Since age was a significant covariate in many of our analyses, we conducted additional exploratory analyses to examine whether age moderated the relationship between light and sleep. Unfortunately, there were no significant interaction effects for age × light.

4. DISCUSSION

The present study assesses the relationship between light exposure and sleep among adolescents with an evening circadian preference.

We examined the association between light exposure and both objective and subjective sleep and found partial support for our first two hypotheses. Lower average light intensity across the 24 hours preceding the night of interest was associated with a later sleep onset and a later next-day sleep offset. Moreover, exploratory analyses revealed that lower average light intensity in the morning (between 4:00–9:00AM) was associated with a later sleep onset as well as a later next-day sleep offset and a later next-day risetime, lower average light intensity in the afternoon (between 2:00–7:00PM) was associated with a later sleep onset, and lower average light intensity in the evening (between 7:00PM-midnight) was associated with longer subjective total sleep time. Additionally, a later time of last exposure to more than 10 lux was associated with a later bedtime, a later time of sleep onset, and shorter objective and subjective total sleep time. These findings are consistent with prior reports that an evening circadian preference is associated with lower intensity light exposure during the day (Martin et al., 2012), that lower intensity light exposure during the day is associated with a later sleep onset (Roenneberg et al., 2003; Wright et al., 2013), and that evening light delays both circadian and sleep timing (Santhi et al., 2012). These data also provide a scientific basis for interventions that alter light exposure either behaviorally or via the administration of bright light (Harvey et al., 2018; Richardson et al., 2018).

Our findings build on prior research by demonstrating a specific link between daytime light exposure and subsequent nighttime sleep for adolescents with an evening circadian preference. Indeed, we observed that a later transition to dim light (<10 lux) delays objective sleep onset and subjective bedtime and contributes to shorter objective and subjective total sleep time. Additionally, higher average light intensity in the evening hours also results in shorter subjective total sleep time. Adolescents are likely to be exposed to brighter light later in the evening due to a convergence of factors including a biological shift towards a later bedtime, slower accumulation of and greater tolerance for sleep pressure, and increased

technology use (Cain & Gradisar, 2010; Jenni et al., 2005; Roenneberg et al., 2004). Moreover, adolescents are being asked to engage with technology and light in the evening in order to complete their homework and also in response to changing cultural norms which is increasing the use of technology for socializing (Adams et al., 2017; Hoyt et al., 2018). As a result, adolescents are not getting enough sleep, are not timing their exposure to light appropriately to ensure an adequate opportunity to sleep, are more sensitive to evening light and are not only using light-emitting devices for academic and socializing purposes, but can also be a way to cope with stress and a negative home environment (Gaarde et al., 2018; Hoyt et al., 2018). Together, these findings provide support for evening light exposure being a particularly important target for intervention. Indeed, prior research has found that artificial light at night could perpetuate an evening circadian preference (Wright et al., 2013). When adolescents are persistently exposed to light late in the evening, their circadian phase will remain delayed.

It is important to also examine the impact of early school start times and other social factors on the relationship between light exposure and sleep. Indeed, shortened total sleep times are likely due to a combination of both later timing of bedtime and sleep onset, as well as early school start times, which restrict the time available for sleep (Crowley et al., 2007). Indeed, while the American Academy of Pediatrics recommends that school begins after 8:30AM (Au et al., 2014) and California (the state where the data was collected) now requires middle schools and high schools to begin after 8:00AM and 8:30AM, respectively (S.B. 328), at the time of data collection (2013–2016), school start times were set earlier than 8:00AM for most students. Early school start times contribute to early morning awakenings and could explain the association between higher average intensity light exposure in the morning and earlier next-day sleep offset and risetime in the present study. The association between morning light and early awakening likely results from externally set waketimes across the week due to school start times before 8:00AM. Future research should continue to examine the direction of this association.

Additionally, while the amount of time spent indoors versus outdoors was beyond the scope of the present study, the link between lower intensity light exposure and a later sleep onset is supported by previous research finding that lower intensity daytime light exposure is often due to increased time spent indoors and is associated with having an evening circadian preference (Harada et al., 2002). Therefore, one possibility is that adolescents with an evening circadian preference are limiting their time outdoors in sunlight that could help advance their circadian rhythms. However, prior research has also found no link between time spent outdoors and chronotype during adolescence (Roenneberg et al., 2015) and hypothesize that adolescents who spend time outdoors in both the morning and afternoon are not experiencing a phase advance, or phase delay, because their bright light exposure is spread across the day instead of fixated in the morning or afternoon. Future studies should consider collecting information about indoor versus outdoor time to better capture whether this association is driven by the source or intensity of light or possibly due to something else.

Our findings must be interpreted with certain limitations in mind. First, actigraphy was used for light measurement. Although actigraphy is commonly used to measure light (Auger et

al., 2011; Wams et al., 2017; Wright et al., 2013), light sensors are at the wrist and may not capture light at the eye. Also, participants did not log light sources or use of sunglasses, blue-blocking glasses, and coverings like sleeves or bedcovers. Future research should consider multiple sensors and daily logs to more accurately discriminate light information. Second, an a priori decision was made to cut the data to examine the prior 24 hours of light exposure, including both daytime light exposure and light at night which has been linked to an evening circadian preference (Vollmer et al., 2012), and to use hierarchical linear modeling to assess how each 24 hour window of light exposure was associated with the sleep interval that immediately followed it. While prior research has utilized 24 hour light variables (Keller et al., 2017; Wams et al., 2017), it is important to note that light history can influence circadian timing and future research should consider the best way to look at the influence of a specific day of light exposure as well as the influence of a longer timeframe. Third, the present sample was drawn from a larger randomized controlled trial that recruited adolescents who had an evening circadian preference and were at risk in one of five health domains. Not all adolescents will experience sleep disturbance, an evening circadian preference, or risk in these health domains, so the findings from this study are most generalizable to a high risk sample. However, we know that sleep problems are associated with increased risk-taking behavior, internalizing and externalizing problems, suicidality, substance use, and physical inactivity as well as a decreased academic performance (Baiden et al., 2019; Hysing et al., 2016; Pieters et al., 2015; Short & Weber, 2018). Moreover, adolescents with an evening circadian preference are at an even greater risk for internalizing and externalizing problems, suicidality, and substance use compared to their peers with a morning or intermediate circadian preference (Gau et al., 2007). Furthermore, the present sample also had increased circadian disruption relative to a community sample of adolescents as measured by interdaily stability (see Table 1; 0.32 for the present sample compared to 0.55 for a community adolescent sample; Mitchell et al., 2017) and a wider phase angle (see Table 1; 2.62 hours for the present sample compared to around 2 hours for a community sample; Crowley et al., 2014), which are associated with poorer health outcomes (Hou et al., 2020). Therefore, an important next step is to examine whether the results of the present study are replicated in other chronotypes or in individuals who are not experiencing health risk. Fourth, treatment for the RCT commenced after the pre-treatment assessment period during which data for the present study was collected. Although participants receiving other sleep treatments (e.g., hypnotics) were excluded, we acknowledge that treatments for non-sleep conditions can impact sleep. Finally, All data were collected whilst school was in session. While we used weekday/weekend as a proxy for school-day/free-day, we cannot exclude the possibility that youth had a sick day or other free day on one or more of the presumed school-days.

5. CONCLUSIONS

In sum, the present study provides support for the link between light exposure and both objective and subjective sleep. Taken together, the results suggest that light intensity and timing are important for sleep timing and longer sleep duration. Given that adolescence is a critical developmental period characterized by a shift towards an evening circadian preference, future studies should examine whether interventions focused on modifying

the *intensity* and the *timing* of light exposure in an adolescent's daily life can influence sleep and circadian timing, given the evidence for an altered circadian response to light contributing to insufficient and delayed sleep during adolescence (Crowley et al., 2018), increased usage of light-emitting devices (Cain & Gradisar, 2010), and light exposure as a modifiable environmental factor for improving sleep (Owens, 2014).

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Highlights

- This study examined light and sleep in teens with an evening circadian preference.
- Lower intensity light was associated with a later sleep timing.
- Lower intensity early morning light contributed to later sleep timing.
- Later timing of light resulted in later sleep timing and shorter sleep duration.

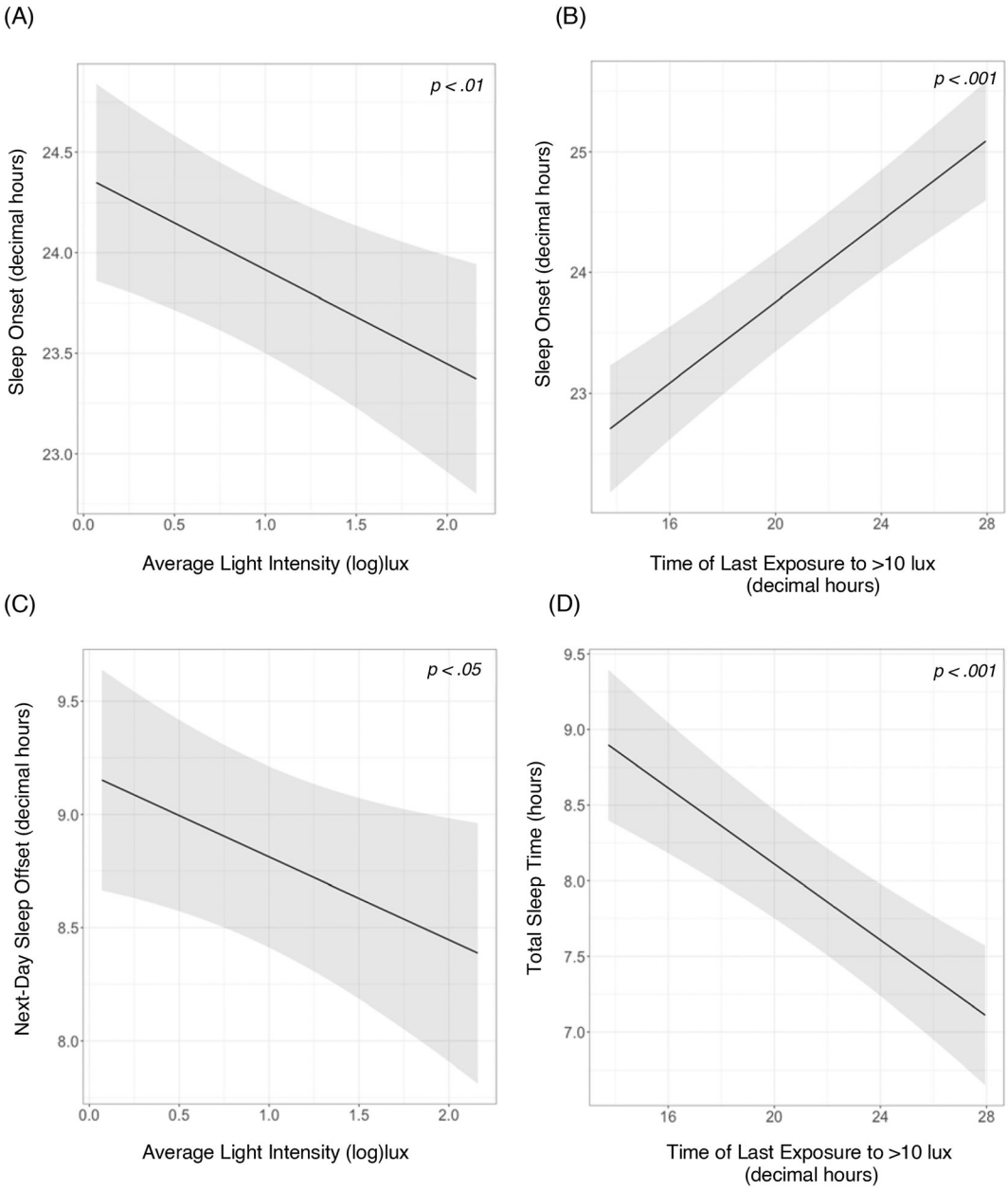

Figure 1 –.

Light Exposure and its relationship to subsequent objective sleep. (A) Increased light exposure across the 24 hour day was associated with an earlier sleep onset in the evening. (B) A later time of last exposure to more than 10 lux was associated with a later sleep onset in the evening. (C) Increased light exposure across the 24 hour day was associated with an earlier time of next-day sleep offset. (D) A later time of last exposure to more than 10 lux was associated with a shorter total sleep time. Note. The black line represents the model predicted values of the outcome. The grey shading around the black line denotes that standard error.

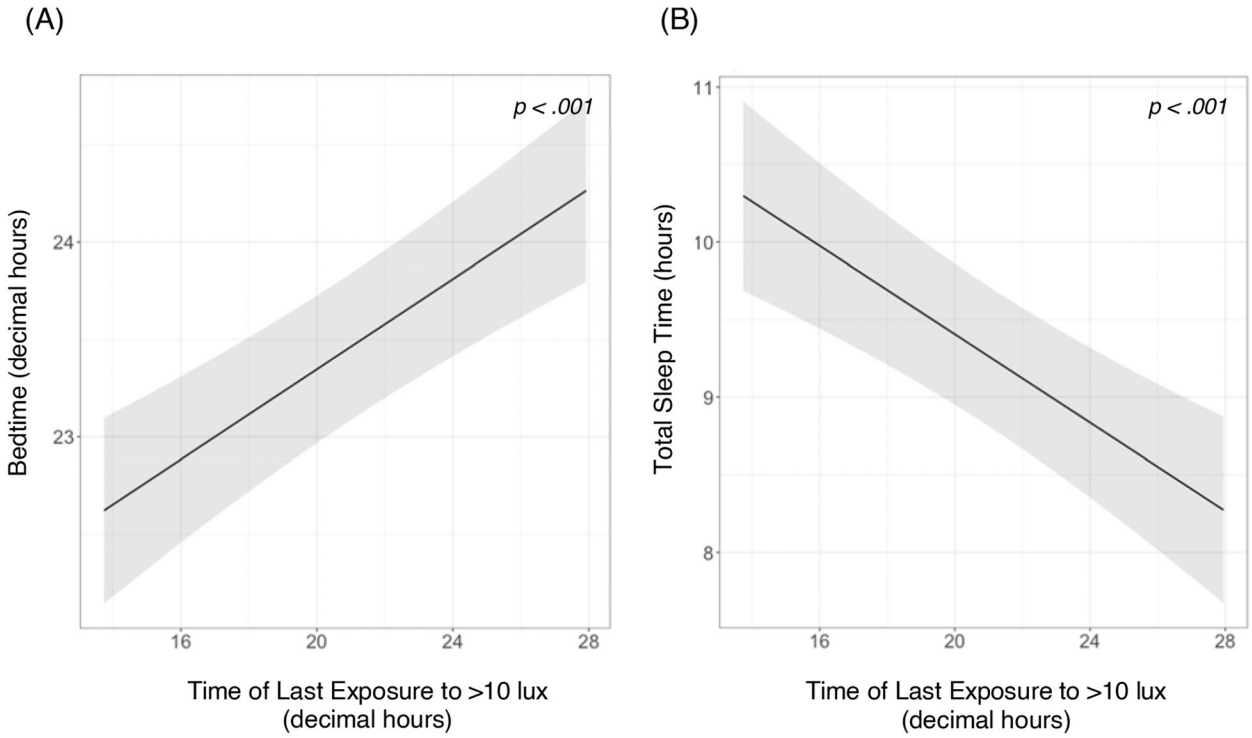

Figure 2 –.

Light Exposure and its relationship to subsequent subjective sleep. (A) A later time of last exposure to more than 10 lux was associated with a later bedtime. (B) A later time of last exposure to more than 10 lux was associated with a shorter total sleep time. Note. The black line represents the model predicted values of the outcome. The grey shading around the black line denotes that standard error.

Table 1.

Participant Characteristics ($N = 99$) and Sleep Variables

	Mean or N	% or SD
Female	59	59.6%
Age (years)	14.76	1.83
DLMO (decimal hr)	21.27	1.07
Children's Morningness-Eveningness Preference Scale	21.32	3.94
Interdaily Stability	0.32	0.18
Actigraphy		
Sleep Onset (decimal hr.)	23.63	0.80
Sleep Offset (decimal hr.)	7.60	0.77
TST (hours)	7.98	0.90
Phase Angle: DLMO – Sleep Onset (decimal hr.)	2.61	1.25
Sleep Diary		
Bedtime (decimal hr.)	23.52	0.88
Waketime (decimal hr.)	7.30	0.58
TST (hours)	7.81	0.98
Phase Angle: DLMO – Bedtime (decimal hour)	2.19	1.06
Weekday Wake-Up Methods (540 total days of data)		
Alarm	177	32.8%
Another Person	125	23.1%
Noise	9	1.7%
Woke Up Naturally	65	12.0%
Not Reported	164	30.4%
Weekend Wake-Up Methods (163 total days of data)		
Alarm	21	12.9%
Another Person	16	9.8%
Noise	3	1.8%
Woke Up Naturally	49	30.0%
Not Reported	74	45.3%

Note: DLMO = Dim light melatonin onset; TST = Total Sleep Time. Interdaily stability is measure of circadian disruption, with higher values reflecting greater synchronization between rest-activity patterns and environmental zeitgebers. Phase angle is a metric of circadian alignment calculated as the time interval in decimal hours between DLMO and bedtime (sleep diary) or sleep onset (actigraphy) (Crowley et al., 2014). DLMO, sleep onset, sleep offset, bedtime, and waketime were set to decimal hours (e.g. 11:00 PM = 23.00) and times occurring after midnight were converted by adding 24.00 to the decimal hour value (e.g. 1:05 AM = 25.08). Total sleep time was set to hours (e.g. 7 hours and 24 minutes = 7.4 hours).

Table 2.

Light Variables.

	Mean ± SD	Minimum	Maximum
Average Light Intensity (log(lux))	0.90 ± 0.39	0.07	2.16
Time of First Exposure to >10 lux (hh:mm)	08:14 ± 2:02	0:26	16:20
Time of Last Exposure to >10 lux (hh:mm)	21:34 ± 2:26	13:44	3:57

Table 3.

Coefficient estimates from hierarchical linear models of the relationship between light and objective sleep.

Outcome	Predictor	B	SE	*t*	*p*	CI	χ^2
Sleep Onset	Average Light Exposure	−.47	.16	−2.94	.003**	−.78, −.16	8.26*
	Time of First Exposure	.04	.03	1.49	.136	−.01, .09	2.25
	Time of Last Exposure	.17	.02	7.60	<.001***	.12, .21	55.64***
Sleep Offset	Average Light Exposure	−.37	.17	−2.17	.031*	−.70, −.03	4.73*
	Time of First Exposure	.01	.03	.44	.662	−.04, .06	0.21
	Time of Last Exposure	.02	.03	.73	.463	−.03, .07	0.54
TST	Average Light Exposure	−.01	.16	−.04	.967	−.03, .07	0.01
	Time of First Exposure	−.03	.03	−.97	.333	−.08, .03	0.92
	Time of Last Exposure	−.13	.02	−5.38	<001***	−.17, −.08	28.56***

*Note: TST = Total Sleep Time (Difference between Sleep Onset and Sleep Offset minus wake after sleep onset); CI = 95% Confidence Intervals; χ^2 = likelihood ratio test assessing goodness of fit comparing model with and without predictor of interest. Weekday/weekend and age as covariates for all models. All light data (measured in lux) were log10 transformed.

*$p < .05$,

**$p < .01$,

***$p < .001$

Table 4.

Coefficient estimates from hierarchical linear models of the relationship between light and subjective sleep

Outcome	Predictor	B	SE	*t*	*p*	CI	χ^2
Bedtime	Average Light Exposure	.08	.15	.51	.607	−.21, .36	.29
	Time of First Exposure	.02	.02	.72	.475	−.03, .06	.51
	Time of Last Exposure	.12	.02	5.69	<001***	.08, .16	31.53***
Waketime	Average Light Exposure	−.20	.14	−1.39	.165	−.47, .08	1.98
	Time of First Exposure	.02	.02	.91	.363	−.02, .07	.87
	Time of Last Exposure	−.01	.02	−.36	.723	−.05, .03	.13
TST	Average Light Exposure	−.30	.20	−1.49	.137	−.69, .09	2.28
	Time of First Exposure	−.02	.03	−.68	.494	−.09, .04	.43
	Time of Last Exposure	−.14	.03	−4.91	<001***	−.20, −.09	23.52***

*Note: TST = Total Sleep Time (Difference between bedtime and waketime minus wake after sleep onset); CI = 95% Confidence Intervals; χ^2 = likelihood ratio test assessing goodness of fit comparing model with and without predictor of interest. Weekday/weekend and age as covariates for all models. All light data (measured in lux) were log10 transformed.

***$p < .001$