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THEORETICAL REVIEW

Can exercise regulate the circadian system of adolescents? Novel implications for the treatment of delayed sleep-wake phase disorder

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SUMMARY

Adolescents are vulnerable to inadequate sleep due to a unique constellation of risk factors. In particular, the puberty-related phase delay in the timing of the circadian system postpones the onset of sleep. Resultantly, disordered sleep is common among teenagers and young adults, with the most common sleep problem being delayed sleep wake-phase disorder (DSWPD). Although current treatments for DSWPD show promise, novel ways to improve our youth's sleep are needed. The purpose of this review is to critically evaluate the evidence for the role of exercise as a method to shift and/or regulate circadian timing, and thus improve sleep, in adolescents and young adults. A growing body of evidence suggests that nocturnal exercise can delay circadian timing. However, exercise administered at different times of the 24-h day may result in phase advances, particularly when the timing of exercise is gradually advanced in small daily increments. The implications of these results for young people's sleep health are discussed and suggestions are provided for ways that exercise could be used clinically, to improve the treatment of DSWPD.

Introduction

Adolescence and young adulthood is a developmental period of rapid physical and psychological change. Many of these changes place youth at heightened risk for inadequate sleep [1]. Indeed, there is a ubiquitous, worldwide trend for later bedtimes and less sleep across adolescence, despite sleep need remaining unchanged [2–4]. Later bedtimes, coupled with the requirement to wake early for educational or vocational commitments, mean the opportunity for sleep might be insufficient, possibly leading to daytime sleepiness, fatigue, and impaired attention, concentration, memory and mood [5].

The trend for later bedtimes during adolescence and young adulthood is thought to be at least partly attributable to puberty-related changes in the adolescent circadian system, with circadian timing becoming gradually later from childhood until early adulthood [6–8]. Circadian rhythms exist in many plants and animals, and result in fluctuations of alertness and sleepiness over the solar day [9]. During adolescence, the circadian system both delays and lengthens (slightly over 24 h), causing peaks of alertness (e.g., 19:00–20:00 h) and sleepiness (e.g., 06:00 h) across the 24 h day, and consequently sleep timing, to become later [2,10–12], as shown in Fig. 1. Additionally, educational (e.g., study), occupational (e.g., part-time work), extra-curricular (e.g., after school sport/music, etc.), and recreational (e.g., technology use, socialising, etc.) obligations, increase the number of tasks that adolescents need to complete in the evening [1]. Adolescents undergo a series of "firsts" (e.g., first job, first relationship etc.) and thus may also be more prone to pre-sleep worry which may further delay sleep onset [13].

A more pronounced delay to circadian timing can lead to a circadian rhythm disorder called delayed sleep-wake phase disorder ((DSWPD; 5). DSWPD occurs when the biological rhythms governing sleep-wake timing (i.e., endogenous melatonin secretion,[1] core body temperature rhythm) are timed significantly later than the 24-h social and physical environment of the individual [5]. This delay results in difficulty falling asleep early enough to ensure sufficient sleep and difficulty waking up at the socially desired time. Consequently, the major sleep period is frequently delayed and truncated, as shown in Fig. 1.

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[1] For some patients DLMO (dim light melatonin onset) may not reliably predict sleep or circadian timing [14].

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Abbreviations

DSWPD	delayed sleep-wake phase disorder
PRC	phase response curve
τ	tau, the time taken to complete one cycle of the circadian rhythm
T-Min	core body temperature minimum
VO_2max	maximal oxygen consumption
Wd	end of weekday sleep
We	end of weekend sleep
ZT	zeitgeber time

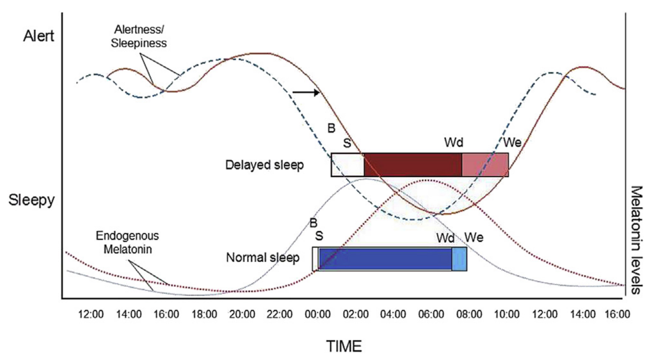

Fig. 1. The delayed circadian rhythm of alertness, endogenous melatonin and sleep (red) compared to normal rhythms and sleep (blue) [15]. Note: Wd = end of weekday sleep; We = end of weekend sleep; B = bedtimes; S = sleep onset. White rectangle indicates sleep latency, which is prolonged in the delayed sleeper. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Delays in circadian and sleep timing are especially problematic for individuals who are required to wake early in the morning, such as adolescents needing to attend school [5,16,17]. Individuals with DSWPD exhibit markedly reduced daytime functioning (e.g., excessive daytime sleepiness, fatigue, low mood) and impaired cognitive performance (e.g., concentration, memory and attention), particularly during the morning. Morning deficits occur due to the delayed circadian nadir and chronic sleep restriction across week days [5,18,19]. Unsurprisingly, DSWPD is most common during adolescence, affecting 1–16% of teenagers [5,19]. It is associated with school lateness, absenteeism and dropout [16,17,20–22]. The lower threshold of prevalence estimates likely do not capture adolescents who have dropped out of school, thus the prevalence is likely to be somewhat higher [19]. For adolescents both with and without DSWPD, the combination of a delayed circadian rhythm and accumulated sleep debt results in sleeping-in on weekends [2,3,23] or late afternoon naps [24]. Both of these compensatory behaviours can delay circadian rhythms even further [2].

Although DSWPD is most common in adolescents and young adults (relative to middle and older adulthood), it can persist into adulthood if not treated. Current recommendations to shift circadian timing of adolescents earlier include controlled light exposure and the administration of exogenous melatonin. Light is the predominant circadian timekeeper helping to stabilise humans' sleep timing [25]. Light suppresses the secretion of endogenous melatonin [26,27]. Melatonin concentrations increase in the evening in dim light conditions, to encourage sleep onset [28]. As such, the administration and gradual advancement of morning bright light (following the nadir in core body temperature rhythm) can advance both circadian rhythms and sleep timing [29,30]. However, ambient bright light is not always available. For example, there is reduced number of daylight hours in some latitudes [31]. Additionally, adolescents may be resistant to using an external device for morning bright light therapy (e.g., light lamps) and may also be reluctant to reduce use of bright light emitting devices in the evening (e.g., smart phone and tablet), particularly if they have sleep onset difficulties [32]. A recent longitudinal study found that sleep problems predicted television and online social media use, but not the reverse, suggesting that young adults may use technology as a way to cope with their sleep problem [32]. Exogenous melatonin, and the gradual advancement of bedtimes [33], can also be administered in the evening to shift circadian rhythms earlier. However, currently, there is a lack of research investigating the long-term safety of melatonin in paediatric samples [34]. Therefore, given the challenges associated with advancing circadian rhythms in adolescents and young adults with DSWPD, together with the plethora of negative sequelae resulting from a delayed circadian phase, researchers and clinicians alike seek novel ways to improve treatment modalities, which may in turn improve long term outcomes for both clinical and non-clinical groups.

One alternate chronotherapy may be scheduled exercise, with appropriately timed exercise potentially advancing circadian rhythms earlier. This occurs because the activity-rest schedule exerts influence over circadian timing independently of light [35–37]. As such, young people may benefit from alterations to the timing of their activity-rest schedules in order to advance or better entrain their circadian rhythms. Regular physical exercise is inexpensive, safe and has concurrent benefits to sleep latencies, sleep quality and mood. In particular, morning exercise has also shown to improve the sleep, mood and daytime functioning (i.e., attention/concentration) of adolescents [38], whilst curtailing late night activities may also curtail phase delay. This is a particularly salient issue given that a significant proportion of teenagers report completing active tasks (e.g., part-time work, exercise, tasks of daily living, socialising) as their primary activity within the last hour before bed (see Fig. 2) [39]. However, further research is required to determine whether a causal relationship exists between evening activities and circadian/sleep timing.

The primary aim of this review is to examine extant scientific literature to determine the effect that the timing of exercise may have

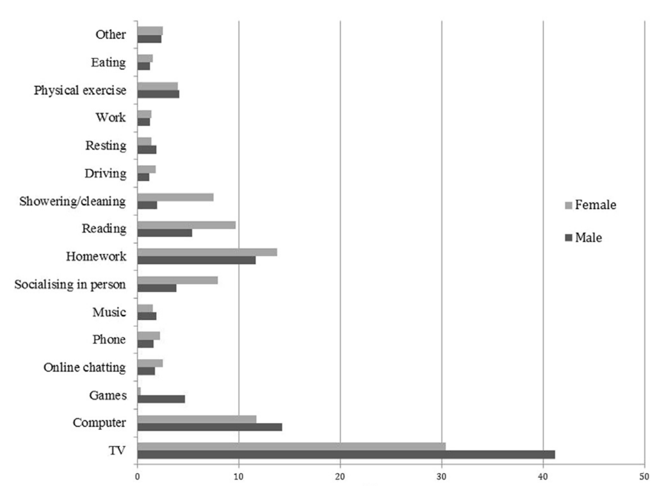

Fig. 2. Proportion of males and females engaged in each activity in the hour before bedtime. Note: some electronic media activities (e.g., computer, phone) could be used for other tasks (e.g., homework).