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Review article

An update on adolescent sleep: New evidence informing the perfect storm model☆

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ABSTRACT

The maturation of sleep regulatory systems during adolescence in combination with psychosocial and societal pressures culminate in a "Perfect Storm" of short and ill-timed sleep and the associated consequences for many youngsters. This model, first described by Carskadon in 2011, guides our current thinking of adolescent sleep behavior. Since the original description, the field has moved forward with remarkable pace, and this review aims to summarize recent progress and describe how this new work informs our understanding of sleep regulation and sleep behavior during this developmental time frame.

A 2011 review paper (Carskadon, 2011) proposed that maturation of bioregulatory mechanisms in concert with psychosocial factors resulted in a "perfect storm" of short, ill-timed, and inadequate sleep in many teens. Two biological systems undergo modifications during adolescence. First, is the sleep/wake homeostatic process, which not only marks sleep recovery and restoration, but also signifies the speed with which the "pressure" for sleep and resulting deficits build across the day. Findings indicated that for more mature adolescents the recovery process did not accelerate, whereas the sleep pressure accumulation process decelerated, from which Carskadon inferred an ease of staying awake longer. The second process in this biological regulatory equation is the circadian timing system, which dictates the timing of many physiological and behavioral rhythms, including alertness and sleep propensity. Findings reviewed by Carskadon indicated a delayed shift in the intrinsic rhythmic system as adolescents mature, hence pushing alertness and bedtimes later into the evening and night and rising later into the morning. Data from the behavioral and psychosocial literature were sparse, yet led to a conclusion that evening light from devices with screens may activate the phase-delaying component of the circadian timing mechanism. Opposing these factors that drive the temporal placement of sleep later were such early morning events as sports practices and an early starting time for school.

In brief, the field has moved forward with remarkable pace since the earlier review was published (Carskadon, 2011), and we aim to detail this progress following a brief overview.

With regard to the homeostatic sleep "drive" process, for example, longitudinal studies have confirmed that the dissipation of sleep pressure does not change across adolescent development (Campbell et al., 2011; Tarokh, Carskadon, & Achermann, 2012). Recommended sleep length guidelines have been proposed by the National Sleep Foundation and the American Academy of Sleep

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Medicine (Hirshkowitz et al., 2015; Paruthi et al., 2016), in both cases based upon expert judgment of the literature. We describe below more recent experimental findings that may provide evidence-based guidance on sleep duration for adolescents, concluding that about 9–9.25 h a night is required for cognitive function/attention (Short, Weber, Reynolds, Coussens, & Carskadon, 2018) and for emotional regulation (Fuligni, Bai, Krull, & Gonzales, 2017). Yet, several studies from around the globe continue to report average sleep durations less than these healthful amounts. For example, in a recent meta-analysis of studies in which sleep behavior was measured from actigraphy in children and adolescents ranging in age from 3 to 18 years, total sleep time decreased with age, with pooled mean estimates in 12–18 year olds of about 7 h on school nights (Galland et al., 2018). The disparity between sleep duration measured in the laboratory (9.25 h) and the home environment (7 h) reinforce an interplay between bioregulatory mechanisms and psychosocial factors.

We note with regard to the circadian timing system, a new study of a juvenile nonhuman mammal species, the marmoset, shows a delay of activity rhythms (Melo, Goncalves, Menezes, & Azevedo, 2016). This study seems to support suggestions of the earlier review that findings from nonhuman vertebrates help to substantiate the biological underpinnings of adolescent phase delay findings. Other new work detailed below has constructed a phase response curve (PRC) to light in late and post-pubertal adolescents and found a pattern that is contrary to predictions about how adolescents differ from adults (Crowley & Eastman, 2017; Crowley, unpublished). These data suggest that the circadian phase delay of late adolescence is not due to difference in circadian phase-shifting responses to light. Furthermore, an investigation of circadian period also showed no difference between older adolescents and adults (Crowley & Eastman, 2018). When combined with evidence for increased sensitivity to evening light (Crowley, Cain, Burns, Acebo, & Carskadon, 2015), as well as longer measured intrinsic period (Carskadon, Barker, Crowley, Rupp, & Van Reen, 2017) both in younger adolescents, a growing sense is emerging that biological changes affecting circadian timing arise earlier in development than previously predicted. One longitudinal study of circadian phase in adolescents (Crowley et al., 2014) proposed a model that links the changes to sleep/wake homeostasis to circadian timing in a manner that helps to explain delayed sleep patterns as adolescents develop.

Materials described below extend the previous review paper significantly by detailing recent findings regarding adolescent sleep behaviors and nonbiological factors that affect sleep, the most prominent of which is the starting time of schools. A major advance with potential to influence the psychosocial landscape of adolescent sleep has been a forceful public health outcry and associated recommendations for delaying the starting times of schools as a means to alleviate both short duration sleep as well as ill-timed and irregular sleeping patterns. The American Academy of Pediatrics (Adolescent Sleep Working Group, Committee on Adolescence, & and Council on School Health, 2014), Centers for Disease Control (Wheaton, Chapman, & Croft, 2016), and the American Academy of Sleep Medicine (Watson et al., 2017) have made the case, based largely on small cross-sectional studies linking school start time to such issues as driving crashes and large epidemiological studies that place short sleep duration of adolescents as a risk factor for serious behavioral and emotional consequences. This message has been taken up by a number of advocacy groups, including Start School Later (www.startschoollater.net), who have undertaken lobbying efforts to implement change. Although these efforts seem to target high school age students, the issue is relevant to and targets middle school students as well (cf, Temkin, Princiotta, Ryberg, & Lewin, 2018). As shown in the systematic review by Wheaton and colleagues (Wheaton et al., 2016), much of the literature in support of delaying school start times has been gathered in the United States, though data from other regions including Hong Kong, China, Israel, Turkey, Switzerland, Spain, and New Zealand also show better sleep outcomes when schools start later. In a recent report from England (Kelley, Lockley, Kelley, & Evans, 2017), a school's start time was shifted from 8:50 am to 10:00 am for 2 years and then shifted back to 8:50 a.m. due to a change in local education administrators. This naturalistic experiment suggested that the recommended 8:30 a.m. school start time may be too early as the number of sick days decreased and performance on general examinations improved during the 2 years in which school started later (Kelley et al., 2017). Finally, Lo et al. (2018) showed increased total sleep and self-reported well-being 1 month following a 45-min delay in school start time in female students at a Singapore high school, with changes sustained at a 9-month follow-up. Authors discussed how in a culture where academic achievement is high priority, delaying school start time was feasible, sustainable, and positively accepted by parents, students, and teachers.

A pattern of restricted sleep on school nights comes from the factors highlighted above that impinge on both ends of the sleep duration equation: bedtimes and wake-up times. Bedtimes on school nights shift later as youngsters transition through adolescence, while rise times remain stable or become earlier. While these age-related sleep timing changes across adolescence have been reviewed previously (Crowley, Acebo, & Carskadon, 2007; Gradisar, Gardner, & Dohnt, 2011), we describe below a more recent longitudinal study in the United States of two age cohorts spanning the second decade (9–19 years) that confirms these findings: sleep onset times measured from actigraphy shifted later as an adolescent got older, while wake-up times shifted earlier as an adolescent transitioned from middle school to high school (Crowley et al., 2014). Interestingly, this paper showed that wake-up times shifted later as an adolescent transitioned out of high school, reflecting the societal pressure of school start time being lifted and wake-up times being less constrained.

Our introduction provides a quick overview and gist of the newer findings that now inform the *Perfect Storm* model. The details that follow allow for a more in-depth review of adolescent sleep biology and behavior.

1. Sleep regulation

We begin with a quick overview of the guiding principles that structure the approach to assessing sleep regulation across adolescence. The Two-Process Model, first proposed by Borbely (1982), with its later refinements (Achermann, Dijk, Brunner, & Borbely, 1993; Borbely & Achermann, 1999; Borbely, Achermann, Trachsel, & Tobler, 1989; Daan, Beersma, & Borbely, 1984) and variations (Dijk & Czeisler, 1995; Edgar, Dement, & Fuller, 1993; Phillips & Robinson, 2007; Phillips, Chen, & Robinson, 2010) continues to guide our hypotheses and inform our understanding of developmental sleep regulatory changes that may explain sleep/wake