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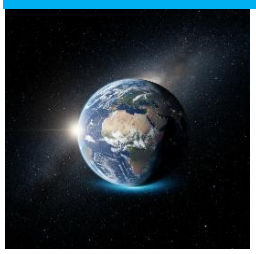

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Circadian alignment as a modifiable target in adolescent mental health: mechanisms and preventive approaches

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Abstract

Adolescence is a developmental period characterized by a physiologically delayed circadian phase and ongoing maturation of neural systems involved in emotional regulation and cognitive control. This developmental configuration increases susceptibility to sleep restriction and circadian misalignment, particularly in the context of contemporary lifestyle patterns marked by high evening screen exposure. Short-wavelength light emitted by electronic devices has been linked to delayed sleep timing and social jetlag, which are common among adolescents.This narrative review synthesizes current evidence on the relationships between circadian rhythm disruption, sleep disturbances and mental health outcomes in adolescents. Particular attention is given to biological mechanisms potentially underlying these associations, including alterations in melatonin signaling, dysregulation of monoaminergic neurotransmission, activation of the hypothalamic-pituitary-adrenal axis, inflammatory pathways and interactions within the gut-brain axis. The review also examines the cognitive and academic correlates of insufficient and irregular sleep during this critical developmental stage. Emerging evidence indicates that circadian misalignment and chronic sleep restriction are consistently associated with depressive and anxiety symptoms, emotional dysregulation and reduced cognitive performance in adolescents. Circadian-oriented strategies, such as reducing evening light exposure, delaying school start times and implementing structured sleep hygiene programs, are discussed as promising approaches to improve sleep patterns and support psychological functioning in this population. By integrating neurobiological, clinical and population-level findings, this review highlights the relevance of circadian health in adolescent mental well-being and underscores the importance of chronobiological considerations in preventive and educational strategies.

Introduction

The circadian rhythm constitutes a fundamental mechanism regulating human physiology, synchronizing hormonal, metabolic and behavioral processes with the light-dark cycle [1-3]. The central pacemaker of this system, the suprachiasmatic nucleus (SCN) of the hypothalamus, integrates environmental signals, primarily light, and coordinates the activity of peripheral clocks in the brain and other tissues [1-3]. Proper circadian synchronization plays an important role in the regulation of sleep-wake patterns, hypothalamic-pituitary-adrenal (HPA) axis, neurotransmission and emotional stability [4-6].

Adolescence represents a developmental period characterized by increased vulnerability of the circadian system to both biological and environmental factors [7]. Puberty is associated with a physiological delay in circadian phase, reflected in later timing of melatonin secretion and a preference for delayed sleep onset and wake times [7]. This phenomenon is referred to as the ,,delayed adolescent chronotype" and is correlated with a higher prevalence of delayed sleep-wake phase disorder (DSWPD) in this age group [7, 8]. At the same time, neurobiological brain development during this period is characterized by intensive remodeling of cortico-limbic structures responsible for emotional regulation, impulse control and stress responsivity [9-11]. The ongoing maturation of these neural networks may increase sensitivity to sleep restriction and circadian misalignment [9-11]. Concurrently, modern lifestyle patterns frequently amplify this biological predisposition. Early school start times and prolonged evening use of electronic devices may create a mismatch between adolescents' endogenous sleep rhythms and socially imposed schedules. This discrepancy is referred to as ,,social jetlag" and is defined as the difference between sleep-wake timing on school days and free days [12,13]. Clinically significant social jetlag (≥2 hours) is estimated to affect approximately 40-50% of adolescents [12,13]. Observational studies suggest that greater social jetlag is associated not only with poorer sleep quality but also with an increased risk of mood disorders, anxiety symptoms and suicidal behaviors [14-16].

In recent years, particular attention has been directed toward evening exposure to blue light emitted by electronic devices as a potential modifiable factor exacerbating circadian phase delay in adolescents. Short-wavelength light (approximately 460-480 nm) most strongly suppresses nocturnal melatonin secretion through activation of melanopsin-containing intrinsically photosensitive retinal ganglion cells, which project directly to the SCN [16-19]. Experimental and observational studies consistently show that even several hours of evening exposure to screen light results in circadian phase delay, reduced sleep duration and increased

sleep fragmentation [20-22]. In adolescents who already exhibit a physiological delay of the circadian rhythm, blue light exposure further intensifies biological clock desynchronization and aggravates social jetlag [12, 23]. A meta-analysis of studies in young populations demonstrated that pronounced social jetlag (≥2 hours) is associated with increased risk of depressive symptoms [14]. Importantly, this relationship is bidirectional - sleep and circadian rhythm disturbances increase vulnerability to psychiatric disorders, while existing emotional difficulties may further exacerbate insomnia and circadian desynchronization [15].

It should be emphasized that adolescence is a period of dynamic psychological maturation, during which neuroplastic processes underlying the development of stable emotional regulation mechanisms are particularly sensitive to stressors and sleep disruption [9, 10]. Chronic circadian misalignment, intensified by blue light exposure, may interfere with the normal development of the stress axis, serotonergic and dopaminergic neurotransmission, and gut-brain axis functioning, thereby increasing long-term vulnerability to depression and anxiety disorders [11, 24].

In light of the growing exposure of adolescents to blue light and the rising prevalence of mental health problems in this age group, understanding the mechanisms linking circadian rhythm disturbances with emotional and psychological functioning is of substantial clinical and preventive relevance. The aim of this paper is to synthesize current evidence regarding the impact of circadian rythm disturbances, particularly those related to blue light exposure, on mood, cognitive functioning and mental health in adolescents, with consideration of underlying biological mechanisms and potential preventive interventions.

Methods

The literature search strategy was conducted using the PubMed database to identify relevant publications. The search was based on combinations of the following keywords: adolescents, circadian rhythm, blue light, sleep-wake problems, social jetlag, mental health. Original research articles including observational studies, randomized controlled trials and experimental studies, as well as systematic reviews and meta-analyses were considered. Preference was given to studies conducted in adolescent populations. However, when necessery to explain biological mechanisms, selected studies involving adult populations and preclinical models were also included. Publications were screened based on titles and abstracts to assess their relevance to the topic of circadian rhythm disturbances and their associations with emotional, cognitive and

psychological outcomes in adolescents. Studies not directly related to the scope of the review or lacking sufficient methodological clarity were excluded. In total, 44 publications, published between 2007 and 2025 were included in final synthesis.

Literature review results

The impact of blue light on the circadian rhythm

Blue light plays a key role in the regulation of the circadian rhythm through the retinohypothalamic pathway [1, 25]. A fundamental component of this system consists of intrinsically photosensitive retinal ganglion cells (ipRGCs) containing the photopigment melanopsin [1, 25], which, unlike rods and cones, primarily mediate so-called non-visual functions, including regulation of the sleep-wake cycle [1, 16, 25]. These cells exhibit the highest sensitivity to short-wavelength blue light (approximately 460-480 nm), at which maximal melanopsin responses are observed [1, 17, 25]. The light signal detected by ipRGCs is transmitted directly to the suprachiasmatic nucleus (SCN) of the hypothalamus, which is regarded as the master circadian clock [25, 26]. The SCN synchronizes rhythms in other brain structures and peripheral tissues and controls the activity of the pineal gland, which under dark conditions synthesizes melatonin - a hormone that signals the onset of the nocturnal phase and readiness for sleep [25, 26]. Exposure to light, particularly short-wavelength light, suppresses nocturnal melatonin secretion, shifts its peak to later hours and delays the phase of the circadian rhythm [1, 25, 26]. Adolescents show particular sensitivity to the effects of blue light [20, 22]. Research indicates that the same light dose may induce stronger melatonin suppression and greater circadian phase shifts in adolescents compared to adults [20, 22], further amplifying the physiological circadian delay observed during puberty [21].

The consequences of chronic evening exposure to blue light extend beyond a mere shift in sleep timing. Sleep-wake rhythm disturbances in adolescents are associated with shorter total sleep

duration, poorer sleep quality, and a higher prevalence of delayed sleep-wake phase disorder [21, 22], and have been linked in observational studies to adverse psychological outcomes, including an increased risk of depressive and anxiety symptoms [21].

The impact of sleep disturbances on mood and mental health in adolescents

Sleep disturbances and biological clock desynchronization induced by evening exposure to blue light emitted by electronic devices may influence central nervous system functioning, emotional regulation, mood and the risk of mental health disorders [6, 14, 27]. Population-based studies indicate that excessive screen time, particularly in the evening hours, is associated with poorer sleep quality, shorter sleep duration, greater severity of depressive and anxiety symptoms and an increased risk of suicidal behaviors among adolescents [6, 14, 15, 27]. However, most of these findings are derived from observational studies and casual relationships remain difficult to establish due to potential confounding factors, including socioeconomic status, pre-existing mental health conditions and lifestyle variables.

One of the proposed mechanisms linking sleep disturbances with mood disorders involves dysregulation of neurotransmitter systems and circadian networks in the central nervous system [6]. Serotonergic, dopaminergic and melatonergic rhythms are closely linked to the circadian rhythm generated in SCN and to the sleep-wake cycle [6, 28]. Melatonin plays an important role not only in regulating sleep-wake rhythm but also in modulating synaptic plasticity and emotional regulation [6]. Its chronic suppression by evening blue light exposure has been hypothesized to impair synchronization between the SCN and limbic structures, such as the amygdala and hippocampus, potentially promoting emotional instability and low mood [6]. Moreover, sleep disturbances have been linked to alterations in monoaminergic transmission (serotonin, noradrenaline, dopamine), systems that play a central role in the pathophysiology of depression and anxiety disorders [23]. The psychiatric chronobiology literature suggests that disturbances of circadian rhythms and monoaminergic systems may constitute one of the fundamental mechanisms underlying many mood disorders [6]. Nevertheless, direct mechanistic evidence in adolescent populations remains limited and much of the current understanding is extrapolated from adult or experimental models.

Another important pathophysiological mechanism involves chronic activation of the hypothalamic-pituitary-adrenal (HPA) axis accompanied by low-grade inflammation [6, 29]. Chronic sleep restriction and circadian desynchronization have been associated with sustained

HPA axis activation, flattening of the diurnal cortisol profile and increased levels of inflammatory markers such as IL-6, TNF-α and CRP [6, 29]. Chronic HPA axis activation and inflammatory processes are characteristic features of both depressive and anxiety disorders. These alterations may negatively affect neurogenesis, synaptic plasticity and the functioning of cortico-limbic networks, including the prefrontal cortex and the amygdala [6, 23]. Because maturation of the prefrontal cortex, responsible for impulse control and emotion regulation, lags behind the development of limbic structures during adolescence, chronic sleep disturbances and circadian rhythm disruption may further exacerbate the imbalance between heightened emotional reactivity and limited capacity for cognitive control [4, 30]. This imbalance has been proposed as a neurodevelopmental mechanism underlying increased impulsivity, exaggerated stress responses and vulnerability to mood disorders and risk-taking behaviors during adolescence [4, 30]. In clinical populations, insomnia and other sleep disturbances frequently co-occur with depression and anxiety disorders, and longitudinal studies suggest that they may precede the onset of full-blown mood disorders, partly through the stress- and inflammation-related mechanisms described above [14, 31].

Increasing attention is also being paid to the gut-brain axis as a potential mediator of the relationship between sleep disturbances and mental health [24]. Experimental studies indicate that sleep fragmentation and restriction has been associated with alterations in gut microbiota composition, disruption of circadian rhythms of the microbial populations and increased intestinal barrier permeability, which may promote endotoxemia and systemic inflammation [24]. Reviews examining the links between circadian rhythms, the gut microbiota and mental health suggest that disruption of biological rhythm synchronization may influence both the diurnal cortisol secretion profile and microbiota variability, potentially contributing to stress susceptibility and affective symptoms [24]. However, much of the mechanistic evidence derives from animal models or adult populations and direct data in adolescent remain limited. In adolescent population, short sleep duration and high screen time, frequently co-occur with poorer diet quality, higher risk of obesity and greater severity of depressive symptoms [24, 27]. These overlapping behavioral and metabolic factors suggest that microbiota changes may interact with lifestyle variables in shaping mental health vulnerability [24, 27]. Nevertheless, current human evidence does not allow for clear conclusions regarding the directionality or mediating role of microbiota alterations in this relationship.

Adolescence is a period of intense developmental changes in brain structures involved in

emotional regulation, impulse control and stress responses, which makes young people particularly vulnerable to the negative effects of chronic sleep deprivation and circadian desynchronization [4, 31]. Sleep disturbances during this critical period may interfere with the coordinated maturation of limbic and cortico-limbic systems, potentially hindering the development of stable emotional regulation mechanisms and contributing to heightened stress reactivity [4, 31]. Furthermore, the relationship between sleep and mental health appears to be bidirectional [14]. Longitudinal data suggest that sleep disturbances may increase the risk of developing depressive symptoms [14], while clinical studies indicate that existing mood and anxiety disorders may, in turn, exacerbate insomnia and further disrupt circadian rhythms [15, 23]. This reciprocal interaction may contribute to a self-perpetuating cycle of sleep problems are emotional dysregulation [23, 31].

Sleep disturbances in children and adolescents are also associated with alterations in cognitive functions and academic performance [5]. Neuropsychological reviews indicate that sleep deprivation and sleep fragmentation are linked to reduced attention, impaired working memory, slower information processing and deficits in executive functions such as planning, response inhibition and cognitive flexibility [5]. In adolescent populations, shorter sleep duration and greater severity of sleep problems have been correlated with lower cognitive test scores and poorer academic achievement, even after adjusting for sociodemographic factors [32, 33]. Sleep deprivation has also been associated with increased impulsivity, irritability and difficulties in emotional regulation, which may negatively affect peer relationships and school functioning [31]. Consequently, chronic sleep problems may contribute to educational difficulties, social conflicts, and reduced self-esteem, which themselves represent psychosocial risk factors for the development of anxiety and depressive disorders [14, 15].

Potential interventions targeting circadian rhythms and blue light exposure

Due to the multidirectional consequences of circadian rhythm disturbances in adolescents, there is growing interest in interventions that could reduce evening exposure to blue light, improve sleep quality and duration and potentially exert beneficial effects on mental health.

One of the primary intervention strategies is the reduction of evening exposure to blue light [34, 35]. Randomized studies using blue light-blocking glasses suggest that their evening use may accelerate the onset of melatonin secretion and improve sleep parameters [36, 37]. In a crossover study in Japanese male schoolchildren (10-12 years), wearing partial blue light-

blocking lenses for three hours before habitual bedtime advanced sleep timing and was accompanied by reduced daytime irritability and disruptive behavior, and improved morning mood, although salivary melatonin levels were not significantly changed [36] These findings suggest potential behavioral benefits, but evidence in adolescents remains limited and heterogeneous, and relies on relatively small samples, and short follow-up periods. Evidence synthesis in adults indicates that results across trials are inconsistent and heterogeneous. A meta-analysis of randomized crossover trials evaluating actigraphy-based outcomes in adults reported substantial heterogeneity in protocols and outcome effects [37] and a Cochrane review concluded that evidence for sleep-related benefits of blue-light filtering spectacle lenses in adults is uncertain and mixed [38]. Taken together, current evidence supports cautious, context-dependent recommendations: reducing screen brightness and short-wavelength exposure in the 1-2 hours before bedtime may be reasonable, but robust conclusions about mood outcomes in adolescents require larger, standardized trials with validated mental health endpoints.

An important systemic intervention is the modification of school start times [39]. Data from observational and quasi-experimental studies demonstrate that delaying school start times is associated with longer sleep duration and improved daytime functioning, including mood and mental health indicators [39, 40]. In a longitudinal study evaluating the effects of a 45-minute delay in high school start time, students reported about 20 minutes longer sleep at the first follow-up [39]. Improvements were also observed in tardiness and disciplinary outcomes, while sustained sleep extension was not consistently maintained over longer follow-up [39]. More recent analyses using causal inference methods suggest that later school start times may be associated with reductions in depressive symptoms and fatigue [40]. Interestingly, as shown in a study by E. Sadikova et al., the greatest mood-related benefits were observed among older students and those with higher screen exposure, highlighting heterogeneity of effects and indicating potential target subgroups [40].

Another important area of intervention includes chronobiological education and sleep hygiene strategies, targeting both evening behaviors (e.g., light exposure, screen time, cognitive arousal) and the strengthening of morning zeitgebers (daylight exposure and regular activity rhythms) [41, 42]. A cluster randomized controlled trial of a theory-based school intervention demonstrated improvements in sleep-related behaviors among adolescents [41] and a randomized controlled pilot study found that sleep education can increase sleep duration in the short term [42]. However, intervention effects vary across studies and may depend on baseline

chronotype, adherence and concurrent lifestyle factors, underscoring the need for standardized outcome measures and longer follow-up.

An interesting aspect of the analyzed interventions is the potential existence of sex-related differences, both in the consequences of sleep disturbances and in responses to strategies aimed at reducing evening light exposure [43, 44]. Observational studies indicate that girls more frequently experience sleep difficulties and perceive a stronger impact of insufficient sleep on psychological and social functioning, which may increase their vulnerability to the adverse effects of evening blue light exposure while simultaneously predisposing them to potentially greater benefits from sleep-improving interventions [43, 44]. Exploratory data from an adolescent digital CBT-I (Cognitive Behavioral Therapy for Insomnia) intervention also suggest sex differences in symptom profiles and treatment response, although subgroup evidence remains limited [44]. Therefore, future randomized trials should prespecify sex-stratified analyses and consider differences in sleep problem profiles when personalizing recommendations.

The most effective preventive and therapeutic strategies are comprehensive in nature and include simultaneous reduction of evening exposure to light and screen-based stimuli (e.g., a ,,no screens" rule 1-2 hours before bedtime, brightness reduction, use of filters or glasses when justified), promotion of physical activity and morning daylight exposure, and maintenance of a regular sleep rhythm (consistent bedtimes and wake times, including weekends) [39-41]. The consistency of fundamental time cues appears to play an important role in circadian alignment and may contribute to better mental health outcomes in children and adolescents [39-41].

Conclusions

Sleep disturbances and circadian rhythm disruption represent important and modifiable risk factors associated with mental health problems in adolescents. The physiological delay of the adolescent chronotype, combined with social pressures and increasing evening exposure to blue light, may contribute to chronic desynchronization of the biological clock during a critical period of neurodevelopment. Evidence reviewed in this article suggests that circadian disruption is linked to alterations in neuroendocrine regulation, monoaminergic signaling, stress responsivity and cortico-limbic maturation, mechanisms that may increase susceptibility to depressive, anxiety and cognitive symptoms. Importantly, the relationship between sleep and

mental health appears to be bidirectional, creating a dynamic interaction in which sleep disturbances and emotional difficulties may mutually reinforce one another. Taken together, current findings support the relevance of circadian health as a meaningful target in adolescent mental health promotion. Interventions aimed at improving circadian alignment, including reduction of evening light exposure, structural adjustments to school schedules and chronobiological education, emerge as promising strategies to improve sleep patterns and psychological functioning. Further longitudinal and intervention-based research is needed to clarify causal pathways and to identify subgroups of adolescents who may benefit most from targeted circadian-oriented approaches.

Disclosure

Author's Contribution

Conceptualization: Natalia Staszko, Kamila Bała, Jakub Zbroniec, Małgorzata Bukowska, Alicja Biskup, Julia Smagowska

Formal analysis: Natalia Staszko, Kamila Bała, Jakub Zbroniec, Małgorzata Bukowska, Alicja Biskup, Julia Smagowska

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Writing rough preparation: Natalia Staszko, Kamila Bała, Jakub Zbroniec, Małgorzata Bukowska, Alicja Biskup, Julia Smagowska

Writing review and editing: Natalia Staszko, Kamila Bała, Jakub Zbroniec, Małgorzata Bukowska, Alicja Biskup, Julia Smagowska

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