

## Synchronizing education to adolescent biology: ‘let teens sleep, start school later’

Paul Kelley<sup>a\*</sup>, Steven W. Lockley<sup>b</sup>, Russell G. Foster<sup>c</sup> and Jonathan Kelley<sup>d</sup>

*<sup>a</sup>Sleep and Circadian Neuroscience Institute, Nuffield Department of Clinical Neurosciences, University of Oxford, Oxford, UK; <sup>b</sup>Division of Sleep Medicine, Department of Medicine, Harvard Medical School, Brigham and Women’s Hospital, Boston, USA; <sup>c</sup>Nuffield Laboratory of Ophthalmology, Nuffield Department of Clinical Neurosciences, University of Oxford, Oxford, UK; <sup>d</sup>International Survey Center and University of Nevada, Reno, NV, USA*

(Received 16 October 2013; accepted 4 July 2014)

Arne Duncan, US Secretary of State for Education, tweeted in 2013: ‘let teens sleep, start school later’. This paper examines early starts and their negative consequences in the light of key research in the last 30 years in sleep medicine and circadian neuroscience. An overview of the circadian timing system in adolescence leading to changes in sleep patterns is given and underpins the conclusion that altering education times can both improve learning and reduce health risks. Further research is considered from education, sleep medicine and neuroscience studies illustrating these improvements. The implementation of later starts is briefly considered in light of other education interventions to improve learning. Finally, the impact of introducing research-based later starts synchronized to adolescent biology is considered in practical and policy terms.

**Keywords:** education; adolescence; school start times; circadian; sleep deprivation; learning; health

### Introduction

Time is a fundamental variable in human biology and in education, yet currently the two disciplines measure time in different ways. For the educator, student development is defined by age and the daily timetable by social conventions that vary between countries, regions and even individual schools. In contrast, biological time is measured in developmental changes in the body, and over the day by our internal biological clock. It is no surprise given the relative novelty of mechanical clocks in evolutionary timescales that our ability to function optimally, including in learning, varies with biological time rather than conventional social times.

---

\*Corresponding author. Email: [paul.kelley@ndcn.ox.ac.uk](mailto:paul.kelley@ndcn.ox.ac.uk)

When social time and biological time are more closely aligned, as in the early years of education, this distinction is not critical. In contrast, in late adolescence the conflict between social time and biological time is greater than at any point in our lives. During adolescence biological changes dictate both a sleep duration of nine hours and later wake and sleep times, a phenomenon found in other mammals (Hagenauer et al. 2009; R uger et al. 2012). At its peak the combination of these two biological changes leads to a loss of two to three hours sleep every school day. Thus, a 07:00 alarm call for older adolescents is the equivalent of a 04:30 start for a teacher in their 50s. Failure to adjust education timetables to this biological change leads to systematic, chronic and unrecoverable sleep loss. This level of sleep loss causes impairment to physiological, metabolic and psychological health in adolescents while they are undergoing other major physical and neurological changes (Hansen et al. 2005; Giedd 2009; Giedd et al. 2012; Sawyer et al. 2012; S rensen et al. 2012; Foster et al. 2013).

The impact of early school times on adolescents is not understood by most educators: a common belief is that adolescents are tired, irritable and uncooperative because they choose to stay up too late, or are difficult to wake in the morning because they are lazy. Educators tend to think that adolescents learn best in the morning and if they simply went to sleep earlier, it would improve their concentration. These assumptions reflect societies' prejudice in favour of early risers in adulthood, exemplified by the proverb:

Early to bed, early to rise  
Makes a man healthy, wealth and wise

This belief finds expression in many cultures, and even in today's business world (Czeisler 2006; Roenneberg 2012). Such conventional wisdom lies behind the misconception that adolescents need to be trained to rise early and to go to sleep early. The truth is that adults need to be educated to adjust to another significant change in adolescents during puberty: a major biological shift in their sleep patterns.

### **The circadian timing system, sleep and adolescence: learning, mood and health**

Like most life on earth, our physiology and behaviour shows a 24-hour rhythm. Every cell in the body has cellular oscillators, and these need to function in synchrony with each other and with the environmental day. This is achieved via a master circadian (24-hour) pacemaker located in the suprachiasmatic nuclei (SCN) of the hypothalamus. The SCN is entrained to the environmental light–dark cycle by specialized photoreceptors within the eye (Foster and Hankins 2007; Lockley and Foster 2012). The SCN in turn co-ordinates the activity of the entire circadian network and most 24-hour behavioural,

metabolic and physiological rhythms including alertness and performance, hormones, core body temperature, metabolism and the different rhythms in key organs such as the lungs, liver and heart (Hilton et al. 2001; Hastings, Reddy, and Maywood 2003). If this entrainment pathway is disrupted at any point, then the biological clocks in different tissues can become uncoupled, resulting in a state of internal desynchrony of the 24-hour oscillator network (Foster et al. 2013).

The sleep–wake cycle is the most familiar 24-hour cycle, but involves more than the SCN. Indeed, sleep is a highly complex state arising from an interaction between multiple brain regions, neurotransmitter pathways and hormones, none of which are exclusive to the generation of sleep. This complexity makes sleep very vulnerable to disruption. As a result, small changes in the brain during development can have a big impact upon sleep, and abnormal sleep will in turn feedback and impact upon health. This is what occurs as a consequence of abnormal sleep that arises from the systemic, chronic and unrecoverable sleep loss when education start times are too early.

The sleep–wake cycle arises from the interplay of the circadian rhythm generated by the SCN pacemaker (alertness) and a homeostatic sleep cycle which increases the pressure to go to sleep with increasing time awake (sleepiness), and dissipates this pressure with increasing time asleep. These processes work in opposition to maintain consolidated wake during the day, and a consolidated sleep during the night.

Their interaction also generates a ‘wake maintenance zone’ (WMZ) which, paradoxically, occurs several hours before sleep is typically initiated (Dijk and Czeisler 1995; Shekleton et al. 2013). This is a major factor in the sleep difficulties experienced by adolescents. In the early evening, the homeostatic drive for sleepiness is usually too low to fully counteract the circadian drive for alertness, resulting in several hours where it is very difficult to fall asleep. In adolescence the timing of the circadian clock shifts later, delaying the phase at which sleep can be initiated, and pushing the WMZ later into the evening. The homeostatic regulation of sleep also changes such that the build-up of sleep pressure becomes slower, meaning that it takes a longer time to reach the critical threshold required to initiate sleep, which also contributes to a later sleep time. The WMZ is the reason why we, including adolescents, cannot simply choose to go to sleep earlier than normal, as the brain is still promoting wakefulness at that time.

These biological changes in the timing of sleep propensity underlie the conflict with education start times; the brain will not allow students to go to sleep early but education times still require adolescents to wake (or be woken) too early in their circadian cycle, systematically restricting the time available for sleep and causing severe and chronic sleep loss. In turn, short sleep duration and chronic sleep deprivation are sleep disruptions that have been linked to negative impacts on cognition, emotional and physical health (Lockley et al. 2004). A recent review cited studies showing that restricted sleep was associated with

impaired immune response, metabolic disorders, diabetes, hypertension, anxiety, depression and obesity (Luyster et al. 2012). The general conclusion of this review was that sleep of less than six hours' duration was potentially harmful. This conclusion was supported in a recent elegant experiment showing the negative impact on the body of a single week with 5.7 hours sleep a night (compared to controls sleeping 8.5 hours), identifying 711 genes up- or down-regulated by insufficient sleep, and a highly significant impact on genes with circadian expression profile (Möller-Levet et al. 2013).

Adolescents also show the impact of short sleep duration and chronic sleep deprivation. Adolescent studies found poor communication, decreased concentration and cognitive performance, unintended sleeps, decreased motor performance, increased risk taking and changes in mood pattern, specifically depression (Millman 2005; Knutson et al. 2007; Hagenauer et al. 2009; Foster et al. 2013; de Souza and Hidalgo 2014). This is hardly surprising, given that older teenagers show the largest discrepancy in sleep duration between free days and workdays of any age group, combined with a need for a longer sleep duration than adults. Other studies have shown that short sleep duration has a pervasive negative impact on their learning and academic performance (Curcio, Ferrara, and De Gennaro 2006), including poor grade performance and poor long-term memory encoding (Carskadon 2011). These studies reflect research with adults summarized in Table 1 (Foster and Wulff 2005; Wulff et al. 2011).

There are other demonstrations that short sleep duration in adolescence on this scale impacts on alertness and performance. Adolescent drivers have a peak rate of accidents in the morning (Czeisler 2009), unusual in older drivers, which illustrates the functional impact of waking at an adverse

Table 1. The impact of severe sleep disruption.

Cognitive responses	Emotional responses	Somatic responses
<i>Reduced:</i>	<i>Increased:</i>	<i>Increased risk of:</i>
Concentration	Motor skills mistakes	Metabolic abnormalities
Performance	Stimulant use	Diabetes II
Attention	Sedative use	Weight gain
Memory encoding	Alcohol use/misuse	Cardiovascular disease
Memory consolidation	Exhaustion	Disorders of the hypothalamo-pituitary-adrenal (HPA) axis
Multi-tasking	Irritability	Reduced immunity
Decision-making	Mood fluctuations	Drowsiness
Creativity	Anxiety	Micro-sleeps
Productivity	Depressed mood	Unintended sleep
Socialization	Frustration/anger	Bodily sensations of pain and cold
Communication	Impulsivity	Hypertension
Empathy		

circadian phase and without enough sleep. When a school district in Kentucky moved school times an hour later students reported sleeping an hour longer, and not staying up later. The impact on school day car crashes involving 17–18-year-old drivers was significant: while the state-wide rate went up 7.8%, the rate for drivers in the school district went down 16.5% (Danner and Phillips 2008), a finding replicated in Virginia (Vorona et al. 2011).

From a wider perspective, in modern societies sleep loss and sleep deprivation have reached epidemic levels. A recent review of the difference between work/education schedules and biological time quantified the extent of this sleep deficit at different ages (Foster et al. 2013). In an international survey ( $N \sim 150,000$ ), questionnaire-based assessments of chronotype show a rapid rise in eveningness throughout adolescence, occurring earlier in girls and coincident with earlier onset of puberty. These changes slowly reverse in early adulthood (starting at mean of 20.2 years), when chronotype begins to advance again, and wake times start to become earlier (Roenneberg et al. 2004).

There is also a radical decline of sleep duration from the beginning of puberty (Figure 1). Previous reports measuring sleep duration over the whole week during term time masked the size of this problem by failing to separate working days and weekends or reporting sleep in the summer. Interestingly,

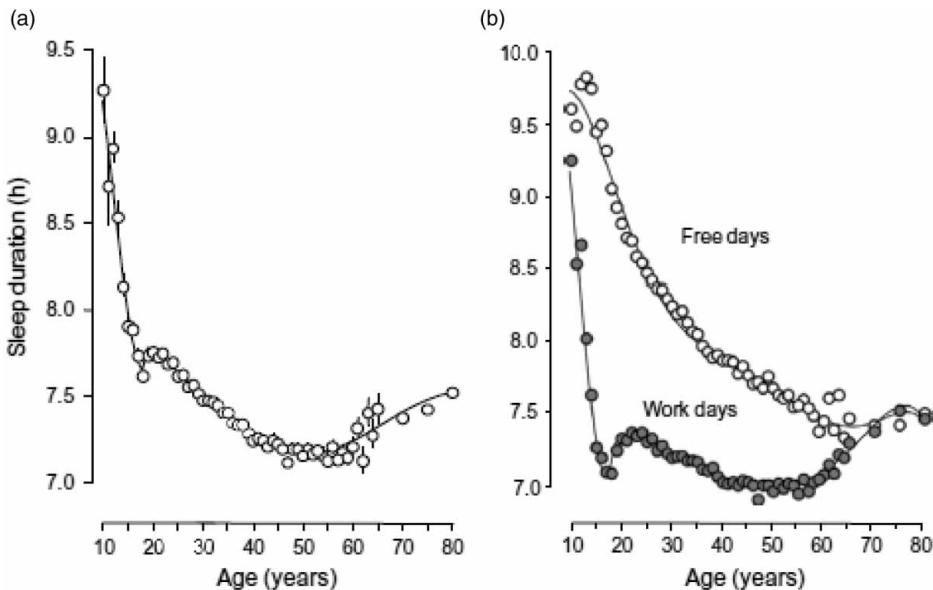


Figure 1. Average sleep duration as a function of age. (a) Weekly averages of sleep duration. (b) Sleep duration for free days (open circles) and for workdays (grey dots). Curves are polynomial fits; vertical lines represent Standard Errors of the Mean ( $\pm$  SEM; in most cases they are larger than the respective symbols). © [Rightsholder]. Reproduced with permission of Foster et al. (2013).

when there is no interference from education, adolescents' sleep during the week matched their weekend sleep (Hansen et al. 2005; Jenni, Achermann, and Carskadon 2005). The cause of this decline in sleep duration is shown in the difference between sleep on education/work days and free days. On education days the difference reaches almost three hours in late puberty (Figure 1). This scale of sleep loss cannot be recovered at weekends, as illustrated by simple arithmetic: losing three hours sleep per day in the week would need more than 15 hours additional hours of sleep per night on the weekend which is both physically and practically impossible.

Advances in understanding sleep and circadian regulation, and the negative consequences of missing two to three hours of sleep a day to meet the demands of education time, give us a new understanding of adolescent behaviour. We now know it is their biological clocks, not laziness, that keeps them in bed in the morning and up late at night. Fortunately, the problems of short sleep duration and sleep deprivation caused by education time is one that can be solved by synchronizing adolescent education time to adolescent biology.

### **Other educational considerations**

Although addressing early start times and consequent shorter sleep duration is the key to synchronizing education to adolescent biology, there are other issues that arise from an educational perspective. Four of these are briefly considered here: memory and sleep; time-in-day differences; individual differences and chronotype; and sleep education.

Sleep has a critical role in long-term memory consolidation (Stickgold 2005; Diekelmann and Born 2010) and disrupting sleep can prevent long-term memory formation (Stickgold, James, and Hobson 2000). In an elegant study, Walker and Stickgold (2010) demonstrated that taught visual discrimination skills were stabilized after subjects slept, but not after the same number of hours awake. Surprisingly they also found that skills actually improved following sleep with no additional instruction at all, whereas the non-sleep group performance did not, a phenomenon also found in other species (Menzel et al. 2001). Sleep also enables insight into problems (Wagner et al. 2004). Interestingly, when a memory is being encoded indicating its importance for future use in a test appears to increase the likelihood of that memory being consolidated in sleep (Wilhelm et al. 2011). Our understanding of specific memory functions and neurobiological processes in sleep is increasing, yet there remain many issues requiring further research (Chauvette, Seigneur, and Timofeev 2012; Grosmark et al. 2012).

Individual differences in sleep/wake patterns are generated by biological factors. For example, a more evening-like behaviour preference (eveningness chronotype) can be generated by a later timing in the circadian cycle or a slower build-up and dissipation of sleep pressure, or both, whereas a more morning-like cycle (morningness chronotype) may be due to an earlier

circadian phase and a more rapid build-up and dissipation of sleep pressure. These chronotypes can be relatively stable in adulthood and are influenced by genetic disposition and sex (Toh et al. 2001; Roenneberg et al. 2004, 2007), with females tending to be more ‘morning type’ due to a tendency to have a shorter circadian period (Duffy et al. 2011). During adolescence students naturally wake later and are alert later in the day, as a group becoming much more likely to be eveningness chronotypes. The circadian effects mean attention changes with the time in the day, with later times associated with both eveningness chronotypes and better attention. Matchock and Mordkoff (2009) found that in late adolescence general attentional scores for all chronotypes were significantly low at 08:00 and twice as high at 12:00, 16:00 and 20:00. Similarly, adolescents perform better in tests later in the day (Hansen et al. 2005; Hahn et al. 2007; Carrell, Maghakian, and West 2011). These effects are easy for educators to explore within schools. For example, as part of a study moving start times to 10:00, students aged 13–14 were given a word pairs test at 10:00 and 14:00, and performed better when tested later (Kelley and Lockley 2013) (Figure 2).

Many studies report similar time-in-day effects in performance on a wide range of cognitive tasks measuring attentional capacities, executive functioning and memory (Goldstein et al. 2007; Schmidt et al. 2009; Haraszti et al. 2014). Hahn et al. (2007) showed these issues were important even in the early transition to adolescence. Taken together, research to date suggests adjusting time-in-day of educational tasks to adolescent wake/sleep patterns and chronotypes is likely to be beneficial.

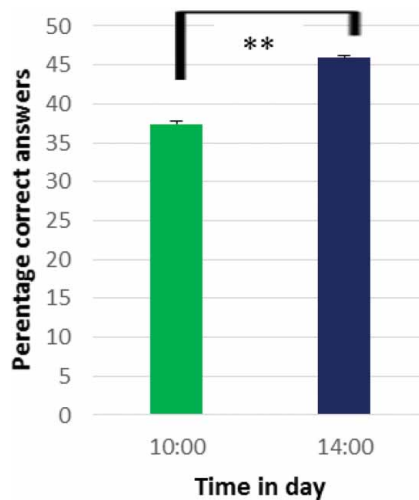


Figure 2. Test score percentage increases by time in day. Matching word pairs tests were given to subjects ( $n = 120$ ) at 10:00 and 14:00. Test scores were significantly higher at 14:00. \*\* $T$ -test repeated measures,  $p < .01$ ; effect size Cohen's  $d = 0.32$ . All data are means  $\pm$  SEM.



Evidence for specific groups within a population is less often the subject of research, whether groups are defined by biological or social factors. The group at the greatest disadvantage in early starting education systems is those with the latest eveningness chronotype, since they have the greatest time misalignment between their biological time and education time. This is reflected in research, with small performance deficits at the beginning of puberty and much greater differences near the end of puberty as the gap increases. A study in Spain showed for students aged 12–16 years evening types performed significantly worse than other chronotypes (Escribano et al. 2012). In Germany, evening-type students in high school showed significantly more use of stimulants and depressants associated with managing sleep such as coffee, cola, alcohol and nicotine when compared with morning-type students (Preckel et al. 2013). In Baden-Württemberg, a study found highly significant differences in Abitur scores (used for German university entrance) with evening types having lower performance (Randler and Frech 2006). Other studies show that evening-type adolescents may have increased risk of health and mental health problems (Giannotti et al. 2002; Hsu et al. 2012). Such findings are consistent with other research on adolescents as a group showing the very rapid impact of shorter sleep duration on neurobehavioural performance (Möller-Levet et al. 2013), and the high incidence of clinical diagnoses of mental health issues during adolescence (Wulff et al. 2011). For example, in circadian rhythm sleep disorders (ICSD-II), the prevalence of delayed sleep phase type has been calculated as 7–16% of US adolescents and young adults (15–24 years of age), or more than 2.9 million cases (Kelley and Lockley 2013).

Education in sleep management for students, families and teachers to address societal factors that can cause delayed or eroded sleep can make an additional contribution to improving adolescent sleep. It is important that sleep education includes the clear evidence that family approaches to sleep regulation can be beneficial in mitigating the role of shortened sleep in depression and suicidal ideation (Gangwisch et al. 2010). Information about 24/7 access to screen-based technologies emitting light, particularly blue-wavelength-enriched light which acts to increase alertness and delay sleep onset, is crucial in the short term until the technology companies address this fault (Rüger et al. 2012). Good sleep hygiene and a lively awareness of cultural, societal and sex differences in onset and impact of later wake–sleep patterns are also important elements in sleep education.

### **Later starts in schools**

Synchronizing education start times to adolescent biology is the obvious way to address the problem of chronic sleep deprivation currently experienced by adolescents on school days. Astronomical time data and changes in sleep patterns from international studies show at the age of 10 biological wake time is about 06:30, so synchronized school starting times would be 08:30–09:00. At the age



of 16 biological wake time is about 08:00, and synchronized school start times 10:00–10:30, and at 18 biological wake time is about 09:00, and synchronized education start times 11:00–11:30 (Kelley and Lockley 2013).

Unfortunately almost all previous studies of later school start times used times *before* 09:00, an approach that significantly underestimated the scale of change needed. Yet even these small changes to times before 09:00 have shown benefits that have led many researchers to call for a change to later start times (for example, Hansen et al. 2005; Jenni, Achermann, and Carskadon 2005; Czeisler 2009; Giedd 2009; Hagenauer et al. 2009; Foster et al. 2013). The strength of the evidence is such that it has led to later start times in some education institutions, and significant advocacy activity by organizations and individuals for systemic change in start times in schools.

Kirkby, Maggi, and D'Angiulli (2011) in a comprehensive review of later start times concluded that the benefits of later starts included better sleep, health and learning, and the benefits were an 'enormous potential payoff' for the organizational costs involved. Jacob and Rockoff (2011) in a review of later start times came to a similar conclusion, asserting they offered major learning improvements from a very well-researched intervention with little or no associated costs.

Large-scale studies consistently indicate positive effects of later starts in education, and this occurs throughout the adolescent age range as measured using different tests of achievement. A powerful additional source of evidence is that positive outcomes were found whether or not later starts were implemented to address sleep issues, or the timing changes were consistent for all students. Even in the early stages of puberty (US grades 6–8 or 11–14 years of age) there is evidence that later start times begin to have an effect on academic outcomes. In a study of data from Wade County, North Carolina, it was possible to compare outcomes within schools with variation in start times across schools because of changes in transport arrangements in the county (Edwards 2012). Analysing large cohorts ( $n > 4000$ ), a start time of an hour later had a significant two-percentile point gain in state-wide maths test scores and similar changes in reading. There were two distinctive findings in the study: first, the benefits were greater for those students at the lower end of distribution of test scores; second, the two-percentile gain in grade 8 scores remained two years later in grade 10.

In one of the first large studies based on sleep science research, seven comprehensive high schools in the Minneapolis Public School District moved the school start time from 07:15 to 08:40 (Wahlstrom 2002). This study used data on more than 50,000 students collected before and after the time changed, and was recently replicated in schools in three different states (Wahlstrom et al. 2014). The self-reported student evidence indicated that students liked the change, slept an hour longer compared to students in two other similar schooldistricts, and reported their attendance, achievement, behaviour and mood improved. Unlike most studies, the assessment included data on a

very wide range of variables, including detailed responses from parents. Parents were very positive about the later start, with 92% liking the change and reporting that their children were easier to live with and families had more conversation time (CAREI 2002).

The impact of early starts was the subject of a particularly compelling case study of the United States Air Force Academy where researchers looked at academic performance of first-year students (18–19 years old) during a three-year period when the start times changed each year in a 07:00–07:50 range (Carrell, Maghakian, and West 2011). The academy used randomized placement of students to instructors and classes, and only some students would have a class at the start times on any particular day, while the rest had additional free time ( $n = 6165$ ). The later the start times of courses for individual students, the better those students performed in the course overall. The significance of student improvement was equivalent to 1 standard deviation improvement in teacher quality. Interestingly researchers found that students assigned to start classes prior to 08:00 performed worse not only in their first period course, but in all of their courses on that day. Moreover, the size of the effect was substantial, with a 1-hour delay associated with a 0.15 standard deviation increase in performance. The researchers contextualized this change comparing it to the 1.0 standard deviation difference between black and white students in the USA. The underlying science of this time-in-day effect arises from waking too early in the biological circadian cycle, the eveningness of older adolescents and the day-long impact of this on cognition (Lockley et al. 2008; Scheer et al. 2008). These findings of particularly poor performance in the first period are supported by analysis of data from 82 Chicago high schools showing similar poor performance in early first period lessons (Cortes, Bricker, and Rohlfis 2010).

There have been schools and universities that have moved starting times to 10:00 am and later (for example, London University's School of Media, Arts and Design starts at 10:30) although most have not been the subject of formal studies. One school in New Zealand changed the start times for students aged 16 or over to 10:30, and analysis showed 14–15-year-old students in the same school (starting at 09:00) reported more sleep loss, more difficulty getting up ( $p < .001$ ) and were significantly less likely to report waking after 07:00 on weekdays ( $p < .0001$ ) than older students starting at 10:30 (Borlase, Gander, and Gibson 2013). Sakarya University in Turkey has two full academic sessions a day (08:00–14:50 and 15:00–21:50), and academic achievement varies by session and chronotype. Most examinations are at 09:30 and both teaching and test start times impact on academic performance, with eveningness types achieving better outcomes in the later session and worse in examinations held early in the day (Beşoluk, Onder, and Deveci 2011). Surprisingly, Shekleton et al. (2013) found general performance was better in the WMZ than earlier in the day. These data suggest that exploration of an upper time limit could be valuable in determining the appropriate end of the education day or educational

provision for groups of adolescents. The success of Asian and other education systems appear to have in classes in the early evening may also be an indication that times up to 20:00 are potentially very productive in adolescent learning.

Studies of later start times have consistently reported benefits to adolescent sleep, health and learning using a wide variety of methodological approaches. In contrast there are no studies showing that early starts have any positive impact on sleep, health or learning.

### **Implications for education policy and practice**

Sleep medicine and circadian neuroscience research is beginning to have a direct impact on education policy and practice with schools considering changing to later start times. School administrators have been asked to consider the potential liability of persisting with early start times in light of the possible risk to children's health and learning (Kelley and Lee 2014). Recently Tennessee changed its education law to encourage training on such biological issues (Tennessee Public Chapter 46, 2013), a move that others might usefully follow. Later starts will benefit young teachers too as many will be late chronotypes (Figure 1), and changes in their training to include an understanding of sleep medicine and circadian neuroscience would be doubly valuable in supporting sleep education in schools.

The financial cost of most other interventions to improve health and attainment in adolescents appears to be far greater than later starts in schools. Implementation of later starts may have some financial costs depending on the education system, though such costs are relative modest in comparison with the positive impact (Jacob and Rockoff 2011; Kirkby, Maggi, and D'Angiulli 2011). The impact of later starts appears to have an impact on high-stakes outcomes for disadvantaged students greater than that achieved with far more costly interventions, for example, smaller class sizes (Edwards 2012). This is particularly important in communities where financially disadvantaged young children approaching adolescence have worse sleep, and those attending Title 1 schools have shorter sleep (El-Sheikh et al. 2013). In England, the cost of a national intervention (the Pupil Premium) to address the performance of financially disadvantaged children is extremely high and has had relatively little impact to date. In contrast, introducing later start times appears to significantly reduce the gap between disadvantaged students and other students (Kelley and Lockley 2013).

There is growing evidence that education policy and practice is beginning to change. Public interest is growing in later school starts with organizations including the National Sleep Foundation, Start School Later campaign and even members of Congress all playing a part in urging implementation of later starts. Legislative proposals in particular are increasing in number in the USA, for example, the House Concurrent Resolution 176 (2009): expressing the sense of the Congress that secondary schools should begin the school day

no earlier than 09:00 in the morning. This is a pragmatic approach encouraging moves to starting times that more closely match biological time in adolescence. More recently Maryland, Virginia and Massachusetts have all considered legislation to move to later starts and momentum may increase following the intervention of the Arne Duncan, US Secretary of State for Education on *Twitter* in 2013 ('let teens sleep, start school later'). The research evidence, epidemiological data and age-specific modelling now can be combined to offer support for implementing evidence-based changes that synchronize education start times to adolescent biology.

The synchronization of education to adolescent biology enables immediate advances in educational attainment and can be achieved with a relatively simple step that does not require new teaching methods, new testing or large additional expenditure. The reduction of health risks through the same intervention requires no new medical methods, screening or treatment. Good policies should be based on good evidence, and the data show that children are currently placed at an enormous disadvantage by being forced to keep to inappropriate education times. Synchronizing education institutions' timings to adolescent biology to enable adequate sleep time seems both practical and necessary, and reflects what can be achieved by considered and well-researched trans-disciplinary interventions based on neuroscience, sleep science and education research (Gabrieli 2009; Meltzoff et al. 2009).

### Notes on contributors

Dr Paul. Kelley is Honorary Clinical Research Associate in the Sleep and Circadian Neuroscience Institute. He led the first research project to synchronize education to adolescent biology based on detailed data of adolescent sleep patterns. His research and advocacy ensured all UK adolescents can study university courses while attending school.

Dr Steven W. Lockley works within the Division of Sleep Medicine, Harvard Medical School, and has a particular interest in Sleep and Circadian Disorders. He is a neuroscientist with extensive research experience of the impact of sleep and circadian misalignment on alertness, performance and health in a range of real-world populations, including doctors, firefighters, students and shiftworkers.

Professor Russell G. Foster is a neuroscientist best known for the discovery of a third class of photoreceptor within the vertebrate eye, which consists of a small sub-set of photosensitive retinal ganglion cells. His current interests include Sleep and Circadian Rhythm Disruption in mental illness.

Professor Jonathan Kelley leads the International Survey Center, a specialist organization that creates, tests and evaluates social science surveys. The Center specializes in metrics, international comparative studies, and survey methodologies.

## References

- Beşoluk, S., I. Onder, and I. Deveci. 2011. "Morningness–Eveningness Preferences and Academic Achievement of University Students." *Chronobiology International* 28 (2): 118–125. doi:10.3109/07420528.2010.540729
- Borlase, B. J., P. H. Gander, and R. H. Gibson. 2013. "Effects of School Start Times and Technology Use on Teenagers' Sleep: 1999–2008." *Sleep and Biological Rhythms* 11 (1): 46–54. doi:10.1111/sbr.12003
- CAREI (Center for Applied Research and Educational Improvement). 2002. *School Start Time Study: Final Report Summary*. Minneapolis: University of Minnesota.
- Carrell, S. E., T. Maghakian, and J. E. West. 2011. "A's from Zzzz's? The Causal Effect of School Start Time on Academic Achievement of Adolescents." *American Economic Journal: Economic Policy* 3 (3): 62–81. doi:10.1257/pol.3.3.62
- Carskadon, M. A. 2011. "Sleep's Effects on Cognition and Learning in Adolescence." *Progress in Brain Research* 190: 137–143.
- Chauvette, S., J. Seigneur, and I. Timofeev. 2012. "Sleep Oscillations in the Thalamocortical System Induce Long-Term Neuronal Plasticity." *Neuron* 75 (6): 1105–1113. doi:10.1016/j.neuron.2012.08.034
- Cortes, K. E., J. Bricker, and C. Rohlf's. 2010. "The Role of Specific Subjects in Education Production Functions: Evidence from Morning Classes in Chicago Public High Schools." IZA Discussion Paper No. 5031.
- Curcio, G., M. Ferrara, and L. De Gennaro. 2006. "Sleep Loss, Learning Capacity and Academic Performance." *Sleep Medicine Review* 10 (5): 323–337.
- Czeisler, C. A. 2006. "Sleep Deficit. The Performance Killer. A Conversation with Harvard Medical School Professor Charles A. Czeisler." *Harvard Business Review* 84 (10): 53–59, 148.
- Czeisler, C. A. 2009. "Medical and Genetic Differences in the Adverse Impact of Sleep Loss on Performance: Ethical Considerations for the Medical Profession." *Transactions of the American Clinical and Climatological Association*, 120: 249–285.
- Danner, F., and B. Phillips. 2008. "Adolescent Sleep, School Start Times, and Teen Motor Vehicle Crashes." *Journal of Clinical Sleep Medicine* 4 (6): 533–5.
- Diekelmann, S., and J. Born. 2010. "The Memory Function of Sleep." *Nature Reviews. Neuroscience* 11 (2): 114–126. doi:10.1038/nrn2762
- Dijk, D. J., and C. A. Czeisler. 1995. "Contribution of the Circadian Pacemaker and the Sleep Homeostat to Sleep Propensity, Sleep Structure, Electroencephalographic Slow Waves, and Sleep Spindle Activity in Humans." *The Journal of Neuroscience* 15 (5): 3526–3538.
- Duffy, J. F., S. W. Cain, A. M. Chang, A. J. K. Phillips, M. Y. Münch, C. Gronfier, and J. K. Wyatt, et al. 2011. "Sex Difference in the Near-24-Hour Intrinsic Period of the Human Circadian Timing System." *Proceeding of the National Association of Sciences of the USA* 108 (S3): 15602–15608. doi:10.1073/pnas.1010666108
- Edwards, F. 2012. "Early to Rise? The Effect of Daily Start Times on Academic Performance." *Economics of Education Review* 31 (6): 970–983. doi:10.1016/j.econedurev.2012.07.006
- El-Sheikh, M., E. J. Bagley, M. Keiley, L. Elmore-Staton, E. Chen, and J. A. Buckhalt. 2013. "Economic Adversity and Children's Sleep Problems: Multiple Indicators and Moderation of Effects." *Health Psychology* 32 (8): 849–859. doi:10.1037/a0030413
- Escribano, C., J. F. Diaz-Morales, P. Delgado, and M. J. Collado. 2012. "Morningness/Eveningness and School Performance Among Spanish Adolescents: Further Evidence." *Learning and Individual Differences* 22 (3): 409–413.

- Foster, R. G., and M. W. Hankins. 2007. "Circadian Vision." *Current Biology* 17 (17): R746–R751.
- Foster, R. G., S. N. Peirson, K. Wulff, E. Winnebeck, C. Vetter, and T. Roenneberg. 2013. "Sleep and Circadian Rhythm Disruption in Social Jetlag and Mental Illness." *Progress in Molecular Biology and Translational Science* 119: 325–346. doi:10.1016/B978-0-12-396971-2.00011-7
- Foster, R. G., and K. Wulff. 2005. "The Rhythm of Rest and Excess." *Nature Reviews Neuroscience* 6 (5): 407–414.
- Gabrieli, J. D. 2009. "Dyslexia: A New Synergy Between Education and Cognitive Neuroscience." *Science* 325 (5938): 280–283. doi:10.1126/science.1171999
- Gangwisch, J. E., L. A. Babiss, D. Malaspina, J. B. Turner, G. K. Zammit, and K. Posner. 2010. "Earlier Parental Set Bedtimes as a Protective Factor Against Depression and Suicidal Ideation." *Sleep* 33 (1): 97–106.
- Giannotti, F., F. Cortesi, T. Sebastiani, and S. Ottaviano. 2002. "Circadian Preference, Sleep and Daytime Behaviour in Adolescence." *Journal of Sleep Research* 11 (3): 191–199.
- Giedd, J. N. 2009. "Linking Adolescent Sleep, Brain Maturation, and Behavior." *Journal of Adolescent Health* 45 (4) : 319–320. doi:10.1016/j.jadohealth.2009.07.007
- Giedd, J. N., A. Raznahan, K. L. Mills, and R. K. Lenroot. 2012. "Review: Magnetic Resonance Imaging of Male/Female Differences in Human Adolescent Brain Anatomy." *Biology of Sex Differences* 3 (1): 1–9, art. 19.
- Goldstein, D., C. S. Hahn, L. Hasher, U. J. Wiprzycka, and P. D. Zelazo. 2007. "Time of Day, Intellectual Performance, and Behavioral Problems in Morning Versus Evening Type Adolescents: Is There a Synchrony Effect?" *Personality and Individual Differences* 42 (3): 431–440.
- Grosmark, A. D., K. Mizuseki, E. Pastalkova, K. Diba, and G. Buzsáki. 2012. "REM Sleep Reorganizes Hippocampal Excitability." *Neuron* 75 (6): 1001–1007. doi:10.1016/j.neuron.2012.08.015
- Hagenauer, M. H., J. I. Perryman, T. M. Lee, and M. A. Carskadon. 2009. "Adolescent Changes in the Homeostatic and Circadian Regulation of Sleep." *Developmental Neuroscience* 31 (4): 276–284. doi:10.1159/000216538
- Hahn, C., J. M. Cowell, U. J. Wiprzycka, D. Goldstein, M. Ralph, L. Hasher, and P. D. Zelazo. 2007. "Circadian Rhythms in Executive Function During the Transition to Adolescence: The Effect of Synchrony Between Chronotype and Time of Day." *Cognitive Neuropsychology* 24 (7): 755–789.
- Hansen, M., I. Janssen, A. Schiff, P. C. Zee, and M. L. Dubocovich. 2005. "The Impact of School Daily Schedule on Adolescent Sleep." *Pediatrics* 115 (6): 1555–1561.
- Haraszti, R. Á., K. Ella, N. Gyöngyösi, T. Roenneberg, and K. Káldi. 2014. "Social Jetlag Negatively Correlates with Academic Performance in Undergraduates." *Chronobiology International* 31 (5): 603–612.
- Hastings, M. H., A. B. Reddy, and E. S. Maywood. 2003. "A Clockwork Web: Circadian Timing in Brain and Periphery, in Health and Disease." *Nature Reviews Neuroscience* 4 (8): 649–661.
- Hilton, M. F., M. J. Chappell, W. A. Bartlett, A. Malhotra, J. M. Beattie, and R. M. Cayton. 2001. "The Sleep Apnoea/Hypopnoea Syndrome Depresses Waking Vagal Tone Independent of Sympathetic Activation." *The European Respiratory Journal* 17 (6): 1258–1266.
- Hsu, C. Y., S. S. Gau, C. Y. Shang, Y. N. Chiu, and M. B. Lee. 2012. "Associations Between Chronotypes, Psychopathology, and Personality Among Incoming College Students." *Chronobiology International* 29 (4): 491–501. doi:10.3109/07420528.2012.668995



- Jacob, B. A., and J. E. Rockoff. 2011. "Organizing Schools to Improve Student Achievement: Start Times, Grade Configurations, and Teacher Assignments." Brookings/Hamilton Project Discussion Paper 2011–08.
- Jenni, O. G., P. Achermann, and M. A. Carskadon. 2005. "Homeostatic Sleep Regulation in Adolescents." *Sleep* 28 (11): 1446–1454.
- Kelley, P., and C. Lee. 2014. *Later School Start Times in Adolescence: Time for Change*. Denver, CO: The Education Commission of the States.
- Kelley, P., and S. W. Lockley. 2013. "Synchronizing Education to Healthy Adolescent Brain Development: Sleep and Circadian Rhythms." Paper presented at the annual meeting of the American Educational Research Association, San Francisco, April 27.
- Kirkby, M., S. Maggi, and A. D'Angiulli. 2011. "School Start Times and the Sleep–Wake Cycle of Adolescents: A Review and Critical Evaluation of Available Evidence." *Educational Researcher* 40 (2): 56–61.
- Knutson, K. L., K. Spiegel, P. Penev, and E. Van Cauter. 2007. "The Metabolic Consequences of Sleep Deprivation." *Sleep Medicine Reviews* 11 (3): 163–178.
- Lockley, S. W., J. W. Cronin, E. E. Evans, B. E. Cade, C. J. Lee, C. P. Landrigan, J. M. Rothschild, et al. 2004. "Effect of Reducing Interns' Weekly Work Hours on Sleep and Attentional Failures." *The New England Journal of Medicine* 351 (18): 1829–1837.
- Lockley, S. W., D. J. Dijk, O. Kosti, D. J. Skene, and J. Arendt. 2008. "Alertness, Mood and Performance Rhythm Disturbances Associated with Circadian Sleep Disorders in the Blind." *Journal of Sleep Research* 17 (2): 207–216. doi:10.1111/j.1365-2869.2008.00656.x
- Lockley, S. W., and R. G. Foster. 2012. *Sleep: A Very Short Introduction*. Oxford: Oxford University Press.
- Luyster, F. S., P. J. Strollo, Jr., P. C. Zee, and J. K. Walsh. 2012. "Sleep: A Health Imperative." *Sleep* 35 (6): 727–734. doi:10.5665/sleep.1846
- Matchock, R. L., and J. T. Mordkoff. 2009. "Chronotype and Time-of-Day Influences on the Alerting, Orienting, and Executive Components of Attention." *Experimental Brain Research* 192 (2): 189–198. doi:10.1007/s00221-008-1567-6
- Meltzoff, A. N., P. K. Kuhl, J. Movellan, and T. J. Sejnowski. 2009. "Foundations for a New Science of Learning." *Science* 325 (5938): 284–288. doi:10.1126/science.1175626
- Menzel, R., G. Manz, R. Menzel, and U. Greggers. 2001. "Massed and Spaced Learning in Honeybees: The Role of CS, US, the Intertrial Interval, and the Test Interval." *Learning and Memory* 8: 198–208. doi:10.1101/lm.40001
- Millman, R. P. 2005. "Excessive Sleepiness in Adolescents and Young Adults: Causes, Consequences, and Treatment Strategies." *Pediatrics* 115 (6): 1774–1786.
- Möller-Levet, C. S., S. N. Archer, G. Bucca, E. E. Laing, A. Slak, R. Kabiljo, J. C. Lo, et al. 2013. "Effects of Insufficient Sleep on Circadian Rhythmicity and Expression Amplitude of the Human Blood Transcriptome." *Proceedings of the National Society of Sciences of the United States of America* 110 (12): E1132–E1141. doi:10.1073/pnas.1217154110
- Preckel, F., A. A. Lipnevich, K. Boehme, L. Brandner, K. Georgi, T. Könen, K. Mursin, and R. D. Roberts. 2013. "Morningness–Eveningness and Educational Outcomes: The Lark Has an Advantage Over the Owl at High School." *The British Journal of Educational Psychology* 83 (Pt1): 114–134. doi:10.1111/j.2044-8279.2011.02059.x
- Randler, C., and D. Frech. 2006. "Correlation Between Morningness – Eveningness and Final School Leaving Exams." *Biological Rhythm Research* 37 (3): 233–239. doi:10.1080/09291010600645780



- Roenneberg, Till. 2012. *Internal Time: Chronotypes, Social Jet Lag, and Why You're So Tired*. Cambridge, MA: Harvard University Press.
- Roenneberg, T., T. Kuehnle, M. Juda, T. Kantermann, K. Allebrandt, M. Gordijn, and M. Merrow. 2007. "Epidemiology of the Human Circadian Clock." *Sleep Medicine Reviews* 11 (6): 429–438.
- Roenneberg, T., T. Kuehnle, P. P. Pramstaller, J. Ricken, M. Havel, A. Guth, et al. 2004. "A Marker for the End of Adolescence." *Current Biology* 14 (24): R1038–R1039. doi:10.1016/j.cub.2004.11.039
- Rüger, M., M. A. St Hilaire, G. C. Brainard, S. B. Khalsa, R. E. Kronauer, C. A. Czeisler, and S. W. Lockley. 2012. "Human Phase Response Curve to a Single 6.5 h Pulse of Short-Wavelength Light." *The Journal of Physiology* 591 (1): 353–363. doi:10.1113/jphysiol.2012.239046
- Sawyer, S. M., R. A. Afifi, L. H. Bearinger, S. J. Blakemore, B. Dick, A. C. Ezech, and G. C. Patton. 2012. "Adolescence: A Foundation for Future Health." *The Lancet* 379 (9826): 1630–1640. doi:10.1016/S0140-6736(12)60072-5
- Scheer, F. A., T. J. Shea, M. F. Hilton, and S. A. Shea. 2008. "An Endogenous Circadian Rhythm in Sleep Inertia Results in Greatest Cognitive Impairment Upon Awakening During the Biological Night." *Journal of Biological Rhythms* 23 (4): 353–361. doi:10.1177/0748730408318081
- Schmidt, C., F. Collette, C. Cajochen, and P. Peigneux. 2009. "A Time to Think: Circadian Rhythms in Human Cognition." *Actas Españolas de Psiquiatría* 37 (2): 68–74.
- Shekleton, J. A., S. M. Rajaratnam, J. J. Gooley, E. Van Reen, C. A. Czeisler, and S. W. Lockley. 2013. "Improved Neurobehavioral Performance During the Wake Maintenance Zone." *Journal of Clinical Sleep Medicine* 9 (4): 353–362. doi:10.5664/jcsm.2588
- Sørensen, K., A. Mouritsen, L. Aksglaede, C. P. Hagen, S. S. Mogensen, and A. Juul. 2012. "Recent Secular Trends in Pubertal Timing: Implications for Evaluation and Diagnosis of Precocious Puberty." *Hormone Research in Paediatrics* 77 (3): 137–145. doi:10.1159/000336325
- de Souza, C. M., and M. P. L. Hidalgo. 2014. "Midpoint of Sleep on School Days Is Associated with Depression Among Adolescents." *Chronobiology International* 31 (2): 199–205. doi:10.3109/07420528.2013.838575
- Stickgold, R. 2005. "Sleep-Dependent Memory Consolidation." *Nature* 437 (7063): 1272–1278. doi:10.1038/nature04286
- Stickgold, R., L. James, and J. A. Hobson. 2000. "Visual Discrimination Learning Requires Sleep After Training." *Nature Neuroscience* 3 (12): 1237–1238.
- Toh, K. L., C. R. Jones, Y. He, E. J. Eide, W. A. Hinz, D. M. Virshup, L. J. Ptáček, and Y. H. Fu. 2001. "An hPer2 Phosphorylation Site Mutation in Familial Advanced Sleep Phase Syndrome." *Science* 291 (5506): 1040–1043.
- Vorona, R. D., M. Szklo-Coxe, A. Wu, M. Dubik, Y. Zhao, and J. C. Ware. 2011. "Dissimilar Teen Crash Rates in Two Neighboring South-Eastern Virginia Cities with Different High School Start Times." *Journal of Clinical Sleep Medicine* 7 (2): 145–151.
- Wagner, U., S. Gais, H. Haider, R. Verleger, and J. Born. 2004. "Sleep Inspires Insight." *Nature* 427 (6972): 352–355. doi:10.1038/nature02223
- Wahlstrom, K. 2002. "Changing Times: Findings from the First Longitudinal Study of Later High School Start Times." *NASSP Bulletin* 86 (233): 3–21.
- Wahlstrom, K., B. Dretzke, M. Gordon, K. Peterson, K. Edwards, and J. Gdula. 2014. *Examining the Impact of Later School Start Times on the Health and Academic*

- Performance of High School Students: A Multi-Site Study*. CAREI. St. Paul: University of Minnesota.
- Walker, M. P., and R. Stickgold. 2010. "Overnight Alchemy: Sleep-Dependent Memory Evolution. Nature Reviews." *Neuroscience* 11 (3): 218. doi:10.1038/nrn2762-c1
- Wilhelm, I., S. Diekelmann, I. Molzow, A. Ayoub, M. Mölle, and J. Born. 2011. "Sleep Selectively Enhances Memory Expected to be of Future Relevance." *The Journal of Neuroscience* 31 (5): 1563–1569. doi:10.1523/JNEUROSC.3575-10.2011
- Wulff, K., S. Gatti, J. G. Wettstein, and R. G. Foster. 2011. "Sleep and Circadian Rhythm Disruption in Psychiatric and Neurodegenerative Disease." *Nature Reviews Neuroscience* 11 (8): 589–599.