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THE IMPACT OF INSUFFICIENT SLEEP ON COGNITIVE AND EMOTIONAL HEALTH IN ADOLESCENCE

Current advances and research needs

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Introduction

Adolescence is a tumultuous time of biological and psychosocial development (1). In the midst of growth and new experiences, teens are exposed to a pernicious near-nightly loss of sleep. Here, we review the science of insufficient sleep in adolescents. We describe a) how insufficient sleep arises during puberty; b) how sleep loss may impact waking behaviour with an emphasis on learning, attention, and emotion; and c) how societal factors might moderate these effects. Though work remains to be done, one thing is clear: while sleep loss is endemic amongst teenagers, neither it nor its consequences need be predetermined.

The perfect storm: one now capable of being predicted

Across the globe, adolescents lose upwards of 10–15 hours of sleep a week (2). Any discussion of this sleep loss begins with the societal pressures we place on developing teens: namely, school, academic demands and social and athletic obligations. If a teen describes a preference for staying up later at night and sleeping in later each morning they risk being stereotyped as 'lazy'. These prejudicial explanations of adolescent sleep have inhibited a compassionate understanding rooted in the fundamental biology of sleep and circadian rhythms. Over the past three decades, however, these interacting processes are now

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understood to create a 'perfect storm' through which insufficient sleep can arise (3, 4; Figure 7.1). Two fundamental shifts occur. First, sleep homeostasis grows more slowly during the day, allowing teens to remain awake longer without catastrophic levels of sleepiness (5). Second, the circadian timing system undergoes a profound phase delay during puberty (6). This delay puts adolescents at odds with the rhythms of everyday life, creating what the field has dubbed *social jetlag* (7). These two biological shifts are conserved across mammalian phylogeny and thus silence the critique that a teen is simply lazy. When these bioregulatory changes come head-to-head with the innumerable forces placed on teens (early school start times, bussing schedules, athletic obligations, evening homework, even developmentally appropriate needs for socialisation) sleep is measurably and consequently deteriorated.

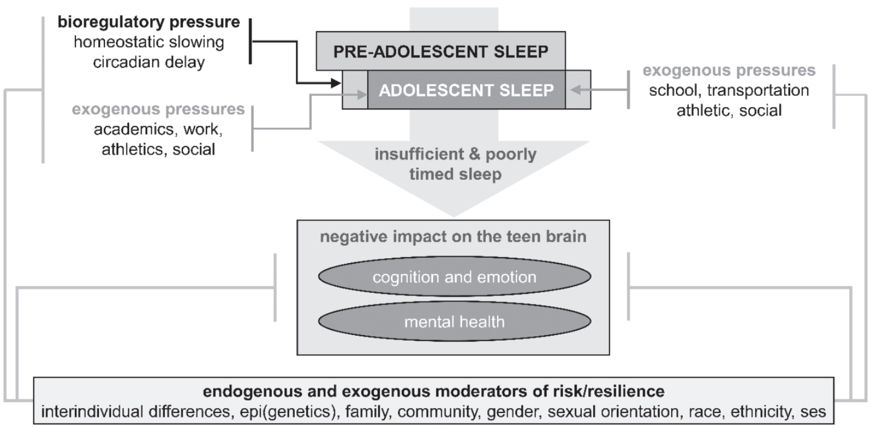

FIGURE 7.1 The 'Perfect Storm' Model of Insufficient Adolescent Sleep Recapitulated. Schematic for understanding insufficient sleep during adolescence: a biological consequence made worse through societal pressures. Top: A simplification of the perfect storm model (3, 4). The bioregulatory changes that occur during puberty: a slowing of sleep homeostatic pressure across wakefulness (Process S) and a delayed circadian timing system (Process C) alter preadolescent sleep by exerting endogenous pressures, moving the ideal sleep opportunity and circadian phase later during adolescence. However, exogenous pressures (e.g., evening demands and school start times) further erode sleep leading to chronically insufficient and poorly timed sleep. Bottom: Consequences of sleep loss and misalignment in adolescents lead to impoverished brain health: cognition, emotion and mental health. Finally – the ultimate quality of life afforded a sleepy teen may be moderated by biological as well as structural factors including economic status and diversity factors across gender, sexual, racial and ethnicity identities.

Groups such as the *Start School Later* movement have pushed to alter school schedules for teens. In the US, California recently became the largest jurisdiction to enact legislation demanding a later (8:30 a.m. at earliest) start time for secondary schools (8). The impact of this change for both teen sleep and its functions remains to be seen. Below we review the science of how insufficient sleep, when left unchecked, can alter brain function and cognitive health, along with societal factors that may impact insufficient sleep in adolescents.

Sleep loss and adolescent cognitive performance

Experimental studies have assessed the impact of sleep restriction on various cognitive processes in adolescents, including memory consolidation (9, 10) and encoding (11), vigilance (12, 13), executive function (13, 14) and abstract thinking (15), as well as on general mood and fatigue. Consensus (16, 17) holds that for adolescents, the effect of sleep restriction may depend both on the cognitive domain and the nature of the curtailed sleep.

Learning and memory

A wealth of data underscores the importance of sleep for learning and memory. Critical for understanding this literature, memory is not one unitary phenomenon, but rather a process in which information, skills or associations are first learned (*encoding*), and then maintained (*consolidation*) to allow for subsequent long-term *recall* and *integration* into knowledge (18). Thus, when considering how reduced sleep affects learning and memory in adolescence, one must distinguish whether reductions in sleep have more influence on some aspects of memory over others.

New learning/encoding

For adolescents, even partial sleep loss can significantly affect new learning and encoding. In one study, Cousins et al. (11) had 15- to 18-year-olds sleep for either five or nine hours per night across five nights, then complete a picture learning task after the 5th night. Following three nights of recovery sleep (nine hours/night), the adolescents who had slept for five hours per night before learning recalled fewer pictures than the nine-hour group. Notably, adolescents' recall was not associated with vigilance or alertness on the day of encoding (similar to prior work at this age; e.g., (19)), suggesting an impact of sleep restriction on encoding ability independent of fatigue or inattentiveness. In a follow-up study (20), 15- to 18-year-olds underwent the same nine- or five-hour-per-night sleep protocol for five nights, but learned novel facts about arthropods (simulating academic content) following the 4th night. Recall tests occurring 30 minutes, three days and 42 days after learning indicated persistent effects of prior sleep restriction on memory, with sleep restricted adolescents recalling 26%, 34% and 65% less material at each respective time-point than those who encoded when rested. Together, these findings indicate that partial sleep restriction can impact adolescents' ability to learn, with long-term consequences for retention.

Memory consolidation and recall

While partial sleep loss negatively impacts adolescents' ability to encode new information, what happens if an adolescent is well-rested during learning but then loses sleep afterward? Contrary to encoding, memory consolidation – the long-term strengthening and storage of previously encoded information – may be less affected by sleep restriction, so long as adolescents are well-rested during learning. Kopasz and colleagues (21) conducted an experiment in which 14- to 16-year-olds engaged in multiple declarative learning tasks (e.g., memory for locations, events, words) after a nine-hour overnight sleep opportunity. Adolescents were then sleep restricted to four hours of overnight sleep (3 a.m.–7 a.m.), followed by a recovery night of nine hours and a recall test. Compared to when adolescents were allotted nine hours, one night of four hours of sleep did not significantly decrease memory recall, suggesting that memory consolidation at this age may be robust, at least in the short term, to partial sleep restriction. In another study, Voderholzer et al. (10) restricted 14- to 16-year-olds across four nights under one of five protocols (9, 8, 7, 6 or 5 hours of time in bed (TIB)). Before restriction, all had a nine-hour sleep opportunity and engaged in two memory tasks (word pairs and procedural learning), with recall assessed twice: after two nights of post-restriction recovery sleep and one month later. At both post-test intervals, memory did not differ across groups for either task, indicating no dose-dependency for either word recall or procedural learning. Furthermore, polysomnography on the last night of sleep restriction indicated that the amount of slow-wave sleep was preserved at the expense of other sleep stages in all protocols, perhaps accounting for comparable memory performance across groups.

More recently, Leong et al. (22) found a similar null effect of longer-term sleep restriction on prospective memory; i.e., memory for actions that must be completed later (for example, remembering to buy items at the grocery store, or to relay a message to a friend). After five nights of either five hours of TIB or nine hours of TIB (both preceded by a week of nine hours TIB), 15- to 18-year-olds across protocols performed comparably (and poorly) on a prospective memory task requiring them to press a certain button in response to specific stimuli. Although the task itself may have been too difficult to detect beneficial effects of longer sleep, Leong et al.'s (22) findings in combination with others imply that if teens have slept well before learning, subsequent short sleep (here, 4–5 hours) may not significantly impair retention.

Although the amount of information adolescents consolidate may not be decreased by partial sleep loss, sleep may still impact which specific information is prioritised for consolidation over others (23). In one study, 15- to 19-year-old adolescents were tasked with memorising a short passage, with specific sections highlighted as 'important' and associated with a reward (9). On Day 3 of a rested baseline (9 hours/night), adolescents were shown the passage for seven minutes and were tested immediately and after one week of either restricted (five hours/night) or control sleep (nine hours/night). While both groups remembered the highlighted sections better than the non-highlighted ones, the mnemonic benefit became even more pronounced at the one-week test only in the control group, suggesting that restricted sleep may impair the adolescent brain's ability to discriminate which information is most critical to retain. Similarly, another study found that partial sleep loss before encoding (five hours/night for seven nights) promotes greater inaccurate/false narratives in eyewitness memories (24). These new lines of research tentatively indicate that sleep loss may affect the adaptiveness and accuracy of adolescent memory consolidation, even if the overall amount of information consolidated is equivalent.

Summary

Recent experiments indicate that partial sleep loss over multiple nights causally disrupts new learning and memory formation in adolescents. Though consolidation of prior memories can still occur, sleep loss can shift the prioritisation of some memories over others for consolidation. Although restriction to 5–6.5 hours of sleep per night (the range used for most recent studies) may seem severe, it is not unreasonable given that <6.5 hours of sleep is common for over a quarter of adolescents (25). Nevertheless, future research should address the effects of more nuanced levels of sleep loss for new learning, as some studies of consolidation have done.

Attention, executive functioning and self-regulation

Sleep loss's impact on adolescent attention and executive functioning is highly relevant for daily living. Executive functioning encompasses processes such as self-regulation, working memory and flexibility, whereas attention involves balancing exploitation and exploration of competing stimuli and information sources (26, 27). For adolescents, attention and executive functions are critical for newly learned activities such as driving. With motor vehicle accidents identified as the second leading cause of death for adolescents in the US (28, 29), it is crucial to study how sleep loss impacts capacities critical to avoid such events.

Attention and vigilance

The impact of sleep loss on vigilance and attention has been long studied in adults. Comparing the effects of staying up late to those of alcohol consumption, researchers in the 1990s found that 18–19 hours of sustained wakefulness produced vigilance impairments comparable to those found among adults with a blood alcohol concentration of 0.05% (30, 31). Furthermore, when sober participants were kept awake for 24 hours, performance on an unpredictable tracking task (using a joystick to follow a constantly moving target) was as poor as that of individuals with a blood alcohol content of 0.10% (above the US legal limit).

Investigating such effects in adolescents is a more recent endeavour, with studies using both laboratory tasks and ecologically relevant measures to substantiate that sleep loss impairs adolescent attention and vigilance. One popular laboratory measure of sustained attention is the psychomotor vigilance task (PVT), in which individuals must continuously attend and respond to a visual stimulus appearing at irregular randomised intervals. When adolescents' sleep is restricted across days, PVT performance deteriorates, with adolescents showing more failures to respond ('lapses'; (32, 33)) and fewer timely responses relative to premature or late reactions (34). Vigilance in young adolescents (~10–11 years) appears particularly vulnerable, as PVT performance decline has been observed even with relatively minor sleep loss (i.e., 10-hour TIB versus 8.5-hour TIB; (34)). In contrast, Campbell et al. (34) found that performance in older adolescents (~15–16 years) did not differ between four days of ten-hour TIB and 8.5-hour TIB. Nonetheless, sleep reduction to a seven-hour opportunity produced clear PVT deficits in both older and younger adolescents.

Agostini et al. (33) had previously reported that severe sleep restriction (five hours TIB/night for five nights) produced PVT deficits in 15- to 17-year-olds when compared to baseline, and that performance was not restored even after two days of recovery sleep. Subsequently, Short et al. (32) modelled older adolescents' sleep need and PVT performance using five-day restriction protocols of five-hour and 7.5-hour TIB/night, finding dose-response effects of both sleep opportunity and number of restriction nights. Both five hours/night and 7.5 hours/night resulted in PVT deficits among 15- to 17-year-olds, but deficits were apparent more quickly in the five hours/night condition (i.e., as early as the third day) than in the 7.5 hours/night condition, in which at least five days were required to demonstrate a significant deficit. Short's modelling further indicated that adolescents should obtain 9.35 hours of sleep per night on average for optimal attention, despite prior findings suggesting short-term resilience to 8.5 hours/night sleep restriction at the same age (34). Overall, these studies provide strong evidence that continued sleep loss impairs vigilance in adolescents, with effects possibly moderated by both the specific amount of sleep lost per day and total sleep loss accumulation across days.

They highlight that adolescence is not monolithic, with key differences arising in young (10–11 years) and older (15–18 years) teens. Understanding the trajectory of these effects is critical to both tease apart mechanisms of cognitive development and bolster the ecological relevance of such data.

Though adolescent sleep loss produces vigilance deficits in tightly controlled experiments, such designs lend one to ask whether these deficits would persist in more ecologically valid settings. One recent study in Israel measured the sleep patterns of adolescents (grades 7–12, mean age 16) using wrist-worn actigraphy on school nights and weekends (35). After showing that adolescents' sleep was indeed shorter on school nights, they then demonstrated comparatively slower reaction times and more lapses on the PVT on subsequent days. Though these results could be confounded by other factors such as increased stress on weekdays relative to weekends, they are in line with the laboratory-based studies above. In another study, researchers experimentally manipulated sleep via two 5-night sleep conditions (short sleep: 6.5 hours/night TIB; long sleep: ten hours/night) but had participants (aged 16–18 years) sleep at home rather than in the laboratory (36). Furthermore, rather than using the PVT, participants completed a simulated driving task to capture a more naturalistic context. Adolescents showed less reliable vehicle control in a rural driving scenario (e.g., lateral drift within their lane) when they were sleep restricted. Together, these studies reinforce that: a) adolescents experience behaviourally impactful sleep curtailment naturally in their everyday lives; and b) the effects of adolescent sleep loss extend to ecologically valid tasks with implications for safety and well-being.

One tentative silver lining in an otherwise sobering account of sleep loss's effects on adolescent attention is that these effects can be alleviated to some extent, at least in older adolescents, by daytime naps. Using a 2-week sleep protocol (with the first 5 days preceded and followed by two nights of extended 'weekend' recovery sleep) and the PVT as an outcome, Lo and colleagues (37) had 15- to 19-year-old adolescents follow nocturnal sleep restriction either with or without daytime naps. For adolescents whose nocturnal sleep was restricted to 6.5 hours TIB, a 1.5-hr daily nap opportunity in the early afternoon allowed them to maintain the same attentiveness levels as after baseline sleep. When adolescents' nocturnal sleep was restricted to five hours, napping for 1–1.5 hours similarly alleviated PVT deficits relative to not napping, but adolescents remained impaired. Thus, these findings support a benefit of naps for older teenagers when a full night of sleep is not possible, though the palliative effects of a nap may depend on the severity of overnight sleep loss. Further work must examine these possibilities in younger adolescents.

Working memory

Working memory is often defined as the ability to hold recent information in mind to inform ongoing behaviour. Under this definition, results are currently mixed regarding how sleep loss impacts adolescent working memory, complicated by inconsistencies in the age ranges studied, the working memory paradigm used and the degrees of sleep loss implemented at different ages. Specifically, recent working memory studies have mostly restricted sleep either to five hours (12, 13) or 6–6.5 hours TIB per night across 5–7 consecutive nights (14, 38–41). In such studies, the most common test employed is the 'N-back' task, in which participants are shown symbols one at a time and must remember whether the current symbol matches that shown a certain number (N) of trials previously. With sleep restricted to five hours per night, adolescents have shown significant performance deficits as early as after night three of restriction (12, 13), whereas adolescents who are only 'mildly' sleep restricted to 6.5 hours/night maintain baseline performance through at least five consecutive nights (38, 39). In contrast, with a visuospatial token task (in which adolescents were required to remember locations of tokens so as not to revisit those locations), Kiriş (14) recently reported that 18- to 19-year-olds showed deteriorated performance after only four nights even when sleep restriction was relatively mild. Similarly, Jiang and colleagues (41) found that 13- to 16-year-old adolescents were slower to respond on serial subtraction and verbal working memory tasks after six-hour TIB/night across five nights, despite no change in accuracy. Thus, sleep restriction as mild as 6- to 6.5-hour TIB/night may produce behavioural changes for some paradigms, though which task demands are required to observe these deficits requires further clarification.

Whether mild sleep loss impairs working memory may also depend on the distribution and timing of sleep bouts. Lo et al. (40) found that when 15- to 19-year-old adolescents were sleep restricted to 6.5 hours daily, they performed better on one- and three-back tasks if their sleep was split into two unequal bouts (five hours of overnight sleep and a 1.5-hour daytime nap) compared to 6.5 hours of overnight sleep. This finding is encouraging for adolescents who cannot feasibly obtain the recommended amount of sleep overnight. Nevertheless, this study is limited by its relatively brief protocol (five consecutive restriction nights and three more after recovery sleep), leaving it unclear whether the beneficial effect of napping would persist across longer-term sleep restriction.

Apart from behavioural differences in working memory, researchers employing fMRI have found that adolescent sleep schedules of 6.5-hour TIB/night will produce differences in neural responses to the N-back task. Beebe et al. (39) reported that after 13.9- to 16.9-year-old adolescents were sleep restricted to 6.5-hour TIB/night for five nights, neural activation in task-positive regions (regions typically active during the task) and neural suppression in task-negative regions (regions typically inactive during the task) were both enhanced during a two-back task when compared to extended sleep (ten-hour TIB). Behavioural performance was similar across the two sleep schedules. Alsameen et al. (38) subsequently examined whether manipulating N-back task difficulty (i.e., from zero-back to three-back) would produce differences in both behavioural and neural outcomes in sleep restricted 14- to 16.9-year-olds. However, after five nights of 6.5-hour TIB, adolescents did not show any behavioural deficits at any difficulty level. Nevertheless, sleep loss impacted adolescents' brain activity, with some brain areas (e.g., medial prefrontal) exhibiting compensatory activation or suppression while others showed a weakening of compensatory activity, particularly during the most difficult task level. Together, these studies indicate that even in the absence of behavioural effects, sleep loss may still result in detectable changes to neural systems underlying working memory. It remains to be determined whether inconsistencies in working memory deficits systematically result from the degree of sleep loss per se or to differences in participants' ages between studies.

Self-regulation, mood and mental health

Bidirectional associations between poor sleep and self-regulation difficulties have been reported in both adults and adolescents, with irregular and insufficient sleep linked to higher rates of depression, anxiety, suicidal ideation and risky decision-making (42, 43) (also see (25, 44) for reviews). In large US samples, the highest odds of serious suicide attempts were observed in adolescents reporting the shortest sleep (≤4 hours per night; (45)). Excessive oversleeping (≥ten hours per night) has also been related to teen suicidality (45), and the effects of sleep on mood may be moderated by demographic factors such as biological sex, gender identity, race and ethnicity (42). Overall, disrupted sleep in both extremes – too much and too little – have been forwarded as potential causes and consequences of altered teen mental health.

Experimentally, many adolescent studies have taken advantage of self- and parent-reported questionnaires to probe the causal effect of sleep loss on mood and self-regulation. Unsurprisingly, most studies have found a negative effect of sleep loss on adolescent mood; experimentally sleep-deprived teens and their caregivers report decreases in teens' positive mood and vigour with increases in confusion, fatigue, hostility and anxiety (13, 46–48). Recently, Booth et al. (47) indicated that while 15- to 17-year-olds' self-ratings of depression, anger and happiness were relatively unchanged by five nights of sleep restriction to 7.5 hours per night, sleep restriction to five hours per night significantly increased depression and anger and decreased happiness. Among 14- to 17-year-olds however, Baum et al. (46) reported that milder sleep restriction – 6.5 hours TIB per night for five nights – also increased self-reported anger, anxiety and confusion and parent-corroborated irritability, suggesting that this intermediate level of sleep restriction may be enough to trigger emotional dysregulation in some adolescents. These findings specify that for older teenagers, sleep curtailment to 6.5 hours or less may result in significant emotional dysregulation.

One obvious limitation of these questionnaire-based studies is participants' own expectations in self-reporting. If adolescents know they will be losing sleep, they likely also expect to be more irritable or 'moody'. While most studies attempt to account for expectancy effects, either by embedding the mood ratings into other control questionnaires (46) or by tightly regulating participants' sleep/wake environmental cues (47), it is uncertain just how successful such methods are at reducing adolescents' expectations. More recent studies have thus supplemented questionnaires with task-based emotion and mood measures, such as pupil response (48) and behavioural reactivity to emotion-inducing stimuli or peer conflicts (48, 49). Overall, these alternative measures corroborate adolescents' subjective reports, though the studies employing them have been limited in their range of sleep restriction. Both McMakin et al. (48) and Reddy et al. (49) used acute restriction paradigms of four hours TIB for one or two nights. Further work should extend these tasks to the sorts of milder, longer-term sleep restriction protocols described above.

Adolescent sleep-related mood disturbances may also be partly eased by daytime napping. In Lo et al.'s (40) study, 15- to 19-year-olds who were sleep restricted to 6.5 hours per day sleep schedules reported higher positive mood when their sleep was split into a 1.5-hour daytime nap and five hours overnight compared to 6.5 hours of overnight sleep. When participants were permitted to sleep for eight hours, mood ratings remained stable regardless of whether these eight hours were split or continuous. Thus, as with other domains, adolescent mood and regulation may benefit from napping, and a split sleep schedule may be a helpful alternative for busy teens when eight hours of continuous overnight sleep is not possible.

Summary

Sleep loss undeniably has the potential to negatively affect adolescents' attention and executive functioning, including working memory and self-regulation. The current literature suggests that attention and self-regulation are perhaps the most vulnerable to even mild sleep loss, whereas the effects of sleep loss on working memory may be more nuanced and dependent on the specific task, degree of sleep loss or age range studied. However, because individual studies often differ in the age ranges assessed and the degree/duration of sleep restriction implemented, it is difficult to draw developmental conclusions at this time. Furthermore, along with sleep relating to mental health via mood, it should be noted that there are studies analysing the exacerbating effects of sleep loss in other psychiatric and neurodevelopmental conditions (e.g., ADHD) that are outside the realms of this chapter.

Societal factors influencing insufficient sleep and its consequences: opportunities for buffering?

In the previous sections, we have identified primary social and biological factors contributing to sleep loss across adolescence, as well as their adverse effects on cognitive and emotional function. In light of what we know about adolescents' unique propensity for sleep loss and its effects on functioning, one final topic of critical importance concerns identifying malleable societal structures that may moderate teen sleep.

School start times

In response to our knowledge of the physiological and social changes compelling adolescents to stay up later in the evenings, some US districts have implemented delayed school start times, with California enacting the first state-wide law requiring high schools to start no earlier than 8:30 a.m. (8). Both school-wide and multisite studies investigating the effects of such policies have reported promising results, with later start times associated with increases in adolescent school attendance (50), longer sleep (51, 52), higher grades (53) and better mental health (44, 50, 53) across both suburban and urban school districts. For adolescents old enough to drive, delaying school start times has led to reductions in drowsy driving and adolescent motor vehicle accidents (28, 53). Finally, changing school start times may aid students with chronotypes that are even later than those predicted by typical adolescent development (see (54) for a discussion of chronotype-specific personalised school start times).

Embracing naps

Although delaying school has already gained momentum in the US and internationally, we must also recognise that logistical and resource-related barriers often prevent this intervention from being feasible. In these cases, daytime napping may be another option to help ameliorate adolescent sleep loss if timed to not substantially influence night-time sleep pressure. Given the nap benefits observed experimentally for memory, attention, executive functions, and self-regulation (37, 40, 55, 56), it is clear that napping benefits adolescent functioning particularly when sleep restricted. However, questions that remain include the duration of nap opportunity that should be provided in schools, and what the optimal timing of the nap period should be relative to varying class schedules.

Addressing socioeconomic and racial/cultural inequities

Alongside implementing sleep interventions directly in schools, addressing social and environmental inequities corresponding to differences in socioeconomic status (SES), race and ethnicity may also help to improve sleep for adolescents. Pérez Ortega (57) recently reviewed factors underlying racial and ethnic disparities in sleep quantity and quality for US adults, pointing to differences in job opportunities/shift work, acculturation stress, racial discrimination, exposure to increased air and light pollution and a lack of culturally responsive education about sleep hygiene on the part of doctors and scientists as contributors to these disparities. Among adolescents, research has mainly focused on family and neighbourhood SES as contributors to disrupted teen sleep (58, 59), with fewer studies focused on the role of external environmental noise, light (outside of personal electronics use) or air pollutants. However, one large-scale study in China indicated that greater exposure to small particulate air pollution predicted greater sleep problems in children aged 2–17 (60). Neighbourhood status in both the US and abroad predicts shorter sleep duration in children and adolescents (ages 0–18; (61)), whereas familial economic instability and caregiver stress have been more closely associated with variability in teen sleep rather than total sleep time (62). Familial SES has also been shown to moderate associations between adolescent sleep and emotional regulation, with adolescents from lower SES backgrounds demonstrating the greatest link between good sleep and emotional function (63).

From a cultural perspective, even fewer studies have evaluated how migration, acculturation or discrimination might affect sleep in adolescence. However, one study evaluating predictors of sleep loss in Mexican-American adolescents (US grade 7 and above) indicated that higher parent acculturation, income and education were paradoxically (along with neighbourhood crime) associated with poorer adolescent sleep health, whereas greater family unity and lower acculturation was related to better sleep health (64). Such results illuminate the importance of an intersectional perspective. Aside from this study, more recent work has focused on how sleep may serve as a protective factor against acculturation stress in high school students migrating to the US from various countries, finding that longer sleep durations predicted a more pronounced decrease in stress and greater cultural adaptation across the first year of immigration (65). Holistically, these studies emphasise a need to consider bidirectional relations between culture-specific variables and sleep health in adolescence, and to evaluate how societal inequities beyond SES may impact sleep and its effect on waking function.

Summary

To improve adolescent sleep, possible interventions include delaying school start times, encouraging daytime naps and addressing broader social inequities contributing to teen sleep loss. With the current forward momentum of policies implementing delayed start times, evidence in favour of this practice is rapidly accumulating, with beneficial implications for students and minimal negative effects. Even so, personalised interventions may need to account for students' individual identities and implement additional strategies to promote sufficient sleep.

Conclusion and urgent research needs

The current chapter reviewed literature indicating the impact of insufficient sleep on developing adolescents' cognition, emotion and mental health, while also pointing to areas of possible intervention. Many of the studies presented provide evidence that parallels the negative impact of sleep loss in adults. However, the root causes of insufficient sleep in adolescents are unique yet well-known scientifically. Insufficient sleep in teens – even of only 1–2 hours a night – when occurring on a near-nightly basis can have, as it does in adults, a profound impact on waking function.

Attention, learning, memory and emotional regulation are all compromised by insufficient sleep with no permanent countermeasure present (even from napping). Unlike in adults, however, teens often lack the agency to change their schedules to better accommodate sleep. The impact of insufficient sleep on cognitive and affective brain function imposed on adolescents coincides with a critical window for psychosocial development, as teens navigate an ever-changing landscape of motivations, opportunities, risks and learning critical for their future quality of life (1). The emergence of mental illness in the second decade provides only an additional lens from which to consider the growing cost of sleep loss for young people. Finally, societal factors including but not limited to economic status, school timing and racial and ethnic health disparities can not only increase the pressures placed on the sleep regulatory system but also moderate or mediate the impact that compromised sleep can have during development. Taken together, the evidence presented here and elsewhere places our field in a unique position. We believe there are at least five distinct needs at this juncture which we highlight below to close this chapter:

First, we need truly developmental experiments. While there is utility in documenting adult-like effects in cross-sectional samples of adolescents, we must also turn to what makes adolescents different than adults. Particularly when experiments include mechanistic neurobiology (be it fMRI of the sleep-deprived brain, EEG of recovery sleep, or hormonal assessments of circadian factors such as melatonin), future work needs to be implicitly placed within a developmental framework. Through such a lens we can identify not only *if* adolescents differ from adults in their susceptibility to sleep loss but also *how*, why and when. Understanding how neurodevelopment interacts with sleep need and is differentially moderated by sleep loss is paramount.

Second, our studies need to progress towards increased ecological validity. Our protocols must move beyond sleep loss manipulations. Total sleep deprivation is an effective manipulation yet not the reality of sleep loss for the vast majority of individuals (save an unfortunate *all nighter*). Chronic sleep restriction moves the needle one step closer towards ecological validity, yet they too lack the true nuance of adolescent life: the co-occurring circadian social jetlag.

The quest for ecological validity extends to our assessments. With much of the public discourse on adolescent sleep need focused on schools, the use of tests directly related to educational achievement and social health – rather than simply our laboratory tests of neurobehavioral function – will close the gap between the literature and the quotidian experience of under-slept teens.

Third, most studies in adolescents focus on whether an effect of sleep loss is present rather than for whom the effect is greatest. We know from data in adults that phenotypic resilience and vulnerability to sleep loss emerges for specific outcomes (e.g., (66)). Moderating factors such as the trajectories of neurodevelopment and the emergence of atypical development (e.g., ADHD, autism) may provide additional pressures determining any one child's individual susceptibility to sleep loss (67). While policy initiatives such as that from California in the US pursue one-size-fits-all increases in sleep opportunity for youth, more phenotypic work would support person-centred solutions.

Fourth, a need for intersectional samples is clear. Interacting factors such as economic, race and ethnic minority status play a large role in risk for impaired physical or mental health in teens in a way that may dovetail back to moderate sleep loss effects. Only by intentionally expanding our studies to underserved teens – and by including explicit tests of moderating influences – can we begin to understand the universality of these effects.

Finally, while this chapter has been principally concerned with sleep loss, future studies must turn to what can be done to buffer resilience. While adolescent biology is a given, and structural factors such as school start times are slow to change, it is incumbent on our work to identify ways to increase sleep at the margin. We can begin to understand the trade-off between how long a teen sleeps and when they sleep to provide better recommendations for teens facing an impossible problem. The short-term and long-term benefits of countermeasures such as naps and even caffeine must be thoroughly examined in the lens of brain-based cognitive and affective health.

More than simply an empirical neuroscientific problem, sleep loss during adolescence is a pressing public health need. Future studies are encouraged to keep that translatability in mind when considering their experimental designs, populations, assessments and ultimate scalability.

References

1 Dahl RE. Adolescent brain development: a period of vulnerabilities and opportunities. Keynote address. Ann N Y Acad Sci. 2004;1021(1):1–22.

2 2004 sleep in America poll: summary of findings. Vol. 4, National Sleep Foundation. 2004. p. 1–58. Available from: www.thensf.org/wp-content/uploads/2021/03/2004-SIA-Findings.pdf

3 Carskadon MA. Sleep in adolescents: the perfect storm. Pediatr Clin North Am. 2011;58(3):637–47.

4 Crowley SJ, Wolfson AR, Tarokh L, Carskadon MA. An update on adolescent sleep: new evidence informing the perfect storm model. J Adolesc. 2018;67:55–65.
5 Jenni OG, Achermann P, Carskadon MA. Homeostatic sleep regulation in adolescents. Sleep. 2005;28(11):1446–54.
6 Roenneberg T, Kuehnle T, Pramstaller PP, Ricken J, Havel M, Guth A, et al. A marker for the end of adolescence. Curr Biol. 2004;14(24):R1038–9.
7 Wittmann M, Dinich J, Merrow M, Roenneberg T. Social jetlag: misalignment of biological and social time. Chronobiol Int. 2006:497–509.
8 Ziporyn TD, Owens JA, Wahlstrom KL, Wolfson AR, Troxel WM, Saletin JM, et al. Adolescent sleep health and school start times: setting the research agenda for California and beyond. A research summit summary. Sleep Heal. 2022;8(1):11–22.
9 Lo JC, Bennion KA, Chee MWL. Sleep restriction can attenuate prioritization benefits on declarative memory consolidation. J Sleep Res. 2016;25(6):664–72.
10 Voderholzer U, Piosczyk H, Holz J, Landmann N, Feige B, Loessl B, et al. Sleep restriction over several days does not affect long-term recall of declarative and procedural memories in adolescents. Sleep Med. 2011;12(2):170–8.
11 Cousins JN, Sasmita K, Chee MWL. Memory encoding is impaired after multiple nights of partial sleep restriction. J Sleep Res. 2018;27(1):138–45.
12 Lo JC, Lee SM, Teo LM, Lim J, Gooley JJ, Chee MWL. Neurobehavioral impact of successive cycles of sleep restriction with and without naps in adolescents. Sleep. 2017;40(2).
13 Lo JC, Ong JL, Leong RLF, Gooley JJ, Chee MWL. Cognitive performance, sleepiness, and mood in partially sleep deprived adolescents: the need for sleep study. Sleep. 2016;39(3):687–98.
14 Kiriş N. Effects of partial sleep deprivation on prefrontal cognitive functions in adolescents. Sleep Biol Rhythms. 2022;20(4):499–508.
15 Randazzo AC, Muehlbach MJ, Schweitzer PK, Waish JK, Walsh JK. Cognitive function following acute sleep restriction in children ages 10–14. Sleep. 1998;21(8):861–8.
16 Kopasz M, Loessl B, Hornyak M, Riemann D, Nissen C, Piosczyk H, et al. Sleep and memory in healthy children and adolescents – a critical review. Sleep Med Rev. 2010;14(3):167–77.
17 Short MA, Chee MWL. Adolescent sleep restriction effects on cognition and mood. In: Progress in Brain Research; 2019. https://doi.org/10.1016/bs.pbr.2019.02.008
18 Diekelmann S, Wilhelm I, Born J. The whats and whens of sleep-dependent memory consolidation. Sleep Med Rev. 2009;13(5):309–21.
19 Beebe DW, Field J, Milller MM, Miller LE, LeBlond E. Impact of multi-night experimentally induced short sleep on adolescent performance in a simulated classroom. Sleep. 2017;40(2).
20 Cousins JN, Wong KF, Chee MWL. Multi-night sleep restriction impairs long-term retention of factual knowledge in adolescents. J Adolesc Heal. 2019;65(4):549–57.
21 Kopasz M, Loessl B, Valerius G, Koenig E, Matthaeas N, Hornyak M, et al. No persisting effect of partial sleep curtailment on cognitive performance and declarative memory recall in adolescents. J Sleep Res. 2010;19(1):71–9.
22 Leong RLF, Koh SYJ, Tandi J, Chee MWL, Lo JC. Multiple nights of partial sleep deprivation do not affect prospective remembering at long delays. Sleep Med. 2018;44:19–23.
23 Saletin JM, Walker MP. Nocturnal mnemonics: sleep and hippocampal memory processing. Front Neurol. 2012;3:1–12.
24 Lo JC, Chong PLH, Ganesan S, Leong RLF, Chee MWL. Sleep deprivation increases formation of false memory. J Sleep Res. 2016;25(6):673–82.
25 Moore M, Meltzer LJ. The sleepy adolescent: causes and consequences of sleepiness in teens. Paediatr Respir Rev. 2008;9(2):114–21.

26 Aston-Jones G, Cohen JD. An integrative theory of locus coeruleus-norepinephrine function: adaptive gain and optimal performance. Annu Rev Neurosci. 2005;28:403–50.
27 Krauzlis RJ, Bollimunta A, Arcizet F, Wang L. Attention as an effect not a cause. Trends Cogn Sci. 2014;1–8.
28 Meltzer LJ, Plog AE, Swenka D, Reeves D, Wahlstrom KL. Drowsy driving and teen motor vehicle crashes: impact of changing school start times. J Adolesc. 2022;94(5):800–5.
29 Yellman MA, Bryan L, Sauber-Schatz EK, Brener N. Transportation risk behaviors among U.S. high school students – youth risk behavior survey, United States, 2019. MMWR Suppl. 2020;69(1):77–83.
30 Dawson D, Reid K. Fatigue, alcohol and performance impairment. Nature. 1997;388(6639):235.
31 Lamond N, Dawson D. Quantifying the performance impairment associated with fatigue. J Sleep Res. 1999;8(4):255–62.
32 Short MA, Weber N, Reynolds C, Coussens S, Carskadon MA. Estimating adolescent sleep need using dose-response modeling. Sleep. 2018;41(4):1–14.
33 Agostini A, Carskadon MA, Dorrian J, Coussens S, Short MA. An experimental study of adolescent sleep restriction during a simulated school week: changes in phase, sleep staging, performance and sleepiness. J Sleep Res. 2017;26(2):227–35.
34 Campbell IG, Van Dongen HPA, Gainer M, Karmouta E, Feinberg I. Differential and interacting effects of age and sleep restriction on daytime sleepiness and vigilance in adolescence: a longitudinal study. Sleep. 2018;41(12):1–8.
35 Orna T, Efrat B. Sleep loss, daytime sleepiness, and neurobehavioral performance among adolescents: a field study. Clocks Sleep. 2022;4(1):160–71.
36 Garner AA, Miller MM, Field J, Noe O, Smith Z, Beebe DW. Impact of experimentally manipulated sleep on adolescent simulated driving. Sleep Med. 2015;16(6):796–9.
37 Lo JCY, Koa TB, Ong JL, Gooley JJ, Chee MWL. Staying vigilant during recurrent sleep restriction: dose-response effects of time-in-bed and benefits of daytime napping. Sleep. 2022;45(4):1–9.
38 Alsameen M, DiFrancesco MW, Drummond SPA, Franzen PL, Beebe DW. Neuronal activation and performance changes in working memory induced by chronic sleep restriction in adolescents. J Sleep Res. 2021;30(5):1–11.
39 Beebe DW, DiFrancesco MW, Tlustos SJ, McNally KA, Holland SK. Preliminary fMRI findings in experimentally sleep-restricted adolescents engaged in a working memory task. Behav Brain Funct. 2009;5:1–7.
40 Lo JC, Leong RLF, Ng ASC, Jamaluddin SA, Ong JL, Ghorbani S, et al. Cognitive effects of split and continuous sleep schedules in adolescents differ according to total sleep opportunity. Sleep. 2020;43(12):1–11 [cited 2022 Dec 4].
41 Jiang F, Vandyke RD, Zhang J, Li F, Gozal D, Shen X. Effect of chronic sleep restriction on sleepiness and working memory in adolescents and young adults. J Clin Exp Neuropsychol. 2011;33(8):892–900.
42 Winsler A, Deutsch A, Vorona RD, Payne PA, Szklo-Coxe M. Sleepless in Fairfax: the difference one more hour of sleep can make for teen hopelessness, suicidal ideation, and substance use. J Youth Adolesc. 2015;44(2):362–78.
43 Zhang J, Paksarian D, Lamers F, Hickie IB, He J, Merikangas KR. Sleep patterns and mental health correlates in US adolescents. J Pediatr. 2017;182:137–43.
44 Owens J, Au R, Carskadon M, Millman R, Wolfson A, Braverman PK, et al. Insufficient sleep in adolescents and young adults: an update on causes and consequences. Pediatrics. 2014;134(3):e921–32.
45 Fitzgerald CT, Messias E, Buysse DJ. Teen sleep and suicidality: results from the youth risk behavior surveys of 2007 and 2009. J Clin Sleep Med. 2011;7(4):351–6.

46 Baum KT, Desai A, Field J, Miller LE, Rausch J, Beebe DW. Sleep restriction worsens mood and emotion regulation in adolescents. J Child Psychol Psychiatry Allied Discip. 2014;55(2):180–90.
47 Booth SA, Carskadon MA, Young R, Short MA. Sleep duration and mood in adolescents: an experimental study. Sleep. 2021;44(5).
48 McMakin DL, Dahl RE, Buysse DJ, Cousins JC, Forbes EE, Silk JS, et al. The impact of experimental sleep restriction on affective functioning in social and nonsocial contexts among adolescents. J Child Psychol Psychiatry Allied Discip. 2016;57(9):1027–37.
49 Reddy R, Palmer CA, Jackson C, Farris SG, Alfano CA. Impact of sleep restriction versus idealized sleep on emotional experience, reactivity and regulation in healthy adolescents. J Sleep Res. 2017;26(4):516–25.
50 Wahlstrom K. Changing times: findings from the first longitudinal study of later high school start times. NASSP Bull. 2002;86(633):3–21.
51 Nahmod NG, Lee S, Master L, Chang AM, Hale L, Buxton OM. Later high school start times associated with longer actigraphic sleep duration in adolescents. Sleep. 2019;42(2):1–10.
52 Widome R, Berger AT, Iber C, Wahlstrom K, Laska MN, Kilian G, et al. Association of delaying school start time with sleep duration, timing, and quality among adolescents. JAMA Pediatr. 2020;174(7):697–704.
53 Wahlstrom KL. Examining the impact of later high school start times on the health and academic performance of high school students: a multi-site study final report. Cent Appl Res Educ Improv Univ Minnesota Minneapolis, MN, USA; 2014.
54 Goldin AP, Sigman M, Braier G, Golombek DA, Leone MJ. Interplay of chronotype and school timing predicts school performance. Nat Hum Behav. 2020;4(4):387–96.
55 Lemos N, Weissheimer J, Ribeiro S. Naps in school can enhance the duration of declarative memories learned by adolescents. Front Syst Neurosci. 2014;8:103.
56 Leong RLF, Yu N, Ong JL, Ng ASC, Jamaluddin SA, Cousins JN, et al. Memory performance following napping in habitual and non-habitual nappers. Sleep. 2021;44(6):1–11.
57 Pérez Ortega R. Divided we sleep. Science. 2021;374(6567):552–5. Available from: www.science.org/doi/10.1126/science.acx9445
58 Marco CA, Wolfson AR, Sparling M, Azuaje A. Family socioeconomic status and sleep patterns of young adolescents. Behav Sleep Med. 2011;10(1):70–80.
59 Mayne SL, Mitchell JA, Virudachalam S, Fiks AG, Williamson AA. Neighborhood environments and sleep among children and adolescents: a systematic review. Sleep Med Rev. 2021;57(2021):101465.
60 Lawrence WR, Yang M, Zhang C, Liu RQ, Lin S, Wang SQ, et al. Association between long-term exposure to air pollution and sleep disorder in Chinese children: the Seven Northeastern Cities study. Sleep. 2018;41(9):1–10.
61 Tomfohr-Madsen L, Cameron EE, Dhillon A, MacKinnon A, Hernandez L, Madigan S, et al. Neighborhood socioeconomic status and child sleep duration: a systematic review and meta-analysis. Sleep Heal. 2020;6(5):550–62.
62 Schmeer KK, Tarrence J, Browning CR, Calder CA, Ford JL, Boettner B. Family contexts and sleep during adolescence. SSM – Popul Heal. 2019:100320.
63 El-Sheikh M, Shimizu M, Philbrook LE, Erath SA, Buckhalt JA. Sleep and development in adolescence in the context of socioeconomic disadvantage. J Adolesc. 2020;83:1–11.
64 McHale SM, Kim JY, Kan M, Updegraff KA. Sleep in Mexican-American adolescents: social ecological and well-being correlates. J Youth Adolesc. 2011;40(6):666–79.
65 Venta A, Alfano C. Can sleep facilitate adaptation for immigrant high schoolers? Longitudinal relations between sleep duration, acculturative stress, and acculturation. Child Psychiatry Hum Dev. 2021;54(1):147–53.

66 Galli O, Jones CW, Larson O, Basner M, Dinges DF. Predictors of interindividual differences in vulnerability to neurobehavioral consequences of chronic partial sleep restriction. Sleep. 2022;45(1):1–14.
67 Owens J, Gruber R, Brown T, Corkum P, Cortese S, O'Brien L, et al. Future research directions in sleep and ADHD: report of a consensus working group. J Atten Disord. 2013;17(7):550–64.