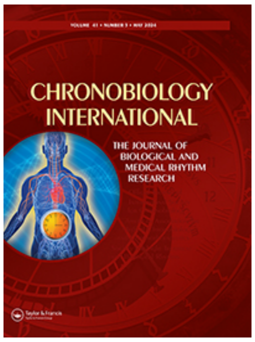

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Sojeong Kim & Melynda D. Casement

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Promoting adolescent sleep and circadian function: A narrative review on the importance of daylight access in schools

Sojeong Kim and Melynda D. Casement

Department of Psychology, University of Oregon, Eugene, Oregon, USA

ABSTRACT
Adolescent sleep disturbances and circadian delays pose significant challenges to mood and daytime functioning. In this narrative review, we explore the impact of light on sleep and highlight the importance of monitoring and managing light exposure in adolescents throughout the day and night. The benefits of daylight exposure in mitigating sleep and circadian disruptions are well-established; however, interventions targeting access to daylight in adolescents remain under-studied and underutilized. The primary aim of this narrative review is to bring attention to this gap in the literature and propose the need for institutional-level interventions that promote access to daylight, especially considering adolescents' early school start times and substantial time spent indoors on weekdays. School-led interventions, such as active commuting to school and outdoor curriculums, have promising effects on sleep and circadian rhythms. Additionally, practical measures to optimize natural light in classrooms, including managing blinds and designing conducive environments, should also be considered. While future studies are necessary to facilitate the implementation of interventions, the potential for these school-level interventions to support adolescent sleep health is evident. Aiming for integration of individual-level regulation and institutional-level intervention of light exposure is necessary for optimal outcomes.

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Sleep; circadian rhythm; light exposure; daylight; adolescents

Introduction

Chronic sleep problem is a significant concern for adolescents, with reports from the Centers for Disease Control and Prevention indicating that 57.8% and 72.7% of middle and high schoolers in the United States obtain inadequate sleep (Wheaton et al. 2018). College students are similarly affected, as a study found over 60% of students aged 17 to 24 were suffering from poor sleep quality (Lund et al. 2010). Adults also experience sleep challenges; 14.5% report significant difficulty falling asleep most days or even daily (Adjaye-Gbewonyo et al. 2022), and over a third do not meet the recommended sleep duration of seven hours (Johnson et al. 2023), pointing to widespread sleep-related problems in both adolescents and adults.

Adolescents, in particular, show the highest prevalence of delayed sleep phase disorder, marked by late bedtimes and wake times that conflict with societal norms (Thorpy et al. 1988). Inadequate sleep duration can result from delayed and irregular sleep because adolescents rise early for school during weekdays. Attempts to catch up on sleep on weekends can lead to greater fatigue in subsequent school days, leading to social jetlag – a term describing the shift in sleep patterns between weekends and weekdays (Taylor et al. 2008). This irregularity in sleep is not without consequence; social jetlag is associated with anxiety and depression symptoms in adolescents (Wong et al. 2015).

The importance of sleep for adolescents encompasses critical aspects of mood, motivation, and cognitive functions. Studies underscore that sleep greatly influences alertness, learning, memory consolidation, and concentration, which are particularly vital for students (Alhola and Polo-Kantola 2007; Foster and Wulff 2005; Gradisar et al. 2022; Kopasz et al. 2010). Moreover, adolescence is a period of increased vulnerability for the development of mood disorders, with disrupted sleep patterns potentially exacerbating this risk (Merikangas et al. 2009). The repercussions of depression in adolescence are profound, often setting a trajectory for recurrent depressive episodes and an elevated risk of suicide in adulthood (Bridge et al. 2006; Carskadon et al. 2004). Consequently, a comprehensive understanding of sleep's multifaceted role in adolescent well-being is crucial, guiding the need for targeted research and interventions.

The "two-process model" by Borbély (1982) and Borbély et al. (2016) proposes that the interaction between the homeostatic sleep drive and the circadian process regulates sleep. The sleep homeostatic process

CONTACT Sojeong Kim sojeongk@uoregon.edu Department of Psychology, University of Oregon, 1451 Onyx St, Eugene, OR 97403

generates a balance between sleep and wakefulness by accumulating sleep pressure during periods of wakefulness and dissipating it during sleep. As wakefulness persists, the urge to sleep intensifies. As sleep occurs, the homeostatic sleep drive gradually dissipates, which enables wakefulness to occur again. The intensity of homeostatic sleep drive is influenced by various factors including the amount and quality of prior sleep. Greater slow-wave activity results during sleep following longer periods of wakefulness, indicating a homeostatic balance between wakefulness and sleep. The homeostatic sleep drive interacts with the circadian process, to determine the timing and duration of sleep. The circadian process gives rise to a rhythmic pattern of approximately 24-hour oscillations between sleep and wakefulness. A circadian drive to stay awake for periods of roughly 16 hours counteracts increasing homeostatic sleep pressure with progressive wakefulness (Achermann and Borbély 1994). Similarly, the circadian sleep period counters the decrease in homeostatic sleep pressure resulting from accumulated sleep, thereby permitting a consolidated 8-hour sleep episode (Dijk and Czeisler 1994). The perfect storm model by Carskadon (2011) and revised by Crowley et al. (2018) adds to the "two-process model;" they propose that additional factors contribute to short and ill-timed sleep among adolescents, including bioregulatory changes to the homeostatic sleep system, delays in the circadian system, psychosocial pressures like academic stress and light exposure, and societal pressures like early school start times.

This paper highlights the critical yet often overlooked impact of daylight exposure on adolescent sleep and circadian rhythm, particularly within school environments where adolescents spend a significant portion of their day. Light serves as a fundamental environmental signal, aligning the biological clock with the natural day-night cycle, while inadequate exposure can lead to circadian disruptions. Nonetheless, if harnessed prudently, light exposure can be a powerful tool in managing sleep-related disturbances and promoting healthy sleep patterns (Dumont and Beaulieu 2007). Despite empirical evidence underscoring the crucial role of daylight exposure in mitigating delayed circadian rhythm across various age groups, including young adolescents and college students (Dunster et al. 2023; Figueiro et al. 2017), practical interventions aimed at increasing daylight accessibility within schools are inadequately explored and underutilized. In addressing this gap, this paper brings to light the scarcity of school-level interventions that facilitate daylight exposure, introducing three innovative approaches that have shown promising impacts on improving sleep and circadian regulation in adolescents. The primary objective of this paper is to advocate for more robust and strategic institutional actions to target the pervasive sleep and circadian disturbances observed in adolescents. We call for the development, assessment, and subsequent implementation of such interventions that can harness the therapeutic potential of light to foster better sleep and circadian functioning in adolescents.

Sleep and circadian rhythm in adolescents

During weekdays, adolescents typically spend a significant portion of their waking hours at school. According to the U.S. Department of Education NCES 2020 data, the average start time for high schools in the United States is around 8:00 am (U.S. Department of Education 2020). However, during the winter months in Washington, D.C., for instance, the sunrise time ranges from 6:57 am to 7:23 am, as reported by WorldData.info (2015). This implies that adolescents, particularly during winter, may have limited access to natural outdoor light, as they often need to enter the school building not long after sunrise. Nevertheless, it is challenging to obtain indoor light levels that are optimal for circadian health. This concern extends beyond the student population, affecting adults as well, who typically work during daylight hours from 8:00 am to 5:00 pm, thus facing similar challenges in gaining adequate exposure to natural light (Torpey 2015).

While the impact of light exposure on sleep and circadian rhythm is a concern for all age groups, our research highlights the adolescent population, whose developmental stage – with its distinct sleep and circadian timing challenges – makes the scarcity of daylight exposure during school days a matter of increased vulnerability. Research has indicated that adolescents show a reduced pressure to recover from wakefulness, which is reflected in lower sleep electroencephalogram slow-wave activity (i.e., Campbell et al. 2012). Moreover, studies have demonstrated that while the accumulation of sleep pressure occurs at a slower rate in older adolescents compared to their younger counterparts (Jenni et al. 2005), the rate at which sleep pressure is dissipated does not change across adolescent development (Jenni and Carskadon 2004; Tarokh et al. 2012). Thus, despite the slower build-up of sleep pressure during wakefulness in adolescents, enabling older adolescents to postpone their bedtime, the dissipation rate of sleep pressure does not change, and the sleep need remains stable at around 9 hours (Fuligni et al. 2019).

Independent of the increased ability to stay awake for longer periods, adolescents naturally experience a shift to later sleep and wake times. This change is regulated by their internal circadian rhythm, which becomes markedly delayed during puberty. Research incorporating self-reported sleep patterns and biological markers, such as salivary melatonin levels, has demonstrated that puberty is associated with a delayed circadian phase (Hagenauer et al. 2009; Roenneberg et al. 2004). The underlying cause is thought to be an extended endogenous circadian cycle that is longer in adolescents than in adults (Carskadon et al. 2004), leading to stronger evening preferences and delayed sleep time (Duffy et al. 2001). Consequently, adolescents who are already at risk of experiencing diminished sleep needs and delayed circadian rhythms, encounter additional challenges in obtaining optimal light exposure during school hours, exacerbating sleep disturbances prevalent in this age group.

The role of light on circadian rhythm

In more recent years, scientific research has broadened our comprehension of light's impact beyond visual function, particularly its critical role in regulating circadian rhythm. A healthy circadian rhythm refers to the state of alignment between an individual's internal clock and the external environment, optimizing the timing of daily activities such as sleep. This rhythm is entrained into the 24-hour cycle by external cues called zeitgebers, the most important of which is the light-dark cycle. Light transmitted through the retina to suprachiasmatic nuclei (SCN) of the hypothalamus affects vital physiological functions and hormonal variations (Cagnacci et al. 1997; Rajaratnam and Arendt 2001). Disruption in this rhythm can lead to a decline in cognitive performance and memory, exacerbated mood symptoms, and sleep disturbances (McClung 2007; Walker et al. 2020). On the other hand, appropriate bright light exposure is known to exert beneficial effects on concentration, alertness, vitality, and mood (Kohsaka et al. 1999; Partonen and Lönnqvist 2000).

The influence of light on the circadian clock is contingent upon a myriad of factors including the timing, duration, intensity, and wavelength. Morning light exposure, particularly from the early to mid-morning period, is known to activate the circadian clock, thereby advancing the rhythm, and promoting earlier sleep onset. Conversely, exposure to light during the early evening to nighttime, predominantly artificial, is associated with delayed circadian timing, which in turn leads to later sleep times. Furthermore, research has also shown that natural daylight also improves the duration and quality of sleep (Figueiro et al. 2017; Roenneberg et al. 2003; Wehr 1990). While individual responses to light can vary based on intrinsic circadian phases, adequate exposure to daylight from 6:00 h to 10:00 h is typically effective in advancing the circadian phase for most individuals. In contrast, light exposure from 18:00 h to 6:00 h has the potential to delay the natural sleep-wake cycle (Andersen et al. 2012).

The spectral composition of light is also an important determinant in regulating circadian rhythm. Light is a form of energy that exists in a specific range of the electromagnetic spectrum and can be characterized by the amount of energy distributed across different wavelengths. The circadian clock is particularly sensitive to short wavelength "blue" light. Exposure to this blue light in the morning is known to advance the circadian phase (Warman et al. 2003), optimizing the timing of sleep. While there is a general agreement that exposure to high-intensity, short-wavelength light in the morning is advantageous, a comprehensive understanding of the circadian system's response to light necessitates careful consideration of the complex interplay between the light's intensity, duration, timing, pattern, and wavelength.

To optimize the use of light for better sleep and circadian regulation, it is fundamental to understand its dual role as a protective and risk factor for disrupted sleep and circadian rhythms. Current literature on light exposure is weighted towards the effects of light-emitting devices – electric devices and home lighting – on sleep, while the literature on interventions using light is angled towards bright light therapy and ways to minimize evening light exposure. Surprisingly, the potential of natural light, despite being the strongest form of illumination, is understudied regarding its benefits and risks to sleep health. While it's crucial to manage light at night to support healthy sleep patterns and circadian rhythms, our research underscores the need to explore how inadequate daylight exposure, especially during school days, contributes to sleep and circadian disturbances in adolescents. We also propose three possible school-level interventions to enhance access to light, to mitigate sleep issues in adolescents.

Light exposure as a protective and risk factor for sleep disruption

Light exposure during the day

Adolescents spend most of the daytime in school during weekdays. Despite the importance of daylight for sleep and overall health, the impact of illuminance while at school on their sleep has not been thoroughly studied. In subsequent paragraphs, we review studies that investigated adolescents' exposure to daylight – both in classroom settings and more broadly – with their sleep quantity, quality, and circadian pattern.

Research has investigated the relationship between adolescents' exposure to daytime light and circadian preference, which is a term used to describe an individual's inclination towards morning or evening activities and their preferred timing of sleep and wakefulness (Duffy et al. 2001). Harada et al. (2002) found that high school students with delayed circadian preferences engaged less in outdoor activities during breaks compared to their early-riser counterparts. They also found that adolescents who remained indoors and those who tended to block daylight from outside during holidays reported significantly longer sleep latency, shallower sleep, and more challenges waking up in the morning. Furthermore, Gasperetti et al. (2021) found that adolescents who had evening preferences slept later on days that they received lower average morning light and woke up later the subsequent day. Similarly, those with evening preferences received lower levels of daylight and reported lower subjective sleep quality, higher work-related fatigue, and less regular social rhythms (Martin et al. 2012). In a controlled study, Figueiro and Rea (2010) explored the effect of wearing orange glasses, which filter out short-wavelength light – light that is notably influential in altering the circadian phase – on the circadian rhythms of 8th-grade students. They found a significantly delayed circadian rhythm in students who wore orange glasses during school hours, as assessed by the dim light melatonin onset (DLMO) – the gold standard measure of circadian rhythm. Altogether, these findings suggest that reduced daytime light is associated with a later circadian preference and sleep time, and other sleep-related issues.

In a study utilizing light sensor wearable devices to track daylight exposure and sleep patterns, Auger et al. (2011) found that adolescents with delayed sleep phase disorder (DSPD-A) were exposed to significantly less morning light than adolescents without sleep issues. Specifically, on school mornings, those with DSPD-A received an average of 350.6 lux, in contrast to the 419.2 lux received by their counterparts. This disparity increased on non-school mornings, with a mean of 575.2 lux for those with DSPD-A versus 711.5 lux for their counterparts. They confirmed that lower morning and afternoon light exposure (nine hours before sleep onset time) corresponded with later sleep onset time, while greater light exposure was linked to longer total sleep duration. These findings underscore the significance of morning light levels as a risk factor for delayed circadian rhythm in adolescents.

Research by Auger and colleagues highlights a marked difference in light exposure for adolescents, with significantly lower levels recorded during school days – less than 800 lux – compared to non-school days, where levels reached up to 2300 lux (as illustrated in Figure 1). This is consistent with the results of Dharani et al. (2012), who reported that during the academic term, adolescents were exposed to adequate light levels (>1000 lux) for only about 7 hours weekly, which increased to nearly 10 hours during school holidays. Classroom settings often fail to provide sufficient lighting, with peak levels reaching 742 lux, falling short of the 1000 lux recommended for circadian rhythm regulation (Fadeyi et al. 2014; Lack and Wright 2007). This is in sharp contrast to outdoor environments where light levels average over 10 000 lux (Lanca et al. 2019), as depicted in Figure 1 This disparity highlights the need

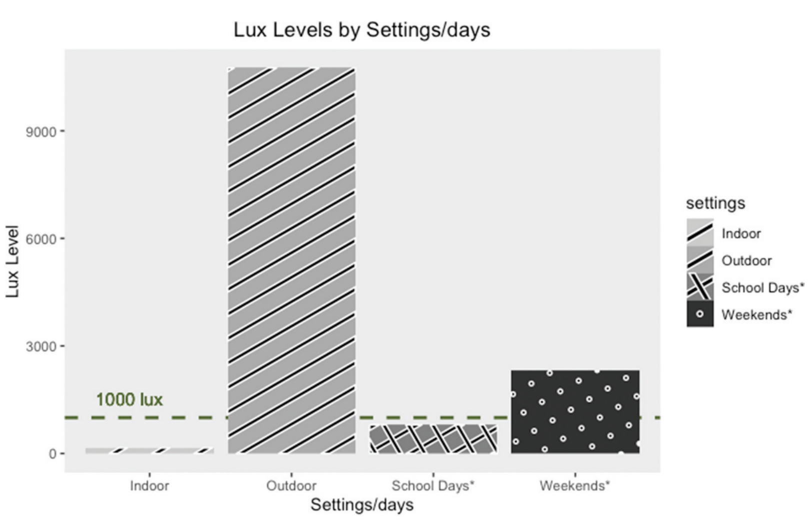

Figure 1. Lux levels by settings and days. Dashed line (1000 lux) represents the recommended minimum morning light exposure for optimal circadian health (Lack and Wright 2007) *represents maximum hourly lux levels.

for high-intensity light exposure during school hours, given that students are predominately indoors during these periods.

Seasonal variations in daylight exposure present additional challenges. During winter months, particularly at high latitudes, there is a noticeable decrease in both the intensity and duration of daylight. This seasonal fluctuation is known to disrupt sleep patterns and circadian timing. For instance, studies conducted in Northern Europe show a notable drop in sleep quality during the winter months (Johnsen et al. 2012). This period is also linked to later sleep onset times, increased daytime dysfunction, and delayed circadian rhythm (Honma et al. 1992; Lowden et al. 2019; Pallesen et al. 2001). Therefore, the impact of seasonal daylight changes should be carefully considered when examining sleep and circadian health.

The importance of daylight exposure for sleep and circadian health extends beyond the youth demographic, encompassing all ages. Research indicates that working adults in offices with ample natural light report better sleep compared to those in windowless spaces (Boubekri et al. 2014; Lee and Boubekri 2020). In the case of older adults, particularly those over 65 who suffer from poor sleep, increased exposure to daylight has been linked to enhanced sleep quality (Flores-Villa et al. 2020).

In summary, the existing body of research indicates that insufficient daylight is associated with many sleep-related problems and delayed circadian rhythm. This is particularly concerning for adolescents during school days when light exposure is often limited. To foster a school environment for optimal circadian health, it is imperative to devise strategies to increase adolescents' access to natural daylight. Future studies should comprehensively investigate how light exposure in school settings affects sleep, using objective measures like actigraphy and Daysimeter devices, which have been validated by the Lighting Research Center (Bierman et al. 2005). Such devices should ideally include photosensors located near the user's eye to capture retinal light exposure as accurately as possible.

It is also crucial to acknowledge that natural light, unlike controlled laboratory light, exhibits significant variability over time, which poses challenges for accurately measuring and quantifying light exposure (Cole et al. 1995). Existing studies often rely on summarizing or averaging light intensity over a specific period, which could overlook the nonlinear dose-dependent response to light (Cajochen et al. 2000). Therefore, precise quantification is crucial to facilitate replication and comparisons across studies. Potential methods for achieving this include using consensus-based light exposure metrics (CIE 2018) or incorporating metrics such as time above the threshold and mean light timing above the threshold, which account for intensity, duration, and timing of light exposure (Peeters et al. 2022). Precise measurement techniques are imperative to deepen our understanding of natural light's impact on adolescent sleep and circadian rhythm.

Furthermore, both within- and between-individual differences in light exposure during the daytime should be assessed in relation to sleep. Day-to-day changes in an individual's light exposure may occur due to varying amounts of time spent outdoors during breaks or differences in classroom activities. Longitudinal studies are needed to determine if these fluctuations within individuals affect the same-day sleep duration, quality, and circadian rhythm. Moreover, between-individual differences should be assessed to determine how an individual's repeated pattern of light exposure is related to their overall sleep and circadian rhythm; some may receive more daylight due to habitual outdoor activities. Lastly, the analysis should extend beyond sleep quantity and quality to include parameters like sleep onset latency, sleep efficiency, and DLMO. Understanding these nuances can reveal the broader impact of daylight exposure on sleep and circadian health. Further research and potential interventions utilizing natural light are discussed in the subsequent sections.

Light-emitting electric devices at night

In the digital age, engagement with devices for work, social interaction, and entertainment is ubiquitous (Gradisar et al. n.d.). Although not as powerful as natural light, growing evidence shows that extended light exposure at night can disrupt the circadian rhythm (Khalsa et al. 2003). With the prevalent use of electric lighting at home and personal electric devices during the evening, adolescents are at greater risk for delayed circadian phase and sleep disturbance. Studies have suggested that device usage is associated with later bedtimes, longer sleep onset latency, reduced sleep length, increased sleep disturbance, and poorer sleep quality (Caumo et al. 2020; Fossum et al. 2014; Lissak 2018). In a study involving 10 280 early adolescents, Nagata et al. (2023) showed that having a television or internet-connected device in the bedroom heightened the risk of sleep disturbances. Furthermore, in a meta-analysis, Carter et al. (2016) found an increased risk of inadequate sleep with bedtime use of portable interactive devices, such as smartphones and tablet PCs. However, this association was less pronounced when considering all other devices not just portable devices (Bartel et al. 2015).

More recently, researchers explored multiple pathways by which light-emitting devices lead to sleep disturbances and shifts in the circadian phase. A prominent one is short-wavelength "blue" light from light-emitting diode (LED)s in devices like smartphones, tablet PCs, and laptops. The circadian system is highly responsive to short-wavelength light, and exposure to such light during nighttime has been observed to induce significant melatonin suppression and postpone the circadian rhythm (Cajochen et al. 2005; Figueiro and Overington 2016; Lockley et al. 2003; Wood et al. 2013). Also, Chang et al. (2015) observed that individuals who read an electronic book before bed compared to those who read a printed book took longer to fall asleep and reported decreased nocturnal sleepiness, along with suppressed melatonin levels.

Contrasting findings emerge from studies where blue-light-blocking glasses showed minimal effect on sleep onset latency among male teenagers compared to a control group (van der Lely et al. 2015). Similarly, Heath et al. (2014) found no significant differences in sleep onset latency between adolescents who used a bright tablet screen, a dim screen, and a filtered short-wavelength screen. Bowler and Bourke (2019) also found that filtering blue light (vs. full blue light wavelength) on tablet devices did not significantly improve sleep quality in undergraduate students. Given the mixed evidence, further investigation is needed to delineate how the duration, intensity, and timing of blue light exposure affect sleep and circadian rhythm. Such research is critical to developing specific guidelines to mitigate the negative influence of light-emitting devices on sleep.

Outdoor artificial light at night

With the emergence of GPS and location data, some sleep health researchers have turned their attention to the impact of outdoor lighting at night in urban parts of the world. Outdoor artificial light at night (ALAN) refers to the presence of human-made illumination during nighttime in outdoor environments, including streetlights, illuminated buildings, and other outdoor lighting installations. According to estimates, ALAN in outdoor environments has shown a yearly increase of up to 20% in numerous urban locations during the latter half of the 20th century (Hölker et al. 2010). Some studies suggest that an increase in LED street lighting, which generates short-wavelength light, may have a significant impact on the human circadian system.

Vollmer et al. (2012) investigated the impact of outdoor ALAN on adolescents' circadian preferences using satellite image data. They found that adolescents residing in urban areas with higher levels of illumination tended to exhibit an evening preference compared to those living in darker rural regions. Paksarian et al. (2020) extended this research, showing that increased levels of outdoor ALAN correlated with later bedtimes for adolescents. Those residing in areas with the highest quartile of outdoor ALAN experienced a bedtime delay of approximately 19 minutes and obtained 11 minutes less sleep compared to those in the lowest quartile. Moreover, higher levels of outdoor ALAN were linked to elevated likelihoods of mood and anxiety disorders in adolescents. However, Patel (2019) noted that the impact of outdoor artificial light at night (ALAN) on sleep duration was minimal when considering other relevant factors at the individual and regional levels, emphasizing the complex determinants of sleep.

Given the burgeoning recognition of the crucial role that light exposure at night plays in regulating sleep and circadian rhythm, it is important to carefully weigh the impact of outdoor ALAN on adolescents' sleep. Further research should investigate whether outdoor ALAN is a risk that is powerful *enough* to cause sleep disruption and delay circadian rhythm. It is also necessary to investigate the interaction between outdoor ALAN, indoor lighting, and light from electronic devices in exerting influence on sleep. Moreover, existing research on outdoor ALAN has primarily relied on subjective measures of sleep. As the field continues to evolve, objective measures of sleep may provide valuable insights for future studies.

Use of light as school-based intervention

The early school start time poses a challenge for adolescents as the lighting within school premises may not adequately activate their circadian system, particularly during winter when the sun rises later than in summer. While electric lighting in classrooms may suffice for visual needs, it may fall short of effectively stimulating the circadian clock (Lack and Wright 2007). Given the significance of natural light exposure in advancing adolescents' circadian rhythms and mitigating other sleep disturbances, allowing more access to natural daylight on an institutional level is paramount. However, the literature remains limited for school-level programs or interventions. We propose that more sleep research should direct attention toward investigating the light environment within schools. To this end, interventions featuring natural light as a component of the school curriculum should be developed and evaluated to determine their impact on adolescent sleep.

Active commuting, characterized by walking or cycling to school, has been posited as an effective strategy for promoting better sleep among adolescents. Martínez-Gómez et al. (2011) found an association between active commuting and prolonged sleep duration, a finding that has been corroborated by Martín-Moraleda et al. (2023) and Villa-González et al. (2019). These studies collectively underscore the role of increased physical activity – a factor consistently linked to improved sleep metrics in comprehensive reviews by Kredlow et al. (2015), Lang et al. (2016), and Wang and Boros (2021)— in promoting better sleep. Notably, moderate exercise is more beneficial for sleep quality than more intense forms of exercise (Wang and Boros 2021), suggesting a nuanced relationship between exercise and sleep. Beyond the intensity and amount of exercise, its timing also crucially influences circadian rhythm entrainment, as proper scheduling of physical activity aligns the internal biological clock with environmental cues (Shibata and Tahara 2014; Weinert and Gubin 2022; Yamanaka et al. 2006). As such, the practice of active commuting stands to offer benefits for both circadian rhythm synchronization and sleep enhancement.

However, the role of natural light exposure during these commutes should not be underestimated. Although not quantified in the above mentioned studies, natural light is a critical zeitgeber that has been demonstrated to have a profound impact on sleep architecture. Exposure to daylight between 6:00 h and 10:00 h, which coincides with the typical commute time to school for adolescents, has the greatest impact on circadian regulation (Andersen et al. 2012).

It is also reported that higher light intensity, ranging from 2,000 to 10 000 lux has shown larger effects in treating various sleep-related problems, including circadian rhythm sleep disorders and insomnia (Andersen et al. 2012). Considering that natural light typically ranges from around 1,500 lux on a cloudy day to 100,000 lux on a sunny day, early morning access to powerful natural light during active commuting may have mediated the effect on sleep. Therefore, this integration of physical activity with natural light exposure presents active commuting as a practical approach for adolescents to improve sleep and circadian synchronization.

In the winter months, the efficacy of active commuting is often compromised. Early school start times and late sunrise times can restrict adolescents' exposure to light during their morning commutes. Additionally, the prospect of active commuting is frequently undermined by poor weather conditions. Therefore, exploring strategies to enhance daylight exposure within classroom settings might offer a more viable solution to these seasonal constraints, a topic that we will expand upon in the following sections.

To elucidate the mechanisms by which active commuting influences sleep and circadian rhythms, future research should dissect the individual and interactive effects of physical activity and daylight exposure. Wearable technology offers a promising avenue for capturing the nuances of these influences by tracking light intake and sleep patterns simultaneously. Comparative analysis across days with a spectrum of light conditions, from the brightness of a clear day to the dimness of an overcast sky, may illuminate the degree to which increased physical activity contributes to improved sleep amidst the natural variations in daylight. Comparing sleep metrics of active commuters wearing light-blocking glasses with those not using the glasses would also offer insight into the specific contribution of physical activity to sleep enhancement in the absence of light exposure. This approach could help isolate the effect of physical activity from the influence of light on sleep and circadian rhythm.

Active commuting is likely to offer parallel advantages to adults, meriting further investigation into its effects. Also, it is important for researchers to explore not only the impact of light exposure during active commuting on sleep, but also its effects on mental health, academic performance, and various social outcomes. Lastly, to gain a comprehensive understanding of the relationship between active commuting and sleep, it is recommended to assess other sleep and circadian rhythm-related variables such as sleep onset latency, sleep efficiency, sleep quality, and melatonin onset in both intervention and control groups. Such multidimensional research would provide a holistic view of the potential benefits of active commuting, thereby informing targeted interventions to promote well-being.

In another school-based intervention study, Dettweiler et al. (2017) examined how a full day per week of outdoor school curriculum affected the cortisol profile in children (mean age = 11.23). Cortisol acts as a synchronizer of the circadian rhythm, and elevated cortisol levels throughout the day have been associated with various sleep problems (i.e., Lemola et al. 2015; Omisade et al. 2010). Moreover, studies such as the Whitehall II study, a large longitudinal cohort study, have suggested that a flatter decline in cortisol throughout the day is related to short sleep (Abell et al. 2016). In Dettweiler et al. (2017) study, the intervention group showed a decline in cortisol from morning to noon over a year follow-up. In other words, students who spent a day per week outdoors for a year showed a steeper decline in cortisol over the day compared to the control group, indicating potential improvements in circadian rhythm and possibly sleep among these adolescents. However, they did not examine sleep-related variables nor the mechanisms for the changes in cortisol profiles. We suspect that increased light exposure during daytime – since it is reasonable to conclude that participants who had to stay outdoors had more access to sunlight – played a role in the decline of cortisol in the intervention group. Previous research has suggested that exposure to bright light in the morning can significantly decrease cortisol levels after exposure (Choi et al. 2019; Jung et al. 2010). However, other studies examining the effect of morning light exposure on cortisol levels have yielded mixed results (Figueiro and Rea 2012; Gabel et al. 2013; Martin et al. 2012). Another possible explanation could be that light exposure during the daytime promoted earlier sleep and longer sleep, which affected changes in cortisol levels. However, the exact mechanism underlying the decline in cortisol in the outdoor intervention group requires further investigation. Future studies should examine whether an individual's exposure to daylight during outdoor curriculum influences circadian alignment and sleep, using wearable devices with light sensors.

Engaging in outdoor activities during the daytime is critical because it is an ideal means of accessing strong light, given that indoor lighting levels typically range below the threshold of 1000 lux, the minimum recommended light level for optimal circadian health. However, integrating outdoor activities into the school curriculum can be challenging, owing to several barriers, including concerns over student safety, time and resource constraints, inclement weather, and student preferences. Given this, placing greater emphasis on improving light environment within classrooms could serve as an initial step. Boubekri et al. (2020) found that studying in daylit classroom spaces led to longer sleep time and higher sleep quality compared to those who studied in classrooms with little or no daylight. It is important to note that activation of the circadian system requires significantly higher light levels on the retina compared to those required for visual perception. Despite this, most lighting technologies utilized in schools are primarily intended to optimize visual perception. As such, it is imperative for educational institutions to consider how to effectively harness the benefits of natural light by fully and functionally utilizing windows. Windows certainly allows for high light levels but can create glare in classrooms. To maximize the circadian benefits and improve sleep in adolescents, effective control of glare with blinds or other window treatments should be employed while preserving access to natural light. A more sophisticated understanding of how to effectively use natural light in school design, considering the ever-changing nature of daylight throughout the day, weather conditions, and seasons, is necessary.

Conclusion

Systematic reviews have suggested that adolescents worldwide obtain insufficient sleep (i.e. (Crowley et al. 2007)., During adolescence, a developmental change occurs in their bioregulatory process; the accumulation of sleep pressure during wakefulness is markedly decreased, making adolescents go to bed later (Gradisar et al. 2022). Not only are they physiologically more prepared to stay awake longer, but adolescents also show a stronger tendency to go to bed later (Hagenauer et al. 2009). These changes in the bioregulatory system contribute to disrupted sleep patterns during adolescence. Given the established connection between sleep disturbances and various cognitive and mental health challenges in adolescents, comprehensive research is necessary for the development and assessment of effective strategies to promote sleep health.

In this narrative review, we described the effect of light on adolescent sleep, focusing on daylight exposure within school environment. We found that literature to date suggests that decreased light received on school days is associated with sleep disturbances. Further investigation is warranted to explore how daylight access influences broader cognitive and mental health aspects, such as learning, memory, academic performance, and overall well-being. Future studies should employ precise and objective measurements of light and sleep to establish a causal link between light exposure and sleep issues. Moreover, research should extend beyond commonly assessed sleep quantity and quality to include parameters such as sleep efficiency, sleep onset latency, and circadian markers like DLMO.

We also discussed the effects of light-emitting devices and outdoor ALAN on adolescent sleep. While some studies report that blue light from LED screens suppresses evening melatonin and delays sleep, others observe minimal difference in sleep parameters. We suggest researchers conduct studies with varying device luminance to understand the extent and intensity of blue light exposure that is related to adolescent sleep and circadian disruption. As for outdoor ALAN, only a few studies to date have examined its effect on

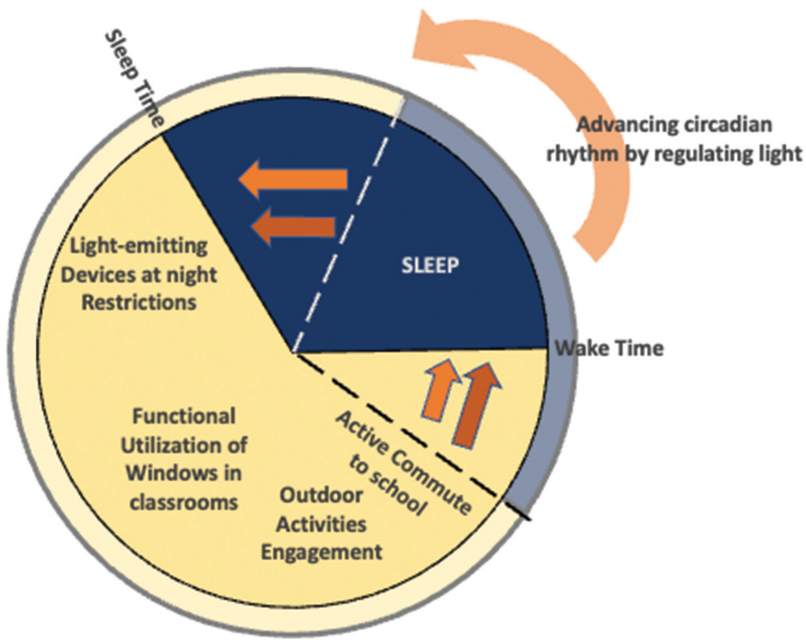

Figure 2. Regulation of light exposure for advancing circadian phase: institutional and individual approaches.

adolescent sleep. Although some found that outdoor ALAN is related to a later bedtime and shorter sleep length, more research should be done to replicate and expand the findings, especially those comparing its influence against other factors like indoor nighttime lighting. Furthermore, we also suggest investigating the association between outdoor ALAN and other contextual and/or environmental factors like housing density, which have implications for sleep health (Hale et al. 2019).

Most importantly, we underscore the urgent need for school-level light interventions targeted to address the sleep challenges adolescents face – a need amplified by the substantial time they spend in educational settings. The current literature is scarce on concrete examples of school-based interventions aimed at enhancing daylight exposure to improve sleep. We proposed three promising strategies: active commuting, outdoor-focused curricula, and improved window treatment in classrooms. These approaches can boost light exposure on school days, with positive implications for both sleep and circadian regulation. Further research is essential to explore and assess such institutional approaches, which leverage the restorative power of light, to support better sleep and circadian health in adolescents. We are optimistic that this will pave the way for more widespread adoption and implementation of these initiatives.

In conclusion, the integration of individual-level regulation of light exposure, such as limiting the usage of light-emitting devices at night, and institutional-level intervention, including the implementation of active commuting programs, outdoor curricula, and the enhancement of daylight access through windows, is a crucial and immediate step towards advancing circadian rhythms and improving sleep in adolescents (Figure 2).

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ORCID

Sojeong Kim http://orcid.org/0000-0003-4970-4116
Melynda D. Casement http://orcid.org/0000-0002-5906-0994

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