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CLINICAL REVIEW

Sleep loss, learning capacity and academic performance

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Summary At a time when several studies have highlighted the relationship between sleep, learning and memory processes, an in-depth analysis of the effects of sleep deprivation on student learning ability and academic performance would appear to be essential. Most studies have been naturalistic correlative investigations, where sleep schedules were correlated with school and academic achievement. Nonetheless, some authors were able to actively manipulate sleep in order to observe neurocognitive and behavioral consequences, such as learning, memory capacity and school performance. The findings strongly suggest that: (a) students of different education levels (from school to university) are chronically sleep deprived or suffer from poor sleep quality and consequent daytime sleepiness; (b) sleep quality and quantity are closely related to student learning capacity and academic performance; (c) sleep loss is frequently associated with poor declarative and procedural learning in students; (d) studies in which sleep was actively restricted or optimized showed, respectively, a worsening and an improvement in neurocognitive and academic performance. These results may been related to the specific involvement of the prefrontal cortex (PFC) in vulnerability to sleep loss. Most methodological limitations are discussed and some future research goals are suggested.

Introduction

Sleep is an active, repetitive and reversible behaviour serving several different functions, such as repair and growth, learning or memory consolidation, and restorative processes: all these occur throughout the brain and the body.[1,2] Thus, during sleep behavioural, physiological and neurocognitive processes occur: these very processes are susceptible to be impaired by the absence of sleep.

Sleep loss is, in fact, one of the most striking problems of modern society.[3] Very often, to cope with our many daily interests, we prefer to sacrifice some sleep time, in the hope that this will not

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induce dangerous effects but will enable us to carry out several other activities. Unfortunately, this is not true and sleep deprivation has various consequences, such as sleepiness and impairments in neurocognitive and psychomotor performance.[4,5] More specifically, in their classic meta-analysis, Pilcher and Huffcut[4] claimed that sleep-deprived individuals functioned at a level that is comparable with the ninth percentile of non-sleep-deprived subjects. These decrements in neurobehavioural functioning after sleep restriction or deprivation are well known and common to all people[6,7] even though some individual differences in vulnerability to sleep loss have been shown.[8]

The last few years have seen an increasing literature on the relationship between sleep, memory and learning capacity (e.g. Ref.[9]). Recent findings have shown that sleep plays an important role in learning processes and memory consolidation,[10,11] although no direct relationships were found between different kinds of memory, such as procedural or declarative memory, and different sleep stages, such as REM or NREM sleep.[12] These studies clearly show that sleep deprivation can impair learning and memory for both motor procedural (e.g. Ref.[10]) and declarative memory systems (e.g. Ref.[13]).

It is well known that the integrity of learning and memory processes are fundamental in school achievement and academic performance, particularly in individuals like children and adolescents who are in a particular developmental phase.[14–18] At this stage in life, adolescents suffer from increasing school, family and social pressure and from an environmentally induced delay of sleep timing,[19–21] together with changes of intrinsic regulatory (both circadian and homeostatic) processes.[22] Taken together, these altered sleep patterns lead to a marked increase in sleepiness[23] that usually facilitates cognitive, emotional, behavioural and academic failure.[22] Surprisingly, not much data exists regarding the specific effects of inadequate sleep and sleepiness on daytime functioning in children.[17] Nevertheless, some experimental evidence reinforces the common belief that disrupted or poor sleep is usually followed by inefficient daytime behaviour and variability in performance. Within these activities, academic performance and/or school achievement should be carefully taken into consideration. As recently pointed out in some literature reviews,[24–26] learning abilities and consequent academic performance are particularly dependent on sleep patterns and sleepiness levels. These impairments in neurocognitive functioning can be observed in several kinds of learners: from school to university students, so that the consequent ability to learn from lessons or from practical activities, such as laboratory work, very often proves to be drastically reduced.

The aim of this review is to focus on the effects of sleep deprivation/fragmentation on 'day-after' learning capacity and academic performance. In order to discuss these issues, we will briefly introduce the most recent findings on the relationships between sleep and learning-memory processes. Then, we will turn our attention to the studies showing the relationship between sleep patterns and schedules on academic performance and learning. Finally, we will discuss studies investigating the effects of induced sleep loss on academic performance and neurobehavioural functioning, with particular attention to learning capacity.

The relationship between sleep and learning-memory processes

For almost a century, several studies showed the beneficial effects of sleep on memory functioning in animals and humans for different types of learning materials.[9,27,28] Recent studies in molecular genetics, neurophysiology, and cognitive and behavioural neuroscience have strengthened the idea that sleep may play an important role in learning and memory, although the extent of this role remains hotly debated.[29] In fact, there is still poor understanding as regards which aspects of memory function are affected by sleep and which processes underlie memory consolidation. Moreover, it is not clear whether memory consolidation is linked to a particular sleep stage, and whether different types of memory (e.g. declarative, procedural) are differentially influenced by sleep stages.

Now human memory is divided into at least two branches: declarative and procedural memory. Procedural knowledge comprises memories of how to perform some skill or how to solve a problem ('knowing how'). These memories, which may pertain to the motor, visual or even verbal domain,[30] are usually unconsciously learned[31] and are often referred to as 'non-declarative'. Declarative material refers to memories accessible to conscious recollection ('knowing that'). This distinction led toward the dual process hypothesis:[9] the effect of sleep state on memory process would be task-dependent, with the procedural memory gaining from REM sleep[10] and declarative memory linked to NREM sleep.[32]

Since the introduction, in the last decade, of this declarative-procedural distinction in human sleep–learning investigations, there has been renewed interest in the relationship between sleep and memory/synaptic plasticity, as shown by a series of studies, mainly focusing on procedural memory testing.[30,33] Firstly, it was shown that selective REM deprivation, but not SWS deprivation, abolishes the overnight performance improvement in a visual perceptual learning task, indicating that the mechanism of procedural memory consolidation depends on REM sleep.[34] Interestingly, no performance improvement was observed after one night of sleep deprivation followed by two recovery nights, suggesting that sleep during the first post-training night is mandatory for memory trace formation in this task.[35] However, another study comparing retention rates following undisturbed periods of early nocturnal sleep (rich in SWS) and late nocturnal sleep (rich in REM sleep), found that only early sleep facilitated visual discrimination memory (i.e., partial sleep deprivation of late REM-rich sleep did not affect performance).[36] In addition, a full night of sleep (i.e., early+late sleep) further tripled this effect. These data would be in line with the alternative point of view, i.e. the hypothesis of a sequential processing of memories during sleep stages,[37,38] suggesting that memory formation is prompted by SWS and then consolidated by REM sleep. Accordingly, the amount of sleep-dependent improvement on the perceptual learning task is linearly correlated with the amount of SWS during the first quarter of the night, and with the amount of REM sleep in the last quarter.[39] Also the NREM-REM sleep sequence seems to be important for the retention of declarative material, since morning recall of pairs of unrelated words is impaired only when sleep fragmentation leads to sleep cycle disorganization, but not when awakenings during the night preserved the sleep cycles.[40]

The beneficial effect of sleep on procedural memory has been investigated also by means of motor skill learning tasks. A finger-tapping task[41] or a nearly identical finger-to-thumb opposition task have been used.[42] A sleep-dependent improvement in performance 24 h after training without further practice has been demonstrated; it is seen only after nocturnal sleep but not across nocturnal wakefulness.[42,43] Interestingly, performance improvement was proportional to the time spent in REM sleep. Other researchers reported that an overnight improvement on FTT was correlated with the amount of stage 2 NREM during the whole night, and especially during the last quarter of the night.[41] Finally, it has been reported that performance in other tasks of verbal procedural memory (word stem priming) and visuo-motor procedural memory (recall of mirror tracing skills) is improved most after late REM-rich sleep, compared with early sleep or with equivalent wake retention intervals.[32,44] On the other hand, in an elegant study, Huber and co-workers[45] gave subjects—prior to sleep—a complex procedural motor adaptation task requiring hand-eye coordination. During post-training sleep, only slow-wave activity (SWA) increased in the right parietal lobe, i.e. the involved area for this kind of task. The extent of the local parietal increase in slow-wave activity in the first 90 min of sleep also strongly correlated with the subsequent amount of performance enhancement (learning) observed the next day, showing a close relationship between local EEG activity and subsequent regional SWA homeostasis.

The effects of sleep on memory for declarative material have received much less attention in recent years, although many of the earlier experiments often investigated the effects of classic tests of declarative memory (e.g. verbal learning tasks) on REM sleep changes following training.[10] Their findings are mixed and quite contradictory. Even when the effects of REM sleep deprivation and NREM sleep interruption were compared,[28,46] no differential effects of the two sleep manipulations on declarative memory were reported. More recently, verbal (recall of paired-associate word lists) and non-verbal declarative memory (recall of spatial locations in a mental rotation task) were investigated and showed more improvement across an interval covering early sleep than across late sleep and corresponding intervals of wakefulness.[32,44] These results were interpreted as indicating that, more than REM sleep, SWS exerts a selective facilitation of declarative memory consolidation in humans. However, it may be that not SWS *per se*, but the inhibition of glucocorticoid release from the adrenals that characterizes early nocturnal sleep, is responsible for memory consolidation. In fact, elevating plasma glucocorticoid concentration during early sleep by administering cortisol[47] or dexamethasone[48] blocked the beneficial effect of early sleep on the recall of paired associates.

On the whole, these results have generally been interpreted as supporting a fundamental role of REM for the consolidation of procedural memories in humans, while SWS-rich sleep seems to have facilitating effects for declarative memories.[30,33] However, several contradictions are still to be resolved. The first regards the actual role of REM sleep for procedural memory consolidation. As a matter of fact, visual discrimination task improvements have been related both to REM sleep[34] and

SWS,[36] while others suggested that both stages are needed to obtain the maximal benefits.[36,39] Moreover, motor skill performance improvements have been related either to REM sleep[42] and stage 2.[41,49] Even the beneficial effects of late sleep on visuomotor and verbal procedural tasks, interpreted as supporting a role for REM sleep in the consolidation of these types of memory,[32,44] can also be viewed as reflecting the involvement of stage 2, as the time spent in both stages is nearly equivalent during the second half of the night. Consequently, in our view, the idea that REM sleep is the most important for procedural memory consolidation[30,33] remains speculative and should be further investigated.

Similarly, evidence for the involvement of SWS in the consolidation of verbal and non-verbal declarative memory[32,44] is far from definitive since, at the present time, it cannot be ruled out that residual amounts of stage 2 or REM sleep during early sleep may contribute to the observed effects.

So, it may be concluded that both REM and NREM sleep are necessary for learning and memory, as some authors have clearly pointed out,[35] and that for an efficient consolidation of both (declarative) knowledge and (procedural) skills, the worst enemy is sleep loss or, also, sleep fragmentation.

Sleep patterns/schedules and academic performance

As seen in the previous section, sleep has a relevant facilitating role in learning and memory processes. Conversely, sleep deprivation and/or fragmentation usually impairs these functions. In the following, we will review the most relevant contributions in the literature investigating the effects of sleep patterns and schedules on academic performance of school and university students. It should be stressed that most of these studies correlated sleep-wake patterns with subjective (self- or parent-reported) academic achievement or with rough estimates of behaviours associated with daytime sleepiness, and, as a consequence, they are intrinsically correlational.

Academic performance from school to university

School achievement has been measured by using different parameters: grade point average (GPA), self-reported average grades, teacher comments/behaviour ratings, parent reports, and school behaviour.[26] Unfortunately, the use of such a plethora of different measures is a limitation to the comparability between different studies. Moreover, rating systems vary across different schools and, consequently, even GPAs appear to be non-objective indices. Thus, the only way to strengthen the findings would be by using multiple measures in the same study.[26]

Based on the responses to a questionnaire filled in by the parents of students, Kahn and co-workers[50] compared health, behaviour, sleep complaints and school performance of normal and poor (longer sleep latencies and frequent nocturnal awakenings) sleepers. A percentage of 21% of poor sleepers failed 1 or more years at school, while similar problems were observed in just 11% of normal sleepers. Moreover, school achievement difficulties resulted more frequent in poor than in normal sleepers. One of the best predictors for this low school achievement has been identified in children's fatigue, i.e. difficulties in morning arousal and the need for afternoon naps.[51]

As an indirect link between sleep and academic performance, it was shown that students with more regular sleep-wake patterns (shorter sleep latencies, fewer night awakenings, later school rise times, earlier rise times on weekends) reported higher GPA,[52,53] whereas students with lower grades reported increased daytime sleepiness, also as a consequence of shorter sleeping nights.[52]

An important contribution was offered by Wolfson and Carskadon,[15] who studied (by means of a health and behaviour survey with self-reported grades) sleep patterns and daytime functioning in about 3000 high school students. They showed that students with higher grades reported more total sleep, earlier bedtimes on school nights and reduced weekend delays of sleep schedules than students with lower grades. These data of better performance as a consequence of 'hygienic' sleep patterns were confirmed by several studies indicating a poorer school achievement, a greater tendency to fall asleep in school, more difficulties in concentration and in focusing attention in students with an evening circadian typology,[54] earlier school starting times[55,56] and a mild delayed sleep phase syndrome.[57]

Another recent study using surveys and self-ratings[58] pointed out that time in bed has no relationship with facility of concentration or paying attention at school, whereas sleep quality and feeling rested at school (index of a good night's sleep) were highly related to a general measure of school functioning. Moreover, children without difficulty getting up displayed more achievement motivation. This was one of the first studies that explicitly stressed the relevance of sleep quality and continuity on school functioning, giving relatively less importance to the merely quantitative amount of sleep (as observed also by Epstein et al.[56] and Pilcher et al.[59]).

In a study with both interviews and surveys administered to first-year college students,[60] researchers observed that sleep habits were highly correlated with academic performance. The official grades (provided by the university register) showed that students with a lower performance were those with later bedtimes and wake-up times on both weekdays and weekend days. The authors proposed that, for each hour of delay in reported rise time during the week, the predicted GPAs could decrease by 0.13 on a scale of 0–4, hypothesizing that this delay could induce a diminished ability to recall complex material learned earlier in class, as suggested by Dotto.[61]

The first study using an objective measure for evaluating sleep patterns of school students was by Sadeh and colleagues.[62] They actigraphically monitored 140 children for 4–5 consecutive nights and collected questionnaires and daily reports filled in by both children and their parents. The main finding was that older children had more delayed sleep onset times and increased daytime sleepiness. These effects were mainly explained on the basis of a conspicuous incidence (18%) of sleep fragmentation. On the basis of these findings, the authors concluded that a strong association does exist between altered child sleep patterns and daytime sleepiness, suggesting a possible causal link between sleep loss and learning/attentional deficits.

In a sample of 5813 healthy Finnish children, Paavonen and collegues[63] identified 17.8% of self-reported sleep complaints (mainly problems of sleep onset, enuresis, night awakenings). These self-evaluated problems correlated significantly with teachers' reports about a reduced academic performance in students with severe sleep complaints as compared to normal sleepers. Similar data were observed in another study,[64] where it was seen that short sleepers ($\leqslant$6 h per night) obtained lower grades (GPA: 2.74) than long sleepers ($\geqslant$9 h per night; GPA:3.24), indicating that those who have more total night sleep tend to have higher grades.

On the other hand, others reported no correlation between total sleep time and GPAs.[65] The authors administered a one-page questionnaire on sleep characteristics and on self-reported school achievement to 1200 high and middle school students; their findings did not support any association between sleep amount and academic performance.

A recent epidemiological survey on Italian high-school students,[66] showed that adolescents reporting a reduced academic performance mainly explained by attention problems in the classroom, tend to have more irregular bedtimes and, consequently, sleep significantly less than their peers who did not complain about attention problems. These data confirm results obtained by the same group in preliminary studies,[67,68] where school achievement and daytime functioning were related to irregular sleep schedules, shorter sleep times, later bedtimes and increased daytime sleepiness, in both children and adolescents.

Steenari and collegues[69] investigated the link between auditory and visual working memory and sleep in a Finnish population of 6 to 13 year-old students. As pointed out by the authors, working memory is necessary in several aspects of daily behaviour, such as learning, reasoning, language comprehension and acquisition of reading ability. Based on actigraphic data, the authors showed that lower sleep efficiency and longer sleep latency were associated with a higher percentage of incorrect responses at all load levels of the task, whereas shorter sleep duration affected only performance at the more-demanding level of the task. Although most correlations were not statistically robust, they were strong enough to be considered of real practical importance.

An interesting study by Sadeh and collegues[70] investigated the associations between sleep and neurobehavioural functioning (NBF) in 135 adolescents aged between 7.2 and 12.7 years. They used an objective, although indirect, measure of sleep (actigraphy) and correlated it with NBF by comparing three groups of different age. Neurobehavioural evaluation was based on several different tasks (motor speed, sustained attention, concentration, memory and learning span, etc) and was compared between good and poor sleepers[62] and within each considered age group. Results did not show any association between sleep duration and/or sleep schedule and NBF as observed by other previous studies.[15,56,71,72] Conversely, a significant correlation was seen between measures of sleep quality and sleep fragmentation with performance decrease reflecting attentional deficit and compromised executive control.[17,73] These effects were much more evident in younger students, who resulted more vulnerable to insufficient sleep.

Another recent study, conducted on 3871 high-school students in Seoul, showed a strong presence of poor sleep quantity and quality, with a consequent sharp increase in daytime sleepiness, that correlates significantly with a decline in academic performance.[74] A similar relation between increased self-reported daytime sleepiness and low grades was seen in a validation study for a new sleepiness scale (Pediatric Daytime Sleepiness Scale, PDSS) conducted on 450 middle school students.[75]

Moreover, by using GPAs on an introductory course of psychology and sleep self-ratings, Howell and co-workers[76] confirmed the correlation between poor sleep quality and reduced academic measures. Similar findings were observed in a Spanish study, where students with sleep complaints, rating themselves tired upon awakening and with daytime sleepiness, tended to fail in class with respect to those who reported a good night's sleep.[77]

All these studies showed that increasing daytime sleepiness, as a consequence of poor quality of sleep, can seriously impair students' cognitive functioning and behavioural performance (e.g. Ref.[15]). Academic performance is, in fact, clearly linked to sleep habits and daytime sleepiness levels.[14,17] This relationship is indirectly supported also by several findings provided by the study of children with sleep-breathing disorders.

Sleep-disordered breathing (SDB) is a spectrum of disorders ranging from primary snoring to severe obstructive sleep apnoea syndrome (OSAS): 10–25% of 3–12 year-old children suffer from primary snoring and 10% of these children can have OSAS.[78] SDB is known to be associated with several behavioural problems, reduced academic achievement[79] and neurocognitive impairments such as learning, memory and problem-solving.[80,81] As an example, Urschitz and collegues[82] showed that snoring and intermittent hypoxia in children were significantly associated with school failures. Specifically, snorers had twice the risk of performing poorly at school: this association became stronger with increasing snoring frequency.[82] Differences in acquisition or recalling new information, rather than difficulties in attention, were hypothesized to be the consequence of sleep fragmentation and repeated night-time arousals, that may adversely impact learning and memory tasks.[82–84] In another study, a group of 54 children with SDB was investigated with respect to academic performance.[9] Among them, only 24 patients were treated with an adenotonsillectomy. At the follow-up, 1 year later, academic performance and grades resulted significantly improved only in the treated group. This study shows that children with academic problems due to night-time breathing disorders may benefit from prospective medical treatment.[79] Similar results of substantial cognitive improvement after adenotonsillectomy were observed in children with OSAS.[85] Unfortunately, these effects of SDB-associated neurocognitive morbidity may only be partially reversible: a learning deficit can develop during early childhood and hinder subsequent school achievement.[86]

Similar negative effects on learning and academic performance were proposed for both obesity[87] and allergic rhinitis.[88]

Effects of imposed sleep loss on learning and academic performance

Results from studies investigating the effects of different sleep patterns and schedules on academic performance showed that students who sleep poorly, with an elevated sleep fragmentation (i.e., reduced sleep quality), with later bedtimes and early awakenings, usually tend to offer a decreased academic performance and a reduced neurobehavioural functioning.[14,25,26] However, the studies seen so far are only 'naturalistic' correlative ones: in this section we shall more deeply review those studies which have tried to experimentally manipulate sleep amount in order to evaluate the effects on subsequent cognitive functioning. These studies are summarized in Table 1.

The oldest study investigating the effects of total sleep deprivation (50 h) in students' motor performance[89] showed significant impairments in psychomotor abilities: such a decrease appeared after only 18 h of wakefulness on reaction times. Other measures required a longer deprivation to show detrimental effects: endurance (34 h of continuous wake), agility, balance and power (42 h), speed (after 50 h).

Nevertheless, the first study which examined the effect of sleep loss on adolescents' psychomotor and cognitive performances was carried out by Carskadon and co-workers.[90] The authors assessed the sleepiness (through the Multiple Sleep Latency Test, MSLT, and subjective ratings) and performance (problem-solving/computational ability, memory, auditory attention, sustained motor activity) of 12 adolescents during 38 h of total sleep deprivation. Results showed an increase in both objective and subjective sleepiness, whereas performance was affected only on memory and computational speed. No statistically significant changes were observed on attention and sustained motor activity. The authors concluded that the response of adolescents to relatively mild sleep deprivation is similar to that of older subjects: as a possible explanation for these data, the authors proposed the so-called 'lapse hypothesis',[91] i.e.

the presence of brief lapses in attention during task completion, that could greatly slow down the subjects' answers. Moreover, similar impairments in problem-solving have recently been observed in adults,[92,93] for which an involvement of the prefrontal cortex (PFC) has been proposed.[17]

The same group[94] also investigated the effect of an acute restriction (one night of 4 h sleep). Nine children were submitted to the same task battery as in the previous study,[90] but they did not show any significant effect after this sleep restriction schedule. Polysomnography indicated that total sleep time increased as a consequence of sleep manipulation, while sleep latency and night-time awakenings were reduced. The authors claimed that these findings suggest that sleep restriction may not always lead to observable decrements as, instead, total sleep deprivation does.

After a total sleep deprivation of one night, 44 college students showed the expected significant decrease of performance on cognitive tasks assessing inference, recognition of assumptions and deduction.[95] Interestingly, although the sleep-deprived subjects performed worse, they reported higher levels of estimated performance and more effort expended on tasks than the non-deprived subjects. This study raises the interesting issue of a reduced awareness of the extent to which sleep loss can impair the ability to complete cognitive tasks. Such a phenomenon suggests that many students could damage their own academic performance by choosing the wrong schedule to deprive themselves before examinations or class work.[95]

The first study aimed at directly assessing learning capacity after sleep loss was done by Randazzo and co-workers.[96] Sixteen children were asked to sleep only 5 h for a single night and then their psychomotor and cognitive performance was assessed, together with sleep propensity as evaluated by the MSLT. Tasks measured attention, vigilance, abstract thinking, memory, learning and creativity. As a consequence of sleep restriction, subjects showed shorter sleep latencies and an impaired performance on verbal creativity (mainly fluency and flexibility) and on abstract thinking. Although easier psychomotor tasks as well as memory and learning tests failed to show differences after sleep curtailment, it should be pointed out that scores in the Wisconsin Card Sorting Test (WCST) were significantly affected, indicating a difficulty in learning new abstract concepts. The authors concluded by observing that a moderate sleep restriction can affect the children's executive functions that '...enable the individual to engage in creative, adaptive learning by initiating and regulating retrieval of knowledge from long-term memory, modifying the knowledge base, and mediating problem-solving'.[96] Surprisingly, these effects were clear, despite a strong motivational effort suggested by a good performance on low-demanding tasks. Since verbal fluency was affected, then here too the key cerebral region could be the PFC.

A subsequent work by the same authors[97] published as an abstract, investigated the effects on cognitive functioning after 3 nights of mild sleep restriction (7 h) on children aged 10–14 years. Results confirmed impairments in verbal fluency and creativity, while no effects were found in a working memory task, computational accuracy and planning ability. Thus, also in an extended schedule of sleep restriction, only higher cognitive functions seem sensitive to sleep loss.

Fallone and co-workers[98] evaluated the effects of an acute (one-night) sleep restriction on sustained attention, response inhibition and on a simulated academic exercise in children aged 8–15 years. They compared two groups of subjects with an Optimized (10 h) and a Restricted (4 h) sleep schedule. Children in the Restricted group resulted more inattentive and showed a higher frequency of observed sleepy behaviours during a simulated academic situation. Moreover, the MSLTs showed an increased sleep propensity in the Restricted group; an increase in sleepiness was also observed in subjective ratings. The authors concluded that sleepiness following acute sleep restriction is not sufficient to produce deficits on performance measures of impulsivity and sustained attention and that these data do not support the hypothesized prefrontal cortical impairment after sleep loss.[17]

The same group performed a study with a prolonged sleep restriction.[99] In this case 27 children were assigned to an Optimized (10 h per night) or Restricted Group (6.5 h per night) and they were asked to maintain their sleep schedule for 6 consecutive nights. Their behaviour was assessed by parents, teachers and in-lab staff, while measures of sleepiness were based on MSLTs and subjective ratings. Results showed that restricting sleep each night to 6.5 h for one week was associated with daytime sleepiness, inattentiveness and academic problems. Again, the main limitation of this study is the fact that it is mainly based on parents and teachers' reports.

After noting a close correlation between objectively assessed sleep quality and NBF in a naturalistic design, Sadeh and co-workers[100] proceeded to an experimental manipulation of sleep amount, assuming that cumulative (3 nights) sleep restriction or extension might lead to, respectively,

Table 1 Studies evaluating cognitive achievement after sleep manipulations.

Study	*N*	Age range (mean)	Sleep manipulation	Sleep/sleepiness variables	Academic/cognitive and performance variables	Key findings
Copes and Rosentswieg,[89]	15	n.a. (15.2)	TSD: 2 nights (50 hs of continuous wakefulness)	n.a.	Motor performance (accuracy, agility, balance, endurance power, RT, speed, strength)	Impairments of psychomotor abilities: RT the most sensitive
Carskadon et al.[90]	12	11.7–14.6 (13.5)	TSD: one night (38 hs of continuous wakefulness)	PSG; MSLT; sleepiness subjective ratings	Problem-solving or computational ability, memory, auditory attention, sustained motor activity	Increase in sleepiness; changes on REC sleep architecture; poor memory and computational speed
Carskadon et al.[94]	9	11–13.2 (12.0)	SR: one night (4 hs sleep alowed)	PSG; MSLT; sleepiness subjective ratings	Problem-solving or computational ability, memory, auditory attention, sustained motor activity	Increase in sleepiness; changes on REC sleep architecture
Pilcher and Walters,[95]	23	n.a. (20.5)	TSD: one night (24 hs of continuous wakefulness)	n.a.	Performance at a critical thinking task	Reduced cognitive achievement; reduced awareness of cognitive impairments
Randazzo et al.[96]	8	10–14 (11.6)	SR: one night (5 hs of sleep allowed)	PSG; MSLT	Attention, vigilance, abstract thinking, memory, learning, creativity	Increase in sleep propensity; impaired performance on verbal creativity and abstract thinking

Randazzo et al.[97]	20	10–14 (n.a.)	SR: three nights (7 hs of sleep allowed)	n.a.	On verbal and figural creativity, working memory task, computational accuracy; working memory, RT, vigilance, planning ability and perceptual organization	Impaired performance on verbal fluency and creativity
Fallone et al.[99]	27	11–13 (n.a.)	SR: six nights (6.5 hs of sleep allowed)	MSLT; sleepiness subjective ratings	Parents, teachers and in-lab staff assessment of subjects' behaviour	Increase of daytime sleepiness, inattentiveness and academic problems
Fallone et al.[98]	45	8–15 (12.0)	SR: one night (4 hs of sleep allowed)	PSG; MSLT; sleepiness subjective ratings	Sustained attention, response inhibition and behaviour in a simulated academic exercise	Increase in daytime sleepiness and sleep propensity; increased inattentive behaviours
Sadeh et al.[100]	37	9.1–12.2 (n.a.)	SR: three night (1 h less than their habitual schedule)	PSG	Motor speed, vigilance and motor reaction, sustained visual attention, response inhibition, visual memory and visual-motor speed, working memory, learning strategies	Decrease in sleep quality, vigilance, attention, memory

n.a.: not available; PSG: polysomnography; REC: revovery night; RT: reaction times; SR: sleep restriction; TSD: total sleep deprivation.

cumulative negative or positive effects on NBF.[101] Subjects were requested to extend or restrict their habitual sleep for 1 hour: this manipulation of sleep time resulted in a mean decrease of 41 minutes for the restricted group, and a mean increase of 35 minutes for the extended group. Subjects were then tested with the same battery (Neuropsychological Evaluation System, NES) used in a previous work.[70] Results showed that this modest experimental manipulation led to distinct effects on performance patterns: in the extension condition, vigilance, attention and memory resulted improved with respect to the sleep restriction condition. The authors claimed that these results have significant implications for learning and school performance, since these tasks are highly correlated with classroom behaviours and achievement tests.[100]

Academic performance is also dependent on school starting time and the delayed sleep phase. As recently reviewed by Wolfson and Carskadon,[26] in fact, children with an early school start time reported much more daytime sleepiness, dozing in class, attention difficulties and poorer academic performance. For example, a study using questionnaires[56] compared the effects of different school starting times: results indicated that the 'early risers' slept significantly less (about 24 min) than 'regular risers'. As a result, the 'early risers' complained more about daytime sleepiness and fatigue and about difficulties in concentrating and paying attention during classes, with a two-fold incidence of dozing off in class. Similar results were observed in the previously discussed Italian survey.[66] Finally, a recent study carried out in the US[102] showed that school starting time caused students to lose up to 2 h sleep per night, but only on weekdays: during weekends, in fact, a kind of recovery occurred. Moreover, as a consequence of school starting time and of early awakening, students provided a better neurocognitive performance in the afternoon than in the morning.

Another facet of the problem is related to the phase delay which is very often seen in young people. This tendency to extend the weekend's sleep schedules (late lights-out time, long sleep-onset latency, late wake-up time) to weekdays is usually called the delayed sleep phase syndrome (DSPS), a habit that perpetuates both sleep onset and awakening problems. An incidence of 17% of DSPS was reported in a university sample.[57] In this subgroup, a delay of over 90 min in bedtime and waking time at weekends compared to weeknights was observed. This marked delay induced an impaired academic performance (lower grades) in students with DSPS compared to a control group. A similar prevalence of DSPS in the population (11.5%) was found in a U.S. study,[103] whose authors suggested a strong role of college lifestyle in the development of this syndrome.

Unfortunately, no studies were carried out with the aim of comparing different sleep/wake schedules, i.e. imposed (or 'optimal') versus non-imposed (chosen by the children/control).

Again, some conclusions can be made on the basis of the literature review. Firstly, poor or fragmented sleep is often associated with behavioural and cognitive difficulties. Secondly, these impairments often reduce academic achievement and learning. Finally, this decrease in neurocognitive functioning can easily be reverted by adopting healthy sleep schedules (fixed bedtimes and waking times, no chronic sleep restriction, etc.).

These conclusions are also related to the daily sleep need in modern life, an issue hotly debated with regard to both the adult (e.g. Ref.[104]) and young population.[22] It is now well known that during puberty and adolescence both SWS and REM sleep start to decrease.[105] At the same time, also sleep quantity and quality result greatly impaired, as a consequence of a dramatic delay of sleep timing induced by increasing psychosocial and environmental demands on children.[14] This cascades into a chronic pattern of insufficient school-day sleep, forced arousals at a biologically inappropriate time, with negative impacts on adolescent cognition, performance, mood and behaviour.[22]

Conclusions

The studies discussed here allow us to draw some conclusions. As a first observation, regardless of the theoretical framework adopted (dual process hypothesis or sequential processing hypothesis), both REM and NREM sleep seem necessary for learning and memory: thus, for an efficient consolidation of both (declarative) knowledge and (procedural) skills, the worst risk is sleep loss or fragmentation.

Moreover, it was shown that an increasing daytime sleepiness, as a consequence of poor sleep quality, can seriously impair students' cognitive functioning and behavioural performance. An association between academic performance and sleep habits or daytime sleepiness levels has also been suggested by children's sleep-breathing disorders or obesity.

Finally, studies with experimental manipulations of the amount and quality of children's sleep confirmed that poor or fragmented sleep is associated with behavioural and cognitive difficulties, with reduced academic achievement and learning. Nonetheless, this decrease in neurocognitive functioning can easily be reverted by adopting healthy sleep schedules, such as fixed bedtimes and waking times, fixed school starting times, and by limiting psychosocial and environmental pressure.

Unfortunately, several methodological limits do exist in this literature. Different indicators are usually used in assessing academic performance: self-reported or actually recorded GPAs (provided by the register), self-reported average grades, teachers' comments/behaviour ratings, parents' reports, and school behaviour.[26] This is a real problem that should be resolved in the near future, since the different outcome measures reported in the literature scarcely overlap: as an example, Wolfson and Carskadon[26] claimed that even grades, seen as the most reliable measure, are usually not equivalent in different school systems. Nevertheless, they do reflect actual child learning abilities since they are closely connected to the school curriculum.[106] On the other hand, others suggest that achievement tests should be a better measure because they are individually administered (thus more reliable for children with learning difficulties) and are more representative of the material taught.[107] Thus, a mandatory need for this field of research is to find a consistent measure for learning capacity and academic performance. Alternatively, in order to obtain broader and more reliable evaluations, a multi-measure approach should be adopted, with grades, tests, as well as both teacher and parent self-reports (as proposed in Ref.[26]).

Moreover, although a great number of studies using surveys have been conducted, very few studies (see Table 1) used an experimental manipulation of sleep timing. Thus, this field needs many more studies investigating specific school-like tasks with laboratory-based paradigms, not neglecting the possibility of a kind of 'Hawthorne effect'.[25,26] Only in this way will it be possible to highlight the actual causal relationship between sleep features, learning capacity and academic achievement.

Finally, some confounding variables should also be taken into consideration. Wolfson and Carskadon quite reasonably proposed[26] the relevant role of environmental and family variables. When comparing students coming from different schools (with different evaluation systems, class size, ethnic presence), different families (with a permissive or an authoritarian style) and with different psychosocial commitments (i.e. extra-curricular activities), a serious bias can be introduced. To avoid these methodological problems, a more careful sample selection is needed.

In humans, several studies have demonstrated that neural systems of the prefrontal cortex involved in executive functioning are more susceptible to sleep deprivation.[5,7] As a result, most neurocognitive functions result impaired by acute sleep loss, such as attention and divergent thinking,[108] language,[109,110] decision-making,[5] memory and response inhibition,[111] and serial subtraction.[112] These data have largely been confirmed by neuroimaging studies (e.g. Refs.[113,114]). Moreover, it is well known that under chronic partial sleep deprivation, neurocognitive deficits can accumulate over time,[6,94] even if a subjective adaptation to the sensation of sleepiness can be experienced. Thus, these effects could be present also in students.[17] In these populations, a PFC deficit could lead to impairments in learning, attention, decision-making and complex, divergent or creative thinking. As a first consequence, academic performance will result reduced or impoverished, and a further effect may also be seen on emotional and social processing, i.e. in the PFC highest level of integration.[17] Moreover, these effects could result in a dangerous cumulative effect that is particularly significant for children, who need much more time than adults to fully recover their normal neurocognitive functioning.

Practice points

1. Students of different education levels (from school to university) are chronically sleep deprived or suffer from poor sleep quality: this is also due to psychosocial, environmental and professional pressure.
2. Sleep quality and quantity induce several effects on a student's life: increased daytime sleepiness, impaired mood, neurocognitive deficits and behavioural changes.
3. The effects of sleep loss are mainly evident on higher cognitive functions (attention, memory, problem-solving, etc); as a result, learning capacity and academic performance may seriously be affected.
4. Studies in which sleep was actively restricted or optimized showed, respectively, a worsening and an improvement in neurocognitive and academic performance: this raises the possibility of an improvement in neurocognitive functioning (and thus of learning capacity and academic performance) as a consequence of healthy sleep schedules.

Research agenda

1. As a first step, it is necessary to find reliable measures of learning capacity and academic performance. Alternatively, a multi-measure approach (grades, tests, teacher and parent self-reports) could be adopted.
2. Moreover, more studies are needed investigating specific school-like tasks with laboratory-based paradigms. This is important in order to pinpoint the actual causal relationship between sleep fragmentation, sleep restriction and learning capacity and academic achievement.
3. Not alternatively, investigations should be carried out on patients with sleep disorders and/or other sleep fragmentation problems, such as sleep apnea or sleep-breathing disorders, restless legs syndrome, obesity, etc.
4. Also, it could be very interesting to carry out prospective studies comparing different imposed sleep/wake schedules (regular or 'optimal') to non- imposed schedules (such as a control) over a complete semester/year, to investigate their differential effects on academic achievement.
5. Finally, an important goal for future research is the study of the so-called long-term effects. Clear answers to the following questions are needed: 'What does chronic sleep deprivation induce in students' learning capacity?', 'Are there such things as developmental time-windows that are particularly sensitive to sleep disruption and, consequently, critical for adult academic performance?', 'Does sleep fragmentation in the critical developmental period impair long-term efficiency of PFC-related functions?'.

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References

1. Krueger JM, Obal F. Sleep function. *Front Biosci* 2003;**8**:d511–9.
2. Benington JH. Sleep homeostasis and the function of sleep. *Sleep* 2000;**23**:959–66.
3. Bonnet MH. Sleep Deprivation. In: Kryger MH, Roth T, Dement WC, editors. *Principles and Practice of Sleep Medicine*. 3rd ed. London: Saunders; 2000. p. 53–71.
4. Pilcher JJ, Huffcut AI. Effects of sleep deprivation on performance: a meta-analysis. *Sleep* 1996;**19**:318–26.
5. Harrison Y, Horne JA. The impact of sleep deprivation on decision making: a review. *J Exp Psychol Appl* 2000;**6**: 236–49.
6. Van Dongen HP, Maislin G, Mullington JM, et al. The cumulative cost of additional wakefulness: dose-response effects on neurobehavioral functions and sleep physiology from chronic sleep restriction and total sleep deprivation. *Sleep* 2003;**26**:117–26.
7. Durmer JS, Dinges DF. Neurocognitive consequences of sleep deprivation. *Semin Neurol* 2005;**25**:117–29.
8. Van Dongen HP, Baynard MD, Maislin G, et al. Systematic interindividual differences in neurobehavioral impairment from sleep loss: evidence of trait-like differential vulnerability. *Sleep* 2004;**27**:423–33.
9. Peigneux P, Laureys S, Delbeuck X, et al. Sleeping brain, learning brain. The role of sleep for memory systems. *Neuroreport* 2001;**12**:A111–24.
10. Smith C. Sleep states and memory processes in humans: procedural versus declarative memory systems. *Sleep Med Rev* 2001;**5**:491–506.
11. Hobson JA, Pace-Schott EF. The cognitive neuroscience of sleep:neuronal systems, counsciousness and learning. *Nature Rev Neurosci* 2002;**3**:679–93.
12. Rauchs G, Desgranges B, Foret J, et al. The relationships between memory systems and sleep stages. *J Sleep Res* 2005;**14**:123–40.
13. Gais S, Born J. Declarative memory consolidation: mechanisms acting during human sleep. *Learn Mem* 2004;**11**:679–85.
14. Carskadon MA. Patterns of sleep and sleepiness in adolescents. *Pediatrician* 1990;**17**:5–12.
*15. Wolfson AR, Carskadon MA. Sleep schedules and daytime functioning in adolescents. *Child Dev* 1998;**69**:875–87.
16. Carskadon MA, Vieira C, Acebo C. Association between puberty and delayed phase preference. *Sleep* 1993;**16**: 258–62.
*17. Dahl RE. The impact of inadequate sleep on children's daytime cognitive function. *Semin Pediatr Neurol* 1996; **3**:44–50.
18. Dahl RE. The development and disorders of sleep. *Adv Pediatr* 1998;**45**:73–90.
19. Andrade MM, Benedito-Silva AA, Domenice S, et al. Sleep characteristics of adolescents: a longitudinal study. *J Adolesc Health* 1993;**14**:401–6.
20. Dahl RE, Lewin DS. Pathways to adolescent health sleep regulation and behavior. *J Adolesc Health* 2002;**31**(Suppl): 175–84.
21. Gau SF, Soong WT. The transition of sleep-wake patterns in early adolescence. *Sleep* 2003;**26**:449–54.
*22. Carskadon MA, Acebo C, Jenni OG. Regulation of adolescent sleep: implications for behavior. *Ann N Y Acad Sci* 2004;**1021**:276–91.
*23. Carskadon MA, Acebo C. Regulation of sleepiness in adolescents: update, insights, and speculation. *Sleep* 2002;**25**:606–14.
24. Samkoff JS, Jacques CH. A review of studies concerning effects of sleep deprivation and fatigue on residents' performance. *Acad Med* 1991;**66**:687–93.

*The most important references are denoted by an asterisk.

25. Fallone G, Owens JA, Deane J. Sleepiness in children and adolescents: clinical implications. *Sleep Med Rev* 2002;**6**:287–306.
*26. Wolfson AR, Carskadon MA. Understanding adolescents' sleep patterns and school performance: a critical appraisal. *Sleep Med Rev* 2003;**7**:491–506.
27. Jenkins J, Dallenbach K. Oblivescence during sleep and waking. *Amer J Psychol* 1924;**35**:605–12.
28. Smith C. Sleep states and memory processes. *Behav Brain Res* 1995;**69**:137–45.
29. Siegel J. The REM sleep-memory consolidation. *Science* 2001;**294**:1058–63.
30. Born J, Gais S. Roles of early and late nocturnal sleep for the consolidation of human memories. In: Maquet P, Smith C, Stickgold R, editors. *Sleep and brain plasticity.* Oxford: Oxford University Press; 2003. p. 65–85.
31. Squire L. Declarative and nondeclarative memory: multiple brain systems supporting learning and memory. *J Cogn Neurosci* 1992;**4**:232–43.
32. Plihal W, Born J. Effect of early and late nocturnal sleep on declarative and procedural memory. *J Cogn Neurosci* 1997;**9**:534–47.
33. Stickgold R. Human studies of sleep and off-line memory processing. In: Maquet P, Smith C, Stickgold R, editors. *Sleep and brain plasticity.* Oxford: Oxford University Press; 2003. p. 41–63.
34. Karni A, Tanne D, Rubenstein BS, et al. Dependence on REM sleep of overnight improvement of a perceptual skill. *Science* 1994;**265**:679–82.
35. Stickgold R, James L, Hobson J. Visual discrimination learning requires sleep after training. *Nat Neurosci* 2000;**3**:1237–8.
36. Gais S, Plihal W, Wagner U, et al. Early sleep triggers memory for early visual discrimination skills. *Nat Neurosci* 2000;**3**:1335–9.
37. Giuditta A, Ambrosini MV, Montagnese P, et al. The sequential hypothesis of the function of sleep. *Behav Brain Res* 1995;**69**:157–66.
38. Ambrosini MV, Giuditta A. Learning and sleep: the sequential hypothesis. *Sleep Med Rev* 2001;**5**:477–90.
39. Stickgold R, Whidbee D, Schirmer B, et al. Visual discrimination task improvement: A multi-step process occurring during sleep. *J Cogn Neurosci* 2000;**12**:246–54.
40. Ficca G, Lombardo P, Rossi L, et al. Morning recall of verbal material depends on prior sleep organization. *Behav Brain Res* 2000;**112**:159–63.
41. Walker M, Brakefield T, Morgan A, et al. Practice with sleep makes perfect: sleep dependent motor skill learning. *Neuron* 2002;**35**:205–11.
42. Fischer S, Hallschmid M, Elsner A, et al. Sleep forms memory for finger skills. *PNAS* 2002;**99**:11987–91.
43. Karni A, Meyer G, Rey-Hipolito C, et al. The acquisition of skilled motor performance: fast and slow experience-driven changes in primary motor cortex. *PNAS* 1998;**95**:861–8.
44. Plihal W, Born J. Effects of early and late nocturnal sleep on priming and spatial memory. *Psychophysiology* 1999;**36**:571–82.
45. Huber R, Ghilardi MF, Massimini M, et al. Local sleep and learning. *Nature* 2004;**430**(6995):78–81.
46. Ekstrand B, Sullivan M, Parker D, et al. Spontaneous recovery and sleep. *J Exp Psychol* 1971;**88**:142–4.
47. Plihal W, Born J. Memory consolidation in human sleep depends on inhibition of glucocorticoid release. *Neuroreport* 1999;**10**:2741–7.
48. Plihal W, Pietrowsky R, Born J. Dexamethasone blocks sleep induced improvement of declarative memory. *Psychoneuroendocrinol* 1999;**24**:313–31.
49. Smith C, MacNeill C. Impaired motor memory for a pursuit rotor task following Stage 2 sleep loss in college students. *J Sleep Res* 1994;**3**:206–13.
50. Kahn A, Van de Merckt C, Rebuffat E, et al. Sleep problems in healthy preadolescents. *Pediatrics* 1989;**84**:542–6.
51. Blum D, Kahn A, Mozin MJ, et al. Relation between chronic insomnia and school failure in preadolescents. *Sleep Res* 1990;**19**:194.
52. Link SC, Ancoli-Israel S. Sleep and the teenager. *Sleep Res* 1995;**24a**:184.
53. Gray EK, Watson D. General and specific traits of personality and their relation to sleep and academic performance. *J Pers* 2002;**70**:177–206.
54. Giannotti F, Cortesi F, Sebastiani T, Ottaviano S. Circadian preference, sleep and daytime behaviour in adolescence. *J Sleep Res* 2002;**11**:191–9.
55. Carskadon MA, Wolfson AR, Acebo C, et al. Adolescent sleep patterns, circadian timing, and sleepiness at a transition to early school days. *Sleep* 1998;**21**:871–81.
56. Epstein R, Chillag N, Lavie P. Starting times of school: effects on daytime functioning of fifth-grade children in Israel. *Sleep* 1998;**21**:250–6.
57. Lack LC. Delayed sleep and sleep loss in university students. *J Am Coll Health* 1986;**35**:105–10.
58. Meijer AM, Habekothe HT, Van Den Wittenboer GL. Time in bed, quality of sleep and school functioning of children. *J Sleep Res* 2000;**9**:145–53.
59. Pilcher JJ, Ginter DR, Sadowsky B. Sleep quality versus sleep quantity: relationships between sleep and measures of health, well-being and sleepiness in college students. *J Psychosom Res* 1997;**42**:583–96.
60. Trockel MT, Barnes MS, Egget DL. Health-related variables and academic performance among first-year college students: implications for sleep and other behaviors. *J Am Coll Health* 2000;**49**:125–30.
61. Dotto L. Sleep stages, memory and learning. *Can Med Assoc J* 1996;**154**:1193–6.
62. Sadeh A, Raviv A, Gruber R. Sleep patterns and sleep disruptions in school-age children. *Dev Psychol* 2000;**36**:291–301.
63. Paavonen EJ, Aronen ET, Moilanen I, et al. Sleep problems of school-aged children: a complementary view. *Acta Paediatr* 2000;**89**:223–8.
64. Kelly WE, Kelly KE, Clanton RC. The relationship between sleep length and grade-point average among college students. *Coll Student J* 2001;**35**:84–6.
65. Eliasson A, Eliasson A, King J, et al. Association of sleep and academic performance. *Sleep Breath* 2002;**6**:45–8.
66. Giannotti F, Cortesi F. Sleep Patterns and Daytime Functions in Adolescents: An Epidemiological Survey of Italian High-School Student Population. In: Carskadon MA, editor. *Adolescent Sleep Patterns: Biological, Social, and Psychological Influences*. NewYork: Cambridge University Press; 2002. p. 132–47.
67. Giannotti F, Cortesi F, Ottaviano S. Sleep, behavior and schoool functioning in school-aged children. *Sleep Res* 1997;**26**:197.
68. Bruni O, Antignani M, Innocenzi M, et al. Influence of sleep and temperament on school achievement. *Sleep Res* 1995;**24**:91.
69. Steenari MR, Vuontela V, Paavonen EJ, et al. Working memory and sleep in 6- to 13-year-old schoolchildren. *J Am Acad Child Adolesc Psychiatry* 2003;**42**:85–92.

70. Sadeh A, Gruber R, Raviv A. Sleep, neurobehavioral functioning, and behavioral problems in school-age children. *Child Dev* 2002;**73**:405–17.
71. Gau S-F, Song W-T. Sleep problems of junior high school students in Taipei. *Sleep* 1995;**18**:667–73.
72. Mercer PW, Merritt SL, Cowell JM. Differences in reported sleep need among adolescents. *J Adol Health* 1998;**23**: 259–63.
73. Jones K, Harrison Y. Frontal lobe function, sleep loss and fragmented sleep. *Sleep Med Rev* 2001;**5**:463–75.
74. Shin C, Kim J, Lee S, et al. Sleep habits, excessive daytime sleepiness and school performance in high school students. *Psychiatry Clin Neurosci* 2003;**57**:451–3.
75. Drake C, Nickel C, Burduvali E, et al. The Pediatric Daytime Sleepiness Scale (PDSS): sleep habits and school outcomes in middle-school children. *Sleep* 2003; **26**:455–8.
76. Howell AJ, Jahrig JC, Powell RA. Sleep quality, sleep propensity and academic performance. *Percept Mot Skills* 2004;**99**:525–35.
77. Salcedo Aguilar F, Rodríguez Almonacid FM, Monterde Aznar ML, et al. Hábitos de sueño y problemas relacionados con el sueño en adolescentes: relación con el rendimiento escolar. *Aten Primaria* 2005;**35**:408–14.
78. Mitchell RB. Sleep-disordered breathing in children: are we underestimating the problem? *Eur Respir J* 2005; **25**:216–7.
*79. Gozal D. Sleep-disordered breathing and school performance in children. *Pediatrics* 1998;**102**:616–20.
*80. Owens J, Spirito A, Marcotte A, et al. Neuropsychological and behavioral correlates of obstructive sleep apnea syndrome in children: a preliminary study. *Sleep Breath* 2000;**4**:67–77.
81. Goodwin JL, Kaemingk KL, Fregosi RF, et al. Clinical outcomes associated with sleep-disordered breathing in caucasian and hispanic children—the Tucson Children's Assessment of Sleep Apnea Study (TuCASA). *Sleep* 2003; **26**:587–91.
82. Urschitz MS, Guenther A, Eggebrecht E, et al. Snoring, intermittent hypoxia and academic performance in primary school children. *Am J Respir Crit Care Med* 2003;**168**:464–8.
83. Kaemingk KL, Pasvogel AE, Goodwin JL, et al. Learning in children and sleep disordered breathing: findings of the Tucson Children's Assessment of Sleep Apnea (TuCASA) Prospective Cohort Study. *J Intern Neuropsychol Soc* 2003;**9**:1016–26.
84. O'Brien LM, Mervis CB, Holbrook CR, et al. Neurobehavioral implications of habitual snoring in children. *Pediatrics* 2004;**114**:44–9.
85. Montgomery-Downs HE, Crabtree VM, Gozal D. Cognition, sleep and respiration in at-risk children treated for obstructive sleep apnoea. *Eur Respir J* 2005;**25**:336–42.
86. Gozal D, Pope DW. Snoring during early childhood and academic performance at age 13–14 years years. *Pediatrics* 2001;**107**:1394–9.
87. Hoban TF. Sleep and its disorders in children. *Semin Neurol* 2004;**24**:327–40.
88. Blaiss M. Current concepts and therapeutic strategies for allergic rhinitis in school-age children. *Clin Ther* 2004; **26**:1876–89.
89. Copes K, Rosentswieg J. The effects of sleep deprivation upon motor performance of ninth-grade students. *J Sports Med Phys Fitness* 1972;**12**:47–53.
90. Carskadon MA, Harvey K, Dement WC. Sleep loss in young adolescents. *Sleep* 1981;**4**:299–312.
91. Williams H, Lubin A, Goodnow J. Impaired performance with acute sleep loss. *Psychol Monogr* 1959;**484**: 1–26.
92. Horne JA. Human sleep, sleep loss and behaviour. Implications for the prefrontal cortex and psychiatric disorder. *Br J Psychiatry* 1993;**162**:413–9.
93. Harrison Y, Horne JA. One night of sleep loss impairs innovative thinking and flexible decision making. *Organ Behav Hum Decis Process* 1999;**78**:128–45.
94. Carskadon MA, Harvey K, Dement WC. Acute restriction of nocturnal sleep in children. *Perc Mot Skills* 1981;**53**: 103–12.
95. Pilcher JJ, Walters AS. How sleep deprivation affects psychological variables related to college students' cognitive performance. *J Am Coll Health* 1997;**46**:121–6.
96. Randazzo AC, Muehlbach MJ, Schweitzer PK, et al. Cognitive function following acute sleep restriction in children ages 10-14. *Sleep* 1998;**21**:861–8.
97. Randazzo AC, Schweitzer PK, Walsh JK. Cognitive function following 3 nights of sleep restriction in children ages 10-14. *Sleep* 1998;**21**:s249.
98. Fallone G, Acebo C, Arnedt JT, et al. Effects of acute sleep restriction on behavior, sustained attention, and response inhibition in children. *Percept Mot Skills* 2001;**93**:213–29.
99. Fallone G, Seifer R, Acebo C, et al. Prolonged sleep restriction in 11- and 12-year-old children: effects on behavior, sleepiness and mood. *Sleep* 2000;**23**:A28.
*100. Sadeh A, Gruber R, Raviv A. The effects of sleep restriction and extension on school-age children: what a difference an hour makes. *Child Dev* 2003;**74**:444–55.
101. Drake CL, Roehrs TA, Burduvali E, et al. Effects of rapid versus slow accumulation of eight hours of sleep loss. *Psychophysiology* 2001;**38**:979–87.
102. Hansen M, Janssen I, Schiff A, et al. The impact of school daily schedule on adolescent sleep. *Pediatrics* 2005; **115**:1555–61.
103. Brown FC, Soper B, Buboltz WC. Prevalence of delayed sleep phase syndrome in university students. *Coll Student J* 2001;**35**:472–5.
104. Ferrara M, De Gennaro L. How much sleep do we need? *Sleep Med Rev* 2001;**5**:155–79.
105. Ohayon MM, Carskadon MA, Guilleminault C, et al. Meta-analysis of quantitative sleep parameters from childhood to old age in healthy individuals: developing normative sleep values across the human lifespan. *Sleep* 2004;**27**:1255–73.
106. Quirk KJ, Keith TZ, Quirk JT. Employment during high school and student achievement: longitudinal analysis of national data. *J Ed Res* 2001;**95**:4–10.
107. Schultz GF. Socioeconomic advantage and achievement motivation: important mediators of academic performance in minority children in urban schools. *Urban Rev* 1993;**25**:221–32.
108. Wimmer F, Hoffmann RF, Bonato RA, Moffitt AR. The effects of sleep deprivation on divergent thinking and attention processes. *J Sleep Res* 1992;**1**:223–30.
109. Harrison Y, Horne JA. Sleep deprivation affects speech. *Sleep* 1997;**20**:871–7.
110. Harrison Y, Horne JA. Sleep loss impairs short and novel language tasks having a prefrontal focus. *J Sleep Res* 1998;**7**:95–100.
111. Harrison Y, Horne JA, Rothwell A. Prefrontal neuropsychological effects of sleep deprivation in young adults—a model for healthy aging? *Sleep* 2000;**23**:1067–73.
112. Drummond SP, Brown GG, Stricker JL, et al. Sleep deprivation-induced reduction in cortical functional

response to serial subtraction. *Neuroreport* 1999;**10**: 3745–8.

113. Thomas M, Sing H, Belenky G, et al. Neural basis of alertness and cognitive performance impairments during sleepiness. I. Effects of 24 h of sleep deprivation on waking human regional brain activity. *J Sleep Res* 2000; **9**:335–52.
114. Drummond SP, Brown GG, Gillin JC, et al. Altered brain response to verbal learning following sleep deprivation. *Nature* 2000;**403**:655–67.